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Integrated monitoring and assessments of marine energy for a small uninhabited island

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Abstract

Marine renewable energy (wind energy, wave energy, and tidal current energy) has important application potential for the construction and development of uninhabited islands, however, it is necessary to assess the richness and stability of resources before energy development. In this study, a marine renewable energy integrated monitoring system was deployed on a small island, Dongluo Island, in the northwestern South China Sea. Based on the observation data over one year, the energy density and availability are systematically assessed. The results show that the renewable energy resources in the sea area around the island have a certain utilization potential, in which the average wind energy density is 81 W/m^2 and the available frequency is 44.6%, the average wave energy density is 1.74 kW/m and the available frequency is 29.2%, and the average tidal current energy density is 32.4 W/m^2 and the available frequency is 18.4%. All three types of energy propagation directions are relatively uniform. In addition, because the seasonal variations of the intensity and stability of the three types of energy are different, the three energy resources show obvious complementary advantages. Although the available frequency of single energy is relatively low, the available frequency will be significantly improved by comprehensively superimposing the three resources. Therefore, for the energy development of the island, it is necessary to integrate and optimize the allocation of different types of marine energy resources.

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Keywords: Energy assessment; Wind energy; Current energy; Wave energy; Uninhabited island

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1. Introduction

Marine renewable energy (e.g., wind energy, wave energy, and tidal current energy) has the advantages of clean, sustainable utilization and great development potential [1]. Island is an isolated zone of energy supply and this issue should be specially considered when it comes to a demand for electricity [2]. Particularly, due to the finite power consumption of small islands and being far away from the mainland, it is difficult and costly to lay a power grid for the islands. Developing ocean energy is an important way to satisfy island power consumption, avoiding problems involved in long-distance power transmission [2–4].

Several studies have been carried out by different authors on the assessment of marine energy, depending on numerical models [3,5,6] and corresponding reanalysis products [4,7,8]. Most of their data were validated by satellite measurement. However, for adjacent areas of small islands, the accuracy of satellite remote sensing or numerical models is usually insufficient due to the rough resolution of data and the limitation of numerical models on the ability to characterize island-scale dynamic processes [5]. Therefore, to assess the marine energy for the waters around the islands, field observations are usually required.

In addition, for the monitoring and assessment of marine energy in islands or offshore areas, it is necessary to synchronously monitor and assess multiple energy types, namely wind energy, wave energy, and tidal current energy. This is because the properties and dynamic processes of winds, waves, and tidal currents are different, and thus the characteristics of different types of energy vary [9]. To make comprehensive use of different types of energy, it is necessary to perform a systematical analysis on the magnitude and variability of all different sources, using data from the same locations or regions, with the same temporal resolution and the comparable metrics [9,10].

In this study, comprehensive monitoring and evaluation of wind, wave, and tidal current energy are carried out on Dongluo Island, a small unmanned island in the northwestern South China Sea (Fig. 1). Real-time monitoring is conducted on the elements of the offshore wind field, wave, and current around the island. Based on more than one year of data, the energy density and variation regularity of wind, wave, and current energy near the island is assessed. According to the assessment results, strategies for utilizing the island's marine energy were discussed.

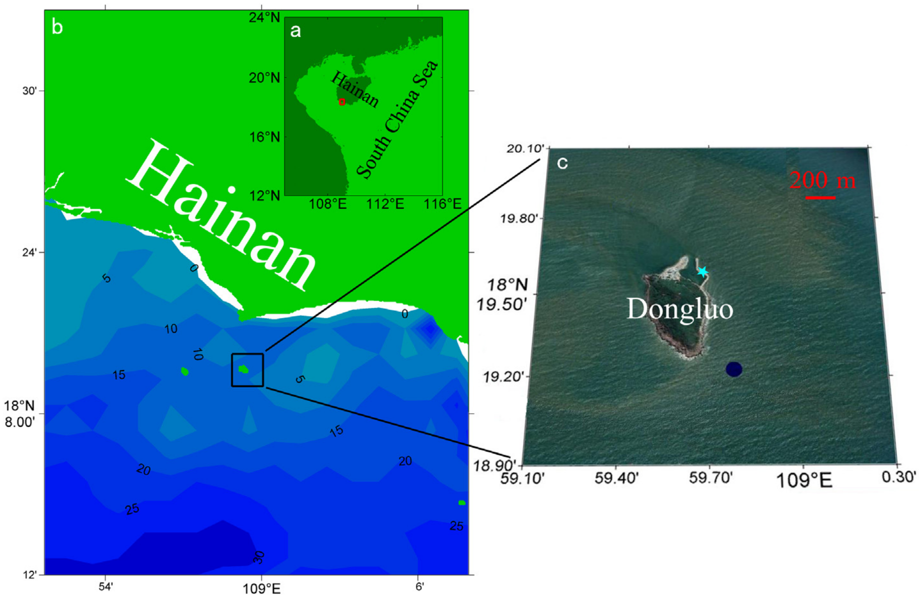

Fig. 1. The geographical location of Dongluo Island (a, the area in the red box is zoomed-in b) and relative to Hainan coast (b, the isobathic line is in meters) and the hydro-meteorological monitoring station near the island (c, the blue dot, and cyan pentacle are the hydrological and meteorological stations, respectively).

2. Data and methods

2.1. Hydro-meteorological monitoring system

The research station is located in Dongluo Island, southwest of Sanya City, Hainan Province, in the northwestern South China Sea (Fig. 1). The island is an uninhabited island with longitude and latitude of 18°19.519′N, and 108°59.658′E. Although the island is only 50 miles from the bustling tourist city downtown, it is still in a state of development. Because the island is small and has only 0.132 km^2, it is uneconomical to lay cables from the city to power the island. How to utilize the surrounding marine renewable energy has become a key issue for the future development of the island.

To assess the marine energy resources of the island, a monitoring system for hydrological and meteorological elements is set up in the offshore waters of the island. The system consists of an underwater unit (blue dot in Fig. 1c) and an island-based unit (cyan pentacle in Fig. 1c). The underwater unit uses a Nortek acoustic wave and current profiler (AWAC) to observe the waves, currents, and water levels upwards on the sea bottom. The island-based unit is an equipment control unit, being combined with a meteorological sensor. The meteorological sensor collects elements such as wind speed and direction through a MetPak weather station by Gill Instruments Ltd. The equipment control unit supplies power to the weather station and the underwater AWAC. Simultaneously, it collects data and sends it back to the remote terminal in the laboratory. The overall structure of the system can be referred to in the literature [11,12].

The system was deployed on Dongluo Island in June 2020. The meteorological monitoring equipment fixed in the island-based unit is located to the northeast of the island. The underwater observation unit is located at about 200 m to the southeast shore of the island, with coordinates of 18.3204°N, 108.9964°E, and a depth of 12 m.

2.2. Assessments of wind, wave, and tidal current energies

The amount of wind energy is defined as the airflow kinetic potential that crosses a section with a certain speed [6–8,13]. Thus, the wind energy passing through a unit area vertically in a unit time is calculated by:

$$P_{wind} = 0.5\rho u_{10}^3 \tag{1}$$

where, $\rho = 1.293$ kg/m^3 is the air density, and u_{10} is the wind speed at 10 m above the mean sea level in the unit of m/s. The wind sensor is located 4 m above sea level, so the observed data need to be converted to u_{10} by [14,15]:

$$u_{10} = \frac{u(z)}{1 + \frac{\sqrt{Cd_{10}}}{0.4} \times \ln\left(\frac{z}{10}\right)} \tag{2}$$

where $u(z)$ is the wind speed measured by the wind sensor, $z = 4$ m is the height of the wind sensor, and $Cd_{10} = 0.0011$ is the drag coefficient.

According to the assessment equation of wave energy resources of Electric Power Research Institute, USA [16], wave energy density is calculated by:

$$P_{wave} = 0.42 H_S^2 T_p \tag{3}$$

where Hs is the significant wave height in the unit of m, and Tp is the peak period in the unit of s.

The tidal current energy is the kinetic energy that a current passes through a certain section. The formula for calculating the kinetic energy of a current passing vertically through a unit area in a unit time is as follows [17]:

$$P_{current} = 0.5\rho_o u_c^3 \tag{4}$$

where, $\rho_o = 1025$ kg/m^3 is the seawater density, and u_c is the current velocity in the unit of m/s.

The stability of energy is a key indicator of energy utilization. The more stable the wave energy resources are, the more beneficial it is to transform them into energy. Conversely, unstable wave energy resources are not only detrimental to energy conversion but may even damage power generation equipment. Therefore, it is necessary to calculate the coefficient of variation (Cv) to assess the stability, through the following equation [7]:

$$C_v = \frac{1}{\overline{x}}\sqrt{\frac{\sum_{i=1}^{n}(x_i - \overline{x})^2}{n-1}} \tag{5}$$

where x_i is the sample sequence and n is the sample number of energy density.

The probabilities of available and rich energy levels are important indicators to measure energy resources richness. Tak the wave energy as an example, when the energy density is higher than 2 kW/m (20 kW/m), it is considered as available (rich) [6,7]. Accordingly, 2 kW/m and 20 kW/m are set as the thresholds of available level and rich level for wave energy. Similarly, for wind energy, the thresholds of available level and rich levels are 50 W/m^2 and 200 W/m^2, respectively [7]. For tidal current energy, currents greater than 0.5 m/s can be utilized, while those greater than 1.5 m/s are rich in resources [18]. Therefore, the available level and rich level of tidal current energy are determined as 60 W/m^2 and 1700 W/m^2 respectively.

3. Results and discussion

3.1. Observation of offshore dynamic parameters

The monitoring results of the wind field, waves, and currents around Dongluo island from June 2020 to September 2021 are illustrated in Fig. 2. It can be seen that the wind speed in the area is between 0–14.3 m/s, the average wind speed is 4.5 m/s, and the wind direction mainly varies between 45° and 180° (E and SE). The wind speed

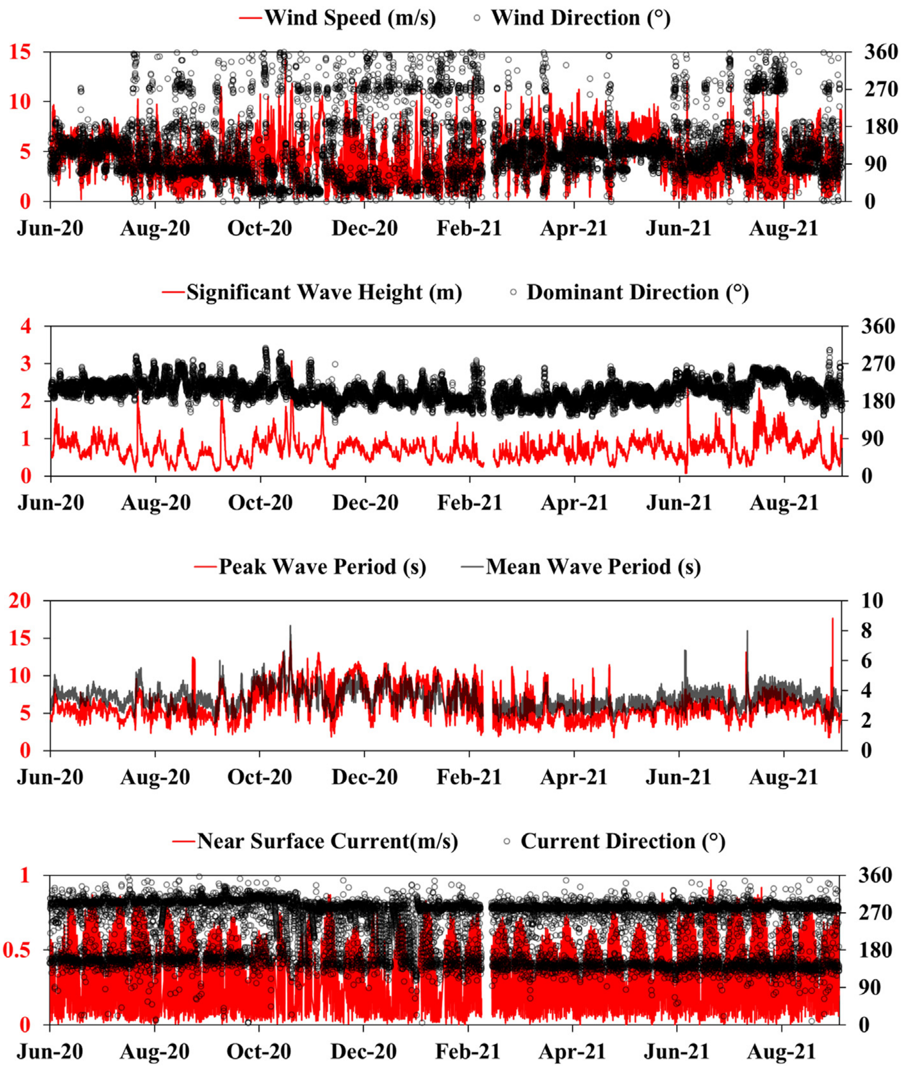

Fig. 2. Observation results of wind at 10 m, wave, and near-surface current from June 3, 2020, to September 8, 2021.

is relatively high in spring and autumn, and the highest measured wind speed of 14.3 m/s appears on October 25, 2020. The wind field in the South China Sea is dominated by monsoon, with strong northeast winds in winter, strong southwest winds in summer, and weak wind speed in spring and autumn [19]. However, due to the blocking effect of the island, the local wind field deflects to the northeast and southeast in winter and summer respectively. The wind speed changes greatly during the winter and summer seasons. Although the maximum wind speed is greater, the overall wind speed is weaker than that in spring. In contrast, in the spring when the east wind prevails, the wind speed is generally more stable with a smaller variation range.

The waves in this area are affected by the terrain, and the wave direction is relatively uniform, mostly between 180° and 270° (SW). It belongs to the nearshore wave propagating from the open sea of the South China Sea to the Hainan coast [20,21]. As the wave transmitted from the deep sea to the shallow water area is reduced by the bottom friction [22,23], the significant wave height is relatively low in the region. The average value in the observation period is only 0.66 m, with a maximum value of 3.1 m. The average wave period is mostly less than 5 s, and the average value is 3.5 s. The peak period is mostly less than 10 s, and the average value is 6.2 s.

The sea nearby the southwest Hainan coast where Dongluo Island is located belongs to a regular diurnal tide current [24]. The current is mainly driven by the tide and changes direction once a day. At high tide, the average current direction is 273° (W); at ebb tide, the average current direction is 139° (SE). The velocity changes with the tide cycle. It is greater than 0.5 m/s in the rising and falling stages, while mostly less than 0.1 m/s during the rising and falling rest, with an average velocity of 0.29 m/s, and a maximum velocity close to 1 m/s.

3.2. Statistical characteristics of wind, wave, and tidal current energies

Based on the observations, the energy density of wind, wave, and tidal current is calculated (Fig. 3). The results show that the sea area is rich in wind energy resources, with an average wind energy density of 81 W/m^2 and a maximum value of 1.47 kW/m^2 during the observation period. Except for several large wave events, the wave energy density is less than 10 kW/m in most time, with an average value of 1.74 kW/m and a maximum value of 51.09 kW/m. The density of tidal current energy is periodic, which is consistent with the variation of the tide. The energy is low in the rising or falling rest, but high in the rising or falling stage, generally not less than 100 W/m^2. The average tidal energy density is 32.4 W/m^2.

Further combined with the propagation direction of energy, the rose diagram of energy density is calculated, as shown in Fig. 4. The results show that the direction of various energy propagation is relatively uniform. For example, under the comprehensive influence of monsoon and island topography, the wind energy in the sea area is mainly SEE during the spring and summer seasons, and is NEE during autumn and winter seasons. It is worth noting that wave energy in the present study is mainly distributed in SSW, which is inconsistent with the situation near the northeast shore of the island. Because the waves are affected by the continental shoreline and underwater topography, they mainly propagate from S to N, which is consistent with the report of Li et al. [12]. However, for the area northeast of the island, the waves would be blocked from the SW, so that the waves mainly come from the SE [12]. In this study, the site faces the open sea, and thus waves propagate mainly from the SSW. As for tidal current energy, its direction is dominated by tidal factors, focusing on west and SE directions. The relative concentration of propagation direction is conducive to the utilization of energy.

The stability and temporal variability of the energy flux affect the possibilities for integrated utilization of different sources [10]. To further analyze the stability and seasonal variation of the energies, the average energy density and variation coefficient of each month are calculated (Fig. 5). The results show that the density and stability of wind energy in the area are the highest in spring, the second in autumn, and the lowest in winter and summer. It is consistent with the seasonal variation of wind speed (Fig. 2). Because the island forms a barrier to the wind field, the northeast wind and southwest wind in winter and summer are more likely to be blocked by the island, so the wind energy is weakened at that time. On the contrary, the seasonal variation of resource density and stability of wave energy is opposite to that of wind energy. It is relatively high in the winter and autumn seasons, followed by summer and is weak in spring. This phenomenon can be attributed to two aspects: Firstly, the hydrologic station for wave energy assessment is farther from the island, as a result, the island blocking effect there is relatively weak, compared to the meteorological station for wind energy; secondly, since the local waves are vitally influenced by the swells propagating from the open sea [21], the intensity changes of local wave energy tend to be consistent with that of the large scale wind field in the South China Sea but different from the local wind field. Compared

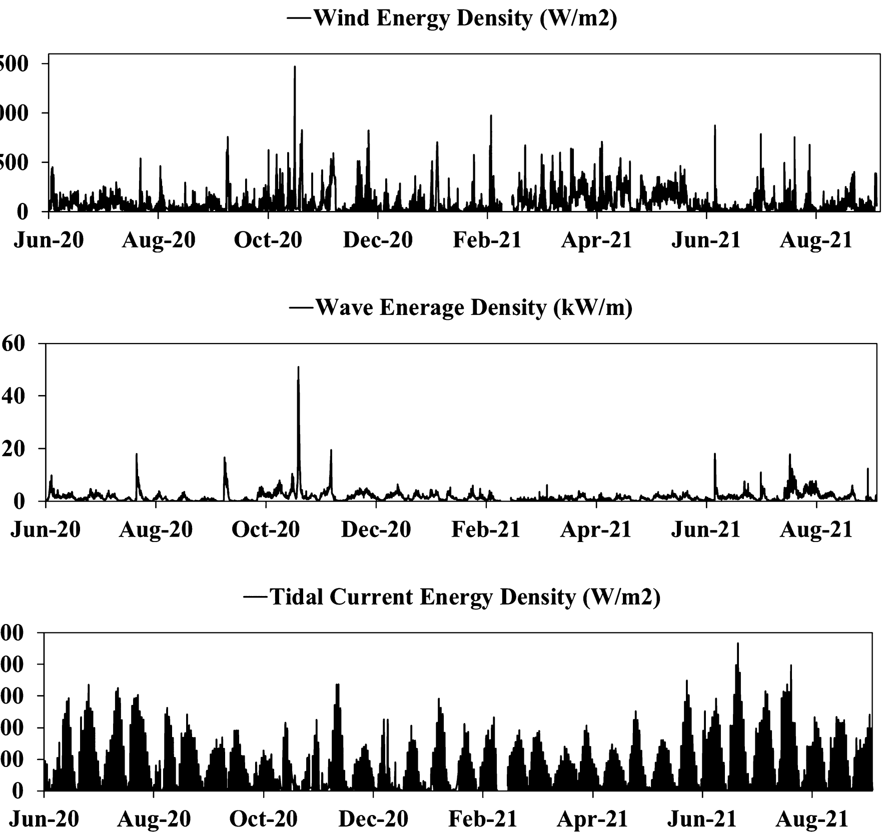

Fig. 3. Energy densities of wind, wave, and tidal current based on the observation result from June 3, 2020, to September 8, 2021.

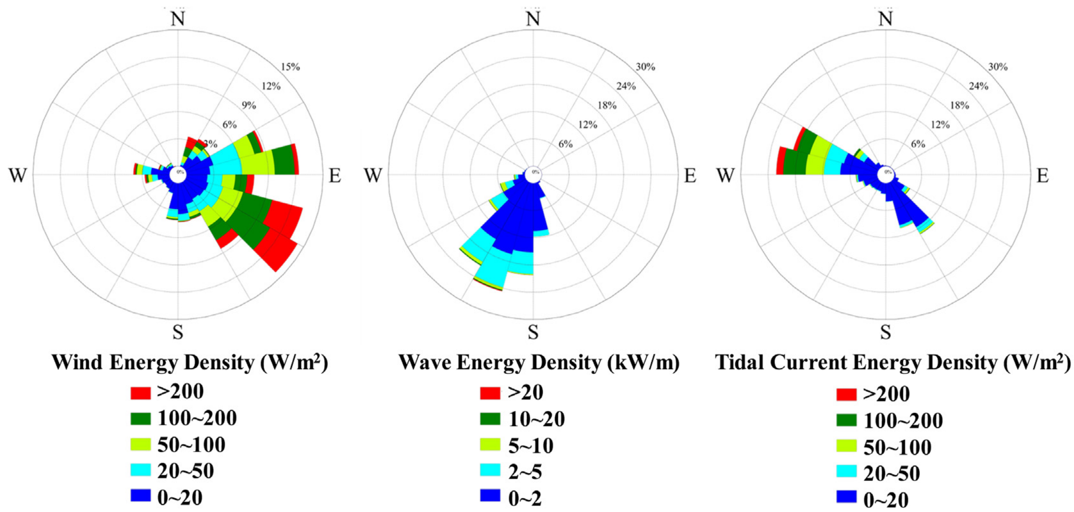

Fig. 4. Energy density roses of wind, wave, and tidal current.

with the observation of the northeast inshore station in the summer of 2018 [12], the offshore station in this study reveals a higher power density and lower stability, suggesting a relatively low influence of the island topography in the offshore area. In addition, the monthly variation in the density and stability of tidal current energy is not as

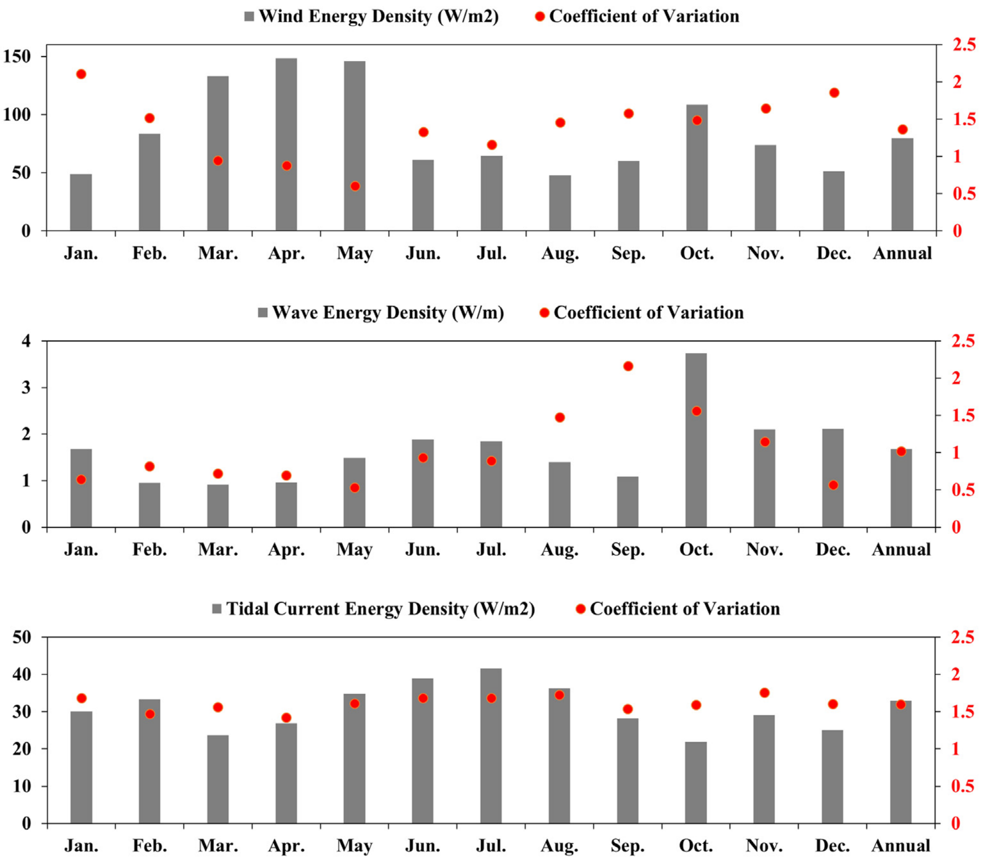

Fig. 5. Monthly average energy densities and variation coefficients of wind, wave, and tidal current.

obvious as those of wind or wave energies, and the range of variation coefficient in different months is less than 0.5.

3.3. Analysis of the availability of wind, wave, and tidal current energies

In the analysis of the density of marine energy resources, the frequency of available or rich energy levels is an important parameter to evaluate the abundance of energy resources. The calculation results of wind, wave, and tidal current energies near Dongluo island from June 2020 to September 2021 are sorted, and the cumulative probability of three energy densities is shown in Fig. 6. According to statistics, wind energy resources are relatively abundant, 44.6% of the observation period is at the available level and 11.7% of the period is at the rich level. The abundance of wave energy is lower than that of wind energy, about 29.2% of the time is at the available level and 0.2% of the time is at the rich level. Due to the limitation of the tidal cycle, tidal energy is only available 18.4% of the time.

Successful integration of different sources must take into account the probability and its variations of renewable energy sources [10]. By further calculating the probability that wind energy, wave energy, or tidal current energy alone, and any of the three energies reach the available level every day (Fig. 7), it can be found that there is a possibility of complementarity between different energy sources. For example, the available probability of wind energy is higher during spring and autumn, but lower during winter and summer; in contrast, wave energy is higher during winter and summer and lower during spring and autumn. This situation is different from the general seasonality of the open region of the South China Sea where both types of energy are the most abundant in winter, and the least abundant in spring [8]. As Wan et al. [7] stated, the joint development of different types of energies is promising for ocean renewable energy utilization. The seasonal variation of two types of energy around Dongluo Island can complement each other, which is an advantage in the complementary use of them while the energy

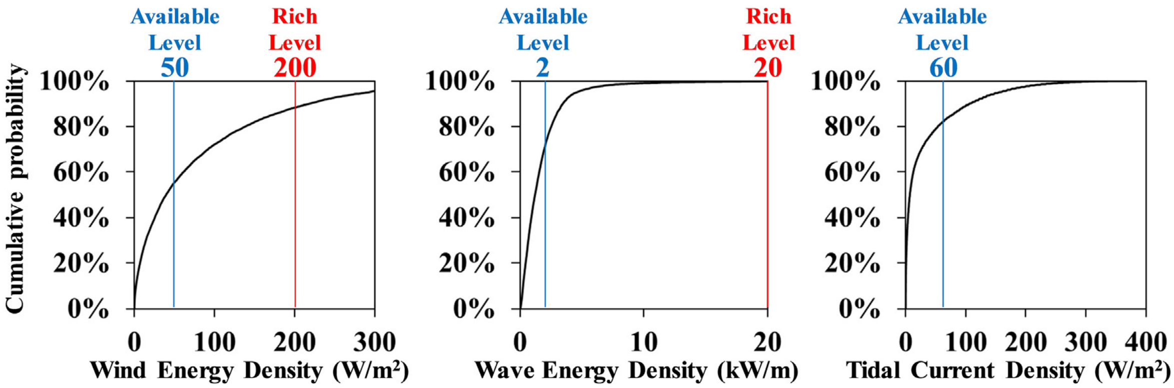

Fig. 6. Cumulative probability curves of energy density for wind, wave, and tidal current energies.

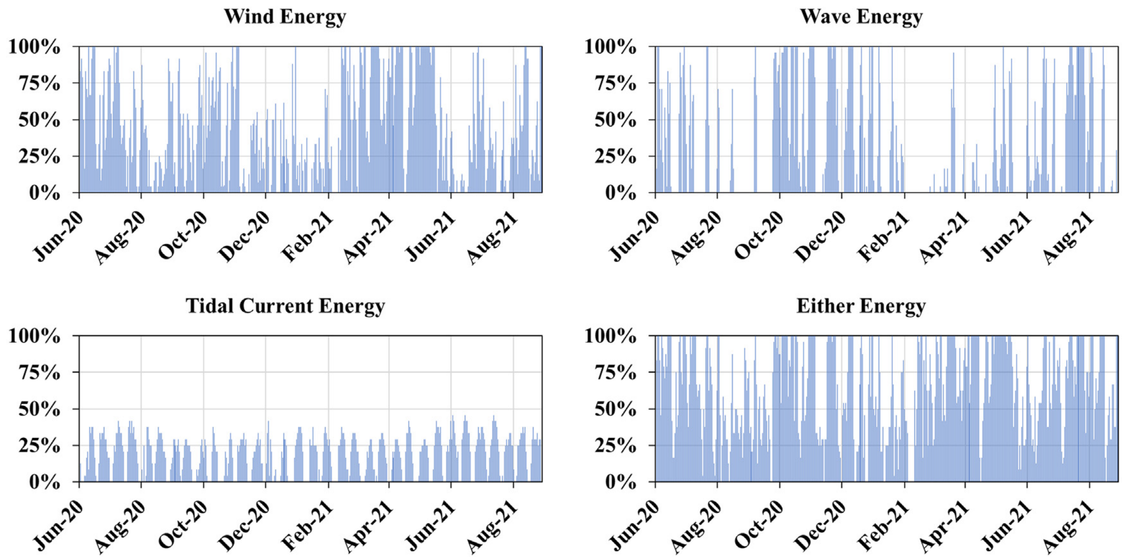

Fig. 7. Daily available frequency of wind energy, wave energy, tidal current energy, and any of the three kinds of energy.

density of the island coast is relatively weaker than the offshore area. In addition, the overall available probability of tidal current energy is not high, its advantage is that it is relatively stable. As long as it is not in the neap tide, it can ensure that there is a certain probability that it is available. Under the comprehensive complementarity of the three energy sources, the integrated available frequencies of the three types of energy are always higher than zero except for the few days with missing data in the observation period, that is, there would be always one energy source available for the island.

The days per year when the available time of wind energy, wave energy, tidal current energy, and any of the three energy reaches 6 h, 12 h, 18 h, and 24 h are calculated (Fig. 8), and the results further confirm the importance of comprehensive operation of multiple energy resources. Although the wind energy resources are relatively rich compared with the other two types of energy, if only wind energy is used, more than 200 days are available for more than 6 h in a year, but less than 100 days when 18 h are available. Although wave energy and tidal current energy are less abundant than wind energy, they can play an important complementary role. If the three types of energy are utilized at the same time, the number of days with effective functions exceeding 6 h, 12 h, 18 h, and 24 h can be met, which can exceed 300, 200, 150, and 100 days respectively in a year. It means that the island's uninterrupted power supply will be achieved throughout the year.

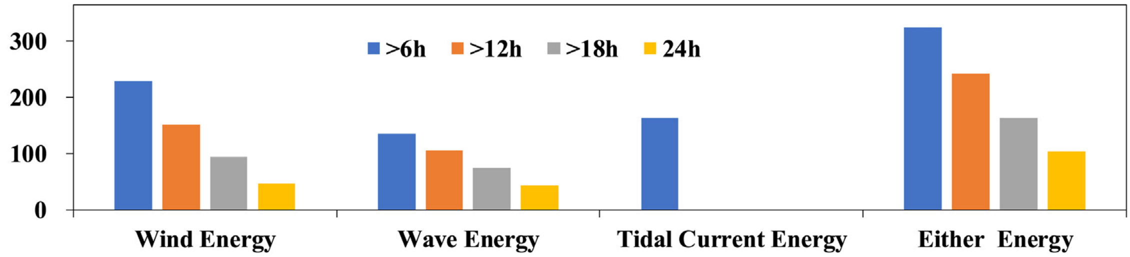

Fig. 8. Days per year when the available time of wind energy, wave energy, tidal current energy, and any of the three energy reaches 6 h, 12 h, 18 h, and 24 h.

4. Conclusions

To support the future development of a small island, Dongluo Island, in the northwestern South China Sea, a hydrological and meteorological monitoring system has been deployed around the island. Based on the observations, the energy resources of wind, wave, and tidal current are systematically assessed. The results show that the area is relatively rich in wind energy resources, followed by wave energy and low tidal current energy, with the frequencies of reaching available levels of the three energy sources being 44.6%, 29.2%, and 18.4% respectively. However, the three energy resources have remarkable complementary potential. The available frequency of wind energy is higher during the spring and autumn seasons, and lower for winter and summer seasons; on the contrary, the available frequency of wave energy is lower for spring and autumn, but higher during winter and summer seasons. Although the available frequency of tidal current energy is at a low level throughout the year, it is relatively stable to ensure the emergence of a certain available frequency. Therefore, combined with the advantages of three types of energy, and optimal allocation are expected to provide a more reliable energy guarantee for the development of the island.

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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