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Abstract: In response to challenges from the COVID-19 pandemic and climate change to achieve the goal of ensuring sustainable economic growth, offshore wind power development not only provides a clean and sustainable source of energy but also provides opportunities for economic growth and job creation. Offshore wind energy projects have been promptly suggested in Vietnam as a result of policy advancement, with the country’s excellent wind resources. The success of an offshore wind energy project is decided mainly by choosing the best location for offshore wind power station (OWPS) construction, which is a complex multicriteria decision-making (MCDM) problem with the coexistence of conflicting factors. There is a problem with incomplete decision information use and information loss during the decision-making process, and it is easy to overlook the interaction difficulty in a fuzzy environment. To address the complex nature of the prioritization problem posed, this study proposes a hybrid MCDM framework combining the spherical fuzzy analytical hierarchy process (SF-AHP) and weighted aggregated sum product assessment (WASPAS). SF-AHP is used in the first stage to determine the significance levels of OWPS evaluation criteria. WASPAS is then utilized to rank locations of OWPS. A comprehensive set of evaluation criteria developed based on the concept of sustainable development has been recognized by reviewing the literature review and interviewing experts to practice the two-stage MCDM model. A real case study for Vietnam is conducted to test the effectiveness of the proposed method. The best location schemes have been determined by using the decision framework. The results of the sensitivity analysis and a comparison analysis demonstrate that the decision framework is practical and robust. Ultimately, the evaluation criteria and methodology presented in this work can serve as a theoretical foundation for the advancement of offshore wind energy and coastal development.

Keywords: renewable energy; offshore wind power station; Vietnam; MCDM; SF-AHP; WASPAS; decision-making process

1. Introduction

Among various renewable energy sources, offshore wind is key to the transition to a zero-carbon energy supply in the context of the whole world facing the global fight against climate change and promoting a post-COVID-19 green recovery. According to the International Renewable Energy Agency (IRENA), the world needs to install at least 180 GW of new wind power each year to keep the global temperature rise below 2°C above preindustrial levels. Located in the monsoon climate zone and shaped by a 3260 km-long coastline, Vietnam is considered a country with great potential for offshore wind power in Asia in particular and the world in general. As reported by the World Bank, Vietnam’s technical offshore wind power potential is approximately 475 GW in water zones 200 km from the coastline, and the technical offshore wind power potential in the water zones ranges from 0 – 185 km up to 600 GW. With this endowment, Vietnam can achieve 11 GW to 25 GW of offshore wind capacity by 2035, which could create up to 700,000 jobs per year and reduce 217 million tons of carbon emissions.

Under the Vietnamese government’s new Power Development Plan with a vision to 2030, a 20 GW of renewable energy capacity, including 10 GW of offshore wind power, aims to meet growing demand and sustainable socioeconomic development and cut 15% of carbon emissions. Toward this goal, experts and researchers assert that policies and support mechanisms play an essential role in building national strategies and marine spatial planning for offshore wind power development. A study by Xuan Son and Thi Gam in 2021 analyzed the current Vietnamese legal and policy framework applying offshore wind power development and Vietnamese regulations to assess the environmental impact to guarantee sustainable wind development. More specifically,
Site selection for an offshore wind power station (OWPS) constitutes a critical phase toward a wind power project. It is a multicriteria decision-making (MCDM) problem that regards many conflicting criteria, including wind resources, construction, environmental impacts, marine spatial planning, power grid access lines, economy, and society. With this, the decision-making of OWPS site selection encounters many difficulties. One primary concern is the ambiguity of information. It is a daunting problem to anticipate the value of each factor precisely during decision-making as a project prework. In addition, information loss is an unavoidable occurrence in a complex and uncertain context. As a result, how information is expressed and handled is an essential consideration in OWPS site selection. As soon as ranking methods are becoming increasingly improved, using an adequate and effective MCDM method to determine the priority of alternatives in OWPS site selection is a requisite step.

From the above perspectives, the aim of this research is to develop an MCDM-based framework for the best site selection of OWPSs. More specifically, the spherical fuzzy sets and analytical hierarchy process (SF-AHP) are integrated into the first stage to determine the significance levels of OWPS evaluation criteria, and then the weighted aggregated sum product assessment (WASPAS) is utilized to rank locations of OWPS. A comprehensive set of evaluation criteria developed based on the concept of sustainable development has been recognized through a literature review and expert opinions to practice the two-stage MCDM model. A real case study for Vietnam is carried out to validate the proposed method.

The AHP is a relative measurement method that can rank multiple alternatives by examining both qualitative and quantitative criteria based on pairwise comparisons. The method is one of the most commonly used MCDM methods to determine the relative importance (weights) of criteria and subcriteria, especially in renewable energy planning and site selection. Even while the approach gathers data from experts, it may not precisely reflect the opinions taken. As a result, fuzzy sets theory has been integrated with AHP, and many types of fuzzy AHP have been developed to capture vagueness in preference. The effectiveness of fuzzy AHP methods has been demonstrated with increasing interest among researchers and practitioners. Such approaches have been implemented on different extensions of fuzzy set theory based on the determination of linguistic statements such as traditional fuzzy sets, type-2 fuzzy sets, interval-valued fuzzy sets, intuitionistic fuzzy sets, neutrosophic sets, Pythagorean fuzzy sets (PSF), and spherical fuzzy sets. The spherical fuzzy set (SFS) is the novel set introduced in 2018 by Kutlu Gündoğdu and Kahraman. It is a three-dimensional fuzzy set created as a combination of Pythagorean fuzzy sets with neutrosophic fuzzy sets. SFS can also be used to realize the criteria to handle ambiguity and fuzziness in linguistic expressions, which is a new perspective for decision-making in a fuzzy environment. The decision maker's indeterminacy level is specified independently of the membership and nonmembership levels of the elements in these sets. Decision-makers define the membership function in SFS on a spherical surface to infer other fuzzy sets, with which they can allow the parameters of this membership function in a broader domain. The historical mapping of different fuzzy set extensions is displayed in Figure 1.
There have been a moderate number of significant studies on OWPS selection in the last ten years, in which MCDM approaches have shown remarkable results in many case evaluations worldwide. Some widely applied techniques in OWPS evaluation include analytic hierarchy process (AHP), analytic network process (ANP), technique for order of preference by similarity to ideal solution (TOPSIS), elimination and choice expressing the reality (ELECTRE), decision making trial and evaluation laboratory (DEMATEL), preference ranking organization method for enrichment evaluations (PROMETHEE). Fuzzy sets theory and grey theory are frequently integrated with MCDM methods to address uncertain and incomplete information/preference. Chauach i et al. 48 presented the multicriteria selection of offshore wind farms with a case study for the Baltic States; the AHP method was utilized to consider economic investment, security aspects, operation costs and capacity performances. Fetanat and Khorasaninejad 49 developed a novel hybrid MCDM approach based on the fuzzy AHP, fuzzy DEMATEL, and fuzzy ELECTRE to assist in the site selection of offshore wind farms in Iran; six criteria (depth and height, environment, distance to facilities, economic aspects, wind resources, and culture) were determined with related subcriteria. A decision framework combining triangular intuitionistic fuzzy numbers (TIFNs), ANP and PROMETHEE was proposed by Wu et al. 21 to select the best location for OWPS in a Chinese case study considering six criteria (wind resources, environment, economic, construction, society, and risks) and the related subcriteria. Lo et al. 49 proposed the grey DEMATEL-based ANP model for location optimization for OWPSs in Taiwan, concerning the following dimensions: wind conditions, marine conditions, shore support conditions, economic impacts, environmental and ecological impacts, and societal impacts. Table 1 provides an overview of studies on the site selection of offshore wind farms.

Table 1. Overview of studies on the site selection of offshore wind farms.

| No | Authors | MCDM Technique | Location         | Main findings                                                                 |
|----|---------|----------------|------------------|-------------------------------------------------------------------------------|
| 1  | Fetanat and Khorasaninejad (2015) | Fuzzy ANP, fuzzy DEMATEL, and fuzzy ELECTRE | Iran              | The optimal site can be chosen from four options, and the method's robustness is proven. |
| 2  | Wu et al. (2016) | ELECTRE-III          | China            | The developed methodology for OWPS site selection is both valid and practical.  |
| 3  | Vasileiou et al. (2017) | AHP              | Greece           | The finding illustrates the potential for offshore wind and wave energy deployment in Greece, particularly in Crete's offshore areas and a longitudinal zone extending from the north-central to the central Aegean. |
The best wind sites are determined by market design, regulatory considerations, and renewable integration targets.

The established methodology is universal to produce offshore wind suitability map for appropriate offshore wind locations, with three high wind suitable areas around the Red Sea found with the minimum restrictions.

The approach is applied to a real-world site selection of offshore wind farms in the Eastern China Sea; it illustrates that maritime safety is a predominant factor.

The decision model proposed is feasible and valid.

Rigorous methodological support is presented for site selection to achieve benefits in coastal management.

Optimal sites are not only determined by their wind resources and costs; decision-makers must pay particular attention to appropriate strategies and policy planning toward OWPS.

Since investment is huge in the installment of OWPSs, it is critical to identify and prioritize viable locations prior to developing expensive OWPSs, as such decisions would assist in achieving the best productivity, reducing socioeconomic costs, minimizing environmental consequences, optimizing social benefits, and developing the concerned regions toward sustainability. The recognition of resources, conditions, economic and environmental dimensions, societal impacts, and political factors is the preliminary and crucial phase for establishing new offshore wind plants. Only a few have taken sustainability issues into account from previous works when devising a site selection framework for offshore wind farms. In this research, the decision criteria based on the perspective of sustainability are extracted through a literature review and recognized by experts, as shown in Table 2.

**Table 2. Summary of criteria considered from the literature reviewed.**

| Criteria                        | Fetanat and Khorasaniinejad (2015) | Wu et al. (2016) | Vasileiou et al. (2017) | Chaouachi et al. (2017) | Mahdy and Bahaj (2018) | Wu et al. (2018) | Wu et al. (2020) | Abdel-Basset et al. (2021) | Lo et al. (2021) |
|---------------------------------|-----------------------------------|------------------|-------------------------|-------------------------|------------------------|------------------|------------------|----------------------------|------------------|
| Wind resources                  | v                                 | v                | v                       | v                       | v                      | v                | v                | v                          | v                |
| Seawater depth                  | v                                 | v                | v                       | v                       | v                      | v                | v                | v                          | v                |
| Undersea geological conditions  | v                                 |                  |                         | v                       | v                      | v                | v                | v                          | v                |
| Marine conditions               | v                                 | v                |                         |                         |                        |                   | v                | v                          | v                |
| Environmental protection        | v                                 | v                |                         |                         |                        |                   | v                | v                          | v                |
| Distance to shore               | v                                 | v                | v                       | v                       | v                      | v                | v                | v                          | v                |
| Electricity networks            | v                                 | v                | v                       | v                       | v                      | v                | v                | v                          | v                |
Traffic condition | v | v | v | v | v | v | v | v
Profit | v | v | v | v | v | v | v | v
Construction, op-
eration, and
maintenance costs | v | v | v | v | v | v | v | v
Local subsidies | v | v | v | v | v | v | v | v
Job creation | v | v | v | v | v | v | v | v
Policy planning | v | v | v | v | v | v | v | v

In this paper, for the first time, spherical fuzzy sets, AHP and WASPAS, are combined for the site selection of OWPS. To the best of our knowledge, the proposed integrated approach is novel and has not been reported elsewhere. The paper’s contributions are presented as follows:

- This paper presents an effective evaluation model for locating offshore wind power facilities. To fulfill the awareness of sustainable development, the model contains a comprehensive set of sustainability indicators.
- The calculations for weighting the criteria are performed using spherical fuzzy sets for a broader linguistic scale of experts’ judgments, which completely reflects the decision-making process in uncertain environments. WASPAS has the capability and more accuracy in ranking the alternatives.
- A thorough investigation of the OWPS site selection in Vietnam is solved for the first time, with a real case study used to test the robustness of the proposed model.
- The paper is directed toward providing a recommendation for the government and practitioners for offshore wind farm site selection.

3. Materials and Methods

3.1. Framework of the Research

This paper introduces an effective integrated assessment model for evaluating and selecting the optimal offshore wind power station (OWPS) case study in Vietnam. The proposed framework includes two stages, which are described in Figure 2. In the first stage, the SF-AHP model determines each criterion’s fuzzy weight and crisp weight. The spherical fuzzy set, represented by a linguistic number, is involved in the AHP model to manage the uncertainties and vagueness by the experts’ judgment. The consistency of the pairwise comparison matrices is checked to ensure the model’s validation. In the second stage, the wind power locations are ranked by using the WASPAS model. Next, a comparison with the existing area, sensitivity analysis of the threshold value, and comparative analysis of the methods are performed to demonstrate the feasibility and applicability of the proposed model.
3.2. Spherical Fuzzy Analytical Hierarchy Process (SF-AHP)

Spherical fuzzy sets (SFS) were newly developed by Kutlu Gündoğdu and Kahraman to handle uncertainty during the quantification of expert judgments. The differences among the intuitionistic fuzzy set, Pythagorean fuzzy set, neutrosophic set, and spherical fuzzy sets are visualized in Figure 3. The SFS consists of three parameters: membership, nonmembership, and hesitancy degrees. The basic procedures of SFS are presented as follows.
Figure 3. Geometric representations of spherical fuzzy sets in 3D space.

Definition 1. Spherical fuzzy set (SFS) $\tilde{A}_S$ is described as follows:

$$\tilde{A}_S = \{x, (\mu_{\tilde{A}_S}(x), v_{\tilde{A}_S}(x), \pi_{\tilde{A}_S}(x)) | x \in X\}$$ (1)

where $\tilde{A}_S$ represents a spherical fuzzy set of the universe $X$:

$$\mu_{\tilde{A}_S}(x): X \rightarrow [0,1], v_{\tilde{A}_S}(x): X \rightarrow [0,1], \pi_{\tilde{A}_S}(x): X \rightarrow [0,1]$$ (2)

and

$$0 \leq \mu_{\tilde{A}_S}^2(x) + v_{\tilde{A}_S}^2(x) + \pi_{\tilde{A}_S}^2(x) \leq 1$$ (3)

where $\forall x \in X$, and for each $x$, $\mu_{\tilde{A}_S}(x), v_{\tilde{A}_S}(x)$, and $\pi_{\tilde{A}_S}(x)$ represent the membership, nonmembership, and hesitancy levels of $x$ to $\tilde{A}_S$, respectively.

Definition 2. Let $\tilde{A}_S = (\mu_{\tilde{A}_S}, v_{\tilde{A}_S}, \pi_{\tilde{A}_S})$ and $\tilde{B}_S = (\mu_{\tilde{B}_S}, v_{\tilde{B}_S}, \pi_{\tilde{B}_S})$ be two SFS. Some arithmetic operations of SFS are described as follows:

- Union:

$$\tilde{A}_S \cup \tilde{B}_S = \{\max\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\}, \min\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\}, \min\{(1 - (\max\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\})^2, (\min\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\})^2\})^{1/2}, \max\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\}\}$$ (4)

- Intersection:

$$\tilde{A}_S \cap \tilde{B}_S = \{\min\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\}, \max\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\}, \max\{(1 - (\min\{\mu_{\tilde{A}_S}, \mu_{\tilde{B}_S}\})^2, (\max\{v_{\tilde{A}_S}, v_{\tilde{B}_S}\})^2\})^{1/2}, \min\{\pi_{\tilde{A}_S}, \pi_{\tilde{B}_S}\}\}$$ (5)

- Addition:

$$\tilde{A}_S \oplus \tilde{B}_S = \{(\mu_{\tilde{A}_S}^2 + \mu_{\tilde{B}_S}^2 - \mu_{\tilde{A}_S}^2 \pi_{\tilde{B}_S}^2)^{1/2}, v_{\tilde{A}_S} + v_{\tilde{B}_S}, (1 - \mu_{\tilde{B}_S}^2)\pi_{\tilde{A}_S}^2 + (1 - \mu_{\tilde{A}_S}^2)\pi_{\tilde{B}_S}^2\}^{1/2}\}$$ (6)

- Multiplication:

$$\tilde{A}_S \otimes \tilde{B}_S = \{(\mu_{\tilde{A}_S}^2 \mu_{\tilde{B}_S}^2 + \mu_{\tilde{A}_S}^2 v_{\tilde{B}_S}^2 + v_{\tilde{A}_S}^2 v_{\tilde{B}_S}^2)^{1/2}, (1 - v_{\tilde{B}_S}^2)\pi_{\tilde{A}_S}^2 + (1 - v_{\tilde{A}_S}^2)\pi_{\tilde{B}_S}^2\}$$ (7)

- Multiplication by a scalar; $\lambda > 0$:

$$\lambda \cdot \tilde{A}_S = \{(1 - (1 - \mu_{\tilde{A}_S}^2)^2)^{1/2}, v_{\tilde{A}_S}, ((1 - \mu_{\tilde{A}_S}^2)^2, (1 - \mu_{\tilde{A}_S}^2) - (1 - \mu_{\tilde{A}_S}^2 - \pi_{\tilde{A}_S}^2)^2)\}$$ (8)

- Power of $\tilde{A}_S$; $\lambda > 0$:
Table 3. The score indices (SI) are determined by Equations (18) and (19):

\[
\tilde{A}_S^2 = (\mu_{\tilde{A}_S}^2 - v_{\tilde{A}_S}^2)^{1/2} (1 - v_{\tilde{A}_S}^2)^{1/2} (1 - v_{\tilde{A}_S}^2)^{1/2} (1 - v_{\tilde{A}_S}^2)^{1/2})
\]  

(9)

**Definition 3.** For SFSs \( \tilde{A}_S = (\mu_{\tilde{A}_S}, v_{\tilde{A}_S}, \pi_{\tilde{A}_S}) \) and \( \tilde{B}_S = (\mu_{\tilde{B}_S}, v_{\tilde{B}_S}, \pi_{\tilde{B}_S}) \), the following are valid under the condition \( \lambda, \lambda_1, \lambda_2 > 0 \):

\[
\begin{align*}
\tilde{A}_S \oplus \tilde{B}_S &= \tilde{B}_S \oplus \tilde{A}_S \\
\tilde{A}_S \otimes \tilde{B}_S &= \tilde{B}_S \otimes \tilde{A}_S \\
\lambda(\tilde{A}_S \oplus \tilde{B}_S) &= \lambda \tilde{A}_S \oplus \lambda \tilde{B}_S \\
\lambda_1 \tilde{A}_S \oplus \lambda_2 \tilde{A}_S &= (\lambda_1 + \lambda_2) \tilde{A}_S \\
(\tilde{A}_S \otimes \tilde{B}_S)^\lambda &= \tilde{A}_S^\lambda \otimes \tilde{B}_S^\lambda \\
\tilde{A}_S^1 \otimes \tilde{A}_S^1 &= \tilde{A}_S^{1+1}
\end{align*}
\]

(10) (11) (12) (13) (14) (15)

**Definition 4.** For the spherical weighted arithmetic mean (SWAM) with respect to, \( w = (w_1, w_2, \ldots, w_n) \), \( w_i \in [0, 1] \), and \( \sum_{i=1}^n w_i = 1 \), the SWAM is calculated as follows:

\[
SWAM_w(\tilde{A}_{S1}, \ldots, \tilde{A}_{Sn}) = w_1 \tilde{A}_{S1} + w_2 \tilde{A}_{S2} + \ldots + w_n \tilde{A}_{Sn} = [1 - \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2)^{w_i}]^{1/2}
\]

\[
\prod_{i=1}^n v_{\tilde{A}_{Si}}^{w_i} \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2)^{w_i} - \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2 - \pi_{\tilde{A}_{Si}}^2)^{w_i}]^{1/2}
\]

(16)

**Definition 5.** For the spherical weighted geometric mean (SWGM) with respect to, \( w = (w_1, w_2, \ldots, w_n) \), \( w_i \in [0, 1] \) and \( \sum_{i=1}^n w_i = 1 \), the SWGM is calculated as follows:

\[
SWGM_w(\tilde{A}_{S1}, \ldots, \tilde{A}_{Sn}) = \tilde{A}_{S1}^{w_1} + \tilde{A}_{S2}^{w_2} + \ldots + \tilde{A}_{Sn}^{w_n}
\]

\[
\prod_{i=1}^n \mu_{\tilde{A}_{Si}}^2 - [1 - \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2)^{w_i}]^{1/2} \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2 - \pi_{\tilde{A}_{Si}}^2)^{w_i} - \prod_{i=1}^n (1 - \mu_{\tilde{A}_{Si}}^2 - \pi_{\tilde{A}_{Si}}^2)^{w_i}]^{1/2}
\]

(17)

In this paper, the SF-AHP model was used to determine the criteria weights of the list of criteria for building the power plant of wind offshore with a case study in Vietnam. The SF-AHP model has five steps, which are described as follows.

Step 1: A hierarchical decision tree is divided into three levels, including the research goal (level 1), list of criteria \( C = \{C_1, C_2, \ldots, C_n\} \) (level 2), and location alternatives \( A = \{A_1, A_2, \ldots, A_m\} \) (within \( m \geq 2 \)).

Step 2: Pairwise comparison matrices are performed regarding linguistic terms, as shown in Table 3. The score indices (SI) are determined by Equations (18) and (19):

\[
SI = \sqrt{100 \times \left[ (\mu_{\tilde{A}_S} - \pi_{\tilde{A}_S})^2 - (v_{\tilde{A}_S} - \pi_{\tilde{A}_S})^2 \right]^2}
\]

(18)

for the AMI, VHI, HI, SMI, and EI.

\[
\frac{1}{SI} = \sqrt{100 \times \left[ (\mu_{\tilde{A}_S} - \pi_{\tilde{A}_S})^2 - (v_{\tilde{A}_S} - \pi_{\tilde{A}_S})^2 \right]^2}
\]

(19)

for the EI, SLI, LI, VLI, and ALI.

Table 3. SF-AHP linguistic terms used for pairwise comparisons.

| Linguistics Terms                  | Symbol | Fuzzy number \((\mu, v, \pi)\) | Score Index (SI) |
|-----------------------------------|--------|-------------------------------|------------------|
| Absolutely more importance        | AMI    | \((0.9, 0.1, 0.0)\)            | 9                |
3.3. Weighted Aggregated Sum Product Assessment (WASPAS)

The WASPAS method was proposed in 2012 and is the combination of the weighted product model (WPM) and weighted sum model (WSM); the procedure is explained as follows:

Step 1: A decision matrix is constructed \( X = [x_{ij}]_{m \times n} \) where \( x_{ij} \) is the performance of the \( i^{th} \) alternative to the \( j^{th} \) criterion, \( m \) is the number of alternatives and \( n \) is the number of criteria.

Step 2: Equations (26) and (27) are used to normalize the decision matrix:

\[
\tilde{S}_{ij} = \frac{v_{ij}^{\tilde{x}_{ij}} - \mu_{\tilde{x}_{ij}}}{\sqrt{\left(3\mu_{\tilde{x}_{ij}} - \pi_{\tilde{x}_{ij}}\right)^2 - \left(\frac{\mu_{\tilde{x}_{ij}}}{2} - \pi_{\tilde{x}_{ij}}\right)^2}}
\]

The second way to follow is to continue without defuzzification. In this case, spherical fuzzy global preference weights are calculated using Equation (25):

\[
\tilde{F} = \sum_{j=1}^{n} \tilde{A}_{S_{ij}} = \tilde{A}_{S_{i1}} \oplus \tilde{A}_{S_{i2}} \ldots \oplus \tilde{A}_{S_{in}} \forall i
\]

where \( \oplus \) is the combination of the weighted arithmetic addition over each global preference weight, as given in Equation (24):

\[
\tilde{A}_{S_{ij}} = \tilde{w}_j^S \cdot \tilde{A}_i = \left(1 - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right), \left(v_{\tilde{x}_{ij}}^{\tilde{x}_{ij}} - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right)
\]

Sort the alternative according to their defuzzified final ratings. The highest value denotes the optimal option.

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\]

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\[
\tilde{A}_{S_{ij}} = \tilde{w}_j^S \cdot \tilde{A}_i = \left(1 - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right), \left(v_{\tilde{x}_{ij}}^{\tilde{x}_{ij}} - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right)
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\]

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\]

where \( \oplus \) is the combination of the weighted arithmetic addition over each global preference weight, as given in Equation (24):

\[
\tilde{A}_{S_{ij}} = \tilde{w}_j^S \cdot \tilde{A}_i = \left(1 - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right), \left(v_{\tilde{x}_{ij}}^{\tilde{x}_{ij}} - (1 - \mu_{\tilde{x}_{ij}})^{w_j^{-S}}\right)
\]

Sort the alternative according to their defuzzified final ratings. The highest value denotes the optimal option.
\[
\bar{X}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}, \text{such that } i = 1, 2, ..., m; j = 1, 2, ..., n 
\]  
(26)

For minimizing criteria (nonbenefit):

\[
\bar{X}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}, \text{such that } i = 1, 2, ..., m; j = 1, 2, ..., n 
\]  
(27)

Step 3: Equation (28) is used to calculate the relative importance of the alternative using the weighted sum model (WSM):

\[
Q_i^{(1)} = \sum_{j=1}^{n} \bar{X}_{ij} w_j, \text{such that } i = 1, 2, ..., m 
\]  
(28)

where \( w_j \) is the weight (relative importance) of the \( j^{th} \) criterion.

Step 4: The relative importance of the alternative is then calculated using the weighted product model (WPM), as shown in Equation (29):

\[
Q_i^{(2)} = \prod_{j=1}^{n} (\bar{X}_{ij})^{w_j}, \text{such that } i = 1, 2, ..., m 
\]  
(29)

where \( w_j \) is the weight (relative importance) of the \( j^{th} \) criterion. In this paper, \( w_j \) is obtained from SF-AHP model.

Step 5: The integrated utility function of the WASPAS model is calculated using Equation (30):

\[
Q_i = \lambda Q_i^{(1)} + (1 - \lambda)Q_i^{(2)} = \lambda \sum_{j=1}^{n} \bar{X}_{ij} w_j + (1 - \lambda)\prod_{j=1}^{n} (\bar{X}_{ij})^{w_j}, \lambda = 0, ..., 1 
\]  
(30)

The value of \( \lambda \) (coefficient value or threshold value of the WASPAS model) is determined using Equation (31):

\[
\lambda = \frac{\sum_{i=1}^{m} Q_i^{(2)}}{\sum_{i=1}^{m} Q_i^{(1)} + \sum_{i=1}^{m} Q_i^{(2)}} 
\]  
(31)

4. Results Analysis

4.1. A Case Study in Vietnam

With 3,000 kilometers of coastline and winds ranging from 5.5 to 7.3 meters per second, Vietnam has an exceptional natural wind potential (not accounting for seasonal variability). Offshore, the best chance for large-scale wind power generation exists. According to the World Bank, Vietnam’s offshore wind potential could be as high as 500 GW. Figure 4 depicts the map of the potential of offshore wind power in Vietnam.\(^5^2\).
In this section, the proposed aggregated framework is executed to identify the most suitable OWPS construction locations. After discussions between experts, six locations were selected as potential alternatives: Ba Ria - Vung Tau, Ben Tre, Binh Dinh, Binh Thuan, Ca Mau, Ninh Thuan, and Soc Trang (Table 4). In addition to reviewing the literature for this evaluation, the criteria system and evaluated alternatives were also determined after consultation with experts through interactive discussions. The appraisements were applied to the 15 most eligible and reliable experts (at least ten years of professional experience in energy-related fields) to increase the objectivity of the results as much as possible. Furthermore, they have made significant contributions to Vietnam’s advocacy of renewable energy development policies. Six assessment dimensions and 15 evaluation criteria were identified after a literature review and expert interviews, as shown in Table 5.
Table 4. List of potential offshore wind locations in Vietnam.

| DMU     | Location         | Wind Speed (m/s) | Wind Density ($W/m^2$) |
|---------|------------------|------------------|------------------------|
| OWPS-01 | Ba Ria - Vung Tau| 6.33             | 235                    |
| OWPS-02 | Ben Tre          | 6.24             | 225                    |
| OWPS-03 | Binh Dinh        | 7.87             | 627                    |
| OWPS-04 | Binh Thuan       | 8.18             | 673                    |
| OWPS-05 | Ca Mau           | 5.94             | 196                    |
| OWPS-06 | Ninh Thuan       | 9.30             | 935                    |
| OWPS-07 | Soc Trang        | 6.25             | 216                    |

Table 5. The criteria used in the paper and their definition.

| Dimensions                  | Criteria                                                | Definition                                                                                                                                 |
|-----------------------------|---------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| C1. Wind resources          | C11. Wind speed and its distribution status             | Based on the average annual wind force, the wind and monsoon conditions in places where wind farms are constructed. The wind speed computation would be based on long-term representative wind speed fluctuations in the area and investigated on site. |
|                             | C12. Effective wind hours                               | Refers to accumulative hours of practical usage of wind power per year (h).                                                               |
| C2. Environmental impact    | C21. Nautical life coordination                         | The distance between OWPS and marine life migration determines the degree of coordination with sea area planning for marine life. Depending on the geographical context, the generator machine’s selection and installation would disrupt the original seabed during construction. At the same time, the turbine would generate noise pollution throughout its rotation, resulting in low-frequency sound waves that would be harmful to marine species engaged in predation or migratory behaviors. |
|                             | C22. Nautical environmental influence                   | The potential for OWPS to degrade the quality of the marine ecology and biodiversity.                                                        |
| C3. Construction and        | C31. Seawater depth                                      | The suitability of OWPS building also takes into account the depth of the sea, the distance from the coast, and the width of the shore.          |
| maintenance conditions      | C32. Undersea geological conditions                      | This criterion assesses regional geological conditions and construction stability based on acquired data and geological prospecting.             |
|                             | C33. Marine conditions                                  | Characteristics of the sea area like waves, tidal current, temperature, storm surge, sea ice, sea bed movement, and erosion must be considered when evaluating the hazard of complex hydrological conditions on project safety. |
C4. Societal impact

C41. Employment

The related manufacturing and service industries would grow with the project's development, and various possible job incentives would surface one after another when determining a construction location for OWPS. As a result, it is required to use employment to assess the impact, such as which station sites affect salary, relevant industries, etc. Knowing the position of the staff, the work environment, and other factors might have an impact on employment.

C42. Policy planning

The central government's and local governments' support and promote wind farm construction; this criterion also considers if necessary legislation and policies have been implemented to encourage offshore wind projects.

C5. Conditions onshore

C51. Distance from the power load center

The distance between the area and the electrical load center is the distance over which electricity is transmitted from the power station to the shore (submarine cable).

C52. Electrical transmission and distribution system

The electrical system's capacity to meet future power supply requirements (e.g., substation, electrical grid).

C53. Traffic condition

Examines the ease with which huge equipment can be transported along the shore (e.g., highway, railway, bridge, airport, dock).

C6. Economic impact

C61. Cost-to-benefit ratio

Typically, the offshore wind power profit and loss balance is utilized in estimations.

C62. Construction, operation, and maintenance costs

This criterion shows the total cost of the OWPS projects, from conception to completion and delivery in its final form, and all operating and maintenance expenditures in the surrounding area after the offshore wind farm is fully operational.

C63. Provincial financial subsidies

Relates to the subsidies promoted by the local government finance.

4.2. Results of the SF-AHP Model

In this stage, an example of the following calculation of the six main criteria presents the SF-AHP procedure: wind resources (C1), environmental impact (C2), construction and maintenance conditions (C3), societal impact (C4), onshore conditions (C5), and economic impact (C6). The same procedures were applied to calculate the relative importance of the potential wind locations concerning the predetermined 15 criteria. A panel of 15 experts with more than ten years of working experience in the renewable energy industry was consulted by interviews to evaluate the effect of criteria on wind offshore plants' evaluation and selection process. Next, the pairwise comparison matrix using linguistic terms, the nonfuzzy comparison matrix, and the normalized comparison matrix of the SF-AHP model are presented in Tables 6–8. The consistency verification of the pairwise comparison matrices was computed as follows:

\[
C_{12} = \frac{SI_{c_{12}}}{SUM_{C_2}} = \frac{4.189}{17.355} = 0.241
\]

\[
MEAN_{c_i} = \frac{0.145 + 0.241 + 0.215 + 0.115 + 0.318 + 0.164}{6} = 0.199
\]
With the six main criteria \((n = 6)\), the largest eigenvector \((\lambda_{\text{max}})\) was calculated to identify the consistency index \((CI)\), the random index \((RI)\), and consistency ratio \((CR)\) as follows:

\[
\lambda_{\text{max}} = \frac{6.496 + 6.212 + 6.251 + 6.883 + 6.197 + 6.571}{6} = 6.435
\]

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} = \frac{6.435 - 6}{6 - 1} = 0.087
\]

where \(n = 6\), \(RI = 1.24\), and the \(CR\) value is calculated as follows:

\[
CR = \frac{CI}{RI} = \frac{0.087}{1.24} = 0.070
\]

As shown in \(CR = 0.070 < 0.1\), the pairwise comparison matrix was consistent, and the result was satisfactory.

### Table 6. The pairwise comparison matrix of the SF-AHP model.

| Criteria | Left Criteria Is Greater | Right Criteria Is Greater |
|----------|---------------------------|---------------------------|
| C1       | AMI  | VHI | HI | SMI | EI | SLI | LI | VLI | ALI | C2 |
| C1       | 6    | 2   | 6  | 1   |    |    |    |     |     | C3 |
| C1       | 5    | 3   | 4  | 3   |    |    |    |     |     | C4 |
| C1       | 5    | 4   | 4  | 2   |    |    |    |     |     | C5 |
| C1       | 1    | 3   | 2  | 4   | 5  |    |    |     |     | C6 |
| C2       | 1    | 3   | 5  | 6   |    |    |    |     |     | C3 |
| C2       | 6    | 4   | 4  | 1   |    |    |    |     |     | C4 |
| C2       | 2    | 4   | 4  | 5   |    |    |    |     |     | C5 |
| C3       | 5    | 5   | 4  | 1   |    |    |    |     |     | C4 |
| C3       | 1    | 5   | 4  | 5   |    |    |    |     |     | C6 |
| C4       | 1    | 3   | 5  | 6   |    |    |    |     |     | C5 |
| C4       | 6    | 5   | 3  | 1   |    |    |    |     |     | C6 |
| C5       | 1    | 3   | 2  | 4   | 5  |    |    |     |     | C6 |

### Table 7. The nonfuzzy comparison matrix of the SF-AHP model.

| Criteria | C1   | C2   | C3   | C4   | C5   | C6   |
|----------|------|------|------|------|------|------|
| C1       | 1.000| 4.189| 3.538| 0.226| 6.215| 1.261|
| C2       | 0.239| 1.000| 0.894| 0.150| 2.371| 0.254|
| C3       | 0.283| 1.119| 1.000| 0.156| 2.292| 0.240|
| C4       | 4.433| 6.687| 6.430| 1.000| 4.534| 4.639|
| C5       | 0.161| 0.422| 0.436| 0.221| 1.000| 0.316|
| C6       | 0.793| 3.938| 4.167| 0.216| 3.162| 1.000|
Table 8. The normalized comparison matrix of the SF-AHP model.

| Criteria | C1  | C2  | C3  | C4  | C5  | C6  | MEAN | WSV | CV  |
|----------|-----|-----|-----|-----|-----|-----|------|-----|-----|
| C1       | 0.145 | 0.241 | 0.215 | 0.115 | 0.318 | 0.164 | 0.199 | 1.296 | 6.496 |
| C2       | 0.035 | 0.058 | 0.054 | 0.076 | 0.121 | 0.033 | 0.063 | 0.390 | 6.212 |
| C3       | 0.041 | 0.064 | 0.061 | 0.079 | 0.117 | 0.031 | 0.066 | 0.410 | 6.251 |
| C4       | 0.642 | 0.385 | 0.391 | 0.508 | 0.232 | 0.602 | 0.460 | 3.166 | 6.883 |
| C5       | 0.023 | 0.024 | 0.026 | 0.112 | 0.051 | 0.041 | 0.046 | 0.287 | 6.197 |
| C6       | 0.115 | 0.227 | 0.253 | 0.110 | 0.162 | 0.130 | 0.166 | 1.090 | 6.571 |

Following that, the integrated spherical fuzzy comparison matrix is calculated in Table 9. Then, the obtained spherical fuzzy weights of each criterion were calculated and are shown in Table 10. For explanation, the following calculation was presented for the spherical fuzzy weights of criteria C1 with \((\mu, v, \pi) = (0.610, 0.388, 0.274)\), as follows:

\[
\mu_{C1} = \left[ 1 - \prod_{i=1}^{n} \left( 1 - \mu_{A_i}^2 \right)^{w_i} \right]^{1/2} = \left[ 1 - (1 - 0.500^2)^{1/6} \right]^{1/2} - (1 - 0.679^2)^{1/6} \right]^{1/2} = 0.610
\]

\[
v_{C1} = \prod_{i=1}^{n} v_{A_i}^w = \left[ 0.400^{1/6} \right]^{1/2} - (0.323^{1/6})^{1/2} - (0.328^{1/6})^{1/2} - (0.708^{1/6})^{1/2} - (0.246^{1/6})^{1/2} - (0.462^{1/6})^{1/2} = 0.388
\]

\[
\pi_{C1} = \left[ \prod_{i=1}^{n} \left( 1 - \mu_{A_i}^2 \right)^{w_i} - \prod_{i=1}^{n} \left( 1 - \mu_{A_i}^2 - \pi_{A_i}^2 \right)^{w_i} \right]^{1/2} = \left[ (1 - 0.500^2)^{1/6} \right]^{1/2} - (1 - 0.679^2)^{1/6} \right]^{1/2} = 0.274
\]

\[
S \left( \vec{w}_{C1}^\top \right) = \sqrt{100 \left[ \left( 3\mu_{A_s} - \pi_{A_s} \right)^2 - \left( \mu_{A_s} - \pi_{A_s} \right)^2 \right]} = \sqrt{100 \left[ \left( 3 \times 0.610 - 0.274 \right)^2 - \left( 0.388 - 0.274 \right)^2 \right]} = 16.915
\]

\[
\bar{w}_{C1}^\top = \frac{S \left( \vec{w}_{C1}^\top \right)}{\sum_{j=1}^{n} S \left( \vec{w}_{Cj}^\top \right)} = \frac{16.915}{16.915 + 12.268 + 11.124 + 20.039 + 9.259 + 15.072} = 0.200
\]

The SF-AHP weights of the six main criteria consist of three parameters: the membership degree \((\mu)\), nonmembership degree \((v)\), and hesitancy degree \((\pi)\) of the element \(x \in X\). The crisp weights of the six main criteria were calculated based on the abovementioned calculation. The criteria of societal impact (C4) with a value of 0.237, wind resources (C1) with a value of 0.200, and economic impact (C6) with a value of 0.178 are determined to be the most critical criteria in the stage of the SF-AHP model. Consequently, the same steps are applied to calculate the significance level of other criteria of the first stage of the paper. The integrated spherical fuzzy comparison matrix of all criteria is presented in Table A1 (Appendix A).

Table 9. The integrated spherical fuzzy comparison matrix.
Table 10. The spherical fuzzy weights from the SF-AHP model.

| Criteria                                      | SF-AHP Weights | Calculations to Obtain Crisp Weights | Crisp Weights |
|-----------------------------------------------|----------------|--------------------------------------|---------------|
|                                              | μ   | ν   | π    | S(\(\hat{w}_j\)) | \(\hat{w}_j\) |
| C1. Wind speed and its distribution status   | 0.610| 0.388| 0.274| 16.915           | 0.200         |
| C2. Effective wind hours                     | 0.462| 0.514| 0.315| 12.268           | 0.145         |
| C3. Nautical life coordination               | 0.420| 0.563| 0.296| 11.124           | 0.131         |
| C4. Nautical environmental influence         | 0.707| 0.296| 0.232| 20.039           | 0.237         |
| C5. Undersea geological conditions            | 0.356| 0.624| 0.282| 9.259            | 0.109         |
| C6. Provincial financial subsidies           | 0.551| 0.437| 0.288| 15.072           | 0.178         |

Table 11 displays the spherical fuzzy weights and crisp weights of the SF-AHP model. The geometrical mean, defuzzification, and normalization procedures are used to calculate the influence level of each criterion. For example, the spherical fuzzy weights of the criteria wind speed and its distribution status (C11) have a membership degree (μ) at 0.506, nonmembership degree (ν) at 0.473, and hesitancy degree (π) at 0.311. Similar to the procedure, the spherical fuzzy weights of the criteria effective wind hours (C12) have membership degrees (μ), nonmembership degrees (ν), and hesitancy degrees (π) of 0.447, 0.538, and 0.310, respectively. The significance level of the criteria of the SF-AHP model is shown in Figure 5. The results show that the five most significant criteria for determining the offshore wind power station are policy planning (C42); construction, operation, and maintenance costs (C62); employment (C41), marine conditions (C33), and wind speed and its distribution status (C11), with significance levels of 7.49%, 7.46%, 7.36%, 7.31, and 7.11%, respectively. Meanwhile, provincial financial subsidies (C63) are specified as the least significant criterion, with a value of 7.70%. The findings suggest that decision-makers should pay more attention to “C42”, “C62”, “C41”, “C33”, and “C11” than other criteria.
4.3. Results of the WASPAS Model

In the second stage, this paper deployed the SF-AHP weights to combine with the WASPAS model for ranking the potential wind plants, which are Ba Ria – Vung Tau (OWPS-01), Ben Tre (OWPS-02), Binh Dinh (OWPS-03), Binh Thuan (OWPS-04), Ca Mau (OWPS-05), Ninh Thuan (OWPS-06), and Soc Trang (OWPS-07). The decision hierarchy tree for the goal of OWPS site selection is depicted in Figure 6.
The weighted normalized matrix for the WSM and weighted normalized matrix for the WPM are displayed in Tables A2 and A3, respectively. The WASPAS model ranks the alternative based on the integrated simple additive weighting and exponentially weighted product model to obtain a compromise solution. Table 12 presents the integrated utility function $Q_i$ of the WASPAS model, which is calculated using the weighted sum model $Q_i^{(1)}$ (WSM) and the weighted product model $Q_i^{(2)}$ (WSM). The results show that the top three offshore wind locations are Binh Thuan (OWPS-04), Ninh Thuan (OWPS-06), and Binh Dinh (OWPS-03), ranking in the first, second, and third positions with scores of 0.798, 0.735, and 0.594, respectively. Figure 7 displays the final location ranking from the WASPAS model.

**Table 12.** The integrated utility function of the WASPAS model.

| DMU    | Location          | $Q_i^{(1)}$ | $Q_i^{(2)}$ | $Q_i$  | Ranking |
|--------|-------------------|-------------|-------------|--------|---------|
| OWPS-01| Ba Ria - Vung Tau | 0.426       | 0.408       | 0.417  | 6       |
| OWPS-02| Ben Tre           | 0.494       | 0.474       | 0.484  | 5       |
| OWPS-03| Binh Dinh         | 0.615       | 0.572       | 0.594  | 3       |
| OWPS-04| Binh Thuan        | 0.842       | 0.754       | 0.798  | 1       |
| OWPS-05| Ca Mau            | 0.329       | 0.252       | 0.290  | 7       |
| OWPS-06| Ninh Thuan        | 0.766       | 0.704       | 0.735  | 2       |
| OWPS-07| Soc Trang         | 0.576       | 0.544       | 0.560  | 4       |

**Figure 6.** The decision tree of the evaluation process.
5. Results Validation

To confirm the reliability and accuracy of the results and to check the robustness of the proposed approach, the following validation methods are compared with existing plant locations, sensitivity analysis, and MCDM technique comparisons.

5.1. Comparison with the Existing Locations

The final ranking of locations of their sustainability for OWPS construction is validated in Figure 8, which displays the provinces’ total capacity of normal status OWPS projects in Vietnam as of 2021. Most projects are now concentrated in Binh Thuan (15,800 MWp), Ninh Thuan (4,280 MWp), and Binh Dinh (2,900 MWp). Offshore wind energy can also be expanded throughout the country toward a clean energy development pathway; however, given the results, the authors recommend further analysis of these areas as they are very promising.

Figure 8. Map of OWPS projects in Vietnam as of 2021.
5.2. Sensitivity Analysis

To demonstrate the robustness and stability of the proposed MCDM model, a sensitivity analysis is conducted for the parameters including the preference coefficient and the index weights. First, a sensitivity analysis of the preference coefficient (i.e., the threshold value of the WASPAS model, \( \lambda \)) is conducted to validate the ranking order. In a previous relevant study, the value of \( \lambda \) was considered to be 0.5 (\( \lambda = 0.5 \)) for base case analysis. However, this setting does not reflect the actual scenario in which various decision-makers have different preferences. Hence, in this paper, the preference coefficient of the WASPAS model fluctuates in the range of \( \lambda = 0, 0.1, \ldots, 1 \), as shown in Table 13. The change result is visualized in Figure 9. The ranking result shows that the optimal location for building the offshore wind station is always the same when changing the values of coefficient preference (\( \lambda \)) from 0 to 1. It can be concluded that Binh Thuan (OWPS-04) is consistently the optimal location to take over. Following that, Ninh Thuan (OWPS-06) and Binh Dinh (OWPS-03) are also ranked second and third positions, which are also more suitable alternatives among other candidates. The reliability and correctness of the proposed model are demonstrated. Decision-maker psychology should be considered when making decisions in determining the optimal wind plant location from multiple alternatives.

**Table 13. The fluctuation threshold value of the WASPAS model.**

| DMU     | Location        | Coefficient Values (\( \lambda \)) |
|---------|-----------------|-----------------------------------|
| OWPS-01 | Ba Ria - Vung Tau  | 0.408 0.410 0.412 0.414 0.415 0.417 0.419 0.421 0.422 0.424 0.426 |
| OWPS-02 | Ben Tre         | 0.474 0.476 0.478 0.480 0.482 0.484 0.486 0.488 0.490 0.492 0.494 |
| OWPS-03 | Binh Dinh      | 0.572 0.577 0.581 0.585 0.590 0.594 0.598 0.602 0.607 0.611 0.615 |
| OWPS-04 | Binh Thuan     | 0.754 0.762 0.771 0.780 0.789 0.798 0.806 0.815 0.824 0.833 0.842 |
| OWPS-05 | Ca Mau         | 0.252 0.259 0.267 0.275 0.282 0.290 0.298 0.306 0.313 0.321 0.329 |
| OWPS-06 | Ninh Thuan     | 0.704 0.710 0.717 0.723 0.729 0.735 0.741 0.748 0.754 0.760 0.766 |
| OWPS-07 | Soc Trang      | 0.544 0.547 0.551 0.554 0.557 0.560 0.563 0.567 0.570 0.573 0.576 |

**Figure 9. Sensitivity analysis of the threshold value of the WASPAS model.**

Second, a sensitivity analysis of criteria is conducted to investigate the impact of criteria on the ranking of wind plant locations. The top five main criteria are selected to fluctuate their weights from \( \pm 10\% \), \( \pm 30\% \), and \( \pm 50\% \), which are policy planning (C42); construction, operation, and maintenance costs (C62); employment (C41); marine conditions (C33); and wind speed and its distribution status (C11). In total, there will be 30 scenarios of sensitivity analysis in this case. Figure 10 depicts that the final ranking results of the seven locations are fundamentally stable. The results show that Binh Thuan (OWPS-04) and Ninh Thuan (OWPS-06) are always ranked first and
second on 10%, 30%, 50% more weight and 10%, 30%, 50% less weight than the base case. Generally, the curve is relatively smooth, revealing that the ranking result of the proposed MCDM model of SF-AHP and WASPAS is stable and applicable.

![Graphs showing sensitivity analysis](image)

(a) Policy planning (C42).
(b) Construction, operation, maintenance costs (C62).
(c) Employment (C41).
(d) Marine conditions (C33).
(e) Wind speed and its distribution status (C11).

**Figure 10.** Sensitivity analysis of the five most significant criteria.

### 5.2. Comparative Analysis

In the MCDM approach, the applicability and rationality of the proposed methods must be proven by comparison with stable and mature methods commonly used in related studies. In this paper, the ranking of wind locations using the integrated SF-AHP and WASPAS models is evaluated by comparison with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Combined Compromise Solution (CoCoSo), and Evaluation Based on Distance from...
Average Solution (EDAS). The TOPSIS method is known as the classical MCDM model based on the concept that the selected alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. The EDAS method could be used most effectively for solving a larger number of complex decision-making problems. Meanwhile, the CoCoSo method has algorithm steps similar to those of the WASPAS method, which was built based on aggregated simple additive weighting and an exponentially weighted product model to obtain a compromise solution.

The comparison of four kinds of ranking methods is shown in Table 14 and visualized in Figure 11. The comparison shows that the ranking of the offshore wind location has given the same result as the model proposed in this paper, which is among integrated models of SF-AHP and WASPAS, SF-AHP and TOPSIS, and SF-AHP and EDAS. The ranking of the SF-AHP and CoCoSo models is slightly different from that of the proposed model. The difference is between Binh Thuan (OWPS-04) and Ninh Thuan (OWPS-06). Hence, the proposed MCDM integrated model is robust, and the obtained result is reliable and can be a useful guideline for decision-makers, investors, or governments in determining the optimal offshore wind plants in Vietnam or related industries.

### Table 14. The comparison of four kinds of ranking methods.

| DMU   | Location       | SF-AHP WASPAS | SF-AHP TOPSIS | SF-AHP COCOSO | SF-AHP EDAS |
|-------|----------------|---------------|---------------|---------------|-------------|
| OWPS-01 | Ba Ria - Vung Tau | 0.417 | 6 | 0.347 | 6 | 4.240 | 6 | 0.290 | 6 |
| OWPS-02 | Ben Tre        | 0.484 | 5 | 0.409 | 5 | 4.764 | 5 | 0.392 | 5 |
| OWPS-03 | Binh Dinh      | 0.594 | 3 | 0.528 | 3 | 5.232 | 3 | 0.567 | 3 |
| OWPS-04 | Binh Thuan     | 0.798 | 1 | 0.681 | 1 | 5.654 | 2 | 0.919 | 1 |
| OWPS-05 | Ca Mau         | 0.290 | 7 | 0.287 | 7 | 0.910 | 7 | 0.092 | 7 |
| OWPS-06 | Ninh Thuan     | 0.735 | 2 | 0.670 | 2 | 5.926 | 1 | 0.825 | 2 |
| OWPS-07 | Soc Trang      | 0.560 | 4 | 0.495 | 4 | 5.090 | 4 | 0.510 | 4 |

**Figure 11.** Ranking results of compared methods.

### 6. Concluding Remarks

The aim of decreasing global greenhouse gas emissions will depend mainly on developing economies such as Vietnam. Critically, the COVID-19 epidemic has highlighted the vulnerabilities in this fossil fuel-based economy, accelerating the transition faster than before. Pathways toward low carbon development, Vietnam is taking steps to tap into its good wind energy potentials. Selecting the appropriate locations for offshore wind plant installation is the topmost decision, which is a complicated multicriteria decision-making (MCDM) problem with the coexistence of multiple factors. There is a problem with incomplete decision information use and information loss during the decision-making process, and it is easy to overlook the interaction difficulty in a fuzzy environment.
In this study, a new design of a comprehensive MCDM framework combining the SF-AHP and WASPAS methods in the presence of experts with fuzzy judgments is proposed to handle the OWPS site selection problem, and a real case study in Vietnam is considered. For this evaluation, SF-AHP in the first stage determines the significance levels of OWPS evaluation criteria. WASPAS is then utilized to rank locations of OWPS. A comprehensive set of evaluation criteria developed based on the concept of sustainable development has been recognized by reviewing the literature review and interviewing experts to practice the two-stage MCDM model. The main findings and achievements of this work are as follows. Locations for OWPS construction in Vietnam were examined concerning 15 criteria; optimal alternatives were successfully determined by the novel combined approach SF-AHP and WASPAS. The criteria of “policy planning”, “construction, operation, and maintenance costs”, and “employment” were recognized as the most impactful criteria in the SF-AHP method. Binh Thuan, Ninh Thuan, and Binh Dinh have been the best areas for OWPS construction according to the final ranking of WASPAS analysis. A comparison with the existing areas for OWPS and sensitivity analysis of criteria are presented to support the obtained results. Additional comparisons are conducted with other MCDM methods (TOPSIS, CoCoSo, and EDAS). Consequently, the priority order of the best locations is very similar, indicating that the proposed methodology is robust. The study provides a decision support tool that assists authorities and decision-makers in developing suitable and effective planning strategies for OWPS projects.

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Appendix A

Table A1. The integrated spherical fuzzy comparison matrix of the SF-AHP model.

|     | C11 | C12 | C21 | C22 | C31 |
|-----|-----|-----|-----|-----|-----|
| C11 | 0.500 | 0.400 | 0.400 | 0.457 | 0.321 | 0.470 | 0.504 | 0.331 | 0.546 |
| C12 | 0.391 | 0.584 | 0.310 | 0.500 | 0.400 | 0.400 | 0.493 | 0.482 | 0.336 | 0.424 | 0.576 | 0.275 | 0.519 | 0.476 | 0.288 |
| C21 | 0.466 | 0.497 | 0.336 | 0.458 | 0.511 | 0.430 | 0.500 | 0.400 | 0.400 | 0.596 | 0.391 | 0.297 | 0.435 | 0.556 | 0.300 |
| C22 | 0.402 | 0.589 | 0.289 | 0.503 | 0.490 | 0.216 | 0.331 | 0.660 | 0.262 | 0.500 | 0.400 | 0.400 | 0.390 | 0.400 | 0.604 | 0.280 |
| C31 | 0.480 | 0.510 | 0.298 | 0.403 | 0.585 | 0.182 | 0.399 | 0.590 | 0.282 | 0.557 | 0.429 | 0.302 | 0.500 | 0.400 | 0.400 |
| C32 | 0.373 | 0.613 | 0.283 | 0.422 | 0.523 | 0.234 | 0.381 | 0.603 | 0.296 | 0.445 | 0.536 | 0.314 | 0.523 | 0.455 | 0.313 |
| C33 | 0.541 | 0.447 | 0.305 | 0.547 | 0.432 | 0.488 | 0.458 | 0.511 | 0.338 | 0.594 | 0.394 | 0.289 | 0.594 | 0.392 | 0.287 |
| C41 | 0.551 | 0.430 | 0.308 | 0.578 | 0.405 | 0.471 | 0.537 | 0.439 | 0.313 | 0.582 | 0.419 | 0.276 | 0.512 | 0.492 | 0.276 |
| C42 | 0.498 | 0.493 | 0.294 | 0.536 | 0.441 | 0.297 | 0.406 | 0.580 | 0.293 | 0.531 | 0.452 | 0.313 | 0.562 | 0.413 | 0.306 |
| C51 | 0.384 | 0.607 | 0.282 | 0.512 | 0.470 | 0.179 | 0.357 | 0.635 | 0.269 | 0.485 | 0.507 | 0.294 | 0.462 | 0.512 | 0.318 |
| C52 | 0.300 | 0.690 | 0.250 | 0.503 | 0.476 | 0.258 | 0.498 | 0.479 | 0.321 | 0.421 | 0.560 | 0.310 | 0.470 | 0.506 | 0.332 |
| C53 | 0.381 | 0.589 | 0.316 | 0.450 | 0.543 | 0.142 | 0.331 | 0.660 | 0.262 | 0.458 | 0.511 | 0.338 | 0.361 | 0.613 | 0.302 |
| C61 | 0.542 | 0.436 | 0.311 | 0.508 | 0.473 | 0.325 | 0.458 | 0.511 | 0.338 | 0.571 | 0.416 | 0.299 | 0.541 | 0.427 | 0.322 |
| C62 | 0.429 | 0.554 | 0.303 | 0.517 | 0.461 | 0.407 | 0.536 | 0.441 | 0.315 | 0.634 | 0.365 | 0.261 | 0.594 | 0.394 | 0.289 |
| C63 | 0.484 | 0.495 | 0.318 | 0.450 | 0.543 | 0.155 | 0.395 | 0.596 | 0.285 | 0.488 | 0.493 | 0.316 | 0.458 | 0.534 | 0.291 |

|     | C32 | C33 | C41 | C42 | C51 |
|-----|-----|-----|-----|-----|-----|
| C11 | 0.565 | 0.241 | 0.305 | 0.398 | 0.599 | 0.280 | 0.368 | 0.628 | 0.272 | 0.441 | 0.556 | 0.286 | 0.567 | 0.424 | 0.299 |
| C12 | 0.496 | 0.476 | 0.332 | 0.386 | 0.607 | 0.279 | 0.373 | 0.621 | 0.273 | 0.404 | 0.586 | 0.293 | 0.419 | 0.573 | 0.289 |
| C21 | 0.569 | 0.412 | 0.311 | 0.493 | 0.482 | 0.336 | 0.407 | 0.582 | 0.293 | 0.529 | 0.459 | 0.304 | 0.593 | 0.397 | 0.291 |
| C22 | 0.500 | 0.486 | 0.314 | 0.340 | 0.659 | 0.252 | 0.319 | 0.685 | 0.228 | 0.386 | 0.612 | 0.278 | 0.453 | 0.544 | 0.285 |
| C31 | 0.418 | 0.571 | 0.293 | 0.346 | 0.650 | 0.253 | 0.414 | 0.592 | 0.257 | 0.378 | 0.612 | 0.279 | 0.472 | 0.511 | 0.314 |
Table A2. The weighted normalized matrix for WSM of the WASPAS model.

| DMU        | Location                  | C11  | C12  | C21  | C22  | C31  | C32  | C33  | C41  |
|------------|---------------------------|------|------|------|------|------|------|------|------|
| OWPS-01    | Ba Ria - Vung Tau         | 0.048| 0.016| 0.031| 0.018| 0.019| 0.026| 0.032| 0.034|
| OWPS-02    | Ben Tre                   | 0.048| 0.015| 0.040| 0.025| 0.031| 0.040| 0.044| 0.034|
| OWPS-03    | Binh Dinh                | 0.048| 0.014| 0.051| 0.036| 0.043| 0.052| 0.053| 0.051|
| OWPS-04    | Binh Thuan               | 0.063| 0.045| 0.048| 0.059| 0.062| 0.069| 0.073| 0.074|
| OWPS-05    | Ca Mau                   | 0.045| 0.013| 0.011| 0.011| 0.012| 0.011| 0.009| 0.017|
| OWPS-06    | Ninh Thuan               | 0.071| 0.062| 0.071| 0.045| 0.048| 0.057| 0.050| 0.054|
| OWPS-07    | Soc Trang                | 0.048| 0.014| 0.051| 0.032| 0.038| 0.049| 0.053| 0.051|

Table A3. Exponentially weighted normalized matrix for WPM of the WASPAS model.

| DMU        | Location                  | C11  | C12  | C21  | C22  | C31  | C32  | C33  | C41  |
|------------|---------------------------|------|------|------|------|------|------|------|------|
| OWPS-01    | Ba Ria - Vung Tau         | 0.030| 0.040| 0.025| 0.027| 0.019| 0.041| 0.019|      |
| OWPS-02    | Ben Tre                   | 0.045| 0.019| 0.036| 0.025| 0.022| 0.031| 0.040|      |
| OWPS-03    | Binh Dinh                | 0.060| 0.014| 0.047| 0.033| 0.041| 0.022| 0.050|      |
| OWPS-04    | Binh Thuan               | 0.075| 0.011| 0.064| 0.058| 0.071| 0.014| 0.057|      |
| OWPS-05    | Ca Mau                   | 0.015| 0.060| 0.011| 0.009| 0.019| 0.075| 0.010|      |
| OWPS-06    | Ninh Thuan               | 0.060| 0.012| 0.058| 0.051| 0.054| 0.018| 0.055|      |
| OWPS-07    | Soc Trang                | 0.045| 0.014| 0.044| 0.033| 0.041| 0.025| 0.038|      |
OWPS-02  Ben Tre  0.972  0.916  0.960  0.951  0.958  0.964  0.963  0.945
OWPS-03  Binh Dinh  0.972  0.913  0.977  0.972  0.977  0.980  0.976  0.973
OWPS-04  Binh Thuan  0.991  0.980  0.973  1.000  1.000  1.000  1.000  1.000
OWPS-05  Ca Mau  0.969  0.908  0.878  0.908  0.902  0.884  0.856  0.898
OWPS-06  Ninh Thuan  1.000  1.000  1.000  0.985  0.984  0.988  0.972  0.977
OWPS-07  Soc Trang  0.972  0.913  0.977  0.964  0.970  0.977  0.976  0.973

| DMU    | Location         | C42 | C51 | C52 | C53 | C61 | C62 | C63 |
|--------|------------------|-----|-----|-----|-----|-----|-----|-----|
| OWPS-01 | Ba Ria - Vung Tau | 0.934 | 0.976 | 0.942 | 0.956 | 0.911 | 0.957 | 0.939 |
| OWPS-02 | Ben Tre          | 0.962 | 0.931 | 0.964 | 0.951 | 0.920 | 0.937 | 0.981 |
| OWPS-03 | Binh Dinh        | 0.983 | 0.916 | 0.981 | 0.969 | 0.962 | 0.913 | 0.992 |
| OWPS-04 | Binh Thuan       | 1.000 | 0.902 | 1.000 | 1.000 | 1.000 | 0.884 | 1.000 |
| OWPS-05 | Ca Mau           | 0.887 | 1.000 | 0.895 | 0.897 | 0.911 | 1.000 | 0.903 |
| OWPS-06 | Ninh Thuan       | 0.983 | 0.907 | 0.994 | 0.993 | 0.982 | 0.898 | 0.998 |
| OWPS-07 | Soc Trang        | 0.962 | 0.916 | 0.977 | 0.969 | 0.962 | 0.921 | 0.977 |

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