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Potential of Offshore Wind Energy in Malaysia: An Investigation into Wind and Bathymetry Conditions and Site Selection

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Abstract: The government has set an ambitious target of renewable energy development in Malaysia. As a promising renewable energy source, wind energy plays an important role in the Malaysia renewable energy roadmap. Compared to onshore wind energy, offshore wind resources with better quality can be provided in the areas away from the coast, which has greater potential to contribute to electricity generation. Wind and bathymetry conditions are two important factors that determine the feasibility and economics of offshore wind turbines. In this paper, an investigation is conducted on wind and bathymetry conditions around Malaysia. The data source mainly originates from the Global Wind Atlas. The conditions of the coastal areas in different states and federal territories of both Peninsular Malaysia and East Malaysia are analysed, with a specific focus on wind speed, wind energy density, and bathymetry conditions in high-wind-speed regions. The data and survey are verified and compared with the past published literature. This paper aims to investigate the wind and bathymetry conditions around Malaysia, assess the potential of offshore wind energy, discuss the feasibility of offshore wind turbines, and provide references for offshore wind development in Malaysia.

Keywords: Malaysia; wind conditions; bathymetry conditions; offshore wind energy

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1. Introduction

Over the past years, a continual increase in the demand for electricity has been a global issue [1]. Consuming conventional fossil fuels results in about 75% of annual global greenhouse gases emissions [2–4]. Humanity is actively exploring the harnessing of energy from the ocean to address this issue [5–7]. In Malaysia, conventional methods, such as utilizing natural gas and coal, still serve as the primary sources (more than 90%) of power generation [8]. In order to cut carbon dioxide emissions and make power generating prices more affordable from renewable sources, Malaysia has set ambitious targets to develop renewable energy as the alternative source of power generation. The goal is to reduce the greenhouse gas emission intensity of the gross domestic product, resulting in a 45% reduction by 2030 compared to 2005 levels [9]. To achieve this, there is a concerted effort to increase the share of renewable energy sources, with the goal of reaching 20% of the total energy sources capacity by 2025 [10]. This ongoing shift from traditional fossil fuels to renewable energy sources marks a highly promising development against climate change in Malaysia.

A number of review papers focus on the development of renewable energy in Malaysia [11–18]. Various promising resources of renewable energy are introduced, including wind energy, bioenergy, solar energy, hydropower, ocean energy, geothermal, and hydrogen, as shown in Table 1.

Table 1. Past review articles on renewable energy in Malaysia.

Reference	Year	Wind Energy	Bioenergy	Solar Energy	Hydropower	Ocean Energy	Geothermal	Hydrogen
[11]	2010	✓	✓	✓	✓		✓	
[12]	2011	✓	✓	✓	✓	✓		
[13]	2011		✓	✓	✓			
[14]	2011	✓	✓	✓	✓			
[15]	2014	✓	✓	✓	✓	✓		
[16]	2015	✓	✓	✓	✓	✓		✓
[17]	2016		✓	✓	✓			
[18]	2019	✓	✓	✓	✓			

Mustapa et al. [11] identified key issues and challenges facing renewable energy development in Malaysia and explored green technology policies for a sustainable future. Shafie et al. [12] reviewed the energy situation and policies in Malaysia, investigating wind, bioenergy, solar, hydropower, and ocean energy along with associated energy and environmental considerations. Ahmad et al. [13] discussed Malaysia's main renewable sources like bioenergy, solar, and hydropower, and government measures to overcome barriers. Ong et al. [14] explored wind, bioenergy, solar, and hydropower as alternatives to ensure reliable and secure energy supply in Malaysia. Ashnani et al. [15] examined renewable scenarios like wind, bioenergy, solar, hydropower, and ocean energy in the context of Malaysia's energy demand, supply, and fuel diversification policies. Petinrin and Shaaban [16] identified the potential of wind, bioenergy, solar, hydropower, and hydrogen in Malaysia and current implementation strategies and policies. Bujang et al. [17] summarized Malaysia's energy supply, demand, and the potential of renewables like bioenergy, solar, and hydropower. Abdullah et al. [18] evaluated Malaysia's energy industry, focusing on the assessment of renewable sources, to support further research and development and achieve the 2025 renewable energy target.

Among the above-mentioned promising renewable resources, wind energy has gained the Malaysian government's attention to prompt exploration of its potential. Wind energy is a significant renewable energy source since it is widely available and is one of the most cost-effective sources for electricity [19,20]. While many regions in Malaysia experience low wind speeds which are not suitable for wind energy generation, some coastal areas and wind-prone locations exhibit significant potential for harnessing wind energy for electricity generation [21]. Malaysia has the ability to generate 500 to 2000 MW worth of electricity from onshore wind turbines [22], playing a vital role in power supply and stability at the national, regional, and local levels. In comparison with other countries over the world, such as Iran with a wind energy potential of 80 GW [23], Morocco with 2600 GW [24], Brazil with 1688 GW [25], and the Netherlands with 7 GW of onshore wind power [26], Malaysia's potential for onshore wind power is less significant, but offshore wind will be the key to unlock wind energy development.

The review papers on wind energy in Malaysia investigate wind energy from different perspectives, including wind conditions, wind speed distribution, wind persistence, and the sizing of wind farms, as shown in Table 2 [10,27–31]. Offshore wind energy has many advantages over onshore wind, including abundant wind resources, reduced environmental impact, lower turbulence, and ample space for installation [32–34]. To the best of the authors' knowledge, there has been no prior research on the wind and bathymetry conditions around Malaysia that could serve as a reference for future offshore wind energy development in

Malaysia. Wind and bathymetry conditions are two significant environmental factors that affect the quality of wind resources, wind loading on the turbine, foundation selection and design, and so on [35–41] . This knowledge gap serves as a key motivation for this paper. We need to clarify that assessing the potential of offshore wind resources in Malaysia is a crucial area of research, but it is out of the scope of this paper.

Table 2. Past review articles on wind energy in Malaysia.

Reference	Year	Perspective
[27]	2012	Site description, measurement mast, wind conditions
[28]	2013	Wind speed distribution, power and energy densities
[29]	2016	Wind energy studies, wind mapping, political and regulatory support
[30]	2016	Wind speed, wind persistence, wind site selection, topography, cost
[10]	2020	Potentiality and assessments, wind speed and direction modelling, wind prediction and spatial mapping, optimal sizing of wind farms
[31]	2021	Geographical wind condition, government policies, challenges in initiation of wind technologies, global perspective of green energy

The objective of this paper is to investigate the wind and bathymetry conditions around Malaysia. The existing sources of wind data of Malaysia include QuikSCAT satellite data [42], National Oceanic and Atmospheric Administration [43], etc., and this study primarily relies on data from the Global Wind Atlas [44]. The conditions of Peninsular Malaysia and East Malaysia are investigated, respectively. The past relevant papers are used to verify and compare with the survey. Two specific locations favourable for offshore wind energy generation are identified, and suitable wind turbine types are provided based on water depth conditions.

The remainder of the paper is organized as follows. The general geographic and climate information of Malaysia is introduced in Section 2. The overall offshore wind conditions and bathymetry conditions are presented in Section 3 and Section 4, respectively. The potential of developing offshore wind energy in Malaysia is discussed in Section 5. Concluding remarks are made in Section 6.

2. General Geographic and Climate Information of Malaysia

Malaysia is geographically located at latitude 2°30′ N and longitude 112°30′ E [45], in the centre of Southeast Asia, close to the equator. It is bordered by Thailand to the north and Indonesia to the south, and it shares maritime boundaries with Vietnam and the Philippines. The country consists of two main regions: Peninsular Malaysia (West Malaysia) and East Malaysia (Malaysian Borneo) on the island of Borneo. These regions are separated by the South China Sea [46]. The total area of Malaysia is approximately 330,000 km^2, with the majority found on the island of Borneo [47], while Peninsular Malaysia makes up about 40% of the total area [45], as shown in Figure 1.

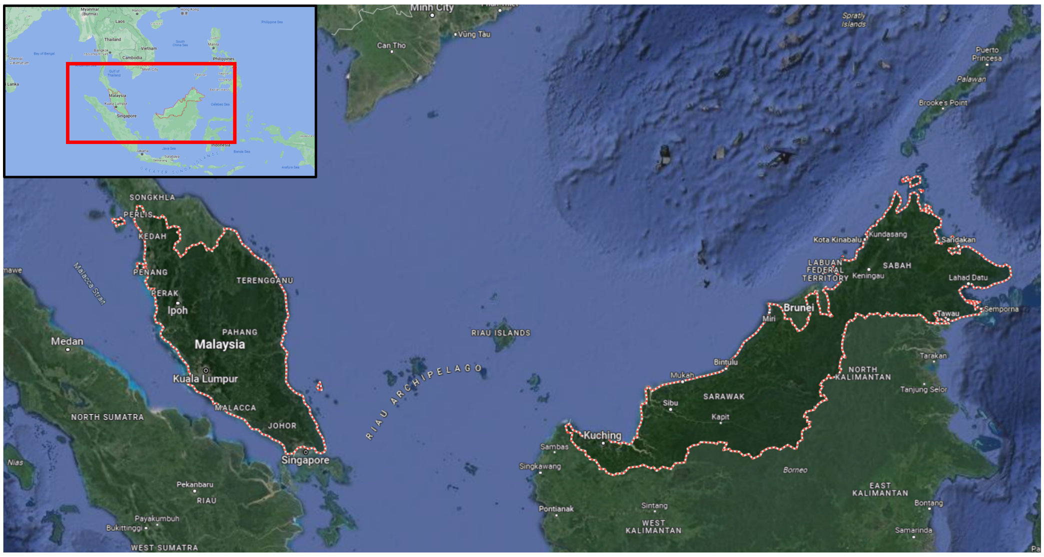


Figure 1. Geographic map of Malaysia.

Malaysia experiences varying wind patterns throughout the year, depending on the region and the month. The climate of Malaysia is characterised by four seasons, which include two monsoon seasons and two inter-monsoon seasons [48]. The Southwest Monsoon lasts from May/June to September, while the Northeast Monsoon occurs from November to March [49,50].

During the Southwest Monsoon, strong winds blow from the southwest, bringing moisture-laden air from the Indian Ocean. In the Northeast Monsoon, winds shift to the northeast, affecting the east coast and parts of Peninsular Malaysia with moist air. Wind speeds are generally below 7 m/s in the Southwest Monsoon, but they can reach up to 15 m/s in the Northeast Monsoon, particularly on the east coast of Peninsular Malaysia. Additionally, between April and September, the impact of typhoons affecting neighboring countries, like the Philippines, may cause strong winds (exceeding 10 m/s) in East Malaysia. As a result, while wind speeds are relatively low throughout Malaysia, certain areas within the country can encounter strong winds during specific times of the year. Notably, during the Northeast and Southwest monsoons, wind speeds between 5 and 20 m/s can be observed in Kijal. This can be attributed to the offshore location of the sites, which reduces obstructions like buildings that could otherwise affect wind speed [51].

3. Offshore Wind Conditions

Malaysia consists of 13 states and three federal territories. The wind conditions analysed in the paper are at the height of 100 m because 100 m is usually the height at which the wind turbine hub is located. The overall mean wind speed conditions at the height of 100 m are illustrated in Figure 2, where the change in color represents the variety of wind speed. The depicted region encompasses Malaysia and a coastal area extending 200 km beyond its borders. The color bar represents the wind speed range of 0 to 8 m/s. The figure shows that the areas with a wind speed higher than 4 m/s are mainly concentrated in the east and north of Peninsular Malaysia and the north of East Malaysia.

Peninsular Malaysia consists of 11 out of the 13 states, and two out of the three federal territories of Malaysia. The states and federal territories include Perlis, Kedah, Penang, Perak, Selangor, Negeri Sembilan, Malacca, Johor, Pahang, Terengganu, Kelantan, Putrajaya, and Kuala Lumpur. Putrajaya and Kuala Lumpur are not near the sea, so these two federal territories are not introduced and discussed.

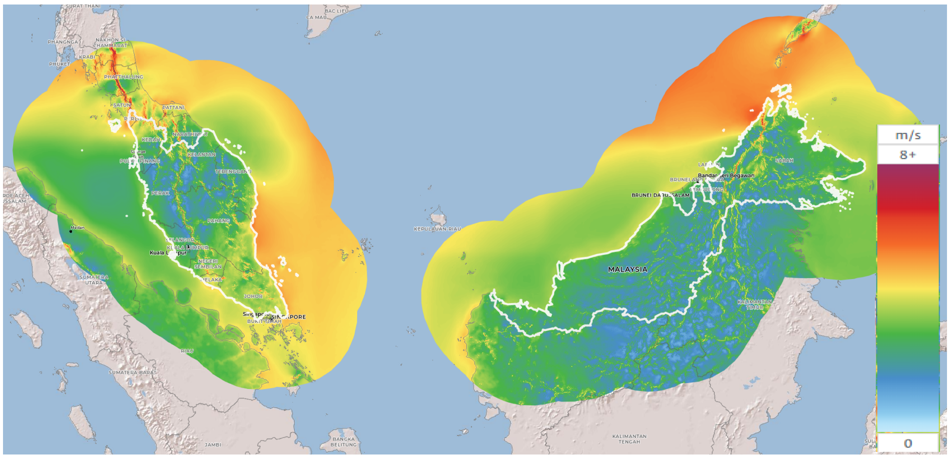
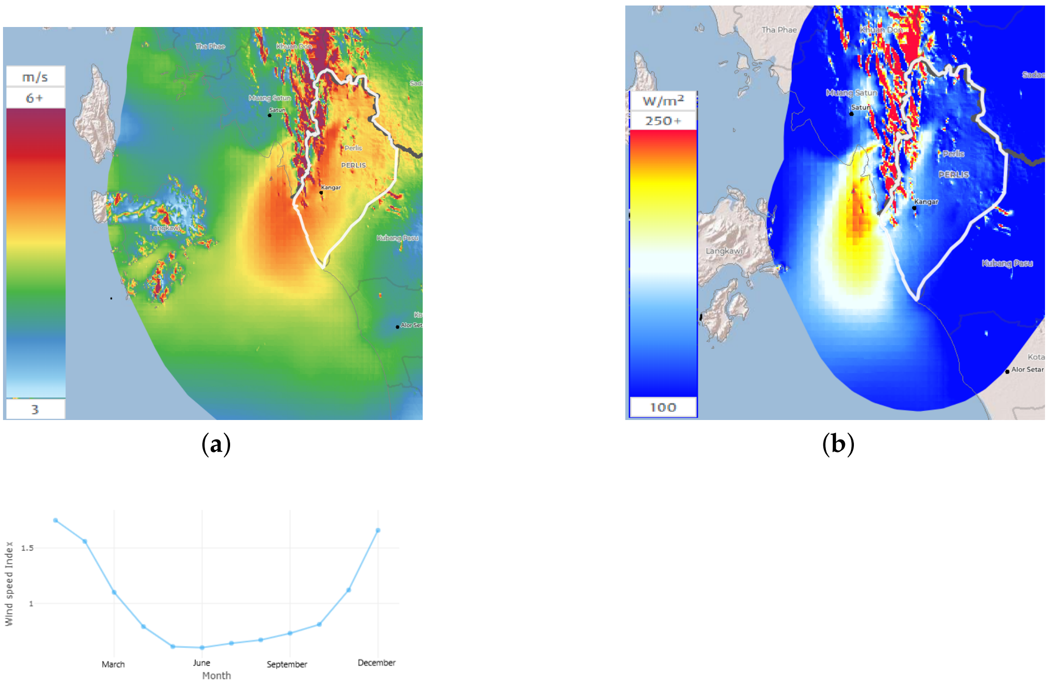


Figure 2. Wind map of Malaysia and a coastal area extending 200 km beyond its borders.

Perlis is the smallest state in Malaysia in terms of land area and population, located on the northwestern coast of Peninsular Malaysia. The wind map covering Perlis and 50 km coastal area is shown in Figure 3a. In the areas located at least 20 km away from the coastline, the wind speed is typically below 4 m/s. In comparison, within a 20 km distance from the coastline, the wind speed can reach between 4.5 m/s and 5.2 m/s. The mean wind power density of Perlis and its 25 km coastal area is illustrated in Figure 3b. Within a distance of 15 km from the coastline, the power density reaches 160 W/m^2 and increases gradually as the area approaches the coast. A peak in power density is formed within a distance of 3 km to 10 km offshore, with density ranging between 220 W/m^2 and 240 W/m^2. The monthly variability of wind speed in this high-power-density area is demonstrated in Figure 3c. From mid-March to mid-October, the monthly wind speed remains below the average, reaching the lowest value in June. The monthly wind speed peaks in December and January, reaching around 1.7 times the average value.

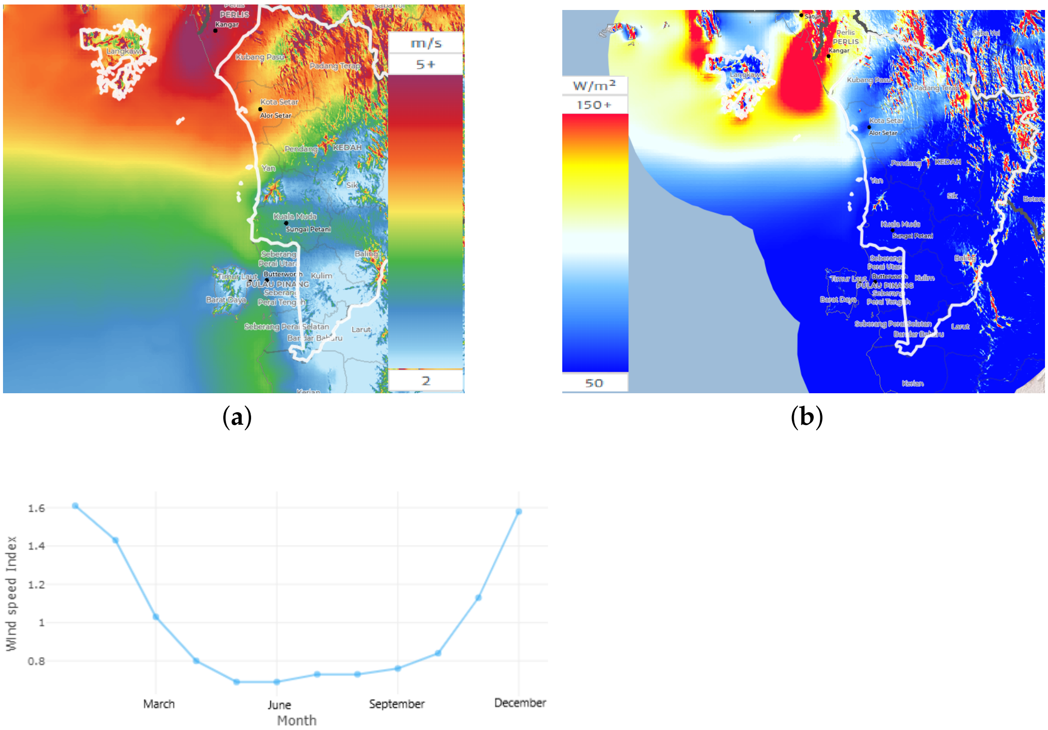


(a) (b)

(c)

Figure 3. Wind conditions at Perlis: (**a**) Mean wind speed at Perlis including 50 km coastal area. (**b**) Mean power density at Perlis including 25 km coastal area. (**c**) Monthly variability of wind speed in the high-power-density area.

Kedah is located in the northwestern part of Peninsular Malaysia, to the south of Perlis. Kedah covers a total area of over 9000 km^2. In the northern region near Perlis, wind speeds range from 4 to 4.5 m/s. In the southern region, wind speeds are lower, between 3.2 and 4 m/s, as shown in Figure 4a. Figure 4b illustrates the mean power density at Kedah and the coastal area within a 50 km radius. The power density at the high-wind-speed region is between 110 and 150 W/m^2. In the southern part of Kedah, the power density decreases gradually to the range of 50–60 W/m^2. Compared to Perlis, the monthly variability of wind speed is less, fluctuating between 0.7 and 1.6 times.



(**a**) (**b**) (**c**)

Figure 4. Wind conditions at Kedah: (**a**) Mean wind speed at Kedah. (**b**) Mean power density at Kedah including 50 km coastal area. (**c**) Monthly variability of wind speed in the high-power-density area.

Penang is situated on the northwest coast of Peninsular Malaysia, south of Kedah. The wind speed is shown in Figure 5. The mean wind speed at the offshore area is between 2.5 m/s and 3.2 m/s. At the area around Penang Island, the wind speed typically remains below 3 m/s.

Perak, Selangor, and Negeri Sembilan are located on the west to southwest coast of Malaysia. As demonstrated in Figure 6a, on the coastlines of these three states, distinct red areas indicate significantly higher wind speeds within 10 km offshore compared to farther regions, ranging between 3.5 m/s and 3.8 m/s. This high-wind-speed zone extends to Makala. Within a 10 km offshore zone, wind speeds reach between 4 m/s and 4.5 m/s, as shown in Figure 6b.

Johor is located in the southern part of Peninsular Malaysia and shares maritime borders with Singapore. On the southwestern side, the wind speeds range between 4 m/s and 4.5 m/s (Figure 7a), with a wind power density of approximately 75 W/m^2 (Figure 7b). On the northeastern coastline, within a 10 km range, the average wind speed increases to 4.5 m/s to 5 m/s, with a wind power density of around 110–120 W/m^2.

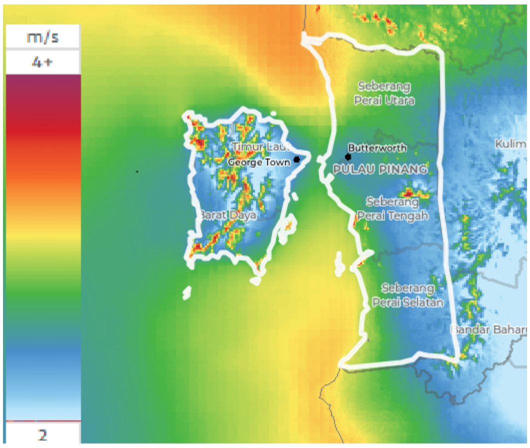
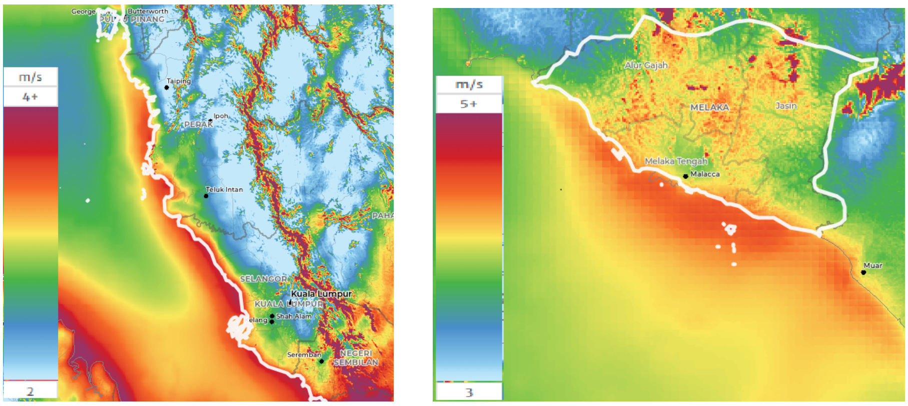
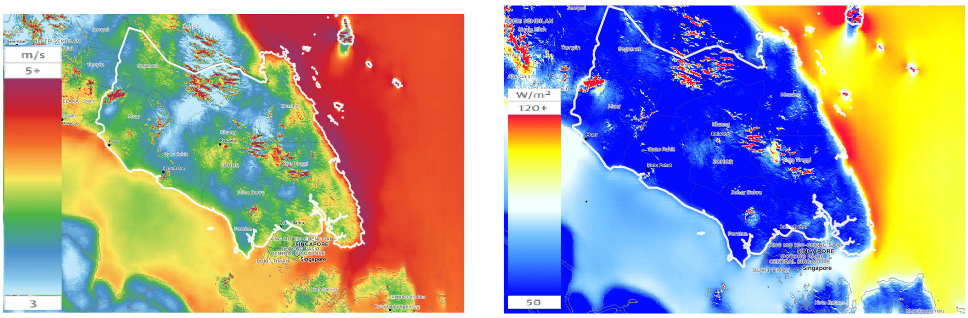


Figure 5. Wind speed at Penang.



(**a**) (**b**)

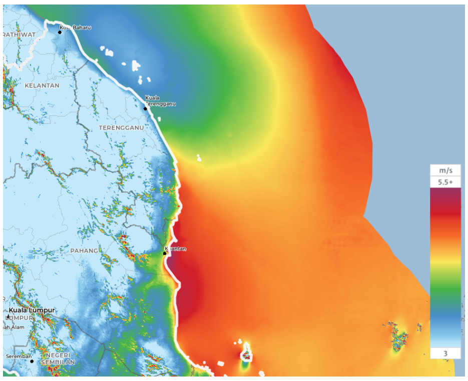
Figure 6. (**a**) Wind speed at Perak, Selangor, and Negeri Sembilan. (**b**) Wind speed at Melaka.



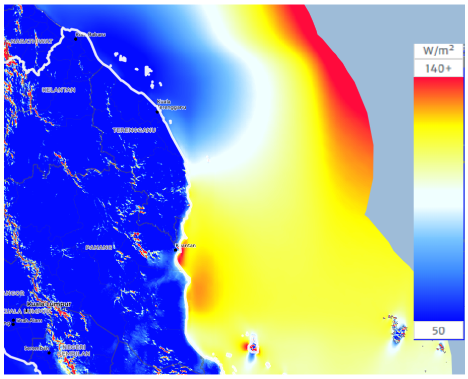
(**a**) (**b**)

Figure 7. Wind conditions at Johor: (**a**) Wind speed. (**b**) Wind power density.

Pahang, Terengganu, and Kelantan are on the east coast of Peninsular Malaysia. In Figure 8a, in Pahang and the southern regions of Terengganu, within approximately 200 km of the coast, wind speeds generally exceed 4.5 m/s. Especially in the area from Chukai to Kampung Hulu Tering, within about 30 km of the coast, wind speeds reach 5–5.5 m/s. Along the coastline from Kota Bharu to Kuala Terengganu, within 50 km offshore, wind speeds are lower, below 3.5 m/s. However, wind speed gradually increases as one moves away from the coast. At around 180 km offshore, wind speeds rise to over 5 m/s.



(**a**)

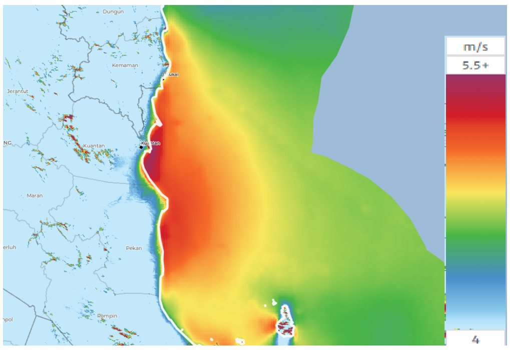


(**b**)

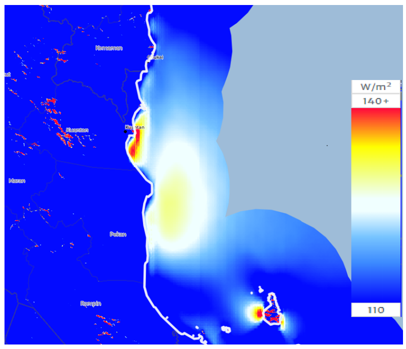
Figure 8. Wind conditions at Pahang, Terengganu, and Kelantan including 200 km coastal area: (**a**) Wind speed. (**b**) Wind power density.

The wind power density at Pahang, Terengganu, and Kelantan including 200 km coastal area is depicted in Figure 8b. In the offshore area located 180 km away from Terengganu, wind power density exceeds 130 W/m^2. There is a large offshore area around 30 km near Pekan with a density of 125–130 W/m^2.

The area with the highest wind power density is near Kutantan (the capital city of the state of Pahang). The wind map with higher resolution of the area near Kuantan is shown in Figure 9a,b. Within 15 km offshore Kutantan, wind speed reaches 5–5.5 m/s and wind power density ranges from 120 W/m^2 to 140 W/m^2. The monthly variability of wind speed in this area is depicted in Figure 9c. Different from the west coast of Peninsular Malaysia, the wind speed reaches the lowest point in April and gradually increases thereafter, peaking in July. Subsequently, the wind speed decreases until October and then rises again to the highest peak.



(**a**)



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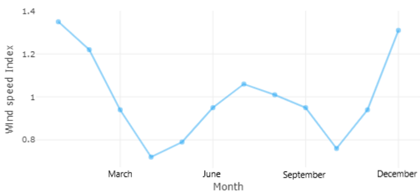


(**c**)

Figure 9. Wind map with higher resolution near Kuantan including 50 km coastal area: (**a**) Wind speed. (**b**) Wind power density. (**c**) Monthly variability of wind speed.

The previous paper provided a summary of the offshore wind resources of Kijal, Malaysia, by analysing the QuikSCAT satellite data [51] (Figure 10). According to the

QuikSCAT satellite data, the annual wind speed at hub height from 25 m to 75 m from this location increases from 6.3 m/s to 7.1 m/s. These values are higher than the results in Figure 9. The reason for this difference may be attributed to variations between databases and differences in statistical years.

East Malaysia comprises the states of Sabah, Sarawak, and the Federal Territory of Labuan. In Figure 11, within 120 km of the coast of Sarawak, wind speeds typically range between 3.2 m/s and 3.8 m/s. Notably, within 30 km of the northern coastline of Sarawak, wind speeds can reach as high as 3.8 m/s to 4 m/s.

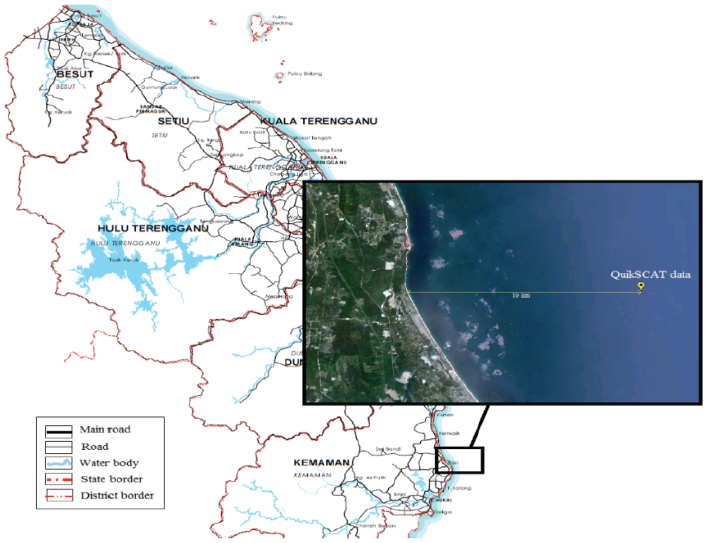


Figure 10. The location where the QuikSCAT wind data are collected in [51].

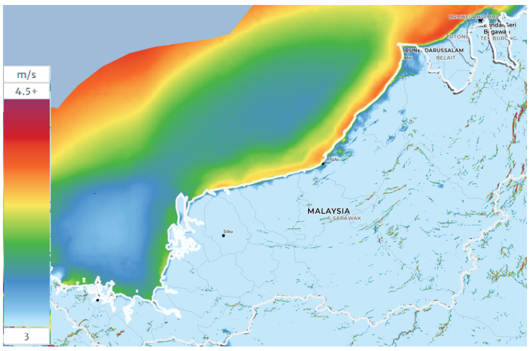
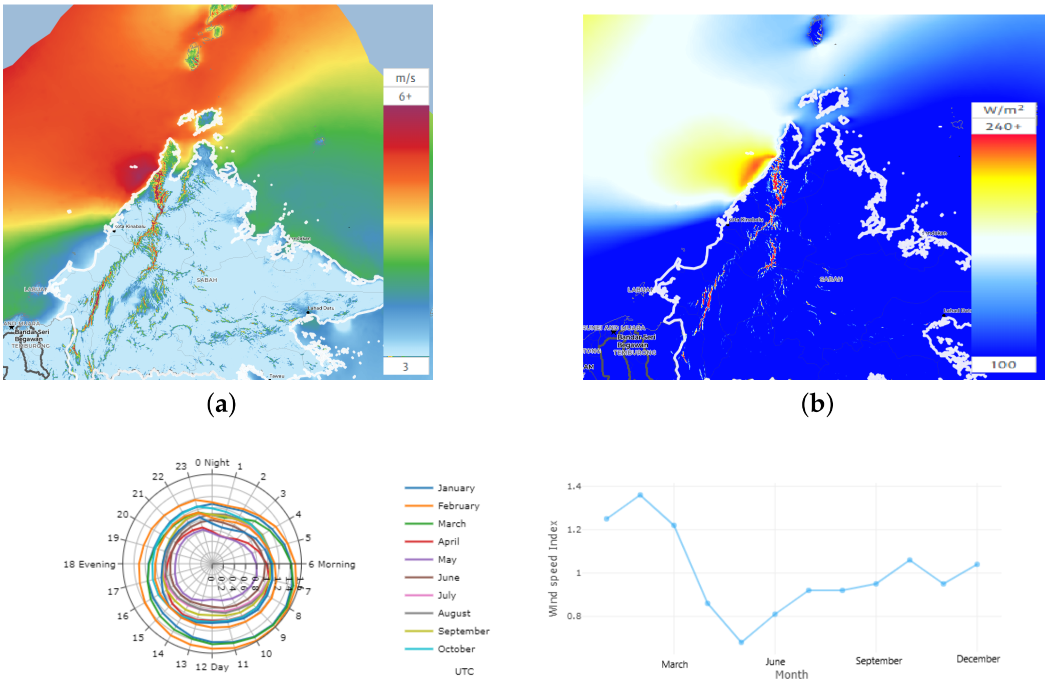


Figure 11. Wind speed at Sarawak.

The Federal Territory of Labuan, due to its geographical location and size, is discussed alongside Sabah. The wind speeds of Sabah and the Federal Territory of Labuan are depicted in Figure 12a. In the northern region of Sabah, wind speeds are notably higher than in other areas. Particularly within 50 km offshore in the northwest, wind speeds can reach 5.5 m/s to 5.9 m/s.

The wind power density is illustrated in Figure 12b. Within 25 km offshore, the wind power density ranges from 220 W/m^2 to 230 W/m^2. A detailed analysis in wind speed variability of this high-wind-speed region is shown in Figure 12c,d. The hourly wind speeds peak from 6 am to 12 pm. Afterwards, the wind speeds gradually decrease and reach a low period between 12 am and 6 am. Wind speeds peak in February, reaching approximately 1.4 times the average wind speed. The wind speed then decreases to the lowest point in May, dropping to around 0.7 times the average. Afterwards, the wind speed gradually increases to around the average level, fluctuating from September to December, and then rising until February.

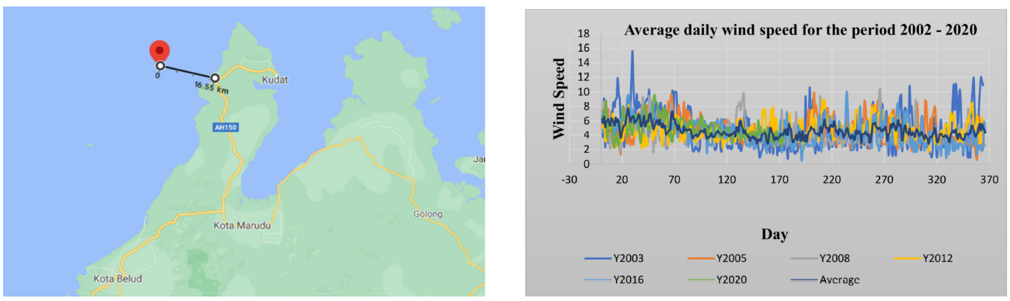


(**a**) (**b**)

(**c**) (**d**)

Figure 12. Wind conditions in Sabah: (**a**) Wind speed. (**b**) Wind power density. (**c**) Hourly vs. monthly wind speed variability in the high-wind-speed region. (**d**) Monthly variability of wind speed in the high-wind-speed region.

A past study assessed the life cycle cost of offshore wind farms in Kudat, which is considered one of the most promising locations for wind energy in Malaysia [52]. In the study, the site of the offshore wind farm was selected to be about 17 km away from the northwest shoreline with a 20 m water depth, as illustrated in Figure 13a. The wind speed data at 5 m elevation were collected from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce [43], and are shown in Figure 13b. The mean wind speed is consistent with the results (around 4.1 m/s) in the wind map of this study.



(**a**) (**b**)

Figure 13. The selected wind farm site in Kudat: (**a**) Location. (**b**) Wind speed [52].

In the paper [53,54], the wind data of 16 locations around Malaysia were collected from the meteorological department of the locality and marine surface observation reports. The distribution of the 16 sites is shown in Figure 14. According to this paper, the average wind speeds of sites 1, 2, 3, 4, 8, and 13 are 3.5 m/s, 4.1 m/s, 3.8 m/s, 3.3 m/s, 3.1 m/s, and 3.8 m/s, respectively. The wind speed data for sites 1, 2, 3, 8, and 13 are all consistent with the data in this study. The wind speed for site 4 in this study is about 4 m/s, which is higher than 3.3 m/s in [53]. Overall, the wind data in this paper are generally consistent with those of [53].

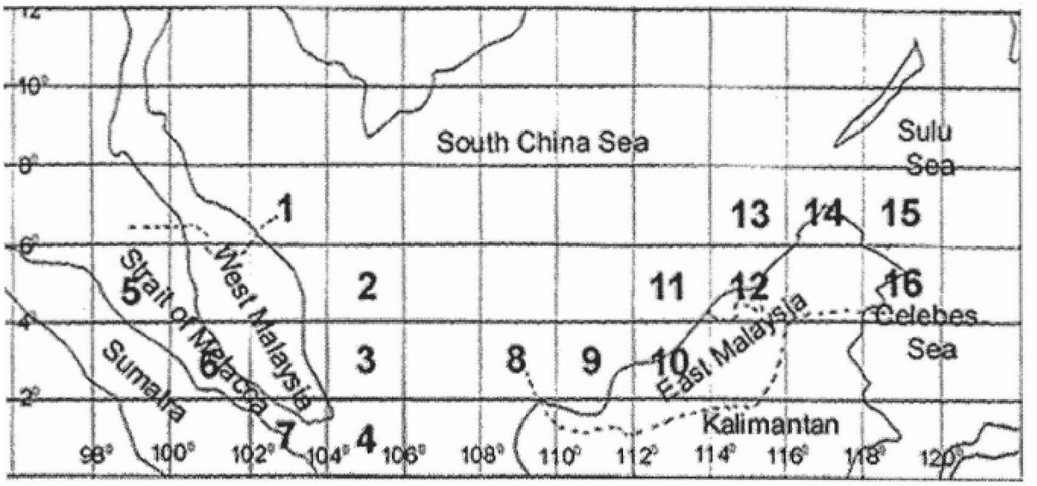
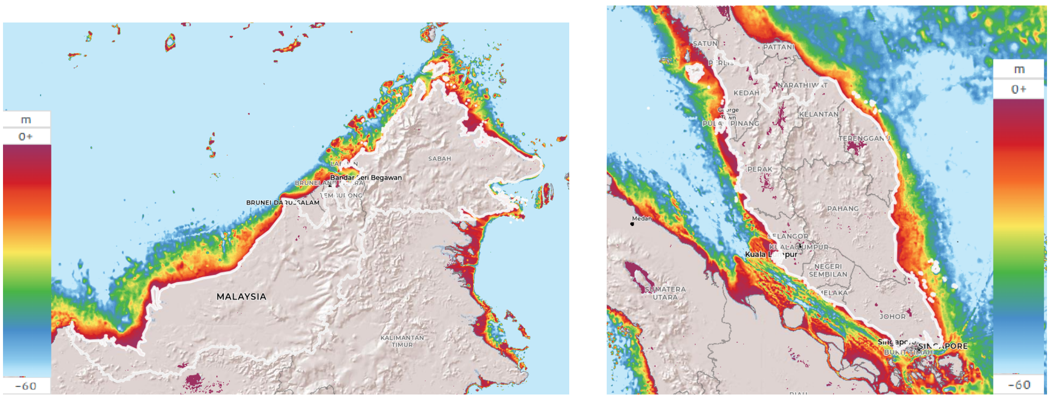


Figure 14. The 16 selected offshore wind farm sites around Malaysia [53,54].

4. Overview of Bathymetry Conditions

Fixed-bottom offshore wind turbines are commonly viable in the areas with water depths that are less than 60 m, while floating wind turbines can be installed in water depths over 60 m [55,56]. In water depths from 60 up to 120 m, tension leg platforms and semi-submersible support structures are the most common designs. In deep waters beyond 120 m, spar-type configurations are the most feasible choice [57]. Moreover, the selection of substructures is largely affected by soil substrate type. The type and strength of the seabed soil can affect the stability of the foundation and the overall structural integrity of the wind turbine. Soil conditions may necessitate modifications of the foundation design, such as the use of larger or more numerous piles, to ensure that the structure can withstand the loads imposed by wind and waves. More information about bathymetry conditions for offshore wind turbines, including water depth and soil substrate type, can be found in [58].

The bathymetry conditions of Peninsular Malaysia and East Malaysia are represented in Figure 15a and Figure 15b, respectively. The range of color bar is from 0 m to 60 m, as 60 m is recognised as the maximum water depth of fixed-bottom wind turbines. Areas with water depths below 60 m are recognised as shallow water areas.



(**a**) (**b**)

Figure 15. Bathymetry conditions in the range of 0–60 m: (**a**) East Malaysia. (**b**) Peninsular Malaysia.

In Kedah and Perlis, within 10 km of the coastline, the water depth is less than 15 m and increases with distance from the shore. At a distance of around 20 km from the shore, the water depth reaches about 25 m. When the distance from the shore exceeds 50 km, the water depth exceeds 60 m, which is not viable for fixed-bottom wind turbines.

In the region including Penang and Perak, the area of shallow water slightly expands compared to Kedah and Perlis. Within 20 km of the shore, the water depth is below 10 m. The water depth continues to increase to about 60 m until approximately 45 km away from the shore.

In the central and northern coastal areas of Selangor, there exists a vast expanse of shallow water. Within 10 km of the coastline, the water depth is consistently less than 10 m. Notably, extending approximately 45 km northwest from Pulau Ketam, there is an area covering roughly 550 km^2, where the water depth remains below 10 m.

The coastal shallow water areas in Negeri Sembilan and Malacca are limited, extending only within 2–3 km from the shoreline. In the southwestern coastal regions of Johor, the area with water depths of 10 m or less is predominantly within approximately 12 km of the shore. In the northeastern region, there are fewer areas with water depths of 10 or less (within 5 km of the shore), but from 5 km to 25 km offshore, the water depth generally remains below 25 m. The region with a water depth of 60 m or more extends continuously to approximately 75 km offshore.

Pahang, especially in the region of Kuala Rompin and Pekan, has extensive shallow water regions. The water depth remains below 30 m within 60 km of the shoreline, increasing beyond 60 m only after approximately 100 km offshore.

Shallow water areas are relatively limited in Terengganu, expanding slightly in Kelantan. In Kelantan and the northern regions of Terengganu, water depths remain less than 30 m within approximately 35 km of the shoreline, with depths exceeding 60 m only after a distance of roughly 120 km offshore.

In the northwestern and northern regions of Sabah, the water depth does not strictly increase with distance from the shore. Within approximately 70 km offshore, there is a mixed distribution of water depths, including areas with depths of less than 20 m and areas ranging from 20 to 60 m. In the northeastern region, the area with water depths less than 10 m noticeably increases, especially in the northern area of Sandakan. Within approximately 30 km offshore, the water depth remains below 10 m, covering a total area exceeding 1200 km^2.

In the northern region of Sarawak, the area with shallow water depths is smaller compared to the southern region. In the northern region, the area with depths less than 60 m extends to roughly 55 km from the shore, while in the south, this distance extends to around 100 km. Particularly, in the areas of Lawas and Sundar, within 30 km of the shore, the water depth remains below 10 m.

We further investigate the bathymetry conditions of Malaysia in the range of 0–120 m and 0–300 m. As shown in Figure 16a, most of the coastal area within 200 km of Peninsular Malaysia has water depths less than 120 m, making it suitable for tension leg platforms and semi-submersible support structures. In East Malaysia in Figure 16b, in the coastal regions of the southern region, the water depth generally remains below 120 m. However, in the northern regions, within approximately 60 km of the coastline, the water depth is less than 120 m. Beyond this 60 km distance, the water depth increases rapidly.

When the range of water depth is expanded to 0–300 m, the bathymetry conditions are illustrated in Figure 16c,d. Compared to the area within the depth range of 0–120 m in Figure 16a,b, very slight variations are found in the area within the depth range of 0–300 m. This phenomenon can be attributed to Malaysia, particularly East Malaysia, where the water depth changes gradually when closer to the shore. However, once a certain distance from the coastline is reached, the water depth increases rapidly. Consequently, the area within the depth range of 120 m to 300 m is quite small.

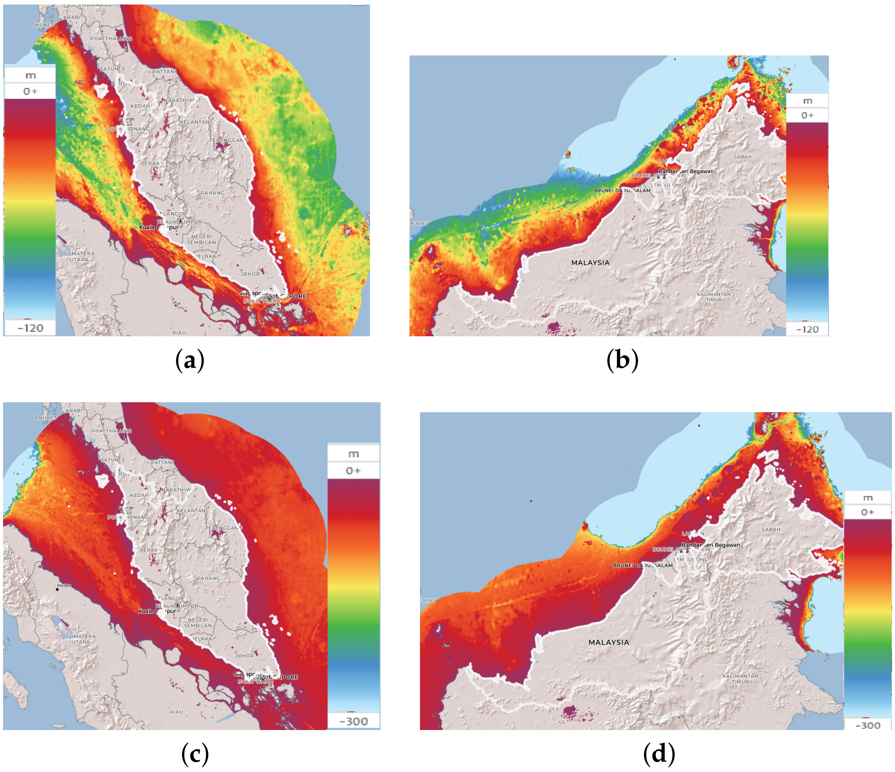


Figure 16. Bathymetry conditions of Malaysia covering 200 km coastal area: (**a**) Peninsular Malaysia (in the range of 0–120 m). (**b**) East Malaysia (in the range of 0–120 m). (**c**) Peninsular Malaysia (in the range of 0–300 m). (**d**) East Malaysia (in the range of 0–300 m).

5. Discussions

Sections 3 and 4 provided an overview of wind conditions and bathymetry conditions. This section aims to identify suitable offshore wind farm installation locations from the perspective of wind and bathymetry conditions.

After comprehensively considering the entire country of Malaysia, we identify two specific locations where wind conditions are more favourable for wind energy generation. The first location is the eastern coast of Peninsular Malaysia, extending from the eastern side of Johor to the southern region of Terengganu. Wind speeds in this area can reach 4.5–5.5 m/s. More detailed wind conditions of this area can be found in Figures 7 and 8. This finding is consistent with [59], where Mersing in this region presents a potential for wind energy development. In the extensive area examined, the most promising region is recognised in Figure 9. Within a 60 km distance of the coast of Pekan and Kuantan, wind speeds exceed 4.8 m/s. Particularly, within 15 km offshore from Kuantan, wind speeds can reach 5.5 m/s, establishing this area as Peninsular Malaysia's prime location with the highest-quality wind resources. Moreover, according to Figure 15b, the water depth of this promising area is below 60 m. This indicates that the installation of fixed-bottom wind turbines is viable. Overall, this region offers excellent wind conditions, shallow water depths, and an offshore distance of less than 15 km, providing favourable conditions for installation, operation, and maintenance.

The second location is located in the northwestern corner of Sabah, as illustrated in Figure 12. As stated in [52], this region is considered as one of the most promising locations for wind energy in Malaysia. Moreover, with 150 kW of wind turbine, the first wind turbine in Malaysia was installed at Pulau Terumbu Layang-Layang, Sabah.

Wind speeds can reach 5.5–5.9 m/s within a 50 km distance of the shore. According to Figure 15a, this area is well-suited for the installation of fixed-bottom wind turbines, primarily due to water depths within 60 km offshore remaining below 60 m. Furthermore, wind speeds in the area extending up to 200 km offshore are not less than 5.3 m/s, containing excellent wind resources. The range of deep water currently in the floating offshore wind turbine industry is within 300 m [60], which means that the area within 60–80 km offshore is suitable for the deployment of floating wind turbines. Overall, this region provides excellent wind resources. Within the region located approximately 60 km offshore, fixed-bottom wind turbines are well-suited, while floating wind turbines are considered appropriate for installation within the area extending from 60 km to 80 km offshore.

6. Conclusions and Future Research

Offshore wind energy, considered as one of the most promising renewable sources, has garnered the Malaysian government's interest, leading to increased efforts in exploring its potential. Offshore wind energy is a key to unlock the renewable energy potential in Malaysia and finally supports the government target to achieve the renewable energy target of 20% by 2025. The development of offshore wind energy ensures a more reliable and consistent supply of electricity, directly contributing to regional energy security and stability. This paper investigated the wind and bathymetry conditions around Malaysia based on data from the Global Wind Atlas. It is found that the eastern coastline of Peninsular Malaysia, spanning from the eastern side of Johor to the southern region of Terengganu, along with the northwestern region of East Malaysia, possesses wind energy resources of high quality. Two distinct locations characterised by favourable wind conditions for the harnessing of wind energy have been identified. The first location is the eastern coast of Peninsular Malaysia, extending from the eastern side of Johor to the southern region of Terengganu, and the fixed-bottom wind turbines are viable. The second location is located in the northwestern corner of Sabah. Within the distance of 60 km offshore, fixed-bottom wind turbines are viable, while floating wind is suitable in the region from 60 km to 80 km offshore. The findings have the potential to serve as valuable references and offer recommendations for future offshore wind development initiatives in Malaysia.

Although this paper investigated the wind and bathymetry conditions surrounding Malaysia and provided suggestions for offshore wind farms, some limitations still exist. First, the decisions regarding offshore wind project development depend on the wind resources in the area, which is not covered in this paper. Future research will estimate Malaysia's offshore wind energy resources based on wind conditions, identify areas with abundant wind energy resources, and reveal the benefits of offshore wind energy utilisation in Malaysia. Second, the two suitable wind farm locations proposed at the end of this paper are only based on wind and bathymetry conditions. Techno-economic analysis can better assess the potential of the selected sites, which will be a future research direction. Third, Malaysia is an example of a mild-resource area compared to other countries with rich wind resources, such as Denmark and the UK. The installation, operation, and maintenance of offshore wind power require a large initial investment. A promising future direction will be to investigate how offshore wind could become economically attractive in Malaysia.

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