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Site selection for hybrid offshore wind and wave power plants using a four-stage framework: A case study in Hainan, China

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ABSTRACT

The site selection for hybrid offshore wind and wave power plants (HOWWPP) is a critical step to a successful HOWWPP project. In this study, a four-stage framework is presented for determining the most suitable marine areas for the siting of HOWWPP. First, wind and wave energy potentials are assessed as a foundation for the implementation of a HOWWPP project. Next, unsuitable areas for the siting of HOWWPP are determined based on exclusion criteria to avoid any potential conflicts of marine spatial planning. Feasible areas (not satisfying the exclusion criteria) are classified and converted into spatial layers separately according to evaluation criteria. Then, the triangular fuzzy analytic hierarchy process is applied to calculate the evaluation criteria weights. Finally, the site suitability of feasible areas is calculated using the weighted overlay approach and then categorized into five classes. To validate the effectiveness of the proposed framework, a case study in Hainan Province of China was conducted. The results indicate that the marine areas with medium to very high suitability are approximately 1312 km^2 (4.7% of the study area) for the deployment of HOWWPP. The obtained results of this study can support potential planners in selecting marine areas for the installation of HOWWPP.

1. Introduction

In the past decades, the global decrease of fossil energy and increasing environmental pollution promote the development of renewable energy sources, such as wave, wind, solar, geothermal, tidal (Argin et al., 2019; Lin et al., 2019; Zeng et al., 2020). However, with widespread applications of renewable energy, concerns are growing about the volatility and intermittent nature of energy itself, which may result in low energy quality (Wu et al., 2019). An independent energy system may not support continuous energy supply because of the characteristics of seasonal and cyclical variations of energy resources (Wan et al., 2018; Sarkar et al., 2019). Fortunately, this challenge can be solved by developing a hybrid energy system, e.g., hybrid offshore wind and wave power plants (HOWWPP) (Aydin et al., 2013; Pérez-Collazo et al., 2015; Loukogeorgaki et al., 2018). The goal of HOWWPP is to exploit the corresponding energy potentials simultaneously in which offshore wind turbines and wave energy conversion systems are combined into one structure (Vasileiou et al., 2017). Such a hybrid energy system can bring multiple benefits, such as stable power output, increased energy yield (Pérez-Collazo et al., 2015).

Building a HOWWPP at a suitable location can maximize the use of renewable resources. The site selection of HOWWPP is a complex, multi-criteria decision-making process, which needs to consider conflicting criteria related to techno-economic, environmental, and social factors. Up to now, many researchers have focused on the site selection of energy systems (e.g., Latinopoulos and Kechagia, 2015; Dhiman et al., 2019; Wu et al., 2020; Genç et al., 2021; Golestani et al., 2021; Lo et al., 2021). However, most of them were focused on a single renewable energy system in the terrestrial environment. The existing approaches do not offer a precise and differentiated assessment of site suitability for locating a hybrid energy system in the marine environment. In addition, not all suitable areas are equally appropriate for energy development. For instance, marine areas that are far away from the shoreline are probably more suitable due to the decrease of noise and visual influence on residents. Moreover, uncertainties exist in any site selection decision-making process because of the complexity and dynamic of the

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Table 1
Summary of GIS-MCDM methods used in the previous literature.

Authors	Study area	Methods	Main findings
Latinopoulos and Kechagia (2015)	Greece	GIS-AHP	The number of wind farm projects currently under study is well below the carrying capacity of the study region.
Flocard et al. (2016)	Australian	GIS-MCE	A total of more than 700 km^2 are identified as optimal locations for wave energy converters.
Cradden et al. (2016)	Europe	GIS-MCE	A dedicated decision-support tool is developed to support multi-criteria site selections specifically for wind and wave energy platforms.
Vasileiou et al. (2017)	Greece	GIS-AHP	There are 12 potentially suitable sea areas in Greece for the siting of hybrid offshore wind and wave energy systems.
Konstantinos et al. (2019)	Greece	GIS-AHP-TOPSIS	The location of the wind farms is accurately determined, and the issues associated with this type of investment are overcome.
Bahaj et al. (2020)	UK, Arabian Peninsula	GIS-AHP-RCR	It identifies the capacity and locations of offshore wind farms in the UK and Arabian Peninsula at a large scale.
Xu et al. (2020a)	Wafangdian	GIS-IAHP-VIKOR	Wind-power facilities are suitable for installation in 30.2% of study regions, but only 3.36% are deemed highly suitable.
Loughney et al. (2021)	UK	GIS-AHP	Ranking order is produced for all 45 sites.
Gil-García et al. (2021)	Gulf of Maine	GIS-AHP-TOPSIS	An area of 8671 km^2 is estimated to be available for offshore wind farm locations.

Table 2
The advantages and disadvantages of different GIS-MCDM methods.

References	Methods	Advantages	Disadvantages
Cradden et al. (2016); Flocard et al. (2016)	GIS-MCE	Easy to calculate and understand	Ignore or simplify the preference of decision; The result is subjective
Latinopoulos and Kechagia (2015); Vasileiou et al. (2017); Loughney et al. (2021)	GIS-AHP	Utilization of expert's experience and knowledge; Simple to use	Difficult to describe index interactions; The result is subjective
Bahaj et al. (2020)	GIS-AHP-RCR	Can reduce time costand complexity to rank the criteria; Simple to use	The model is sensitive to the data quality and availability
Konstantinos et al. (2019); Gil-García et al. (2021)	GIS-AHP-TOPSIS	Can measure the distance of alternatives from the ideal solution; No limitation on sample size and index number	Difficult to address the problem of index compensation; Cannot provide a high-resolution map for alternatives
Xu et al. (2020a)	GIS-IAHP-VIKOR	Can considering group benefit maximization; Easy to reflect the subjective preferences	Has high computational complexity; Fails to find the improvement program of alternatives.

social environment (Wu et al., 2019). It is difficult for decision-makers to quantify their evaluation using a crisp value (Wu et al., 2016). Therefore, information fuzziness and decision-makers' hesitation need to be better addressed in a decision problem.

In this study, a four-stage framework is developed to identify the most suitable marine areas for deploying HOWWPP. The framework is based on a combination of Multi-Criteria Decision Making (MCDM) and Geographic Information Systems (GIS), which can provide a more precise and differentiated evaluation of site suitability. First, the wind and wave energy potentials are assessed as a foundation for the implementation of a HOWWPP project. Second, the marine areas that cannot satisfy the basic requirements are excluded based on the exclusion criteria for identifying an unsuitable area. Also, each evaluation criterion is respectively applied for classifying the feasible areas and then creating a series of spatial layers. In the third step, the triangular fuzzy analytic hierarchy process (FAHP), one of the MCDM approaches, is implemented to gain the relative weights of the evaluation criteria for dealing with the issues of uncertainty in the site selection decision-making process. Finally, site suitability for locating HOWWPP is evaluated by using the weighted overlay approach. To validate the usefulness of the proposed framework, a case study in Hainan Province of China was conducted. The findings of this study may help related planners to find the optimal location for HOWWPP and promote the development of offshore wind and wave energy resources.

The main novelty of this study is that we develop and test a new framework for selecting the most suitable marine areas for the deployment of HOWWPP. The proposed framework is based on a combination of GIS and MCDM, which can offer a more precise and differentiated assessment of site suitability from the perspective of space for locating HOWWPP. The advantage of the proposed approach is that uncertainty of experts' opinions is decreased to a minimum by using the FAHP approach and the application of in-built GIS tools for spatial analysis helps to improve the computation efficiency. The obtained results can reflect the ranking of the site suitability for each assessment unit using a grid pattern. We apply the proposed framework to a case study region in Hainan Province, China. In fact, this approach based on a combination of the GIS and MCDM has not been used so far for the identification of the suitable marine area for deploying HOWWPP in China. The obtained results can help the concerned government to effectively implement the HOWWPP project. In addition, although Hainan Province has been used as the case study, the proposed methodology can be easily applied to other marine areas to support the site selection of HOWWPP.

The rest of the paper is organized as follows. Section 2 presents an extensive literature review. In Section 3, the criteria system for HOWWPP site selection is presented. Section 4 introduces the methodological framework used in this study. Section 5 provides the results of the analysis. Section 6 conducts the discussions. In Section 7, conclusions are summarized, and suggestions for future research are presented.

2. Literature review

2.1. Application of GIS-MCDM methods to the site selection of power plants

In recent years, GIS-MCDM methods have been widely used in the site selection of power plants, as summarized in Table 1.

In this study, we specifically review those studies that address the site selection of wind and/or wave power plants. For example, Al-Yahyai et al. (2012) created a land suitability index to find suitable areas for locating wind farms in Oman by combing GIS with an analytic hierarchy process (AHP). Latinopoulos and Kechagia (2015) further calculated the same index under various policy scenarios in Greece by using GIS and Multi-Criteria Evaluation (MCE). Villacreses et al. (2017) used GIS with four MCDM approaches to determine the optimal position for deploying wind farms in continental Ecuador. More recently, Xu et al. (2020a) presented a combined GIS, interval Analytic Hierarchy Process (IAHP),

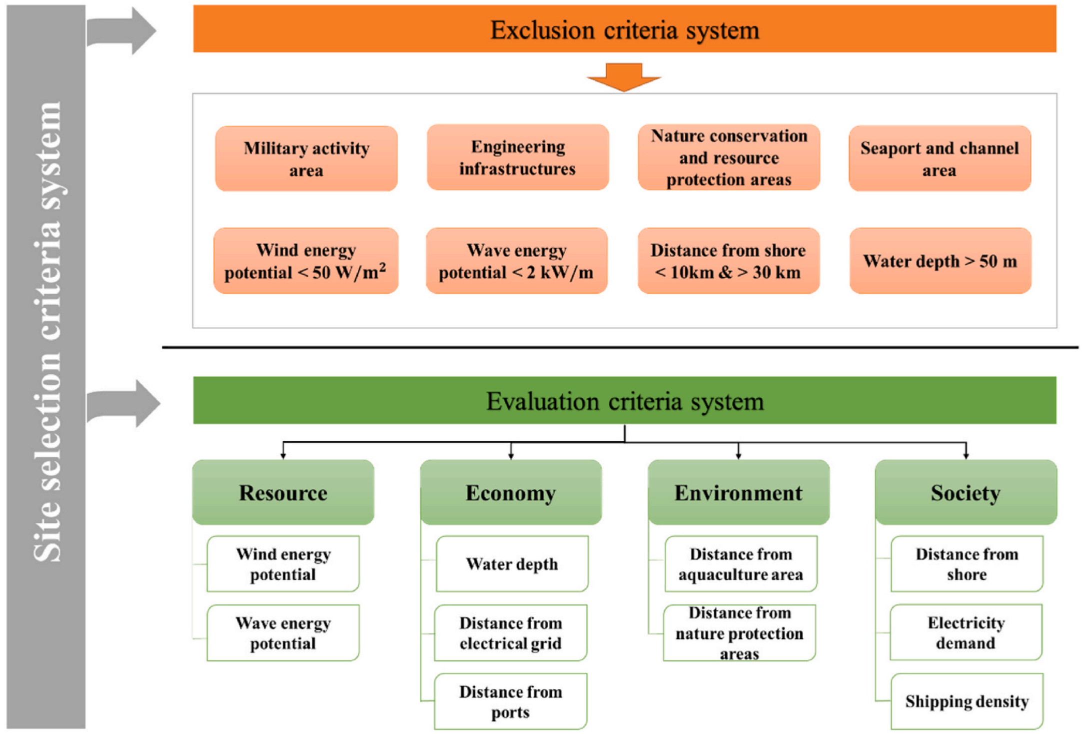

Fig. 1. Criteria system of site selection on HOWWPP.

and stochastic VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method to help identify suitable locations for wind plants in Wafangdian. Bahaj et al. (2020) used a cost-effective method for offshore wind farm planning by combining representative cost ratio (RCR), GIS, and AHP. In addition, Gil-García et al. (2021) proposed a framework by integrating AHP, GIS, and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) approaches to assess the optimal selection of offshore wind sites.

Concerning the site selection of wave power plants, Nobre et al. (2009) introduced a GIS-based multi-criteria analysis methodology for the determination of the best location to site a wave energy farm. Flocard et al. (2016) developed a spatial multi-criteria evaluation model to determine appropriate areas to construct a wave power plant. However, the studies that examine the site selection of hybrid offshore wind and wave energy systems are relatively few. One example is Cradden et al. (2016), which developed a GIS-based decision-support tool to facilitate multi-criteria site selections for combined wind-wave power plants. Another example is Vasileiou et al. (2017), which used a GIS-based AHP approach to find the optimal locations in Greece for the implementation of wind and wave farms. They developed a GIS database to map eligible marine areas, and then evaluated and ranked these areas using the AHP method.

These existing works showed that there are many successful attempts to apply GIS combined with different MCDM methods in wind and/or wave farms site selection. The advantages and disadvantages of the methods in the previous studies are summarized in Table 2. However, most focused on the site selection of a single energy system. Moreover, the existed approaches do not support a precise and differentiated evaluation of site suitability for deploying a hybrid energy system in the marine environment. In particular, the fuzziness and completeness of evaluation information in the site selection decision-making process are always simplified. Therefore, this paper develops a four-stage framework for the site selection of HOWWPP, which can provide a more precise and differentiated assessment. Furthermore, the triangular FAHP technique is used to address the uncertainty in experts' judgment in the decision-making process.

2.2. Criteria system for siting wind and/or wave power plants

The criteria system plays an important role in the site selection of HOWWPP. To establish a comprehensive criteria system, an overview of the related criteria for the site selection of wind and/or wave power plants is necessary. Generally, the criteria can be classified into two groups: exclusion criteria and evaluation criteria (Ayodele et al., 2018).

2.2.1. Exclusion criteria system

The exclusion criteria are applied to identify the unsuitable areas and feasible areas for deploying renewable energy power plants. Some studies have analyzed these criteria. For example, Wu et al. (2016) considered military area, port and sea route, engineering infrastructures, and nature conservation area as exclusion criteria in wind power station construction. Flocard et al. (2016) emphasized the main non-implementing areas including protected areas, submarine pipelines, navigation routes, and fisheries. Vasileiou et al. (2017) deemed that wind speed, wave energy density, water depth, and distance from shore are essential exclusion criteria. Kim et al. (2018) divided exclusion criteria into three groups: marine-based human activities, nature reserve and landscape protection, and marine environment and marine ecosystem. In addition, Wu et al. (2019) used military exercise areas, marine protected areas, and marine operation areas as exclusion criteria. Loughney et al. (2021) outlined the set of exclusion criteria, including landmass, fisheries, military training areas, subsea facilities, marine protected area, maximum depth, etc.

2.2.2. Evaluation criteria system

The second category is the evaluation criteria, which can be used for classifying the feasible areas. Fetanat and Khorasaninejad (2015) used depths and heights, distance to equipment, environmental problems, economic factors, resource technical levels, and culture as evaluation criteria. Kim et al. (2016) assessed the site suitability for an offshore wind power plant in the coastal areas of Jeju Island, considering wind energy density, water depth, protected area, fishing ground, harbor, etc. In the work of Vasileiou et al. (2017), which presented a framework including wind speed, wave energy density, water depth, vessel density, distance from shore, distance from electrical grid, population served, and distance from harbors for the siting of wind and wave power plants. Wu et al. (2018) regarded wind energy, natural environment, navigation environment, and conditions for wind turbines as essential factors to the site selection of an offshore wind farm. In another study, Vagiona and Kamilakis (2018) took wind speed, population served, vessel density, and distance from conservation areas into account as evaluation criteria. Through multiple rounds of discussions, Feng (2021) built the evaluation index system, which includes wind speed, distance to grid, total construction cost, etc. Díaz and Soares (2021) further built twenty-three evaluation criteria from six aspects, namely ocean condition, viability, logistics, facilities, marine environment, and techno-economic.

The previous studies regarding the site selection criteria system are quite useful in informing our approach. According to related literature and experts' opinions, we determine the site selection criteria system finally used in this study. In addition, although some relevant criteria have extensive applicability (e.g., wind velocity), others are very obviously based on national legislation (e.g., distance from shore). Therefore, we adjust these criteria to conform to the relevant Chinese legislation.

3. Criteria system for HOWWPP site selection

Establishing an appropriate criteria system has an obvious influence on the site selection decision-making process. The criteria in this study were classified into two groups: the exclusion criteria and the evaluation criteria (See Fig. 1). The former aims to exclude the site that is unsuited to construct HOWWPP because of the complex marine spatial planning. The latter focuses on the evaluation and ranking of feasible areas.

3.1. Exclusion criteria for HOWWPP site selection

For identifying the unsuitable areas for the deployment of HOWWPP, a set of exclusion criteria was considered to help to avoid any potential conflicts of marine spatial planning. Generally, marine uses involve aquaculture, military, sea routes, engineering, etc (Kapsimalis et al., 2013; Yin et al., 2018). Following an extensive review of related literatures (e.g., Kim et al., 2016; Wu et al., 2016; Vasileiou et al., 2017; Argin et al., 2019; Emeksiz and Demirci, 2019), eight exclusion criteria were identified as follows:

- *Military activity area:* These marine areas used for military activities such as military training and exercises are considered unsuitable for HOWWPP.
- *Engineering infrastructures:* Areas near maritime infrastructures (e.g., cable, natural gas pipeline, etc.) cannot be considered eligible for the implementation of a power plant.
- *Nature conservation and resource protection areas:* Nature conservation and resource protection areas can be classified into two categories: nature conservation areas and resource protection areas. Nature conservation areas include national parks, natural monuments, and flora and fauna habitat; Major components of resource protection areas include oil/gas areas and aquaculture farms. The deployment of HOWWPP in those regions is not feasible considering the conflict with the existing marine planning.
- *Seaport and channel area:* To avoid interference with ship navigation, the seaport and channel area are excluded from the feasible area. Specifically, marine areas with high volumes of traffic can be considered as channel areas.
- *Wind energy potential* < 50 W/m^2*:* The offshore power plant should be installed in marine areas, where wind energy is high enough to make energy systems technically and economically feasible. In general, the wind energy density below 50 W/m^2 is considered to be not feasible (Zheng et al., 2013; Zhao et al., 2016; Yang et al., 2019). Therefore, marine areas with a wind energy density of less than 50 W/m^2 are excluded.
- *Wave energy potential* < 2 kW/m*:* Obviously, the economic and technical feasibility of this hybrid energy system also relies on wave energy potential. Wave energy is unavailable when the density is less than 2 kW/m (Yaakob et al., 2016; Kamranzad et al., 2017; Yang et al., 2019). Therefore, these areas with wave energy density below 2 kW/m are excluded.
- *Water depth* > 50 m*:* Water depth is an important spatial constraint because the turbine foundations should be secured (Argin et al., 2019). According to the technical viability of offshore power plants, the water depth is currently set as less than 50 m (Zountouridou et al., 2015). The areas with a water depth higher than 50 m cannot be regarded as suitable for the deployment of HOWWPP.
- *Distance from shore* <10 km *&* >30 km*:* The siting of the power plant close to the shore may result in some negative impacts, such as noise, aesthetics impacts (Vasileiou et al., 2017). According to the Chinese policies, the distance from the shore to the power plants should be more than 10 km (Wu et al., 2018). In addition, the installation far away from the shore would increase costs. In this case, the selected limitation is bigger than 10 km and less than 30 km (Kim et al., 2016; Yue and Yang, 2009). Therefore, the marine area that is less than 10 km and bigger than 30 km away from shore is excluded.

3.2. Evaluation criteria for HOWWPP site selection

To identify the spatial rating of the feasible areas that pass the exclusion criteria, ten evaluation criteria were considered. These criteria are related to environmental, economic, resource, and social aspects. It has been selected according to the available literature (e.g., Fetanat and Khorasaninejad, 2015; Wu et al., 2016; Vasileiou et al., 2017; Loukogeorgaki et al., 2018; Wu et al., 2018; Argin et al., 2019) and the availability of data. The selected evaluation criteria are as follows:

- *Wind energy potential:* The wind energy density in a candidate region is very critical for the economic and technological performances of a wind turbine (Höfer et al., 2016). The most preferable areas are those with higher wind energy density (Vasileiou et al., 2017). Therefore, the area with higher wind energy potential would be assigned a higher score.
- *Wave energy potential:* A hybrid power plant focus on the collaborative utilization of wind and wave energy resources. Similarly, the area with a bigger wave energy density gets a higher score.
- *Water depth:* Water depth is related to the foundation cost (Dicorato et al., 2011). It is obvious that the area with the smallest water depth is the most suitable for the implementation of HOWWPP.
- *Distance from electrical grid:* The value score of a suitable marine area is increased by its proximity to an electrical grid since it would reduce costs related to cabling and power losses over long-distance transmission (Höfer et al., 2016).
- *Distance from ports:* Ports can provide support in the installation and maintenance process of HOWWPP. Therefore, the regions with the smallest distances from ports can be regarded as the most suitable ones (Vasileiou et al., 2017).
- *Distance from aquaculture area:* The power-generation equipment would produce noise impact during the running process, having a negative influence on the growth of marine animals due to the generated low frequency of sound waves (Wu et al., 2020). Areas far away from aquaculture areas can be considered as the most suitable ones.
- *Distance from nature conservation areas:* Nature conservation areas include natural parks, natural reserves, flora and fauna habitat, etc., which protect nature and wildlife (Kim et al., 2018). The birds may be hit by turbine blades if turbines locate near their habitats. Consequently, marine areas far away from the nature conservation areas can be considered as the most suitable ones.

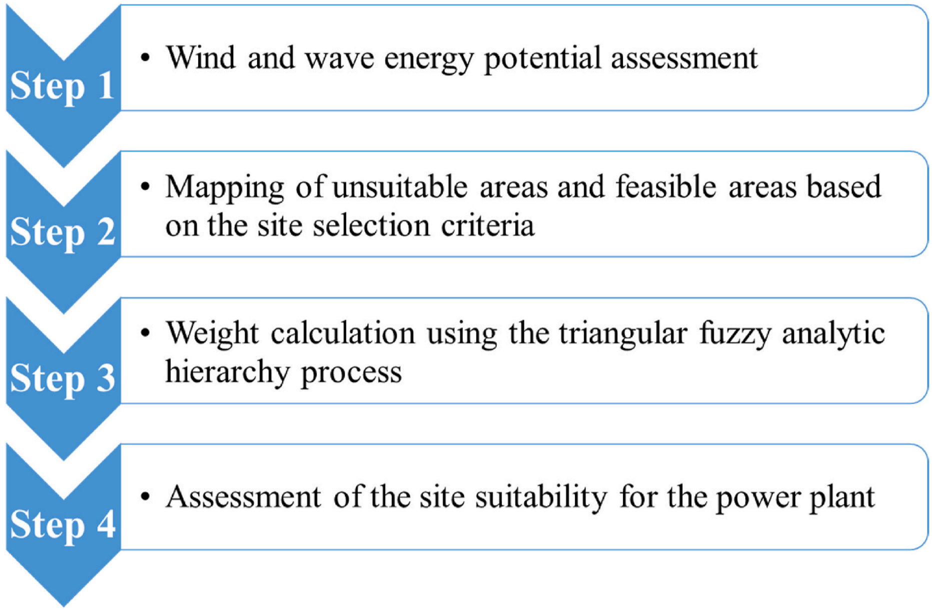

Fig. 2. The flowchart of the proposed methodology.

Table 3
Value scores of the evaluation criteria.

Criteria	Value score					
	Not suitable (0)	Very less suitable (1)	Less suitable (2)	Medium suitable (3)	High suitable (4)	Very high suitable (5)
Wind energy potential (W/m^2)	0–50	50–100	100–150	150–200	200–250	>250
Wave energy potential (kW/m)	0–2	2–3	3–4	4–5	5–6	>6
Water depth (m)	>50	40–50	30–40	20–30	10–20	0–10
Distance from electrical grid (km)	~	58–70	46–58	34–46	22–34	0–22
Distance from ports (km)	~	46–55	37–46	28–37	19–28	0–19
Distance from aquaculture area (km)	0–1	1–8	8–16	16–24	24–32	>32
Distance from nature conservation areas (km)	0–1	1–6	6–12	12–18	18–24	>24
Distance from shore (km)	0–10	26–30	22–26	18–22	14–18	10–14
Electricity demand (billion kW)	~	1–1.5	1.5–2.5	2.5–4	4–6.5	>6.5
Shipping density (number/km^2)	>20	16–20	12–16	8–12	4–8	0–4

Table 4
Triangular fuzzy conversation scale (Lee, 2010).

Linguistic scale	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally important	(1,1,1)	(1,1,1)
Weakly more important	(1,3/2,2)	(1/2,2/3,1)
Moderately more important	(3/2,2,5/2)	(2/5,1/2,2/3)
Strongly more important	(2,5/2,3)	(1/3,2/5,1/2)
Extremely more important	(5/2,3,7/2)	(2/7,1/3,2/5)

Table 5
RI of random (Alonso and Lamata, 2006).

n	3	4	5	6	7	8	9	10	11
RI(n)	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51	1.53

- *Distance from shore:* Distance from shore has an important influence on the maintenance and installation cost (Sarker and Faiz, 2017). Therefore, the most preferable region is those with the smallest distance from shore. However, the distance from shore should be more than 10 km to avoid visual and noise impact (Wu et al., 2018).
- *Electricity demand:* HOWWPP needs to meet consumer demand. The higher the electricity demand, the more necessary the establishment of power plants (Jun et al., 2014). The electricity demand in a candidate area was estimated by the average annual electricity consumption of the local province.
- *Shipping density:* This criterion is related to maritime safety. The ship navigation cannot be disturbed by HOWWPP, thus to avoid collision (Wu et al., 2018). Therefore, the areas characterized by lower traffic flow can be regarded as the most suitable ones.

4. Methodological framework

The methodological framework is based on a combination of MCDM and GIS. MCDM provides a useful method to address such a complex

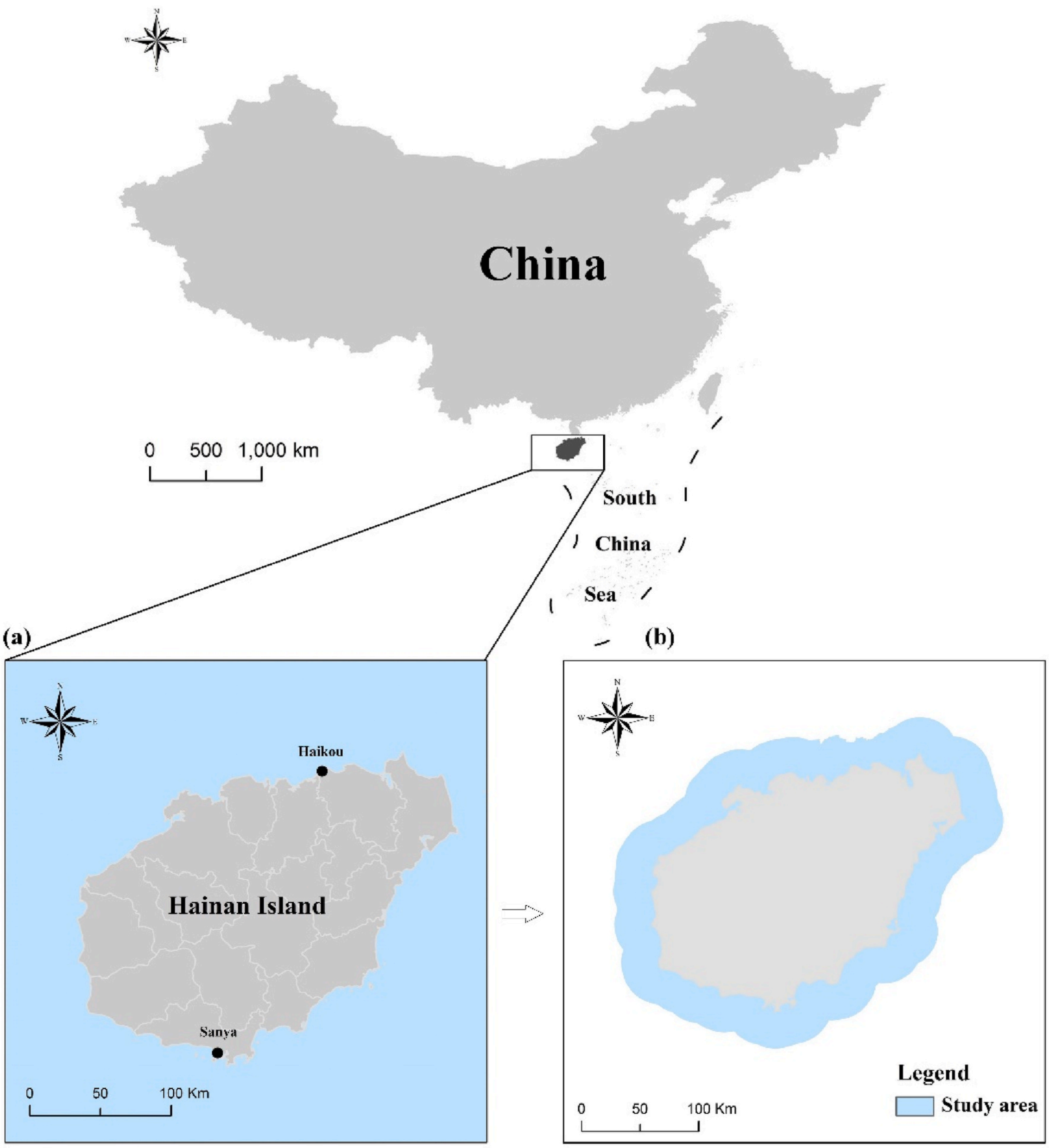

Fig. 3. (a) Location of Hainan Province and (b) Definition of the study area.

decision-making problem (Wu et al., 2020; Barzehkar et al., 2021). The process of applying an MCDM method involves the collection, storage, processing, and analysis of spatial data related to each criterion, which can easily be finished by the application of GIS (Vasileiou et al., 2017). Consequently, the combination uses of MCDM and GIS can provide a powerful tool to effectively solve the marine development planning of offshore renewable energy sources.

The methodological framework for the site selection of HOWWPP comprises four steps, as shown in Fig. 2. In Step 1, wave and wind energy potential are evaluated. Step 2 produces the unsuitable areas map and the feasible areas map according to the site selection criteria. In Step 3, the criteria weights are calculated based on the triangular FAHP. Assessment of the site suitability for the power plant is conducted using the weighted overlay technology in Step 4.

4.1. Energy potential assessment

Sufficient wind and wave energy resources in a candidate area are the foundation for the construction of HOWWPP. Wind energy density is a quantitative indicator of representing the wind energy available, showing the flow of kinetic energy per unit related to the wind given in units of watts per square meter (Kumar et al., 2020). The wind energy density can be calculated as follows (Emeksiz and Demirci, 2019; Zheng et al., 2019):

$$D_{wind} = \frac{1}{2}\rho_a V_h^3 \tag{1}$$

$$V_h = V_{10}\left(\frac{h}{10}\right)^{\alpha} \tag{2}$$

where D_{wind} represents the wind energy density, V_h represents the sea surface wind speed at height h, ρ_a represents the standard sea-level air density (1.225 kg/m^3), V_{10} represents the sea surface wind speed at a height of 10 m, and α represents the surface roughness coefficient set as 0.2 mm. In this study, wind speed at 50 m was calculated since the data included only measurements at a height of 10 m.

Table 6
Dataset and sources.

Data	Period	Source
Water depth	2021	The General Bathymetric Chart of the Oceans (https://www.gebco.net/)
Wind and wave field	2016–2020	European Centre for Medium-Range Weather Forecasts (https://www.ecmwf.int)
Ship location	2017	Chuanxun Wang (http://www.shipxy.com/)
Coastline	2018	Global Self-consistent, Hierarchical, High-resolution Geography Database (https://www.ngdc.noaa.gov/mgg/shorelines/)
Seaport	2021	World seaports catalogue, marine and seaports marketplace (http://ports.com/)
Channel	2020	Yan et al. (2020)
Military activity area	2020	Maritime Safety Administration of the People's Republic of China (https://www.msa.gov.cn/)
Engineering infrastructures	2019	Maritime Safety Administration of the People's Republic of China (https://www.msa.gov.cn/) and the environmental impact assessment report of subsea pipeline in Dongfang (China National Offshore Oil Corporation, 2019)
Electrical grid	2017	The 13th Five-Year Plan of Hainan Province for Electric Power Development (Development and Reform Commission of Hainan Province, 2017)
Nature conservation and resource protection areas	2018	The Tidal Flat Planning of Aquaculture Waters during 2018–2030 (Department of Agriculture and Rural Affairs of Hainan Province, 2018)
	2015	Hainan Comprehensive Planning during 2015–2030 (The People's Government of Hainan Province, 2015)
Electricity consumption	2016–2020	Hainan Statistical Yearbook during 2016–2020 (Hainan Provincial Bureau of Statistics, 2020)

Concerning wave energy potential, similarly, wave energy density can be used to calculate the wind energy available, representing the wave power per unit of crest length. It can be obtained using the following expression (Reguero et al., 2015):

$$D_{wave} = \frac{\rho_w g^2}{64\pi} H^2 T \tag{3}$$

where D_{wave} represents the wave energy density, ρ_w represents the water density, g represents the gravitational acceleration. H represents a significant wave height, and T represents the mean wave period.

4.2. Mapping of unsuitable areas and feasible areas

Based on the criteria system of HOWWPP site selection, a series of spatial maps were created for each criterion using the spatial analysis techniques of GIS. On that basis, the unsuitable area map can be produced by integrating each spatial map of the exclusion criteria. The rest of the marine areas (not satisfying the exclusion criteria) are defined as feasible areas. Furthermore, to classify and rank the feasible areas, a threshold value for each evaluation criterion is necessary. Obviously, choosing an appropriate threshold value for each evaluation criterion would improve results. Table 3 shows the threshold values of evaluation criteria for each suitable class based on a literature survey (Yue and Yang, 2009; Zheng et al., 2013; Zountouridou et al., 2015; Kim et al., 2016; Kamranzad et al., 2017) and expert opinion. According to the threshold values, each evaluation criterion was used to classify the feasible areas for applying the weighted overlay approach.

4.3. Determination of weights using FAHP approach

For obtaining the relative weight of each evaluation criterion, the FAHP approach presented by Calabrese et al. (2013) was used. The relative importance of the items in a pair is compared based on linguistic terms (e.g., weakly more important, moderately more important, etc.). The linguistic values are then converted into triangular fuzzy numbers (TFN) using Table 4. Every TFN includes a triplet (l_{ij}, m_{ij}, u_{ij}) where l_{ij} indicates the smallest value, m_{ij} the most probable value and u_{ij} the highest possible value (Zhou et al., 2020). In this study, five experts were invited to create a pairwise comparison matrix based on the triangular fuzzy conversion scale as shown in Table 4. The experts are from different universities and colleges, e.g., China University of Mining and Technology, Tongji University, and Zhejiang University of Water Resources and Electric Power. Their research fields involve marine spatial planning, renewable energy technology, environmental and sustainability assessment, coastal management, and subsea engineering.

The comparison matrix is as follows:

$$\widetilde{A} = (\widetilde{a}_{ij})_{n\times n} = \begin{bmatrix} (1,1,1) & \cdots & (l_{1n}, m_{1n}, u_{1n}) \\ \vdots & \ddots & \vdots \\ (l_{n1}, m_{n1}, u_{n1}) & \cdots & (1,1,1) \end{bmatrix} \tag{4}$$

where

$$\widetilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) = (\widetilde{a}_{ij})^{-1} = \left(\frac{1}{u_{ji}}, \frac{1}{m_{ji}}, \frac{1}{l_{ji}}\right), \; i,j = 1,\dots,n; i \neq j \tag{5}$$

is a *TFN* that represents the relative importance of item i with respect to j performed from the perspective of the upper-level criterion. $\widetilde{A}$ is a comparison matrix.

Then, the relative weights of the criteria can be obtained by applying the FAHP method to the comparison matrix. The FAHP approach comprises four steps as follows:

Step 1. Conversion of fuzzy matrices

The fuzzy comparison matrix is converted into a crisp comparison matrix using the centroid defuzzification method (Yager, 1981). The translating formula is (Wang and Elhag, 2007):

$$a_{ij}(\widetilde{a}_{ij}) = \frac{l_{ij} + m_{ij} + u_{ij}}{3}, \; i,j = 1,\dots,n \tag{6}$$

Step 2. Consistency test

To justify the degree of consistency of the crisp comparison matrix, the consistency index (CI) and the consistency ratio (CR) are obtained as follows:

$$CI = \frac{(\lambda_{max} - n)}{n-1} \tag{7}$$

$$CR = CI / RI(n) \tag{8}$$

where λ_{max} represents the largest eigenvalue of the matrix, n represents the order of the matrix, $RI(n)$ represents the random index (Table 5).

The matrix is considered as consistent only if CR is smaller than 10% (Forman, 1990). It is necessary to create a new pair-wise comparison judgment when a matrix is inconsistent. The procession has to be continued until the consistency is reached.

Step 3. *Local weights*

Local weights of criteria can be calculated by summing up each row of the matrix $\widetilde{A}$ and then normalizing the row sums to calculate $\widetilde{S}_i$ by Eqs. (9) and (10).

$$\widetilde{RS}_i = \sum_{j=1}^{n} \widetilde{a}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right), \; i = 1,\dots, n \tag{9}$$

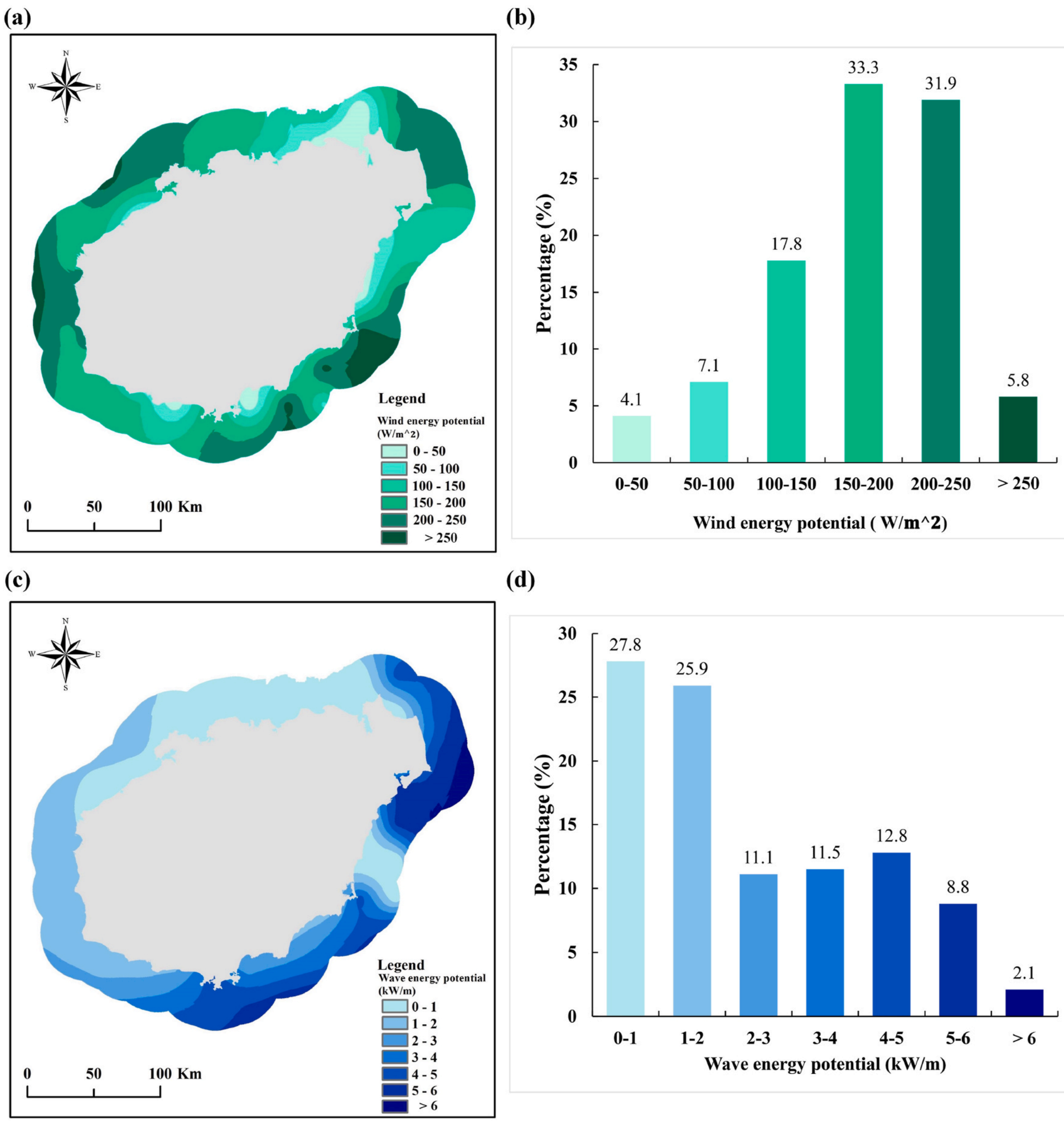

Fig. 4. Distribution of wind and wave energy potential in Hainan Province. (a) Spatial distribution of wind energy potential, (b) area proportions of different levels of wind energy potential, (c) spatial distribution of wave energy potential, and (d) area proportions of different levels of wave energy potential.

$$\widetilde{S}_i = \frac{\widetilde{RS}_i}{\sum_{j=1}^{n}\widetilde{RS}_j} = \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{j=1}^{n} l_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j=1}^{n} u_{kj}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} m_{kj}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{j=1}^{n} u_{ij} + \sum_{k=1,k\neq i}^{n}\sum_{j=1}^{n} l_{kj}}\right) = (l_i, m_i, u_i),\ i = 1, \ldots, n \tag{10}$$

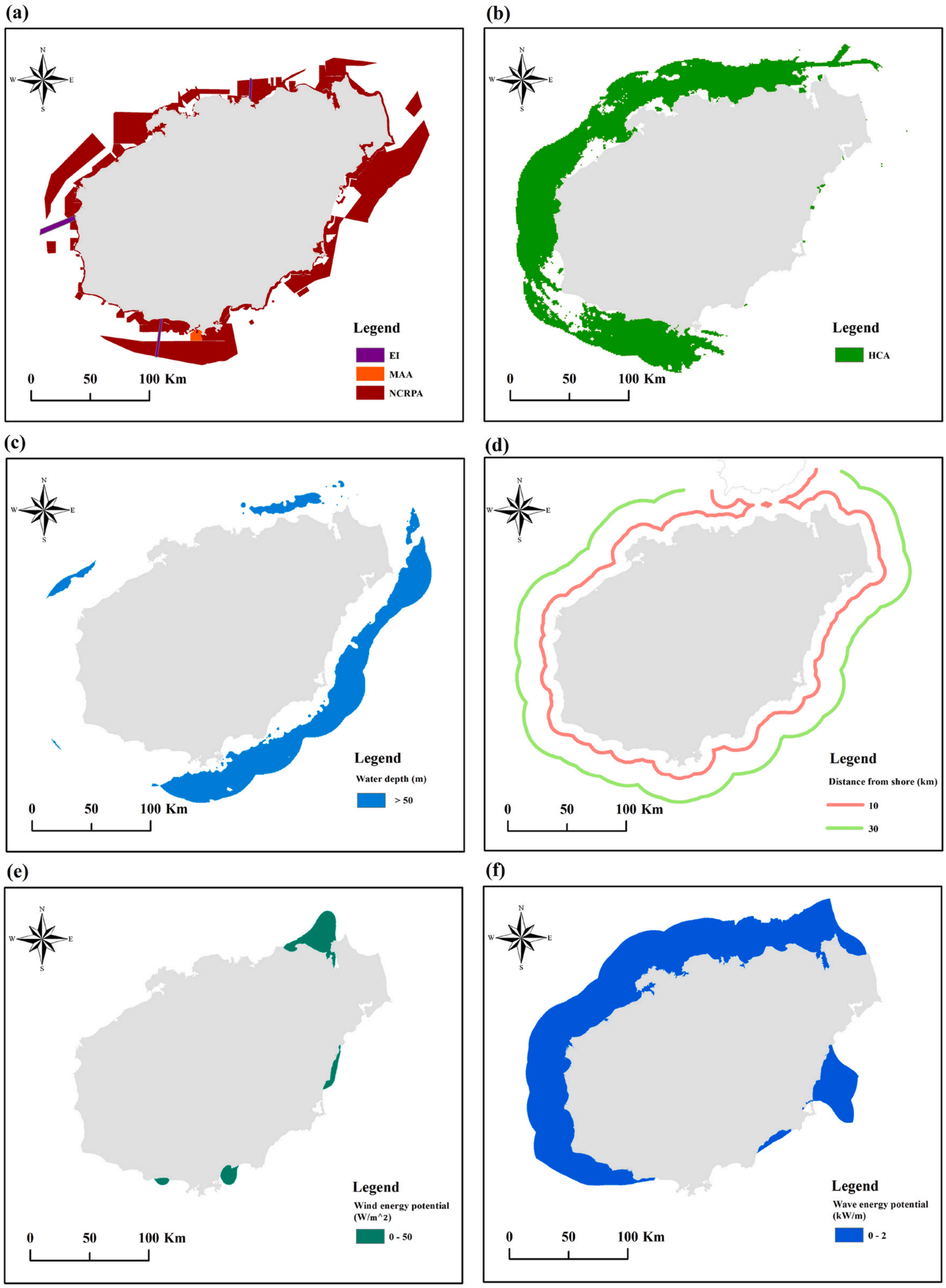

Fig. 5. Maps of each exclusion criterion: (a) engineering infrastructures (EI), military activity area (MAA), and nature conservation and resource protection areas (NCRPA), (b) seaport and channel area (SCA), (c) water depth >50 m, (d) distance from shore <10 km & > 30 km, (e) wind energy potential <50 W/m^2, and (f) wave energy potential <2 kW/m.

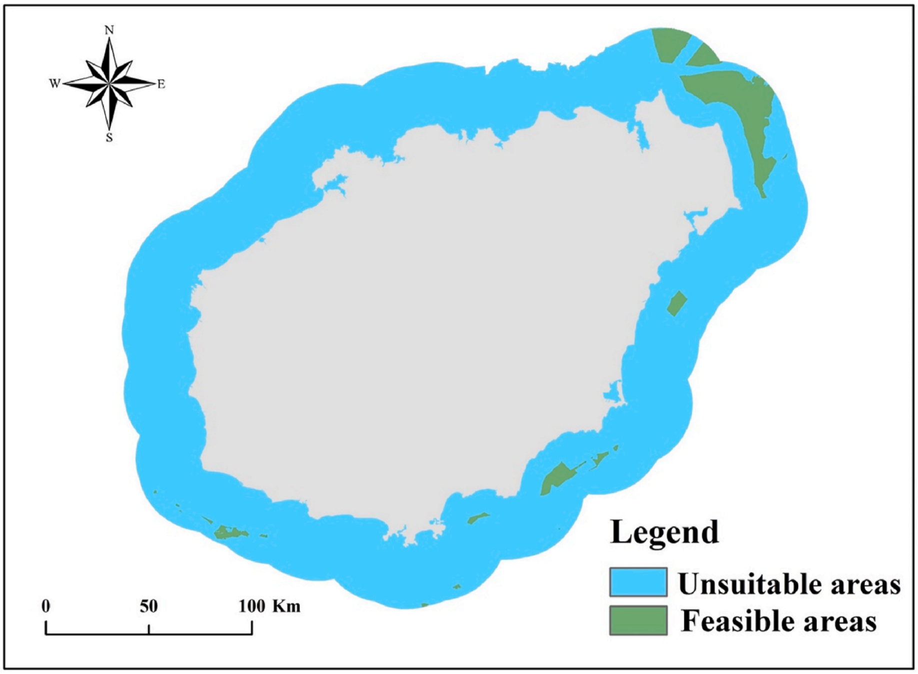

Fig. 6. Distribution of the unsuitable areas and the feasible areas.

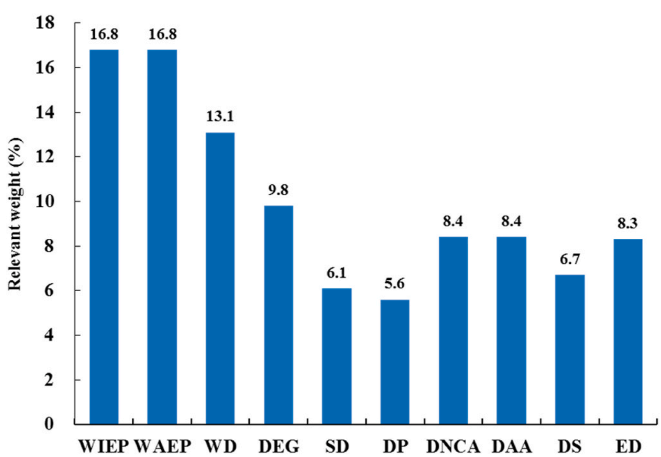

Fig. 7. The weights of evaluation criteria.

Then, the crisp weights (w_i) are obtained converting fuzzy weights as follows:

$$w_i = S_i(\widetilde{S}_i) = \frac{l_i + m_i + u_i}{3}, \ i = 1, \ldots, n \tag{11}$$

After normalization, the normalized crisp weight vectors (W) are:

$$\mathrm{W} = \left(w_1^{'}, w_2^{'}, \ldots, w_n^{'}\right) \tag{12}$$

Step 4. Global weights

Global weights of criteria can be obtained by multiplying local weights of sub-criteria along with the hierarchical structures. The global weights of criteria belonging to the highest hierarchical level are equal to the local weights (Calabrese et al., 2016).

4.4. Assessment of site suitability

The final step of the procedure is to assess and rank the site suitability of the feasible areas using the weighted overlay approach. Specifically, the suitability is classified into five classes (Very Less, Less, Medium, High, and Very High) according to the natural discontinuity grading method in ArcGIS 10.5 software (Xu et al., 2020b). The equations for suitable area assessment are as follows:

$$P_c = \sum_{q=1}^{r} w_{cq} * s_{cq} \tag{13}$$

where P_c represents the suitability score at cell *c*, w_{cq} represents the weight of criterion *q* at cell *c*, and s_{cq} represents the suitable value of criterion *q* at cell *c*, *q=1, …,r,* where *r* represents the number of criteria used in this study.

5. Case study

5.1. Study area and data

China has accelerated the development of renewable energy in response to global climate change in recent years. Among different energy resources, wind and wave energy are abundantly rich in China (Zhou et al., 2015; Wang et al., 2018; Liu et al., 2019). To convert wind and wave into energy, power plant installations are needed (Liao, 2016). Up to now, China has the largest installation of wind power generation capacity, and the installed capacity would reach 400 GW by 2030 (Liu et al., 2019). Wind and wave energy cover most of the new energy yield in China. However, China's power plants generate less electricity than similar-sized power plants in other countries, such as in the United States (Lu et al., 2016). One important reason is that the power plants are not located in an optimal position, e.g., sited in locations with poor energy resources (Lewis, 2016). A suitable site for construing HOWWPP can quickly achieve natural energy goals.

Hainan Province (18°10′– 20°10′N and 108°37′– 111°03′E) is the largest tropical island in China (33,920 km^2). It is located in the north of the South China Sea (Fig. 3a) and separated from mainland China by the Qiongzhou Strait (Xie, 2003; Zhai et al., 2014). Hainan Province has great potential to develop offshore wind energy and wave energy (Hong and Möller, 2011; Lin et al., 2019). The annual wind power density of most of the offshore areas reaches above 150 W/m^2, while the overall

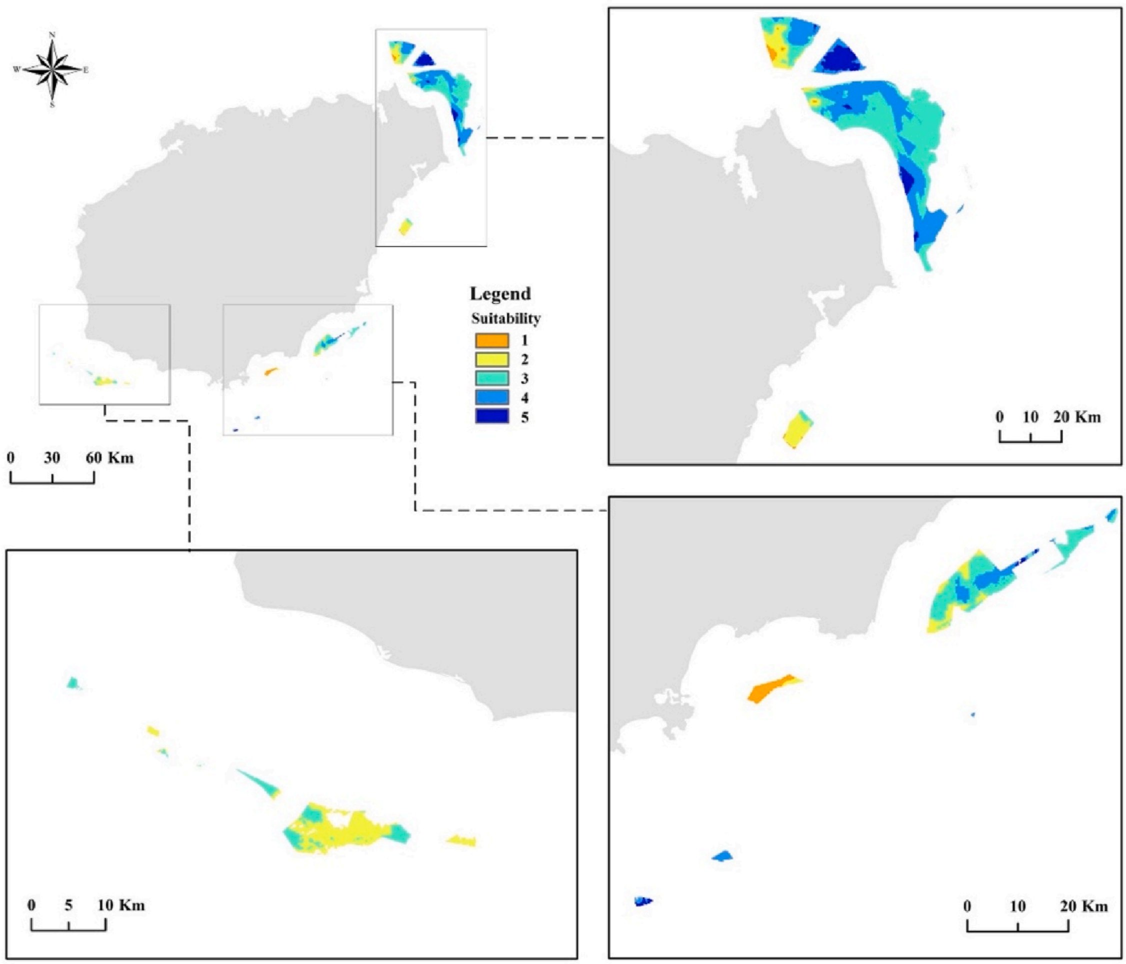

Fig. 8. Suitability area.

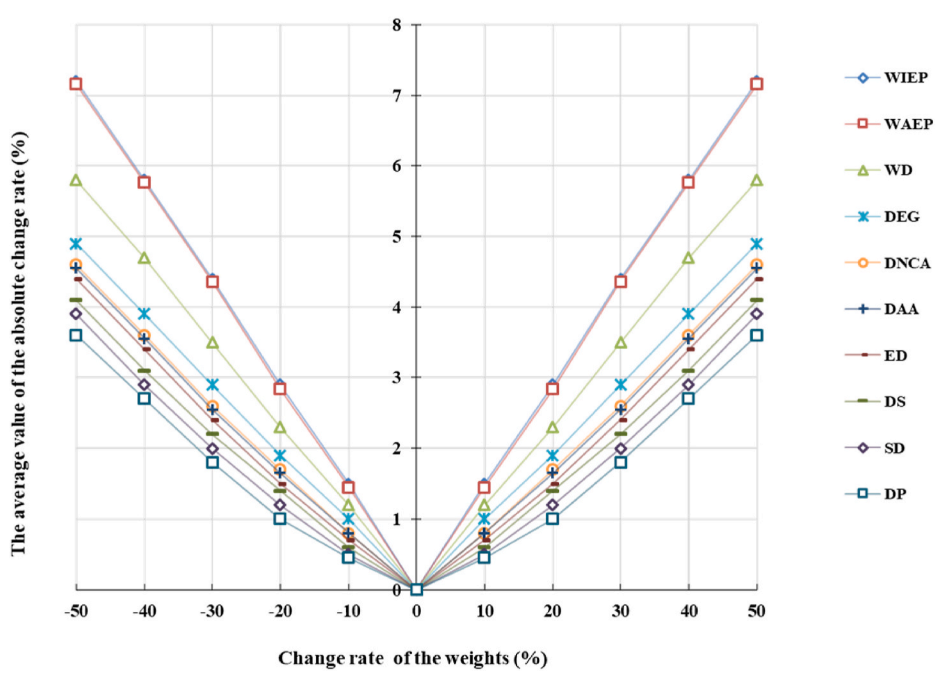

Fig. 9. The average value of the absolute change rate for suitability evaluation under simulations.

occurrences of exploitable wave energy (energy flux >2 kW/m) exceed 50% (Da et al., 2011; Lin et al., 2019). Yue and Yang (2009) pointed out a maximum distance from the shore is 30 km for exploiting offshore energy by considering cost-effectiveness. Therefore, the study area in this paper is these marine areas whose distance from the shore is less than 30 km (Fig. 3b).

The data used in this study were collected from different sources. Table 6 presents a list of the data, including data name, period, and source.

5.2. Result analysis

5.2.1. Energy potential analysis

Regarding wind energy resource utilization, marine areas can be considered available when the wind energy density is higher than 50 W/m^2 (Zheng et al., 2013). Fig. 4a and b shows the spatial variation and area proportions of different levels of wind energy potential in Hainan Province. Only 4.1% of the study area needs to be excluded, mainly located in the northern part sea of Hainan Province and parts of the coastal areas of southern and eastern Hainan Province. Totally, 95.9% of the study area is available, showing great utilization potential. In this aspect, as already shown in various studies (e.g., Da et al., 2011; Wan et al., 2018). Hainan Province has abundant wind energy resources.

Concerning wave energy resource utilization, it is available when the wave energy density is higher than 2 kW/m (Kamranzad et al., 2017). The spatial variation and area proportions of different levels of wave energy potential in Hainan Province are presented in Fig. 4c and d. 46.3% of the study area can be considered available and is mostly concentrated in the eastern and southern sea of Hainan Province. These areas with the lowest level of wave potential (less than 1 kW/m) cover 27.8% of the study area, mainly located in the northern sea of Hainan Province. 25.9% of the study area is located in areas with wave potential ranging from 1 kW/m to 2 kW/m and most of them are located in the western sea of Hainan Province. It is in line with the estimation shown in Lin et al. (2019), which shows that wave energy in these regions continues to be less than 2 kW/m.

5.2.2. Unsuitable areas and feasible areas

Due to legal regulations and physical restrictions, some restricted areas need to be excluded according to the exclusion criteria. Fig. 5 shows the spatial distribution of each exclusion criterion. Most of the areas are considered unavailable due to wave energy potential, water depth, seaport and channel area, and nature conservation and resource protection areas.

Based on these criteria, the unsuitable area map and the feasible area map can be obtained, as shown in Fig. 6. After excluding the restricted marine areas, approximately 5.6% of the study area remains available for wind and wave utilization, which corresponds to 1547.3 km^2. As shown in Fig. 6, these areas in the northeastern sea of Hainan Province show the largest potential according to the size of the feasible areas. In addition, some areas in the southern sea of Hainan Province also have a high potential.

5.2.3. FAHP weights

Using the FAHP technique, the relative weights of each evaluation criterion are obtained, presented in Fig. 7. The pairwise comparison matrix is considered as consistent since CR is equal to 0.04 (<0.1). As shown in Fig. 7, it is clear that the weights of wind energy potential (WIEP) and wave energy potential (WAEP) are the largest (both equal to 16.8%), indicating these two criteria are the most important for estimating the suitability of the deployment of HOWWPP. Water depth (WD) follows with a weight of 13.1%. The weights of these three criteria account for a percentage of 46.7%, showing that the suitability of a sea area for the siting of HOWWPP mostly depends on the available renewable energy sources and the water depth, which are very important factors for making energy systems technically and economically feasible. Distance from electrical grid (DEG) also gets a considerable weight of 9.8%. In addition, distance from nature conservation areas (DNCA) and distance from aquaculture area (DAA) have the same weight (8.4%). The rest of the criteria, i.e., electricity demand (ED), distance from shore (DS), shipping density (SD), and distance from ports (DP), obtain the respective weights of 8.3%, 6.7%, 6.1%, and 5.6%.

5.2.4. Evaluation and ranking of feasible areas

The score maps of marine areas for each evaluation criterion were conducted based on the value scores firstly (see Figure A1 in Appendix A). Then, ten score maps related to the criteria were overlaid by using the weighted overlay technique for producing a suitability map, in which the suitability is categorized into five classes (See Fig. 8). The results show that the marine areas with medium to very high suitability (4.7% of the study area, 1312 km^2) are mainly located in the northeast and southeast of the study area. This is because as follows: wind and wave energy density are relatively high and water depth is suitable for the deployment of HOWWPP in these areas. Moreover, all marine areas with high suitability are farther away from nature conservation, aquaculture area, and ship navigation areas. In the south of the study area, appropriate areas are small and regarded as very less suitable to less suitable zones (0.9% of the study area, 251 km^2). The important criteria that contribute to the results are the distance from aquaculture areas, wave energy potential, or both.

6. Discussions

6.1. Sensitivity analysis

The weight of each criterion is the most sensitive parameter in MCDM, which may result in considerable uncertainty (Höfer et al., 2016). Here, we conducted a sensitivity analysis by changing the weights of each criterion from −50% to 50% with a step size of 10%. The uncertainty of the results was calculated by the average value of the absolute change rate of suitability score (ACR). Fig. 9 shows ACR values for site suitability evaluation. The ACR values show a linear increase with different gradients when the change rate of the weights increases. A higher gradient represents a higher sensitivity of the criterion for the evaluation results (Xu and Zhang, 2013). The ranking of the ACR values for these criteria is as follows: WIEP、WAEP > WD > DEG > DNCA、DAA > ED > DS > SD > DP. It is noted that WIEP and WAEP are the most sensitive, whereas DP is the least sensitive criterion. In addition, all the ACR values are markedly lower than the change rate of the weights, which shows that the evaluation results are relatively reliable (Qiu et al., 2017).

6.2. Data and its limitations

The data used in this study were collected from different sources, such as governments, international organizations, and commercial firms. Data quality can influence the selection of a location in a variety of ways. In general, the accuracy of the result can often be improved with higher resolution data. However, this cannot be achieved forever due to cost restraints and technological limitations within the data collection process (Li et al., 2000). Therefore, wind and wave field data with a resolution of 0.125° was used for calculations in this study, which is an appropriate tradeoff considering computation time and accuracy. In addition, some factors such as seabed geology were not considered due to lack of spatial data, and more complete and accurate spatial data would provide better results. Despite these limitations, however, the result obtained in this study is considered to be effective in supporting decision-making and planning concerning a HOWWPP project.

7. Conclusion

In this study, a four-stage decision framework based on the combination of GIS and MCDM is presented and applied to assess the location suitability of HOWWPP. After assessing wave and wind energy density in potential areas, two sets of criteria, i.e., exclusion criteria and evaluation criteria, are defined according to thorough literature reviews and experts' opinions. The exclusion criteria are used to identify the feasible and unsuitable areas while the evaluation criteria are further applied for ranking the feasible areas. Then, the experts are invited to conduct a pairwise comparison based on the triangular FAHP approach to justify the relative importance of each evaluation criterion. Using the weighted overlay technology, the location suitability map is produced for deploying HOWWPP, in which the suitability is categorized into five classes (i.e., very less, less, medium, high, and very high).

A practical case study was conducted in Hainan Province of China to demonstrate the usefulness of the proposed framework. The suitable area was identified successfully, and the results reveal that the marine areas with medium to very high suitability (4.7% of the study area, i.e., 1312 km^2) are mainly located in the northeast and southeast of the study area, while less and very less suitable zones (0.9% of the study area, i.e., 251 km^2) are found to be mainly concentrated in the southern part of the study area. It is clear that sufficient space will still be available even if those sites that are classified as medium to very high suitability are utilized. The sensitivity analysis further shows a high degree of stability of results. This study found favorable conditions for electricity production from wind and wave in Hainan, China. Moreover, the proposed framework is expected to apply to other marine areas for supporting the site selection process of HOWWPP.

This study has several limitations that require further research and development. First, it is challenging to collect the pairwise comparison matrix provided by experts. Because inviting an appropriate number of experts in different fields is difficult. In addition, further research also needs to investigate the combination of another MCDM method (e.g., TOPSIS) and GIS for the siting of the hybrid energy systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106035.

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