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Application of a GIS-Based Multi-Criteria Decision-Making Approach to the Siting of Ocean Thermal Energy Conversion Power Plants: A Case Study of the Xisha Sea Area, China

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Abstract: In order to achieve the goals of carbon neutrality and reduced carbon emissions, China is increasingly focusing on the development and utilization of renewable energy sources. Among these, ocean thermal energy conversion (OTEC) has the advantages of small periodic fluctuations and large potential reserves, making it an important research field. With the development of the "Maritime Silk Road", the Xisha Islands in the South China Sea will see a growing demand for electricity, providing the potential for OTEC development in this region. Optimal site selection of OTEC power plants is a prerequisite for developing thermal energy provision, affecting both the construction costs and future benefits of the power plants. This study establishes a scientific evaluation model based on the decision-making frameworks of geographic information systems (GISs) and multi-criteria decision-making (MCDM) methods, specifically the analytic hierarchy process (AHP) for assigning weights, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to reclassify the factors, and weighted linear combination (WLC) to compute the suitability index. In addition to commonly considered factors such as temperature difference and marine usage status, this study innovatively incorporates geological conditions and maximum offshore distances of cold seawater based on cost control. The final evaluation identifies three suitable areas for OTEC development near the Xuande Atoll and the Yongle Atoll in the Xisha Sea Area, providing valuable insights for energy developers and policymakers.

Keywords: ocean thermal energy conversion (OTEC); site selection; GIS applications; geo-spatial multi-criteria evaluation

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1. Introduction

According to the World Meteorological Organization's Greenhouse Gas Bulletin, released in November 2023, the concentrations of the three major greenhouse gases—carbon dioxide, methane, and nitrous oxide—in the Earth's atmosphere reached record highs in 2022. The bulletin calls for changes in industrial, energy, and transportation systems, as well as overall lifestyle adjustments. Facing the global challenge of reducing carbon emissions and controlling climate warming, China has set goals for peak carbon emissions and carbon neutrality. Improving the energy structure and increasing the proportion of energy consumption accounted for by new energy sources is imperative. The Xisha Islands are a crucial hub of the 21st Century Maritime Silk Road and an important transportation base in the South China Sea. Currently, the Xisha Islands primarily rely on traditional diesel generators for power generation. As the "Maritime Silk Road" continues to develop, the future electricity demands of the Xisha Islands are expected to increase. On islands far from the mainland, green, environmentally friendly, and renewable ocean energy is a highly suitable choice.

Among marine energy sources, ocean thermal energy is more stable compared to other forms, with smaller periodic fluctuations. Particularly in the South China Sea, ocean thermal energy resources are abundant, and the development conditions are favorable [1]. Ocean thermal energy conversion (OTEC) technology utilizes the temperature difference between the warm surface water and the cold deep water of the ocean, generating electricity based on the Rankine cycle. The specific principle involves using the warm surface seawater to heat and vaporize low-boiling-point working fluids (in the closed cycle), or reducing the pressure to evaporate warm surface seawater (in the open cycle), which drives a turbine to generate electricity [2]. At the same time, the cold seawater extracted from the deep sea condenses the exhaust steam back into liquid form, completing the systemic cycle [2] (see Figure 1). OTEC power plants are mainly divided into land-based types, which are built onshore, and offshore types, which are constructed on fixed platforms or floating structures at sea [2]. Both types of power plant have their advantages and disadvantages. Land-based OTEC power plants can withstand harsher weather conditions and are easier to maintain, but they require long-distance seawater transportation, leading to significant energy consumption. Offshore OTEC power plants are closer to the cold seawater intake area, but are exposed to wave loads, increasing maintenance difficulties [2].

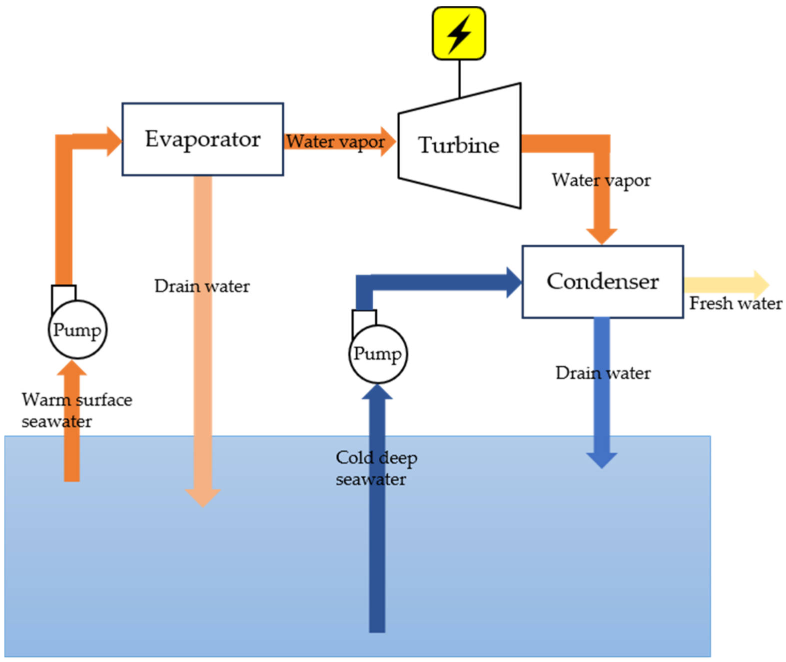

Figure 1. A simple diagram of an open-cycle OTEC system.

OTEC can promote sustainable development for small and medium-sized islands in many ways [3]. In addition to power generation, OTEC technology has a wide range of integrated applications, including desalinated water, deep ocean water applications, and seawater air conditioning [4–7]. OTEC has great development potential and is highly suitable for exploitation in the Xisha Sea Area.

To develop and utilize OTEC in the Xisha Sea Area, it is necessary to analyze site selection issues for OTEC power plants. Both land-based and offshore OTEC require consideration of suitable cold seawater intake locations. Zhang et al. (2016) [8] analyzed potential sites in the South China Sea based on factors such as the temperature difference between surface and deep seawater, seasonal indices, and the distance of cold seawater from the shore. Lynn et al. (2018) [9] considered the temperature difference between surface and deep seawater and salinity as site selection factors. Garduño-Ruiz et al. (2021) [10] adopted a more comprehensive evaluation approach, including factors like the distance of cold seawater from the shore, the temperature difference between surface and deep seawater, the distance from the power plant to the grid, extreme events, protected areas, and socio-economic conditions. Hall et al. (2022) [11] considered temperature differences around the study area, the shortest distance to the coast, the distance to port, marine protected areas, and coastal space usage, resulting in a more comprehensive site selection outcome. However, current research on OTEC site selection in the Xisha Sea Area mainly focuses on factors such as the temperature difference between surface and deep seawater, as well as the distance of cold seawater from the shore, with limited discussion of other elements, as seen in the work of Bai et al. (2018) [12] and Yan et al. (2023) [13]. Additionally, other studies on OTEC site selection have mostly been based on a few pre-determined candidate locations, from which the best sites were then analyzed. This study places greater emphasis on site selection in the entire research area, aiming to identify several candidate locations, a fundamental and necessary step in OTEC site selection research. Moreover, this study incorporates the geological conditions in the research area as one of the evaluation factors, an aspect that has been largely overlooked in other OTEC site selection studies.

For site selection problems involving multiple factors, such as those for OTEC power plants, multi-criteria decision-making (MCDM) methods are commonly used. Nobre et al. (2009) [14] employed a GIS-based MCDM approach to analyze various factors, including water depths, seabed sediment types, underwater cables, marine protected areas, port locations, coastlines, grid locations, military exercise zones, significant wave heights, and wave periods, for selecting a wave energy farm site on the southwest coast of Portugal. Shorabeh et al. (2022) [15] also used a GIS-based MCDM approach for wind farm site selection, considering factors such as wind speed, distance to large power plants, distance to small power plants, altitude, and vegetation. Shao et al. (2023) [16] adopted a GIS-based MCDM approach to evaluate multiple factors for tidal energy power plant site selection. Büyüközkan et al. (2024) [17] proposed a novel MCDM approach for selecting regions with the potential for developing renewable energy resources, such as biogas energy, geothermal energy, hydro energy, solar energy, and wind energy, in Turkey. Elkadeem et al. (2024) [18] utilized a GIS-based MCDM approach to identify and classify areas suitable for installing agrivoltaic systems in Sweden. Mazzeo et al. (2020) [19] emphasized the need to consider the integrated effects of geographical, climatic, and economic factors when planning and making decisions regarding renewable energy systems. This study employs the GIS-based MCDM method to conduct a comprehensive multi-factor evaluation for OTEC power plant site selection in the Xisha Sea Area. The GIS-based MCDM method has rarely been used for OTEC site selection, and no previous studies have applied this approach in the Xisha Sea Area for OTEC site selection with a comprehensive consideration of multiple factors. This paper aims to obtain a relatively objective and comprehensive result for the Xisha Sea Area through this method, providing a theoretical basis for future OTEC development.

The structure of this study is as follows: Section 2 describes the data and analysis methods used in this study. Section 3 outlines the exclusion and weighted factors considered during site selection, and provides the redistribution results of the weighted factors, ultimately identifying suitable locations for OTEC development. Section 4 presents the discussion, and Section 5 concludes the study.

2. Materials and Methods

2.1. Study Area

The Xisha Sea Area is located in the northwestern slope area of the South China Sea (15°43′~17°07′ N, 111°11′~112°54′ E). This area contains more than 40 islands, islets, reefs, and sandbanks, which are administered by Sansha City, Hainan Province, with the city government seated on Yongxing Island. The residents of the Xisha Islands primarily live on Yongxing Island, Zhaoshu Island, Yagong Island, and Jinqing Island. Figure 2 shows the geographical location and topography of the Xisha Sea Area, with red dots indicating the locations of inhabited islands. The bathymetric data is sourced from GEBCO [20]. The seabed topography of the Xisha Sea Area is closely related to the distribution of the islands, with the terrain generally sloping steeply from the center of the islands and then gradually leveling off. Surrounding the islands are relatively flat continental slopes, with water depths ranging between 800 and 1500 m [21]. The Xisha Sea Area is located in a low-latitude region with abundant solar radiation, receiving approximately 2900 h of sunlight annually. As a result, the region experiences high temperatures year-round, with an average annual temperature of 26–27 °C [21]. According to population statistics, the Xisha Islands have about 2000 permanent residents [22].

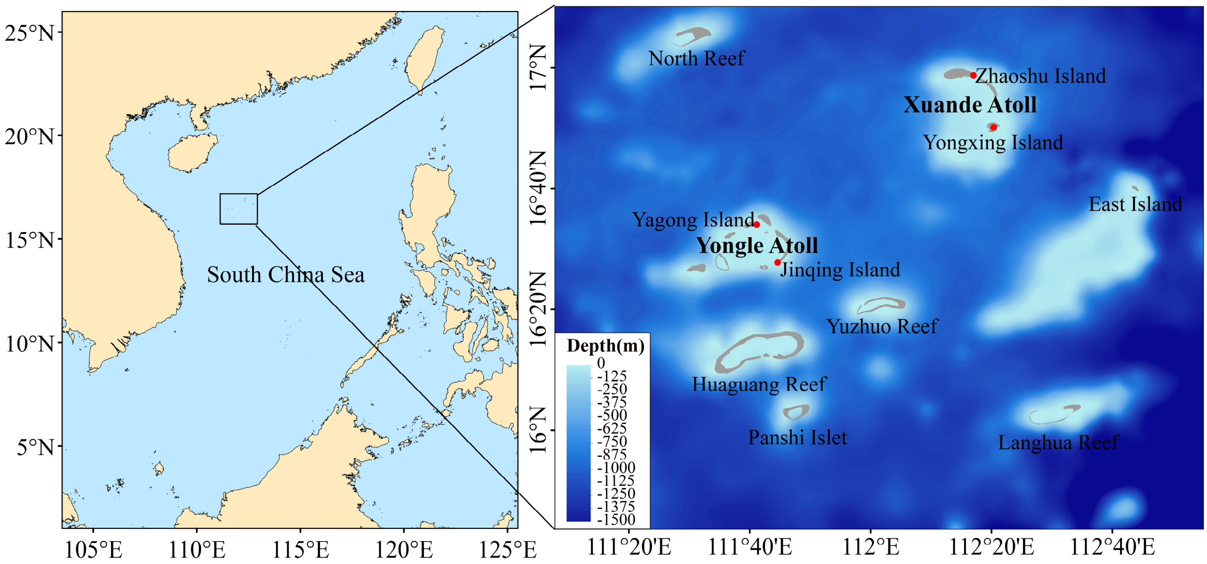

Figure 2. Study area with bathymetric data sourced from GEBCO. Red dots indicate the locations of inhabited islands.

2.2. Data

(1) Seawater Temperature Data

This study uses seawater temperature data from the Hybrid Coordinate Ocean Model (HYCOM) reanalysis [23–25]. These data are part of the Global Ocean Data Assimilation Experiment of the United States. The horizontal grid employs the Arakawa C-grid and a standard Cartesian coordinate system, while the vertical uses hybrid coordinates. The HYCOM with hybrid coordinates provides a more accurate representation of the real ocean compared to traditional models using a single vertical coordinate system. This study collected HYCOM seawater temperature data from 1994 to 2015, with a spatial resolution of $1/12° \times 1/12°$, a temporal resolution of 1 day, and 40 vertical layers.

(2) Marine Geological Data

This study collected maps of surface sediment type distribution and seabed geological hazard distribution in the Xisha Sea Area. These maps, which are derived from internal sources, are the results of geological surveys conducted by the Guangzhou Marine Geological Survey from 2014 to 2017 in the Xisha Sea Area.

(3) No-Anchoring Zone and Shipping Routes

The no-anchoring zone and shipping routes information used in this study are sourced from the global shipping information service system [26].

Table 1 provides an overview of the data layers used in this study, including details such as the layer name, source, spatial resolution, and layer type (vector or raster).

Table 1. Thematic layers used.

Layer Name	Source	Spatial Resolution	Layer Type
HYCOM seawater temperature	Naval Research Laboratory, Florida State University.	$1/12° \times 1/12°$	raster
Geological hazards	Guangzhou Marine Geological Survey	-	raster
No-anchoring zone and shipping routes	Beijing Guojiaoxin Communication Technology Development Co., Ltd.	-	raster
Mud content in seabed sediments	Guangzhou Marine Geological Survey	-	raster

2.3. GIS-Based Muti-Criteria Decision-Making Methods

GIS-based multi-criteria decision-making (MCDM) methods have become modern decision support systems that integrate spatial data with value judgments to solve complex spatial suitability problems [27]. Geographic information systems (GISs) are tools used for collecting, storing, analyzing, and interpreting all types of spatial and geographical data, and enable the management of spatial data through a graphical database. GISs allow for the visualization and geo-mapping of spatially referenced data, while the MCDM approach helps to structure the decision-making process by enabling the weighting of multiple conflicting criteria and the ranking of decision alternatives [27].

After importing seawater temperature data, marine geological data, no-anchoring zones, and shipping route information into ArcGIS, analysis can be conducted based on their geographical characteristics and spatial relationships. This study employs MCDM methods to comprehensively analyze these data. The MCDM approach is a systematic method for the comprehensive analysis of the influencing factors relevant to decision objectives, ultimately leading to decision solutions. When using this method, it is common to assign weights to each influencing factor and to score each factor with a suitability value, which is a numerical result on a given scale [14].

This study uses the analytic hierarchy process (AHP), a commonly used method for weighting evaluation criteria, to assign weights to various factors [28]. The basic idea of the AHP [29] is to decompose a complex decision-making problem into a hierarchical structure of interrelated levels, and to perform pairwise comparisons of factors at each level to determine their relative importance within that level. Simplified, if there are n different and independent factors (A_1, A_2, …, A_n) to consider for the site selection of OTEC power plants, their weights are (W_1, W_2, …, W_n). Although the exact weights are not known in advance, pairwise comparisons of the factors can be made, and a relative importance scale (Saaty scale) ranging from 1 to 9 can be used to express these comparisons (see Table 2). These comparisons can be represented in an $n \times n$ matrix A, as shown in Equation (1). Here, a_{ij} represents the Saaty score of factor i relative to factor j, with a_{ij} values according to Table 2, and a_{ji} being the reciprocal of a_{ij}.

Table 2. AHP Pairwise Comparison Matrix [29].

Importance Preference	Saaty Scale (a_{ij})
A_i and A_j are equally important	1
A_i is slightly more important than A_j	3
A_i is significantly more importance than A_j	5
A_i is very significantly more important than A_j	7
A_i is extremely more important than A_j	9
Intermediate values	2, 4, 6, 8

After obtaining the comparison matrix A, the consistency ratio (CR) has to be calculated. When the CR is less than 0.1, it indicates that the matrix is consistent and can be used to calculate the weights. The method for calculating the CR is detailed in Equation (2), where

CI is the consistency index, λ_m is the principal eigenvalue of the comparison matrix, and RI is the random index, which depends on the matrix size (n) and is listed in Saaty (1980) [30].

To calculate the weights of the factors, the sum of each column in the matrix is computed to obtain S_j (see Equation (3)). Each element in a column is then divided by the corresponding column sum to obtain the normalized values. The average of the normalized values for each row is then used to determine the weight W_i (see Equation (4)) of each factor.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ . & . & \dots & . \\ . & . & \dots & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (1)$$

$$CR = \frac{CI}{RI} = \frac{\lambda_m - n}{n-1} \quad (2)$$

$$S_j = \sum_{i=1}^{n} a_{ij} \quad (3)$$

$$W_i = \frac{1}{n}\sum_{j=1}^{n} \frac{a_{ij}}{S_j} \quad (4)$$

After assigning weights, each factor needs to be quantitatively analyzed to obtain specific values according to a given scale. This study employs the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for quantitative assessment of each factor [31,32]. TOPSIS uses "distance" to measure the proximity of each alternative to the ideal solutions. There are two types of ideal solutions: the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS). For each factor, the distances between the factor's conditions and the PIS and NIS are calculated to obtain normalized scores. The TOPSIS helps in selecting the alternative that is closest to the PIS and farthest from the NIS.

Finally, a multi-criteria evaluation is conducted using the Weighted Linear Combination (WLC) method. This approach multiplies the normalized score of each factor by its corresponding weight to obtain an overall suitability index which is used to identify optimal areas with potential for OTEC development within the study area. The formula for calculating the overall suitability index is as follows:

$$SI_k = \sum_{i=1}^{n} W_i x_{ik} \quad (5)$$

where SI is the suitability index of cell k, W_i is the weight of factor i, and x_{ik} is the normalized score for factor i at cell k.

Figure 3 illustrates the decision-making framework used in this study. All the work is based on the GIS. After defining the study area, we determined the exclusion criteria and evaluation criteria through a literature review and data collection (these criteria are provided in Section 2.4). The exclusion criteria help identify areas with potential for OTEC development. Using an MCDM approach, weights are assigned to each evaluation criteria and reclassified to a normalized score. Then, WLC is applied to perform a weighted overlay analysis, which further identifies the suitability area.

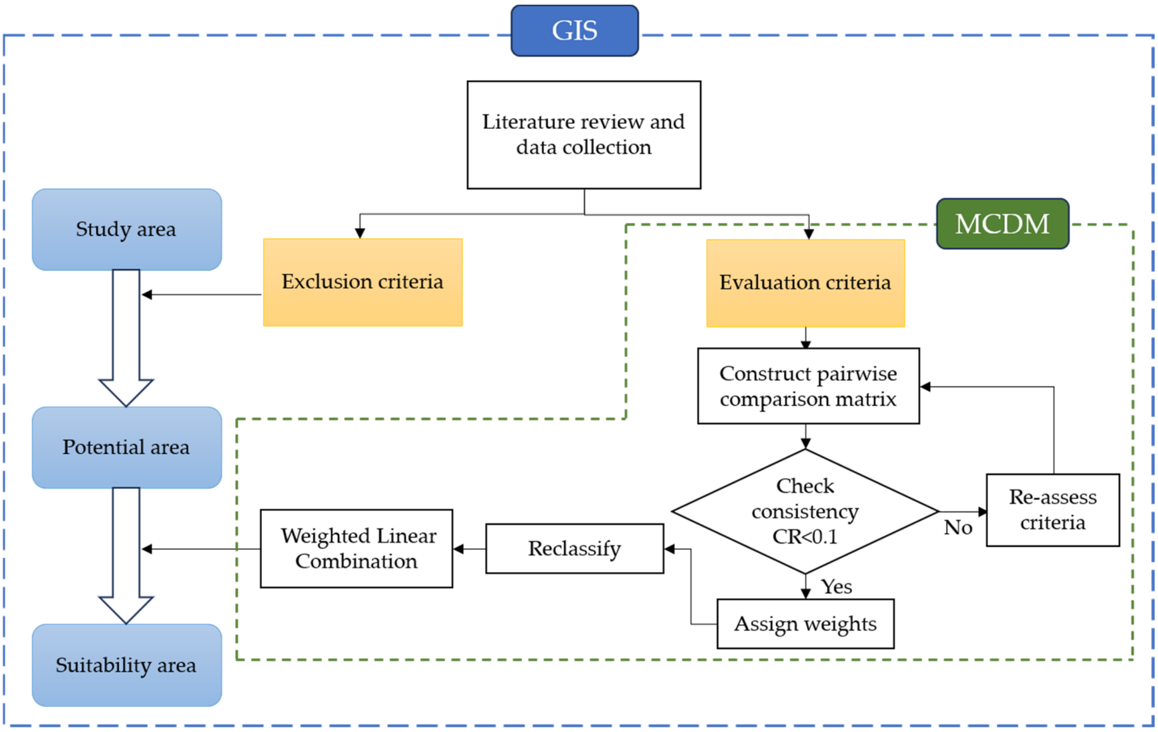

Figure 3. Framework for site selection of OTEC in Xisha Sea Area.

2.4. Criteria for Site Selection

2.4.1. Exclusion Criteria

The farther an OTEC power plant is located from the shore, the higher the associated costs and energy losses [33]. The International Renewable Energy Agency (IRENA) considers that for small islands, the cost of building an OTEC plant is relatively high, but it is economically feasible if the plant is constructed within 10 km of the coast [34]. In the book *Offshore Ocean in China: Marine Renewable Energy*, published by China's State Oceanic Administration, it is stated that building an OTEC plant within 20 km of the shore incurs acceptable costs [35]. To maximize the assessment area, we chose the relatively flexible distance of 20 km. This study also designates the following locations as unsuitable for deployment:

(1) Areas with Submarine Geological Hazards

Submarine geological hazards within the study area include active faults, shallow bedrock, and buried paleo-river channels. These hazards could trigger submarine landslides that could affect subsea structures such as the submarine cables or seawater intake pipelines associated with OTEC power plants [36–38]. Therefore, it is recommended to avoid areas with submarine geological hazards (Figure 4).

(2) No-anchoring Zones

No-anchoring zones are defined areas established as routing measures primarily to protect sensitive marine habitats, such as seagrass beds, coral reefs, and shellfish beds, or to prevent anchor damage to underwater infrastructure like pipelines and cables. Activities such as sand dredging, piling, anchoring, and trawling are strictly prohibited within these zones. The no-anchoring zone in the Xisha Sea Area is represented as a narrow, claw-shaped area enclosed by red dashed lines in Figure 5. This narrow no-anchoring zone extends from the northwestern part of the study area to the Xisha Islands and branches into two paths at the Yongle Atoll—one extending southwestward and the other eastward past Yongxing Island, then turning southward.

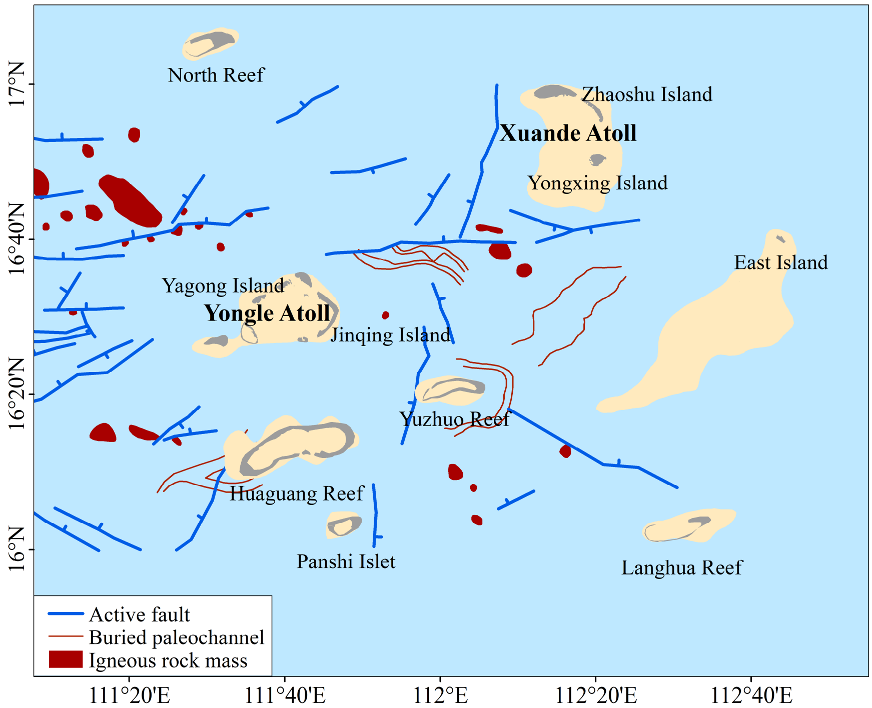

Figure 4. Distribution of geological hazards.

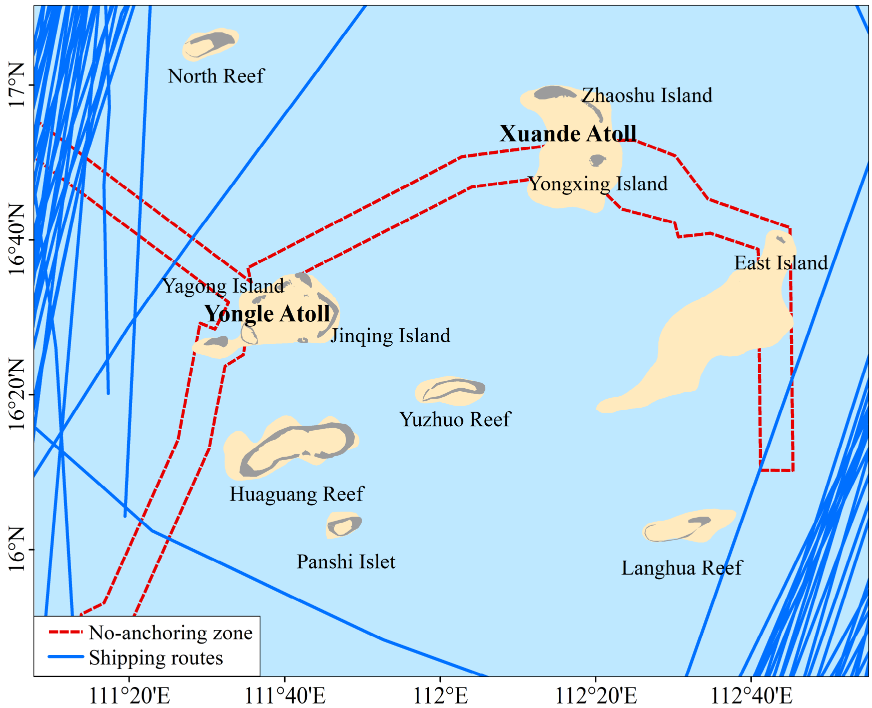

Figure 5. No-anchoring zone and shipping routes.

(3) Shipping Routes

OTEC power plants should avoid shipping routes to protect the power generation facilities and prevent interference with normal vessel operations. According to maritime chart information provided by the Global Shipping Information Service (https://www.myships.com/index.html (accessed on 25 May 2024)), large vessels such as Very Large Crude Carriers (carrying more than 200,000 tons), Aframax tankers (carrying less than 120,000 tons), and Suezmax tankers (carrying around 150,000 tons) pass through the surrounding waters of the Xisha Sea Area (shown as blue solid lines in Figure 5).

2.4.2. Evaluation Criteria

The factors considered for weighting include:

(1) Temperature Difference Between Surface and Deep Seawater

OTEC technology generates power by exploiting the temperature difference between warm surface water and cold deep seawater. Therefore, this temperature difference is a critical factor in OTEC site selection, as areas with larger temperature gradients are typically more favorable for efficient energy generation, making it a key focus when evaluating potential locations [8–13]. The generally accepted optimal temperature difference for OTEC development is around 18~20 °C [1]. However, the temperature difference between surface and deep seawater in the ocean does not always fall within this range, so the temperature difference needs to be considered as a weighted factor. For an OTEC system, the greater the temperature difference, the higher the system's efficiency [39].

(2) Distance to Inhabited Islands

Not all islands in the Xisha Sea Area are inhabited. The main inhabited islands include Yongxing Island, Zhaoshu Island, Yagong Island, and Jinqing Island. For a land-based OTEC plant, it is preferable for the cold seawater source to be as close to the shore as possible, since pipelines must be laid to extract deep cold seawater. For an offshore OTEC plant, the issue of power transmission must be considered. The distance of the cold deep seawater source from the shore has consistently been one of the key considerations in OTEC development [8–13], as longer pipelines can increase both construction and maintenance costs, making proximity to the shore a critical factor in site selection. The transmission of electricity through submarine cables inevitably leads to significant energy loss and high installation costs, so close proximity to the shore is also preferable for these systems. Generally, it is recommended that the horizontal distance between the cold seawater source and the shore should not exceed 20 km [35].

(3) Distance to the Nearest Islands

If close proximity to inhabited islands is not possible, the closer to any island, the better. Areas situated more than 20 km from the nearest island are not considered suitable for the cold seawater intake area of an OTEC plant.

(4) Mud Content in Seabed Sediments

The construction of an OTEC plant requires the laying of seawater pipelines or submarine cables to extract deep-sea cold seawater or transmit electricity. To protect against damage from bottom trawls and ship anchors, the pipelines and cables typically need to be buried in the seabed [40–42]. Different types of seabed sediments can affect the stability of these pipelines or cables [41–43]. For a floating OTEC plant that requires anchor-based mooring, the sediment type also affects the stability of anchoring. Generally, submarine cables, pipelines, and anchors are laid on sand or mud, and usually not on rocks [43,44]. If the geotechnical resistance is low, the sediments are prone to erosion, leading to reduced stability [42]. When the mud content is 25–50%, erosion resistance is strong, but as mud content increases further, erosion resistance gradually weakens [41,45]. Therefore, in this study, the mud content in the sediments is used to assess the suitability for anchoring and laying submarine cables or pipelines.

All the criteria used for site selection in this study are listed in Figure 6.

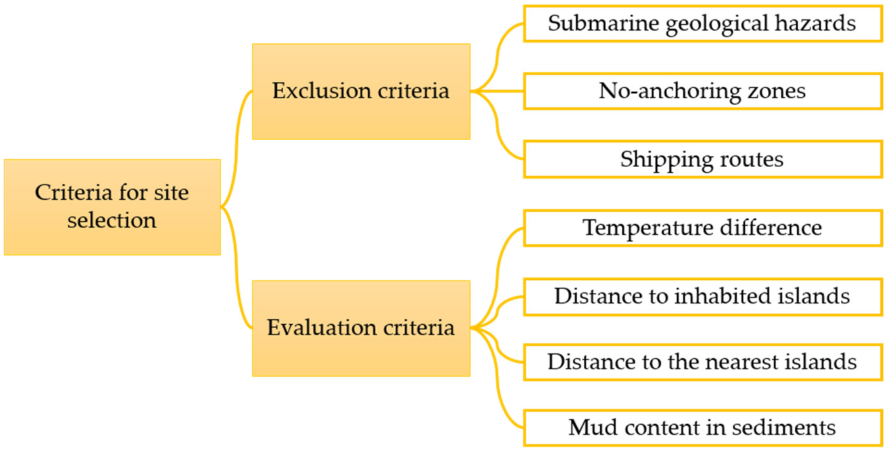

Figure 6. Summary of criteria in this paper.

3. Results

3.1. Potential Marine Areas

The potential marine areas within the study region are shown in Figure 7. This figure is derived from overlays of thematic maps such as seabed geological hazard zones, the no-anchoring zone, and shipping route areas, with areas beyond 20 km from the coastline removed. The potential marine area in the study region is 9153.8 km^2, accounting for approximately 29.8% of the study area. It is primarily located around several major islands and reefs in the Xisha Sea Area. The potential development regions are largely concentrated around uninhabited islands and reefs but are fragmented due to constraints such as the no-anchoring zone and geological hazards.

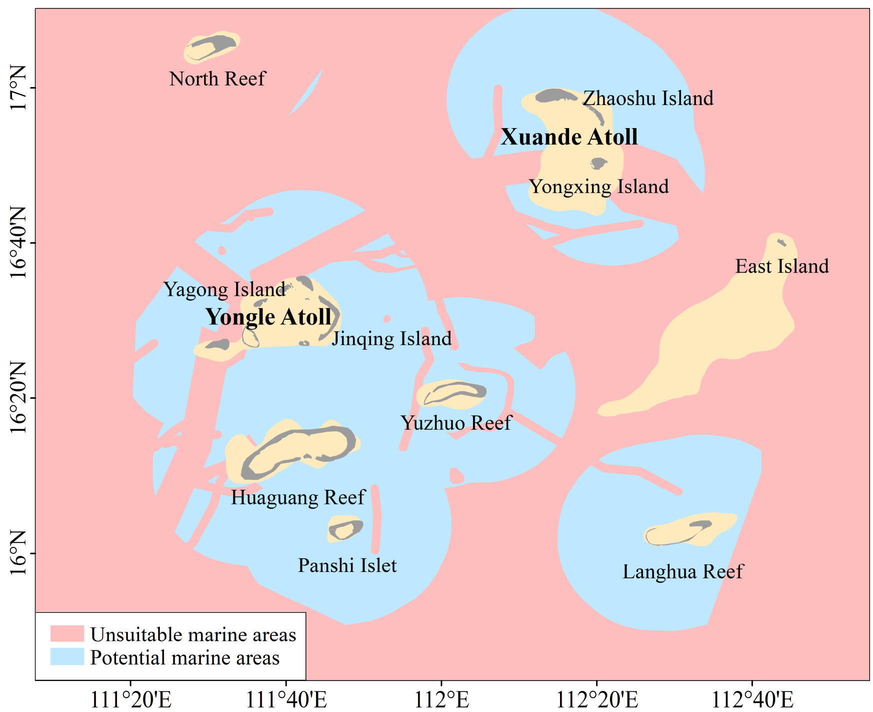

Figure 7. Potential marine areas.

3.2. Weighting Factors

The AHP method was used to assign weights to each quantifiable factor, prioritizing them based on their relative importance.

(1) Temperature Difference Between Surface and Deep Seawater

For an OTEC system, the temperature difference between warm surface water and cold deep seawater significantly affects the efficiency of the thermal cycle. The greater the temperature difference, the higher the efficiency [46]. If the temperature difference is too low, the system may not produce a positive power output. Therefore, the temperature difference is the most critical factor.

(2) Distance to Inhabited Islands

Inhabited islands are the main sources of power demand. The closer the development site is to inhabited islands, the lower the losses in power or cold seawater transmission, which can reduce construction costs and facilitate maintenance and emergency response. However, this factor is less critical than temperature difference, which directly affects power generation efficiency.

(3) Distance to the Nearest Islands

Although inhabited islands are the primary consideration, other uninhabited islands may serve as relay points or support sites for power transmission. When ideal sites are not available near inhabited islands, considering the distance to all islands can provide more flexibility in site selection. Nonetheless, this factor is less important than seawater temperature difference and distance to inhabited islands.

(4) Mud Content in Seabed Sediments

The mud content in seabed sediment primarily affects the design of the anchoring system for offshore OTEC plants, the laying of cables or seawater pipelines, and potential environmental impacts during installation [47]. Although mud content influences construction complexity and stability, it has a relatively minor direct impact on power generation efficiency and power transmission. Therefore, compared to other factors, seabed sediment type is relatively less important.

Thus, the factors are ranked in order of importance as follows: temperature difference between surface and deep seawater, distance to inhabited islands, distance to nearest island, and mud content in seabed sediments. The comparison matrix is shown in Equation (6). The *CR* of this comparison matrix is 0.043, which is less than 0.1, indicating that the matrix has good consistency. Using the AHP method, the weights of these factors were determined, as shown in Table 3.

$$A = \begin{bmatrix} 1 & 3 & 5 & 7 \\ 1/3 & 1 & 3 & 5 \\ 1/5 & 1/3 & 1 & 3 \\ 1/7 & 1/5 & 1/3 & 1 \end{bmatrix} \tag{6}$$

Table 3. Criteria weights used in this study.

Criteria	Weight
Temperature difference	0.5579
Distance to inhabited islands	0.2634
Distance to nearest island	0.1219
Mud content	0.0569

3.3. Reclassification of Factors

Different weighted factors have varying characteristics, scales, and measuring units. Therefore, a common comparable scale needs to be defined. The TOPSIS method is used to re-evaluate each weighted factor for potential marine areas in the study region, reclassifying them into a universal scale of 0 to 1, where 0 represents the worst value for OTEC development potential and 1 represents the best value. The reclassification results are shown in Figures 5 and 6.

(1) Temperature Difference Between Surface and Deep Seawater

In this study, the temperature difference is calculated using surface seawater temperature and deep seawater temperature. If the water depth is less than 1000 m, the deep seawater temperature is taken from near the seafloor. If the water depth is at least 1000 m, the temperature at 1000 m depth is used. The calculated temperature difference is shown in Figure 8a. Generally, the temperature difference increases with distance from the islands. In areas beyond 20 km from the islands, the temperature difference can exceed 20 °C. The TOPSIS method is applied to reclassify the temperature difference for quantitative analysis, setting the NIS at 18 °C and the PIS at 20 °C. The quantized results are normalized, and the reclassified results are shown in Figure 8b, where areas with greater temperature differences have higher values.

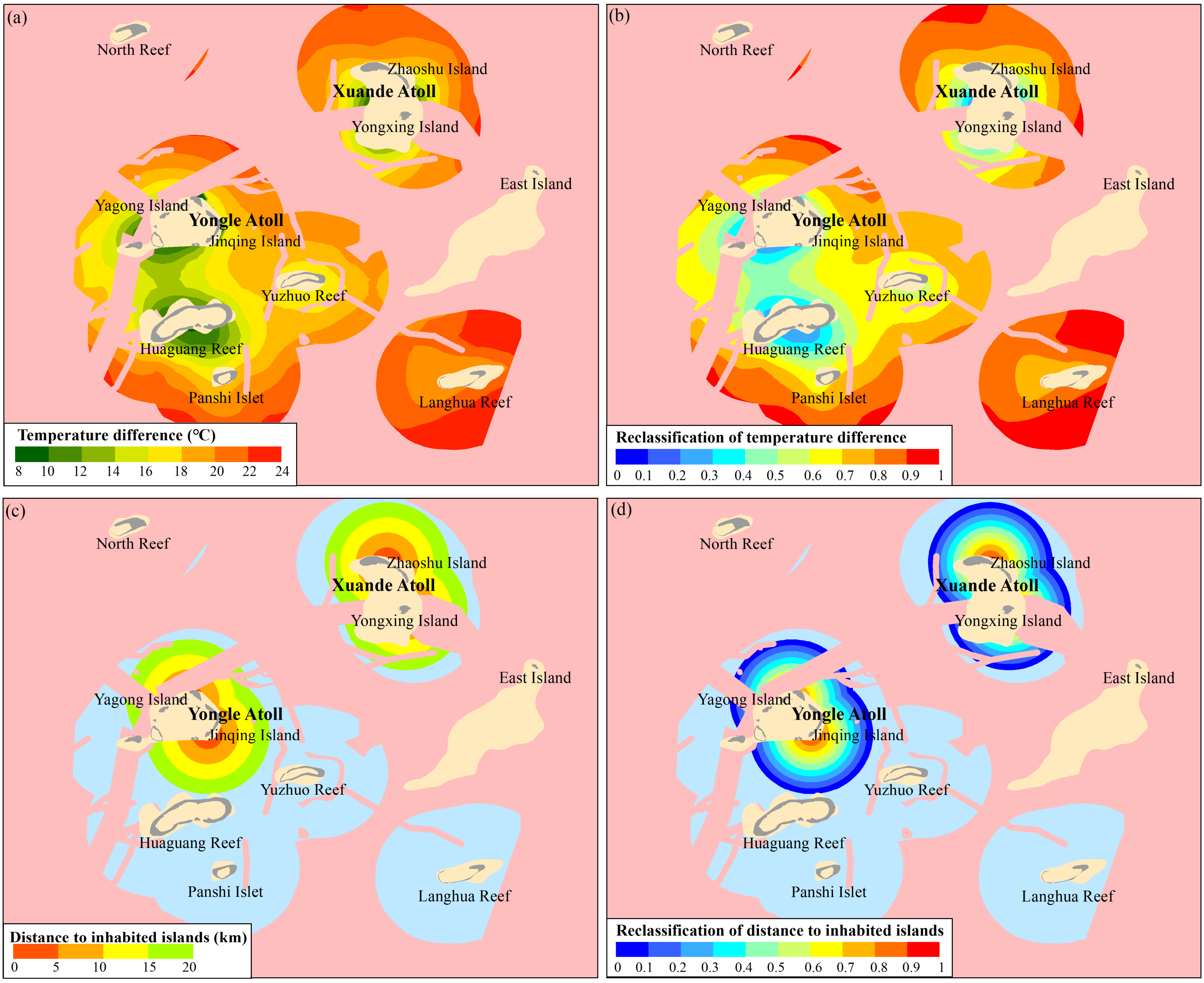

Figure 8. (**a**) Temperature difference; (**b**) reclassification of temperature difference; (**c**) distance to inhabited islands; (**d**) reclassification of distance to inhabited islands.

(2) Distance to Inhabited Islands

Residents in the study area mainly live on Yongxing Island, ZhaoShu Island, Yagong Island, and Jinqing Island. To control the costs of power transmission or pipeline construction for the OTEC system, areas beyond 20 km from inhabited islands are not considered suitable for OTEC development or as cold seawater intake areas. The distances to these four inhabited islands are shown in Figure 8c, with the NIS set at 20 km and the PIS set at 0 km. Areas closer to inhabited islands have higher scores. The reclassified results are shown in Figure 8d.

(3) Distance to the Nearest Islands

Although other islands are not primarily residential areas, they still hold the potential for OTEC development. Figure 9a shows the distances to the nearest islands within the study area. Areas situated more than 20 km from the nearest islands are not considered suitable for OTEC development. The Negative Ideal Solution (NIS) is set at 20 km, and the Positive Ideal Solution (PIS) is set at 0 km. As before, closer distances to the nearest island result in higher scores. The reclassified results are shown in Figure 9b.

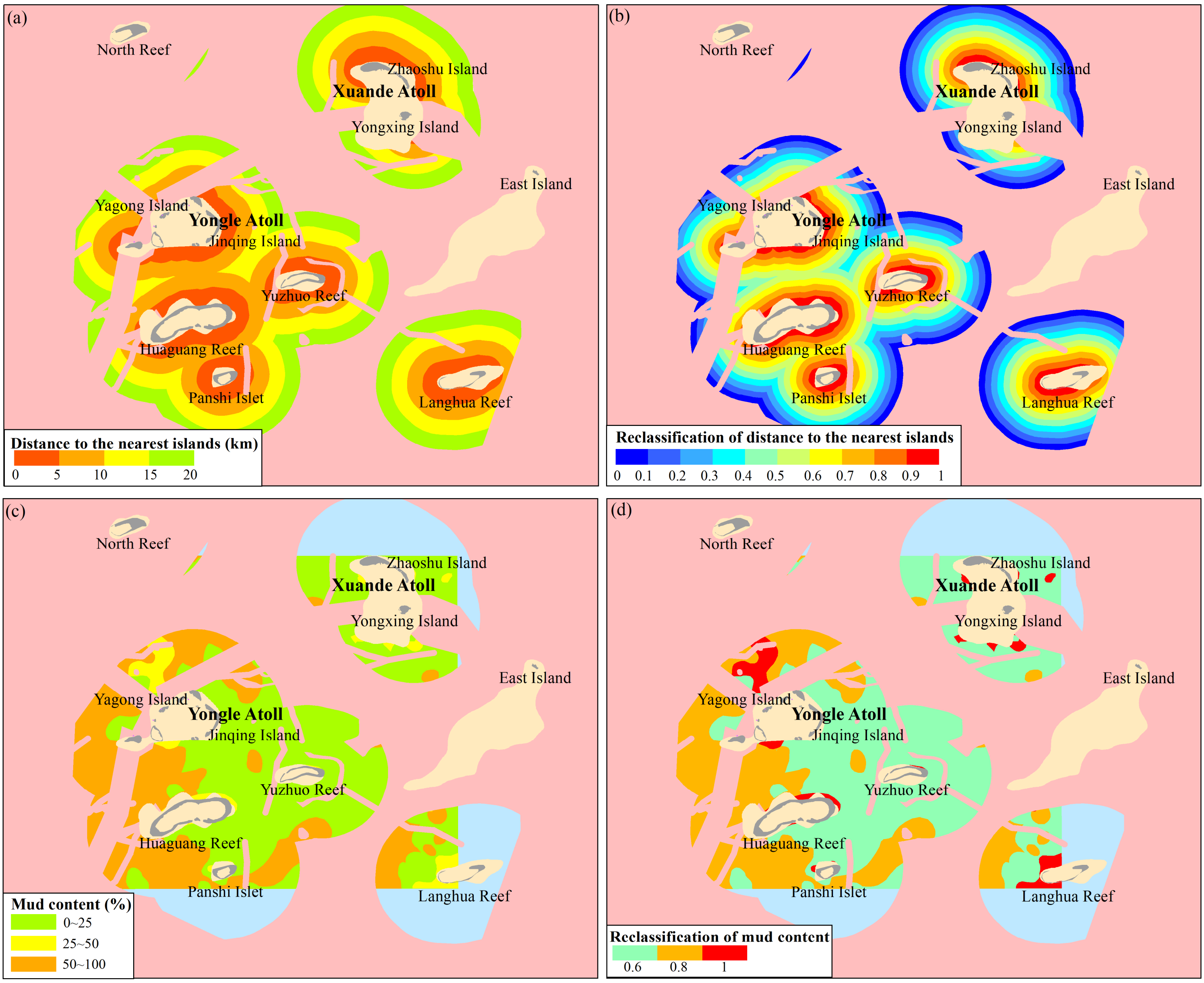

Figure 9. (**a**) Distances to the nearest islands; (**b**) reclassification of distance to the nearest islands; (**c**) mud content; (**d**) reclassification of mud content.

(4) Mud Content in Seabed Sediments

The seabed sediments in the study area are mainly sand–mud mixtures, which are relatively suitable for laying seabed cables or pipelines. This study evaluates the erosion resistance of sediments based on mud content, as shown in Figure 9c. When the mud content is less than 25%, the erosion resistance is weak; when the mud content is between

25% and 50%, the erosion resistance peaks; however, as the mud content increases further, erosion resistance gradually decreases but remains slightly stronger than sediments with mud content less than 25% [41,45]. The reclassification results for mud content are shown in Figure 9d, with scores decreasing in the order of mud content ranges of 25–50%, 50–100%, and less than 25%.

3.4. Suitability Index

After reclassifying each factor to a common scale, the suitability index (SI) is calculated by combining these values with the weighted factors (Figure 10). Due to incomplete coverage of seabed sediment type data in the study area, regions without sediment data were assigned a median value of 0.8 for the SI calculation. These areas are marked with black diagonal lines in the figure to indicate that the SI results may be less accurate.

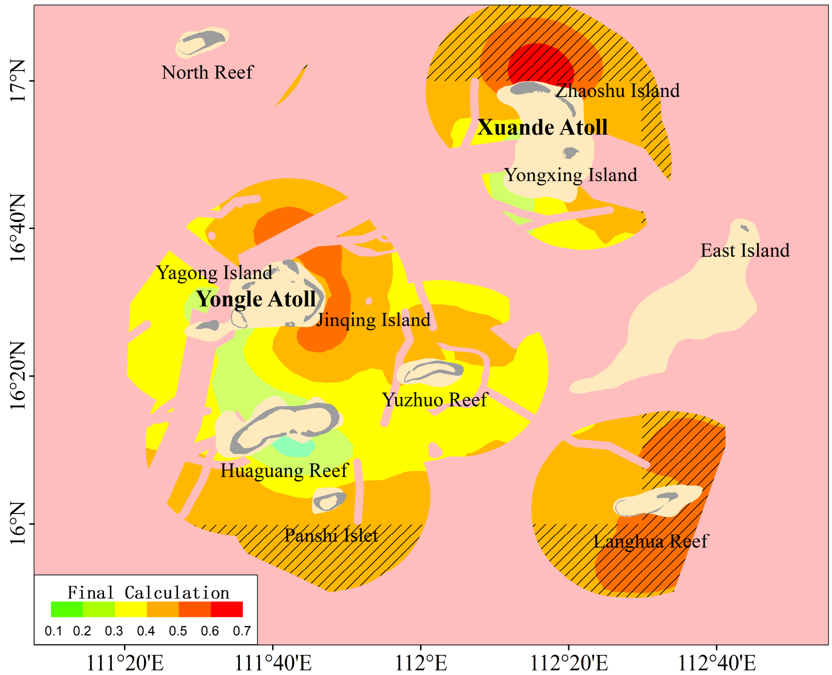

Figure 10. Suitability index.

The results indicate that most areas around the reefs have an SI greater than 0.5, making them generally suitable for OTEC cold seawater intake zones, such as the eastern and northern waters of the Yongle Atoll, the eastern and northern waters of the Xuande Atoll, the northern waters of the Yuzhuo Reef, the Panshi Islet, and the surrounding waters of the Langhua Reef. Small portions of the area have SIs greater than 0.6, making them very suitable for OTEC cold seawater intake zones, such as the waters east of the Yongle Atoll, north of the Xuande Atoll, and around Langhua Reef. A very small portion of the area, located north of the Xuande Atoll, has an SI exceeding 0.7, making it particularly suitable for OTEC cold seawater intake zones. The remaining areas with an SI less than 0.5 are less suitable for OTEC cold seawater intake zones.

3.5. Suitable Site Selection

Based on the SI results, four areas have been identified as highly suitable for OTEC cold seawater intake zones (areas with an SI greater than 0.6): the northern area of the Xuande Atoll, the eastern area of the Yongle Atoll, the northern area of the Yongle Atoll, and the waters surrounding the Langhua Reef. Except for the area around the Langhua Reef, which is quite distant from inhabited islands, the remaining two areas are located near inhabited islands, such as Jinqing Island and Zhaoshu Island.

The eastern area of the Yongle Atoll is the most suitable for development, as it is relatively narrow and lies very close to several islands east of the atoll. It is also in close proximity to Jinqing Island, one of the inhabited islands, offering favorable development conditions and a strategic location. The most suitable site for an OTEC plant could be here, located equidistant from both Yagong Island and Jinqing Island, to supply power to both islands. Alternatively, the OTEC plant could be built directly on Jinqing Island to reduce costs.

The northern area of the Yongle Atoll is moderately suitable for development, as it is relatively close to Yagong Island, one of the inhabited islands, but is separated by a no-anchoring zone. If a shore-based OTEC plant or an offshore OTEC plant that transmits electricity to the island is to be constructed, the laying of submarine pipelines or cables would face significant regulatory challenges. It is recommended to construct an offshore OTEC plant combined with seawater-based hydrogen production or other energy storage methods at this location, utilizing more flexible power transmission methods.

The area north of Zhaoshu Island is generally suitable for an OTEC plant, offering excellent geographical positioning and favorable temperature difference conditions between surface and deep seawater. If an OTEC plant is built here, it could supply power to both Zhaoshu Island and Yongxing Island, the two inhabited islands. However, this area lacks seabed sediment data.

Among the four areas, the Langhua Reef is the most remote and lacks seabed sediment data in its surrounding waters. The cost of transmitting electricity from an OTEC plant at this location would be relatively high.

Therefore, this study identifies the eastern waters of the Yongle Atoll, the northern waters of the Yongle Atoll, and the northern waters of the Xuande Atoll as areas with development potential. It is recommended to prioritize the development of the eastern waters of the Yongle Atoll, as this area is close to inhabited islands and is almost centrally located in the Xisha Sea Area. If an OTEC plant, combined with seawater-based hydrogen production, is constructed here, the energy could also be transported to other inhabited islands. The northern area of the Xuande Atoll is the second most highly recommended for development, as it also offers favorable natural conditions for the construction of an OTEC plant and is closer to Yongxing Island, the seat of the Sansha City Government, providing a reliable power supply for important facilities.

4. Discussion

The South China Sea is rich in OTEC resources, offering stable energy that can be effectively exploited year-round [48]. Among these areas, the Xisha Sea Area also supports year-round exploitation, with cold deep seawater close to shore, providing favorable development conditions [13,49]. China could initially conduct early-stage development trials of OTEC in the Xisha Islands [50], where some scholars have already conducted site selection research for OTEC power stations [8,12,13]. A comparison of their site selection results with those of this study is shown in Figure 11. The development sites recommended by refs. [8,12] are marked by a green dot east of Yongxing Island in Figure 11. The sites recommended by ref. [13] are represented by four red triangles in the figure. These studies considered the distribution of OTEC resources and the distance from Yongxing Island.

There is some similarity between their site selection results and those of this study. For example, one of the sites in reference 13 is located within the potential development area identified in this study, specifically in the northern waters of the Xuande Atoll. This consistency likely arises from the fact that both this study and previous ones prioritize the seawater temperature difference, which is crucial for the normal operation of OTEC plants.

However, there are also notable differences. The site selections in refs. [8,12,13] are primarily concentrated around Yongxing Island, with most sites located to the east of the island. Three of these sites fall within the no-anchoring zone, where the construction of OTEC facilities would likely encounter significant policy resistance. Another site, farther from Yongxing Island, is within a region that this study identifies as generally suitable for cold seawater intake zones for OTEC plants based on the SI. Previous studies did not consider the potential for OTEC development near the Yongle Atoll, but instead focused on site selection around Yongxing Island. The main reason for this difference is that this study conducts site selection for OTEC plants across the entire Xisha Sea Area, taking into account not only the distance from Yongxing Island but also from other inhabited islands, which better reflects the electricity demand in the Xisha Sea Area. In addressing distance factors, this study limits the distance to 20 km based on cost control considerations. By combining the distance factor with the temperature difference and suitable geological conditions, we identified a broader area suitable for development, providing a wider range of options for policymakers involved in OTEC development in the Xisha Sea Area. Moreover, by excluding no-anchoring zones, shipping routes, and seabed geological hazard zones during the site selection process, this study avoids selecting sites in areas unsuitable for OTEC construction, thereby reducing potential construction challenges and policy resistance, and offering developers a more feasible decision-making framework.

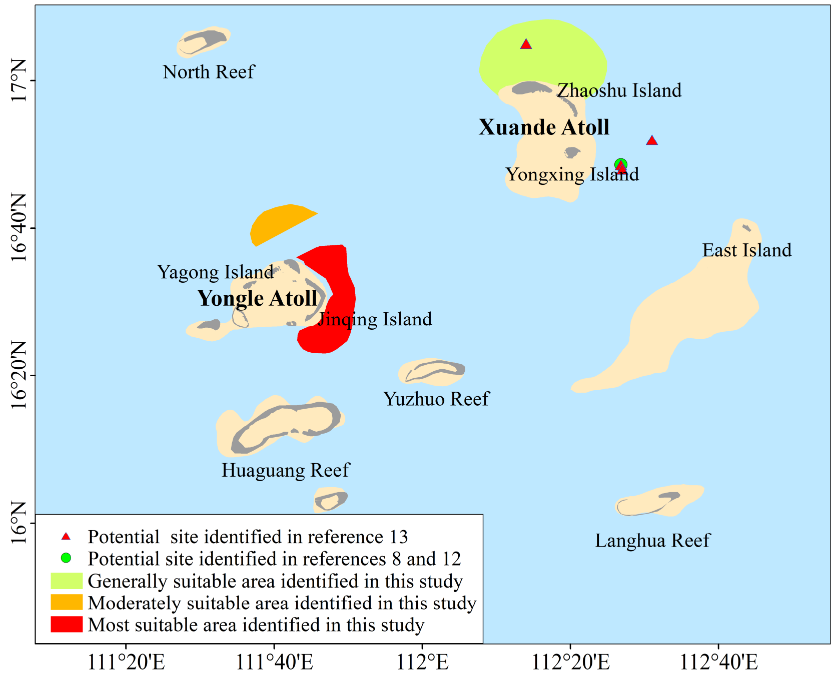

Figure 11. Comparison of potential sites for OTEC.

Nevertheless, this study has certain limitations, as the factors considered in the evaluation are not comprehensive. For instance, we were unable to obtain planning data from the Sansha City government for the Xisha Sea Area, so we could not rule out the possibility of including protected natural areas or military zones where offshore engineering may not be permitted. Additionally, our information on seabed geology is incomplete. Therefore, policymakers and energy developers should further investigate the planning and geological conditions in the Xisha Sea Area when referencing the results of this study to ensure that their projects face minimal policy resistance and operate under safe construction and operational conditions.

To enhance the accuracy of site suitability results in future research, additional exclusion criteria should be considered. These criteria may include underwater archaeological and historical areas, military zones, marine protected areas, and underwater cables and pipelines. Although the current permanent population in the Xisha Sea Area is only about 2000, we believe that with the development of the Maritime Silk Road, the number of residents and tourists in the Xisha Sea Area will increase. Therefore, beaches, tourist zones, and bathing water sites of excellent quality should also be included in the exclusion criteria. Furthermore, additional evaluation criteria, such as distance from local ports, distance from marine protected areas, distance from bathing waters of excellent quality, and proximity to power facilities, should be incorporated. The inclusion of these criteria may reduce the area and number of regions suitable for OTEC development, making the suitable areas more dispersed or remote, which could lead to increased development costs. However, excluding underwater archaeological and historical areas, military zones, marine protected areas, and underwater cable and pipeline zones can reduce the risk of encountering policy resistance during project development and increase the feasibility of project approval. Additionally, locating OTEC projects away from marine protected areas and high-quality water bodies can minimize potential impacts on ecosystems and promote sustainable development. Avoiding tourist areas and high-quality bathing waters can help improve public acceptance and reduce potential social conflicts.

The research methodology can be further improved by conducting sensitivity analyses on the site selection results, examining how changes in the weights of different evaluation criteria affect the outcomes, thereby helping to validate the rationality of the evaluation framework. After obtaining the site selection results, computational models can be used to simulate the selected areas, assessing potential environmental impacts and economic benefits to verify the reliability of the site selection results.

5. Conclusions

In response to global warming and to reduce carbon emissions, China has set carbon peaking and neutrality goals while increasing its focus on renewable energy. With the development of the Maritime Silk Road, the Xisha Islands, a key maritime hub, are expected to face greater power demands. The Xisha Sea Area holds significant potential for ocean thermal energy conversion (OTEC) development.

This study addresses the critical issue of OTEC plant site selection in the Xisha Sea Area using a GIS-based multi-criteria decision-making approach. By setting exclusion criteria (e.g., geological hazards, no-anchoring zones, and shipping routes) and evaluation criteria (e.g., temperature differences and proximity to inhabited islands), we identified four suitable areas for OTEC development: the northern and eastern waters of the Yongle Atoll, the northern waters of the Xuande Atoll, and the waters around the Langhua Reef. The most promising sites for development are the eastern waters of the Yongle Atoll and the northern waters of the Yongle Atoll, followed by the northern area of the Xuande Atoll. However, the Langhua Reef is too remote for cost-effective electricity transmission. The northern waters of the Yongle Atoll may be ideal for offshore OTEC plants combined with energy storage, while both the Yongle and Xuande Atolls are suitable for shore-based or offshore plants due to their proximity to inhabited islands.

This study aims to provide theoretical support for policymakers or energy developers in deciding on the construction of OTEC plants in Xisha, and the method can also be applied to other areas of the South China Sea, providing a reference for decision-makers considering the development and utilization of ocean thermal energy in the South China Sea.

However, this study is only preliminary, basic research, and there are still many limitations. In the future, we will further incorporate social, environmental, and military–political factors into our evaluation framework, and validate our results through sensitivity analysis and modeling simulations to enhance the reliability, feasibility, and public acceptance of the site selection outcomes.

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