Evaluation of resource spatial-temporal variation, dataset validity, infrastructures and zones for Vietnam offshore wind energy

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Abstract:

The shortage of reliable datasets and resource assessments, resource variations, and lack of marine planning are the technical challenges facing offshore wind energy development in Vietnam. This pioneering paper comprehensively addresses these challenges by first screening available datasets to select cross-calibrated multi-platform (CCMP) data and validating them with measurements. The resource is divided into four zones of 100 NM-width from the coastline. The wind energy density (WED) and capacity factor (CF) are calculated using an 8 MW reference turbine. The assessment of the zoned resource and infrastructures is based on the location of synchronous power sources and ports, along with the variation of WED and CF. Zone 3, comprising of the Binh Thuan and Ninh Thuan seas, the southern part of Zone 2 (Phu Yen and Khanh Hoa), and the northern part of Zone 4 (Ba Ria and Vung Tau) are found to have the highest wind energy potential, where the annual accumulated WED is 80 GWh/km^2. The five year CF and average wind speed in Phu Quy island were 54.5% and 11 m/s, respectively. These zones, with moderate resource variation and excellent ports are the most suitable for offshore wind energy development. Zones 1 and 4 are recommended for far-offshore wind farms. This work is useful to various environmental groups and is a crucial input to marine and power planning.

Keywords: **CCMP data, marine and power planning, offshore wind energy, ports, spatial and temporal variation, Vietnam sea.**

Classification numbers: **1.3, 2.3**

Introduction

Countries around the world are facing the problems of environmental pollution and energy security and renewable energy emerges as an optimal method to solve those problems [1]. The use of wind energy has had positive impacts on society and the environment, including the reduction of greenhouse gas emissions, job opportunities, and the promotion of sustainable development [2]. Offshore wind power productivity can be 1.5 times that of onshore plants because offshore wind speeds are greater and more stable [3]. In addition to providing electricity to the grid, offshore wind power plants can help improve the quality of life in island areas far from the shore [4] and potentially supply power to gas for renewable fuels [2].

Resulting from rapid economic development, the energy demands made by the industrial, transportation, commercial, and residential sectors of Vietnam have significantly increased and most of the country's electricity is generated by hydropower and fossil fuel power until now [5]. However, recently there has been an exhaustion of sites for hydropower plants and a revelation of negative impacts caused by hydropower to the local environment and ecology [6]. From the latest national Power Development Plan (PDP) in Vietnam [7, 8], so-called the "*Adjusted PDP VII*" that projects into 2030, coal-fired power is expected to grow strongly from a share of 33% (12.9 GW) in 2015 to 43% (55.1 GW) in 2030, which is abnormally high. The share of renewable energy (excluding large hydropower plants) installed capacity will be 9.9% in 2020 (1% from wind) and 21% (5% from wind) in 2030, which is very low in comparison with the country's potential.

The exploitation of renewable energy sources seems to be the only way to reduce the large share of coal-fired power in Vietnam. The country is likely to have a huge opportunity for developing offshore wind energy [9] because of its more than 3,000 km of coastline and 1 million km^2 sea area. Vietnam offshore wind is seated in the top ten of global potential markets,

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*Corresponding author: Email: ducnd@vnu.edu.vn as reported by the Global Wind Energy Council [10]. However, besides political impetus [11], there are a number of major domestic technical obstacles to offshore wind policymakers and developers in Vietnam. The first two obstacles are (i) the shortage of reliable offshore wind, metocean, and seabed data sets and (ii) the severe lack of a comprehensive assessment of offshore wind resources and infrastructures.

Doan, et al. [12] made the first attempt to simulate the offshore wind over an area limited to southern Vietnam using a numerical simulation model, however, it was without validation of the simulated wind data. A second and more complete attempt was made with the recent use of numerical simulations validated by two sets of wind data obtained from (i) six ground-based weather stations on islands off the coast of Vietnam and (ii) QuikSCAT (Quick Scatterometer), an Earth observation satellite with a coarse spatial resolution of 25 km [13]. The absence of up-to-date marine planning, where the offshore wind development zones and foreshore grid connections have never been studied and designated, is the third major obstacle to offshore wind policymakers and developers in Vietnam. In a first initiative, maps of potential offshore wind zones in Vietnam with 30 m and 60 m water-depth contours were proposed [14].

There are many studies that assess wind energy potential around the world by using data obtained from satellites and wind observation stations [15]. Such datasets were used in Kirklareli, Turkey [16], in Turkey [17], and in Tehran, Iran with data from a period between 1995 and 2005 [18]. Measured data were utilised to assess the wind energy potential in Malaysia from ten meteorological stations over ten years [19], in Egypt [20, 21], and in Oman based on a five-year hourly wind dataset obtained from weather stations [22]. Statistical methods were used in Morocco [23, 24] and in Jordan [25] via Weibull distributions. Not only wind characteristics, but also wind power generation, was investigated in Jordan [25], Nigeria [26], and Ireland [27]. Offshore wind resources have been accessed by many countries. Wind speed and rose, energy rose and density, and air density of a south-western sea area in South Korea were analysed from meteorological mast data [28]. The potential application of the hyper-temporal satellite Advanced Scatterometer data for offshore wind farm site selection in Irish waters was investigated and the data was validated by *in situ* measurements from five weather buoys [29]. Thus, the use of data from satellite observations and from measurements to assess wind energy potential is widely accepted. In this work, cross-calibrated multi-platform [30] data are used after validation with measurement data.

The great challenge behind wind energy is its high dependence on wind speed that fluctuates greatly at all time scales, that is, minutes, hours, days, months, seasons, and years [31]. Understanding the temporal variations of the wind is of key importance to the integration and optimal utilization of wind in a power system [32]. Wind power assessment, therefore, plays a key role in dealing with the stochastic and intermittent nature of wind and the challenges involved with the planning and balancing of supply and demand in any electricity system [32, 33]. Such spatiality in power sources and transmission is apparent in Vietnam, where renewable generation capacities are mostly installed in the south and the major demand centres are in the southern and northern regions [34].

A large geographic spread of installed capacity can reduce wind power variability and smooth its production. It is essential to understand the wind power spatiality in order to address power system constraints in systems with large and growing wind power penetrations [35]. The spatial and temporal correlation of wind power across ten European Union countries was examined from three years of hourly wind power generation data [35]. A spatial analysis of offshore wind resources in Africa revealed that more than 90% of the resources are concentrated in coastal zones associated with three African power pools and suggested that a joint and integrated development within these power pools could offer a promising approach to utilising offshore wind energy in Africa [36].

The major challenges to government and national marine authorities are how to manage the planning, consent, installation, and operation of offshore wind projects and how to integrate those activities effectively into other activities and strategies such as natural/cultural heritage site designations, military/aviation, shipping, fishing, and ports or harbour restrictions [2]. In this context, marine spatial planning (MSP) is a new way of looking at how the marine area is used and preparation of how best to use it in the future [37]. The increasing number of uses and users of the ocean leads to more conflicts, whereas zoning the ocean in space and time has been shown to reduce these conflicts [38]. Additionally, planned use of the marine environment can minimise losses and maximise gains for conflicting sectors [39]. Such lessons can be learned from the Great Barrier Reef Marine Park (GBRMP) [40] and the ongoing MSP development in Europe.

In an objective summary, this paper aims at addressing the number of technical challenges to the development of offshore wind in Vietnam. The CCMP data validated with measurement data from seven meteorological stations were the input to contend with the shortage of reliable wind data. The severe lack of resource assessment is initially addressed by evaluating the temporal and spatial variation of offshore wind speed and directions over seasonal, annual, and inter-annual periods. Based on the approach of time and space zoning [38], the lessons learned, expert consultations, temporal variation of temperature, and the offshore wind resource, the ocean area 100 NM off the coastline of Vietnam is classified into four zones. Prior to evaluating the offshore wind resource and infrastructures in this work, a set of criteria and data including temporal variation in temperature, synchronous power sources and transmission, seaport facility, offshore wind power, and density and capacity factors are discussed. Such validated wind data, infrastructure data, and the evaluation of resource potential, density, temporal, and spatial variations will be input for further work by policymakers, energy and marine planners, industry developers, and researchers. Such initial zoning and zone evaluation will be crucial, in combination with other sectors, to the development of MSP and power plan in the country.

Methodology

The methodology of this paper is depicted in Fig. 1. The first step, after selecting a dataset, is to validate the dataset by comparing their surface wind speed probability distribution with that of the measurement data from seven meteorological stations. If the comparison shows that the dataset is usable, the next step is to extrapolate the wind speed at different heights and evaluate the temporal and spatial variations of wind speed and direction. Using that evaluation and zoning criteria, the potential offshore wind area is divided into four zones for marine and energy planning and management. The last two steps are to calculate the wind energy potential, capacity factor, power distributions, and to evaluate their temporal and spatial variations for each zone. Prior to these steps, information on how wind power would be converted is required, which can be input by power curves of the reference wind turbines. In this study, a LEANWIND 8 MW turbine [41] is selected as the reference.

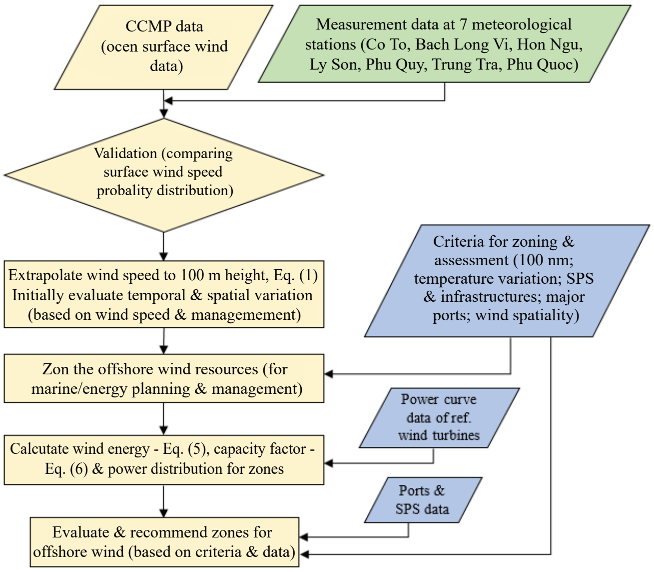


Fig. 1. Methodology flowchart of the study. SPS: synchronous power source**.**

Dataset selection and validation

The surface wind dataset is used in research obtained from the CCMP project published by the U.S. National Aeronautics and Space Administration (NASA) [30, 42]. This project aimed to obtain multi-instrument ocean surface wind velocity, which is used to analysis meteorology and oceanography. This dataset is built from combining cross-calibrated satellite winds from remote sensing systems by using variational analysis (VA) [42]. This method creates a gridded surface wind analysis with high spatial resolution (0.25 degrees) that can minimize the deviation of data. The cross-calibrated satellite wind data from the CCMP dataset contains data from a number of microwave satellite instruments. These microwave radiometers, such as the special sensor microwave imager sounder (SSMIS) and WindSat [43], were used to gather information about wind speed. Microwave scatterometers, such as QuikScat and SeaWinds, were also applied to obtain wind speed and directions by the development of a geophysical model function. Wind velocity is observed and analysed at 10 meters above sea level. The spatial resolution of the dataset was 0.25 degrees in latitude and 0.25 degrees in longitude. Especially important, the dataset has a high temporal resolution of 6 h and a timespan of 25 years, from 02 July 1987 to 31 December 2011, as listed in Table 1. Because the entire CCMP data over the course of 25 years is very large, this study used wind data from the last five years of the dataset (from 2007 to 2011). The CCMP dataset was then validated by comparison with the observed data from several meteorological stations located in Vietnam. The temporal resolution of measured data for comparison with CCMP is 6 hours; similar to that of the CCMP data. The measurement stations are also placed at a height of 10 m above sea level. Thus, the two datasets have a similar temporal resolution and height. In this study, the surface wind speed probability distribution between the CCMP data and the measurement data from seven meteorological stations along the coast and on several islands for five years (from 2007 to 2011) is compared.

Table 1. Information of the CCMP dataset [30].

Region	Global
Northernmost latitude (degree)	78
Southernmost latitude (degree)	-78
Westernmost longitude (degree)	0
Easternmost longitude (degree)	360
Time span	1987-Jul-02 to 2011-Dec-31
Spatial resolution (Latitude × Longitude)	$0.25^\circ \times 0.25^\circ$
Temporal resolution (hour)	6

Estimation of wind energy potential

In order to assess the relevant wind energy potential to the wind turbines, the wind speed at various heights is required. The CCMP dataset used in this research contains wind speed at 10 meters in height above sea level. The wind power law, commonly used for extrapolating wind speed from the sea surface to specific heights [24, 44, 45], is adopted as follows:

$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha} \tag{1}$$

where the parameter α is the power law exponent, v_1 is wind speed at height z_1, and v_2 is wind speed at hub height z_2. According to Davenport [46] and Hsu [47], the magnitude of the power law exponent was found to be approximately 0.1 under natural conditions of the sea. It is noted that this theoretical extrapolation approach is for a preliminary assessment, particularly at a larger scale and spatial variation. Future research to obtain measurements and higher resolution data for wind profiles at turbine hub height are recommended before planning the offshore wind development zones and marine spaces.

Wind turbines convert the kinetic energy of wind into electrical energy. By operation classification, there are two basic types of wind turbines: vertical axis and horizontal axis, where the horizontal axis wind turbines are more popular than the vertical axis ones. The power output of a horizontal axis wind turbine is calculated by using following equation [48, 49]:

$$P(v) = \begin{cases} 0, & v < v_i \\ P_f(v), & v_i \leq v < v_r \\ P_r, & v_r \leq v < v_o \\ 0, & v_o \leq v \end{cases} \tag{2}$$

where the parameters P_r, v_i, v_r, and v_o are the rated power, cut-in wind speed, rated wind speed and cut-out wind speed of the reference wind turbine, respectively, and $p_f\ (v)$ is the nonlinear relationship between wind speed and electric power:

$$P_f(v) = \frac{1}{2} \times \rho \times A \times C_p \times v^3 \tag{3}$$

In Eq. (3), A is rotor swept area of the reference wind turbine, ρ is the air density and C_p is the overall efficiency coefficient, valued between 0.3 and 0.5, which varies with both wind speed and rotational speed of the turbine.

The energy conversion output of a wind turbine over a time period can be determined from:

$$\mathrm{E_{out}} = \sum_{t=1}^{N} \mathrm{P(v)} \times \mathrm{T_t} \tag{4}$$

where T_t is the temporal resolution (h) and N is the number of spans in the time period.

Energy production from the wind farm over the time period is calculated as follows:

$$E_{\mathrm{windfarm}} = \sum_{i=1}^{N_t} E_{\mathrm{out}} \tag{5}$$

where N_t is the number of wind turbines in the wind farm.

The capacity factor represents the ratio between the actual electrical energy output and the maximum possible electrical energy during the time period and depends on both wind turbines and site characteristics. The annual CF is defined as follows:

$$CF = \frac{E_{out}}{E_r} \times 100\% \tag{6}$$

where the annual maximum possible electrical energy is defined as follows:

$$E_r = P_r \times (24h/day) \times (365days) \tag{7}$$

Zoning and assessment criteria of offshore wind resource zones

Based on the beneficial approach of time and space zoning discussed in [38], the lessons learned from the GBRMP [40], and from the ongoing MSP development in Europe and other countries [38], the following set of criteria is proposed to initially zone the offshore wind resources in Vietnam and to assess the zones:

(a) *Sea area of 100 nautical miles (185.2 km) from the coastline:* this distance is adopted as it is the maximum distance that offshore wind farm can be deployed in the near future at economical costs.

(b) *Temporal variation in temperature over the year:* this affects the characteristics of coastal and marine biology and human activities at sea, including fishing and tourism.

(c) *Synchronous power sources and main electricity transmission lines:* synchronous power sources are hydropower, gas, and oil-fired power plants. Main electricity transmission lines include 500 and 220 kV lines. These power infrastructures are essential to the spatial distribution and intermittency of renewable energy sources in criterion (e) and the delay in expansion/upgrading the electricity grid required [34].

(d) *Existing or potential major seaports and container terminals:* these are the key elements of the supply chain required for the assembly, transportation, and installation of offshore wind turbines components including the blades, towers, substructure, and foundations [2]. In order to accommodate installation vessels, offshore developers require a port draft of up to 10 m, quayside of up to 300 m, and water way of up to 200 m [50]. The transportation of monopiles using heavy lift cargo vessels and their installation by jack-up vessels require drafts of about 9.5 m and 5.8 m to Chart Datum of water, respectively [51]. The overall lengths for heavy lift cargo vessels approach 170 m [51].

(e) *Temporal and spatial variation of wind resources:* parameters characterising the quality of wind resources directly obtained from wind data are wind speed and wind direction. Temporal variation means the change of wind speed over months, seasons, and years. Both wind speed and its temporal variation govern the energy output of a wind turbine as in Eq. (4), and consequently control the capacity factor, as defined in Eq. (6). Both wind speed and its spatial and temporal variation influence the energy production of wind farms as shown in Eq. (5), and the energy storage and the integration of the wind farms into the grid. At larger scales, spatial and temporal variation affect the stability and operation of the national/regional power system [32, 35].

The theoretical potential of wind energy is however limited by a number of constraints including ecology, supply chains, other sectors, and political and natural reasons. In identifying the unsuitable areas for onshore wind in Vietnam, exclusion criteria including high altitude, political areas (cities, urban centres, road, railway, airport, etc.), water areas, protected areas, and living areas, were used [11]. When studying offshore wind potential, a number of exclusion criteria for onshore wind are not applicable or need to be updated, and new criteria should be defined for finer zoning and practical assessment in future studies.

Results and discussion

Data validation

The CCMP dataset was compared with the observed data from seven meteorological stations. The locations of the seven meteorological stations are shown in Table 2 and Fig. 2. Fig. 3 shows the wind speed probability distribution of both the CCMP data and measurement data. The shape of the probability distribution of the CCMP data is very close to the measured data. Notably, the shape of the distributions of the two data sources are almost identical at the Co To, Hon Ngu, and Ly Son stations. From Fig. 3, it can also be seen that the area around Phu Quy island has the largest wind speed. Phu Quy is a part of the Ninh Thuan province. In the North Sea, Bach Long Vi island also has strong wind in that area.

Table 2. Location of meteorological stations of Vietnam.

No.	Station	Latitude	Longitude
1	Co To	20.98	107.77
2	Bach Long Vi	20.13	107.72
3	Hon Ngu	18.8	105.77
4	Ly Son	15.38	109.15
5	Phu Quy	10.52	108.93
6	Truong Sa	8.65	111.92
7	Phu Quoc	10.22	103.97

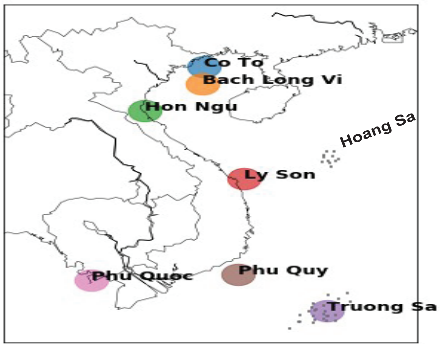
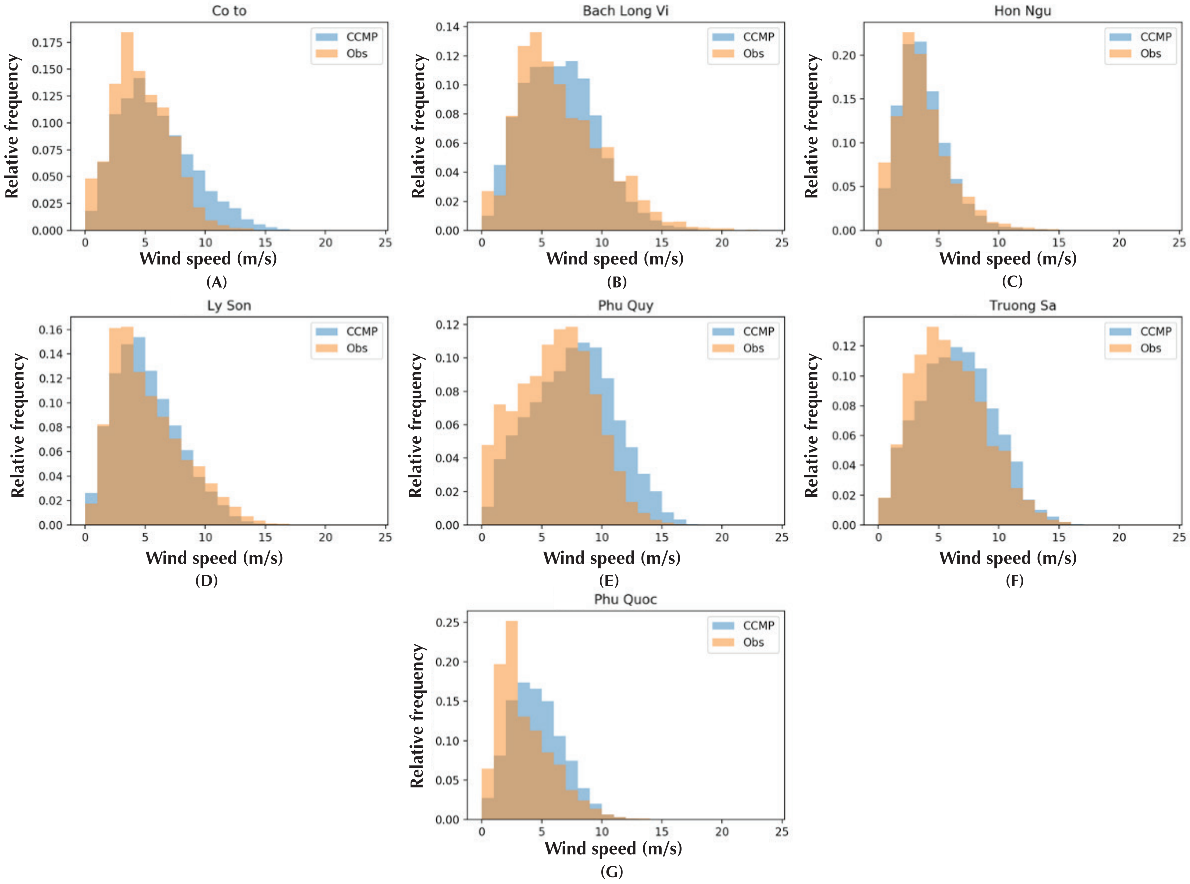


Fig. 2. Location of meteorological stations on the map.



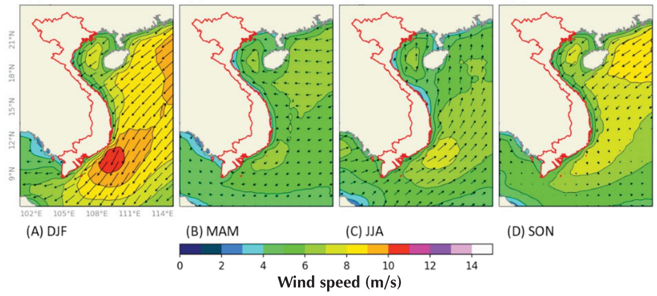
(A) (B) (C) (D) (E) (F) (G)

Fig. 3. Surface wind speed probability distribution of the CCMP data and observed data from the seven meteorological stations over the five-year period 2007-2011.

Evaluation of spatial and temporal variation of offshore wind resources

The seasonal variation of wind speed and direction over the period 2007 to 2011 can be evaluated from Fig. 4, where the study considers four seasons: winter being December - January - February (DJF), spring including March - April - May (MAM), summer including June - July - August (JJA), and autumn including September - October - November (SON). In the winter months, the north-eastern monsoon is stronger than the winds during the other seasons in Vietnam. The south-western monsoon is quite strong in the summer months June - July - August (JJA).

Figure 5 shows the wind speed at a turbine hub elevation of 100 m averaged from 2007 to 2011, however this data was not verified due to the shortage of measured data. In the offshore areas around Phu Quy island, the wind speed is largest with an average of about 11 m/s. It is approximately 9 m/s at Tonkin Gulf in the northern sea. The inter-annual wind speed of the four islands: Bach Long Vi, Ly Son, Phu Quy, and Phu Quoc, from 2007 to 2011, are shown in Fig. 6, which is obtained by plotting the monthly averaged wind speed over five years. The largest wind speed is about 12 m/s in Phu Quy island in January. The lowest wind speed range is from 2.765 to 7.347 m/s during this period in Phu Quoc. The mean wind speed ranges from 3.578 to 9.682 m/s and from 2.91 to 9.275 m/s in Bach Long Vi and Ly Son, respectively.



(A) DJF (B) MAM (C) JJA (D) SON

Fig. 4. Seasonal average surface wind speed within five years from 2007 to 2011.

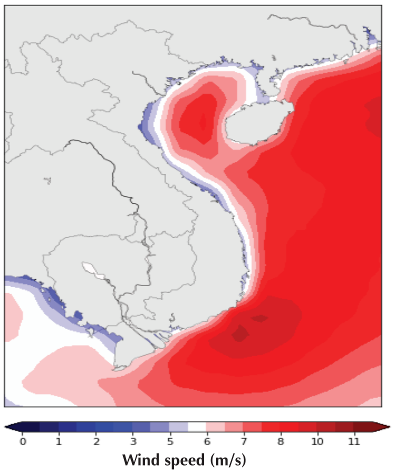
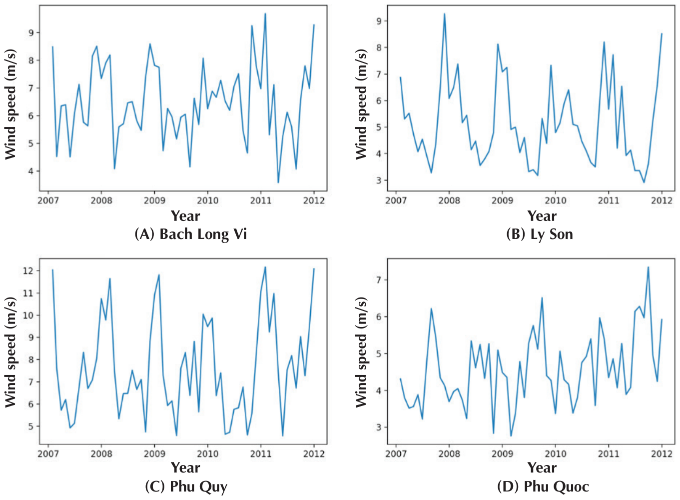


Fig. 5. Wind speed average at 100 m above sea level from 2007 to 2011.



(A) Bach Long Vi (B) Ly Son (C) Phu Quy (D) Phu Quoc

Fig. 6. Inter-annual wind speed at the four islands over the period 2007-2011.

Zoning and assessment of zone infrastructures for offshore wind energy

Based on the consultation with marine and island management experts along with the criteria discussed in the above section, the offshore wind resource in Vietnam was first classified into four zones with their boundaries shown in Fig. 7. Zone 1 is the region with the coldest winter of the four zones and consists of eight provincial sea areas extending from Quang Ninh province to Ha Tinh province. Zone 2, where the winter is moderately cold, has a sea area comprising of seven coastal provinces starting from Quang Binh to Binh Dinh. Zone 3 is less affected by the winter monsoon and is made up of five provincial seas from Phu Yen to Ba Ria - Vung Tau. Zone 4 is the sea region from Ho Chi Minh city to the Kien Giang province, is the least affected by the winter, and has the highest average temperature over the year.

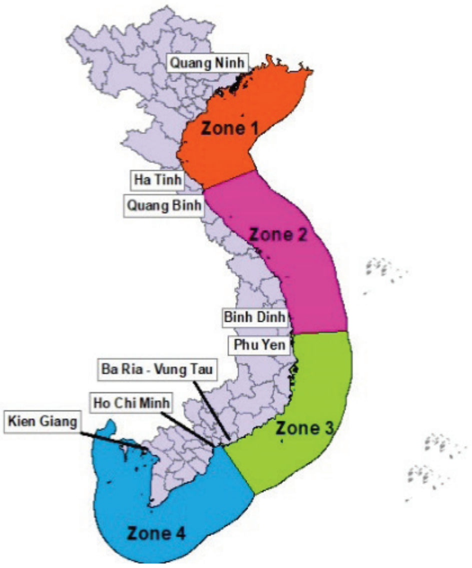


Fig. 7. Proposed four zones of Vietnam's offshore wind resources.

Second, the offshore wind resource zones classified above were assessed by using criteria (c) - (e) listed above. Fig. 8 reveals the existing synchronous power sources and major transmission lines in Vietnam [52] as required by criterion (c). The region in the north of the country is a large area containing diverse sources of electricity. The provinces along the northern border import some of their electricity from China. Additionally, there are major coal-fired power plants in the north eastern provinces. The major hydropower plants are located the north western provinces: Son La, Tuyen Quang, and Hoa Binh.

The continental shape of the northern central region is long and narrow. The electricity supply in this area comes from two main sources, hydropower and imported electricity from Lao, and is carried by 500 kV lines along this area. The source of electricity for the mainland along southern central region is mainly supplied by hydropower plants. In order to enhance the transmission of electricity to this area, 220 kV and 500 kV lines have been installed. Gas/oil-fired power plants are the main supply of electricity in the southern region where some of the electricity is exported to Cambodia. The spatiality of the power sources and transmission systems are displayed in Fig. 8 as required by criterion (c) as previously discussed [34]. It is worth noting that the country's major demand centres are the southern and northern regions [34].

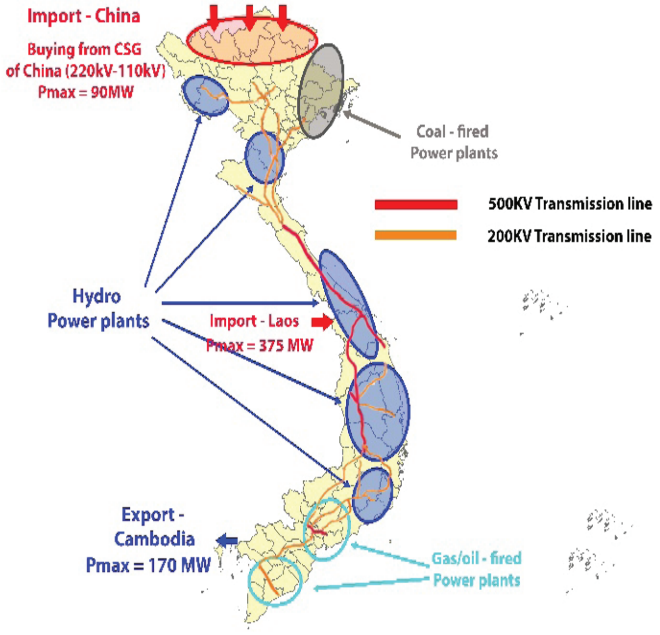


Fig. 8. Major synchronous power sources and power transmission lines in Vietnam [52].

The major seaports and container terminals are mapped in Fig. 9 and listed in Table 3 as required by criterion (d). Major ports with channel depths greater than 10 m and maximum acceptable vessel size of 30,000 dead weight tonnage (DWT) can be found in Zone 1, the southern part of Zone 2, Zone 3, and Zone 4. The following three container ports in Vietnam: Hai Phong and Dinh Vu in Zone 1 and Tan Cang Sai Gon in Zone 4, are among the top 20 container of Southeast Asia [53]. Especially, the Van Phong International Transhipment Terminal under development in Van Phong Bay, Khanh Hoa province of Zone 3, which has a depth range of 15-20 m, a large area, and anticipates a maximum vessel size of 9,000 TEUs (twenty-foot equivalent units) or approximately 120,000 DWT. Considering the important characteristics of a seaport, including draft/channel depth, size of vessels accepted, and the available area, the port facilities in Zone 3 are the most favourable for offshore wind farm development. Those in Zone 1 and 4 are also of good capacity.

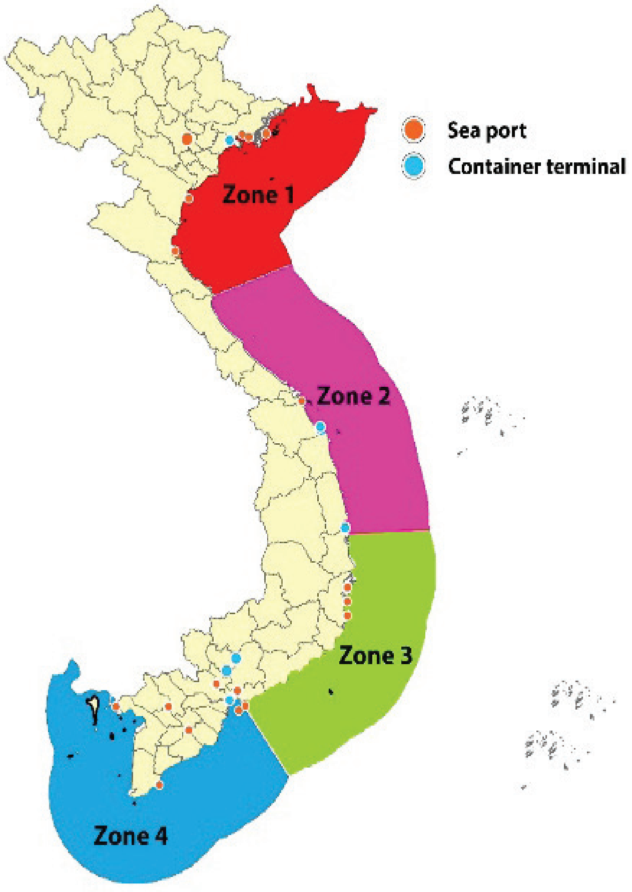


Fig. 9. Location of major ports, container terminals, and in-land river ports accessible to large vessels (data source: [54, 55]).

Table 3. Characteristics of major ports in Vietnam.

No.	Berth Length (m)	Berth draft zero tide (m)	Channel draft zero tide (m)	Vessel accepted (DWT)	Area (ha)
Zone 1					
1	3×680	13.0	13 - 20	50,000	15 [55]
	Quang Ninh [55]				
2	3×594	13.0	10.0	50,000	18.1
	Cai Lan International [55]				
3	5×848	8.5	5.5	40,000	29 [55]
	Hai Phong - Chua Ve [55]				
4	2×427	8.9	7.3	40,000	24 [55]
	Dinh Vu - Hai Phong [55]				
5	5×956	9.1	9.4		51
	Hai Phong - Tan Vu [55]				
Zone 2					
1		8.5	8.5	20,000	11.0
	Nghi Son, Thanh Hoa [55]				
2		12.0	11.0	30,000	8.2
	Chan May, Hue [55]				
3		12.0	10 -17	45,000	30
	Da Nang [55]				
4		12.0	10.5	30,000	36
	Quy Nhon, Binh Dinh [55]				
Zone 3					
1		11.8	11.1	20,000	8.0
	Nha Trang, Khanh Hoa [55]				
2		9.7	10.2	30,000	89
	Cam Ranh, Khanh Hoa [55]				
3	12,000 (total)	15~20		120,000 [56]	740
	Van Phong [57] (Potential)				
4		14	9.3	60,000	13.0
	Phu My, Baria - Vung Tau [55]				
Zone 4					
1	5×706	11.5	8.5	30,000	38 [55]
	Tan Cang [57]				
2	2,667 (total)	10.5	8.5	50,000 [55]	30.0
	Sai Gon [57]				
3	816 (total)	11.0	8.5	36,000 [55]	28.0
	Ben Nghe [57]				

Evaluation of wind energy potential and variation for each zone

In order to evaluate the wind energy potential and its variation, information regarding how the varying wind speed would be converted by the wind turbines to wind power is necessary. Such information is often revealed from the power curves of wind turbines. Given that offshore wind could enable the deployment of larger turbines and that three-bladed horizontal axis wind turbines (HAWTs) are mature and commercial, two large HAWTs with a power rating of 8 MW and with publicly available power curves, Vestas V164-8.0 [58, 59] and LEANWIND (LW) [41], are considered in this study. The parameters of the two turbines are listed in Table 4. The Vestas V164-8.0 is in use by several offshore wind farms such as Burbo Bank Offshore, the United Kingdom, and Norther N.V., Belgium [60]. However, it would be more difficult to design a support structure for the Vestas V164 [41]. Additionally, the rated wind speed of the Vestas V164-8.0 is 13.0 m/s and higher than that of the LW turbines (12.5 m/s) as shown in Table 4. The LW turbine is therefore cost-saving, able to meet the short to medium-term requirements of the offshore wind industry [41], and more suitable for the wind conditions in Vietnam. Accordingly, the LW 8 MW is chosen for the estimation of wind energy potential in this paper. Fig. 10 presents the power curve of the LW turbine used to estimate the energy production from wind speed. The reasonable distance of wind turbines chosen to minimise the wake effects in the prevailing wind direction is $10D_r$, and in the crosswind direction is $4D_r$ [61]. However, the wake effects due to adjacent turbines in the wind farms are not considered in this study [61].

Table 4. Information of Vestas V164-8.0 and LW 8 MW reference turbines.

Parameter	Vestas V164-8.0 [58]	LEANWIND 8 MW [41]
Rating power, P_r (kW)	8000	8000
Cut-in wind speed, v_i (m/s)	4	4
Rated wind speed, v_r (m/s)	13.0	12.5
Cut-out wind speed, v_o (m/s)	25	25
Rotor diameter, D_r (m)	164	164
Rotor speed range (rpm)	4.8-12.1 [59]	6.3-10.5
Rotor swept area, A_r (m^2)	21,124	21,113.36
Hub height, H_{hub} (m)	105	110

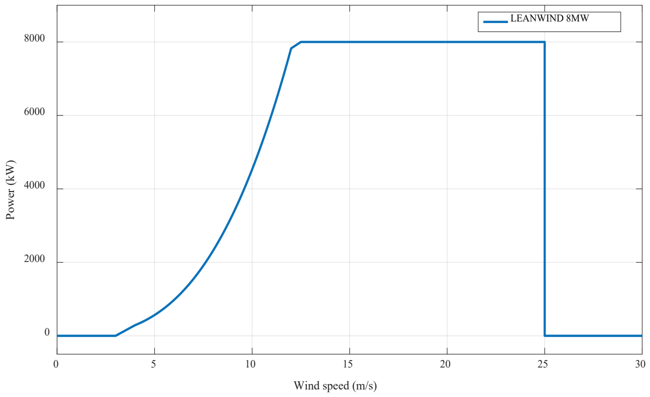


Fig. 10. Power curve of LEANWIND 8 MW turbine. Plotted from data in [41].

The seasonal accumulated wind energy density of the four zones from 2007 to 2011 is illustrated in Fig. 11, where the highest density of energy among the four zones is seen to occur during the winter months. Meanwhile, the second largest wind energy density occurs during autumn. On the other hand, the lowest power density occurs during the spring and the summer. It is apparent from Fig. 11 that Zone 3 contains the highest wind energy potential during the four seasons in Vietnam.

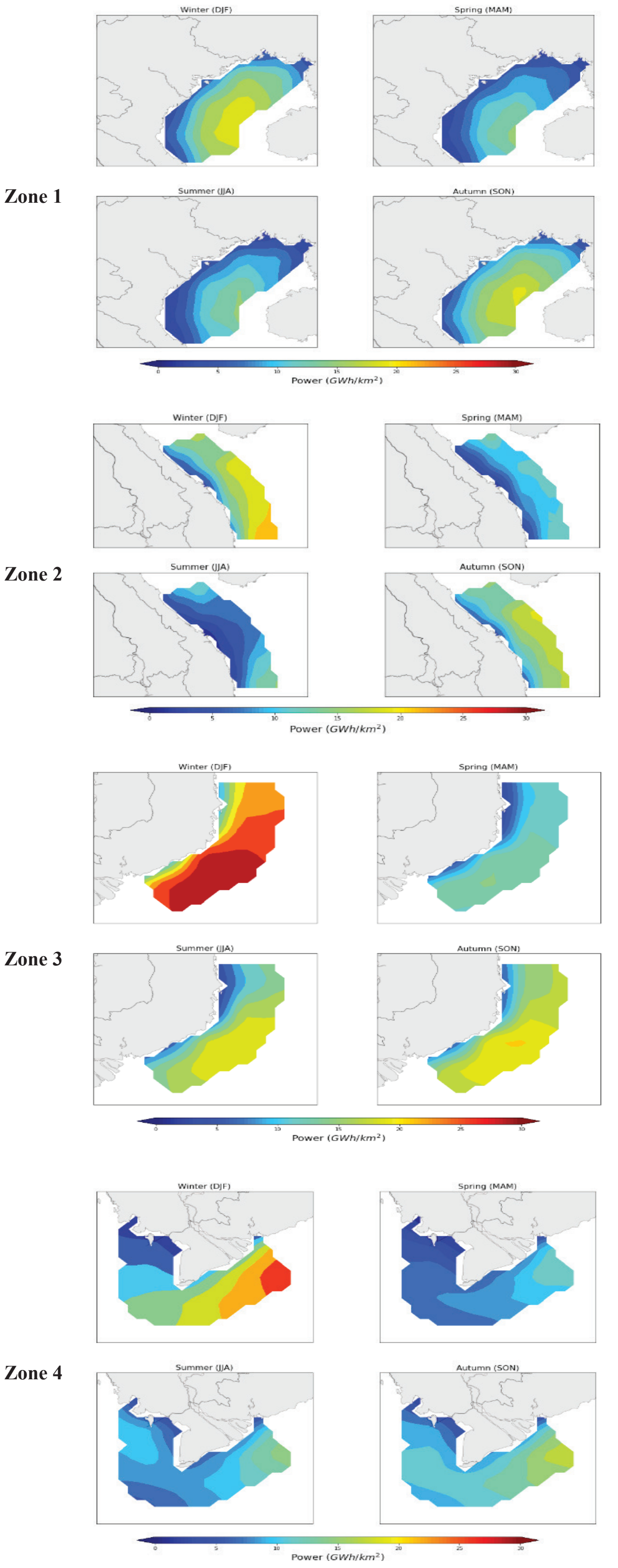


Fig. 11. Seasonal accumulated wind energy in four offshore zones in Vietnam.

Table 5 summarises the maximum seasonal accumulated wind power in the four zones. The highest value is that of Zone 3, during winter, with a value of 28.95 GWh/km^2. The season with the least wind energy potential occurred during spring and had the smallest value of 11.87 GWh/km^2 in Zone 4. Fig. 12 compares the annual accumulated wind density of the four zones between 2007 and 2011. It can be clearly seen that the annual accumulated wind energy density is about 80 GWh/km^2 at Zone 3, which is larger than in the other areas. The areas in Zone 2 and Zone 4 had wind energy densities similar to Zone 3. In Zone 1, the area around the latitude and longitude of 19.8 and 108, respectively, had the largest offshore wind energy potential. Bach Long Vi island is closest to that location.

Table 5. Maximum of seasonal wind energy in offshore wind zones (GWh/km^2).

Season	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Winter	19.28	22.17	28.95	26.69
Spring	14.79	12.97	13.63	11.87
Summer	14.63	14.22	19.73	14.63
Autumn	18.33	18.49	20.15	17.34

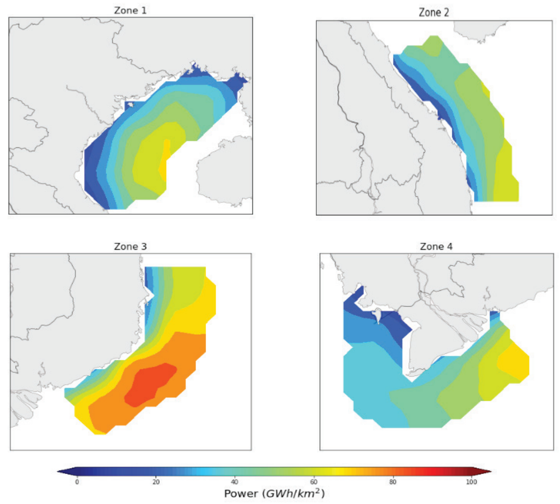


Fig. 12. Annual accumulated wind energy in four zones.

Capacity factor

The seasonal and annual CFs of the four zones using the LW 8 MW turbine power curves are shown in Figs. 13 and 14, respectively, where only the areas with a capacity factor greater or equal to 25% are shown. The north eastern monsoon enables CFs to reach their highest value. As a result, the transformation of wind energy into electricity by turbines is at its highest. Particularly, the area far from Phan Thiet city, about 120 km to the northwest, has a maximum capacity greater than 80%. Moreover, the annual average capacity factor in this area also had the highest value (about 60%) compared with the other zones. In contrast, the offshore area from Quang Binh to Quang Nam in Zone 2 is not effective for the operation of wind turbines in the summer.

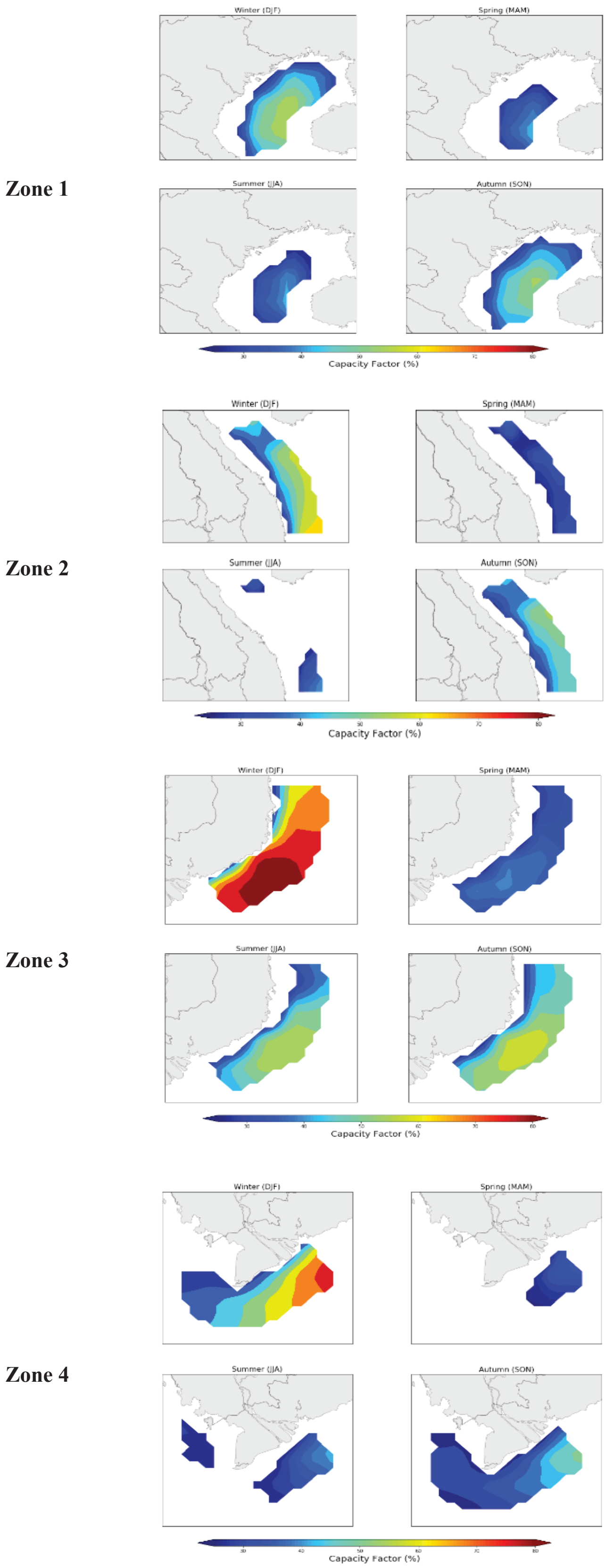


Fig. 13. Seasonal average capacity factor in four offshore wind zones using LW 8 MW turbines, only areas with CF≥25%.

Figure 15 showed the inter-annual CFs at four islands during the period 2007-2011. The authors selected four islands (Bach Long Vi, Ly Son, Phu Quy, and Phu Quoc) from four different zones (Zone 1, Zone 2, Zone 3 and Zone 4, respectively) to investigate. One particularly interesting fact highlighted by Fig. 15 is the offshore wind potential is very high around Phu Quy island. The CF in this area during the year 2011 reached 68% and the average over the 2007-2011 was 54.4%. There was a considerably high CF around Bach Long Vi island where the average figure during 2007-2011 reached 40.4%. In contrast, the CF was the lowest at Phu Quoc island, where the maximum figure was only 24.4% in the year 2011 and the five-year average was 17.7%. The inter-annual temporal variations in CF was also observed for the four islands, where the figure for Bach Long Vi in 2009 was 34.3%, compared to its highest value of 44.1% in 2010. The CF for Phu Quy island had the highest potential area in 2010 with 42.8% and only 67.7% in 2011. Such inter-annual temporal variations are important input to planning and designing energy storage systems, grid and synchronous power sources, as well as for energy demand management.

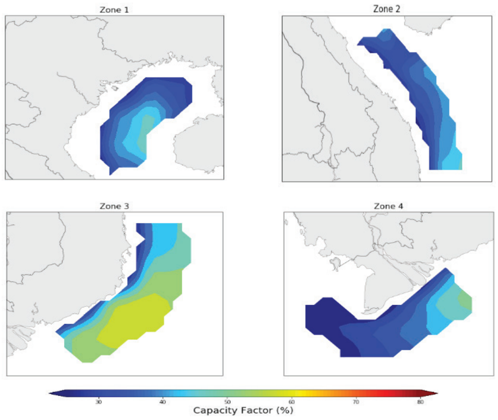
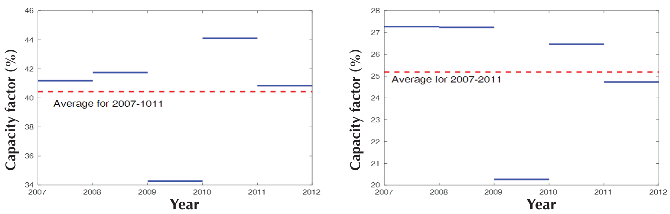
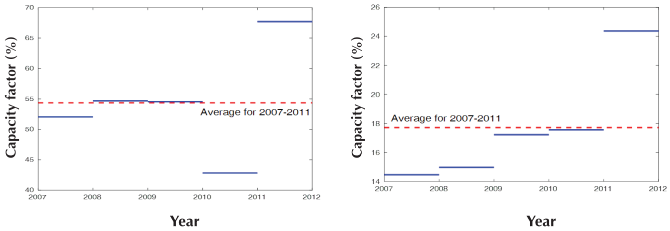


Fig. 14. Annual average capacity factor in four offshore wind zones using LW 8 MW turbines.



(A) Bach Long Vi

(B) Ly Son



(C) Phu Quy

(D) Phu Quoc

Fig. 15. Inter-annual capacity factor in four islands in the period 2007-2011. (A) Bach Long Vi (Zone 1), **(B)** Ly Son (Zone 2), **(C)** Phu Quy (Zone 3), and **(D)** Phu Quoc (Zone 4).

Wind power density distribution

Information about wind power distribution is shown in Figs. 16 and 17 and is important to assessing project feasibility, designing energy storage systems, and power transmission networks [33]. Based on the recommended layout of offshore wind farms [61], up to two LW turbines (8 MW) per one square kilometre can be installed. Therefore, the maximum power distribution for one square kilometre is 16 MW. In the Tonkin Gulf (Zone 1), the power distribution increased gradually to 100 NM (about 185 km) from the coastline of Vietnam. As similarly observed in the two previous sections, Zone 3 had the highest potential for offshore wind energy in relation to the other three zones. The maximum annual average power distribution in Zone 3 was about 9.3 MW/km^2. The area around Phu Quoc island had the lowest potential for wind energy in Zone 4. Fig. 18 provides the time histories of the inter-annual wind power density at the four islands between 2007 and 2011. Clearly, Phu Quy island had a higher wind power density than any other island. The maximum value of wind power density was 15.42 MW/km^2, which was higher than other regions. In Bach Long Vi, Ly Son, and Phu Quy, wind power density did not change much over the years. Meanwhile, there was a large changed over the years in Phu Quoc. There was a big gap in the maximum value of wind power density between 2008 and 2011 with 4.081 MW/km^2 and 8.001 MW/km^2, respectively. From Fig. 18 it can also be seen that the wind power density rose during the winter at all islands.

Based on the above sections, the evaluation of each zone using criteria (b) - (e) is summarised in Table 6. Zone 3, the southern part of Zone 2, and Ba Ria-Vung Tau in Zone 4 were found to be the most suitable for offshore wind energy development, especially considering their high capacity factors and moderate variation of power density, the fact that the resource is not far from shore, and its excellent port facility. Given the high demand in energy and good port capacity, but the potential resource is further offshore, Zone 1 and Zone 4 are recommended for future development when far offshore wind farms become more cost-effective.

This study, however, focused on natural aspects such as wind speed and direction, and physical aspects including reference turbines, synchronous power sources, transmission lines, and ports. Environmental, biological, governance, political, and management factors that can influence the evaluation of offshore wind zones were not considered.

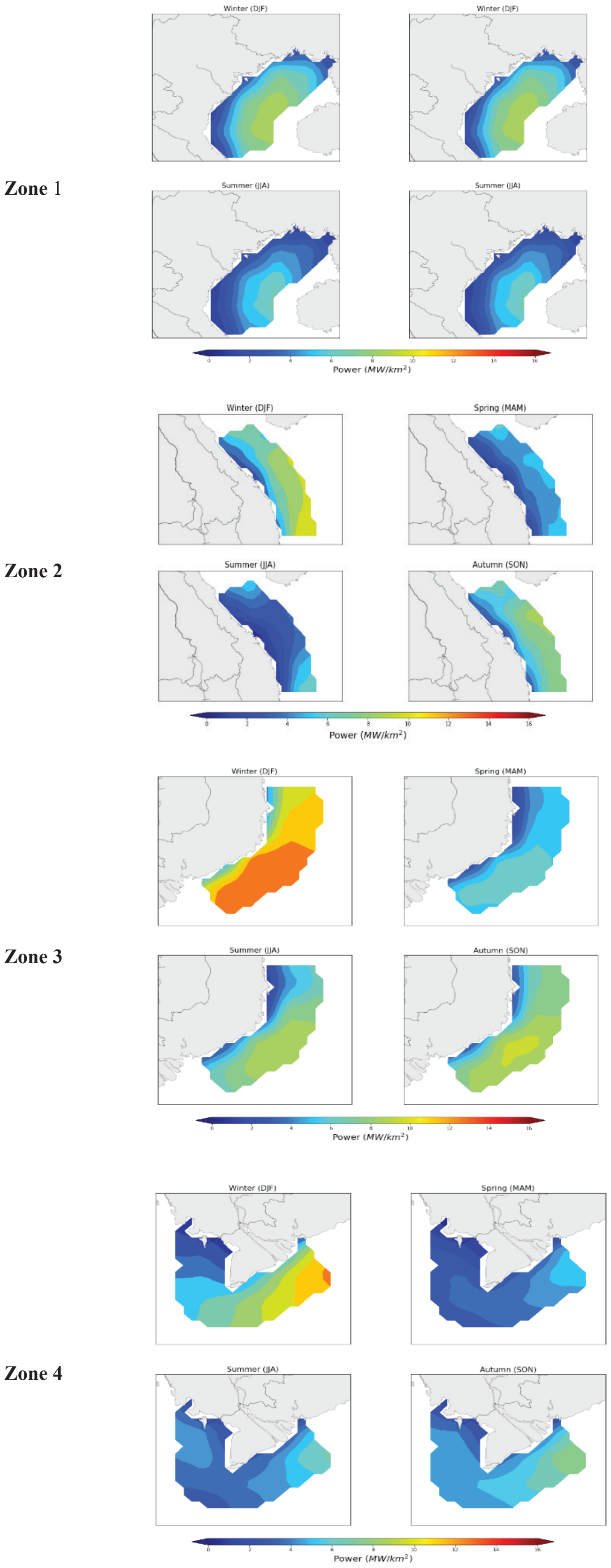


Fig. 16. Seasonal average power distribution in four zones.

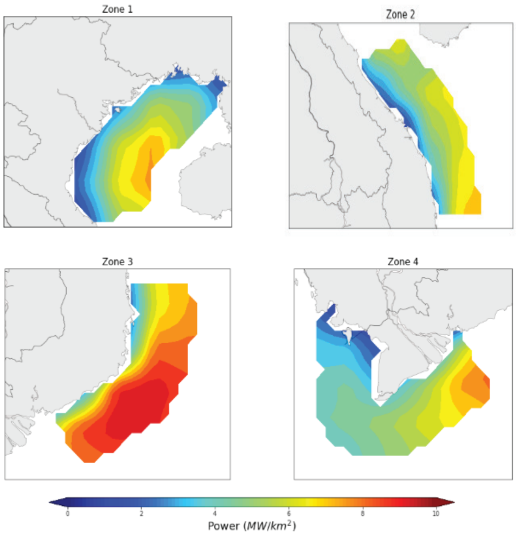
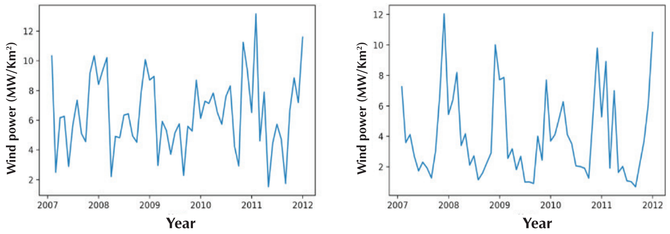
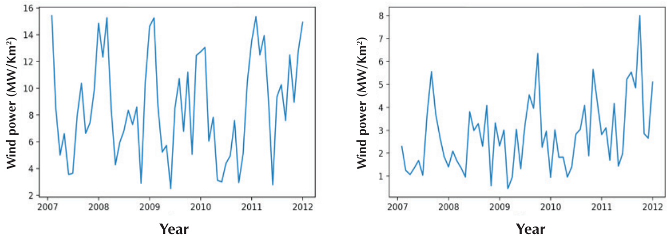


Fig. 17. Annual average power distribution in four zones.



(A) Bach Long Vi (B) Ly Son



(C) Phu Quy (D) Phu Quoc

Fig. 18. Inter-annual wind power density in four islands period 2007-2011. (A) Bach Long Vi (Zone 1), **(B)** Ly Son (Zone 2), **(C)** Phu Quy (Zone 3), and **(D)** Phu Quoc (Zone 4).

Table 6. Summary of zone evaluation for offshore wind energy.

Criteria	Zone 1	Zone 2	Zone 3	Zone 4
Temperature variation	Very strong, 4 seasons, coldest winter	Strong, 4 seasons, moderate cold winter	Moderate, 2 seasons, less affected by monsoon	Weak, 2 seasons, least affected by winter
Synchronous power sources & transmissions	Hydropower, coal-fired	No major SPS. Main transmission lines available	Hydropower, Main transmission lines available	Gas/oil-fired
Ports	Very good (Cai Lan, Dinh Vu), larger areas needed	Poor in northern. Good in southern end close to Zone 3 (Chan May, Quy Nhon)	Excellent, large area available (Cam Ranh, Van Phong, Phu My)	Good (Tan Cang, Sai Gon), larger area needed
Wind energy potential (energy & power density, 5-year CF)	14-19 GWh/km^2; CF 30-45% (Bach Long Vi 40%); 4-7 MW/km^2	12-22 GWh/km^2; (large in southern); CF 25-40% (Ly Son 25.2%); 5-6.5 MW/km^2	14-29 GWh/km^2; CF 40-65% (Phu Quy 54.5%); 8-10 MW/km^2	12-27 GWh/km^2; strong near zone 3; CF 25-50% (Phu Quoc 17.8%), 4-8 MW/km^2
Wind temporal variation	Moderate, peak in winter	Moderate, peak in winter	Moderate	Strong, peak in winter
Wind spatial variation	Strong, centred zone far offshore	Strong, long zone very far offshore	Moderate, large zone closer to shore	Centred zone to northeast (Zone 3)

Conclusions

The shortage of reliable datasets, lack of comprehensive assessment of offshore wind resources and infrastructures, wind temporal and spatial variations, and integration of offshore wind development and operation into other marine strategies and activities have been highlighted as the major domestic challenges to offshore wind policymakers and developers in Vietnam. Addressing these challenges has been strategically presented, in which the CCMP data over the five year span 2007-2011, were validated with measurement data from seven meteorological stations. The offshore wind power resource was initially assessed by using temporal and spatial variations of offshore wind speed and directions. Based on expert consultations, temporal variation of temperature, the offshore wind resource in Vietnam was classified into four sea zones extending up to 100 NM from the coastline: (1) Quang Ninh to Ha Tinh, (2) Quang Binh to Binh Dinh, (3) Phu Yen to Ba Ria - Vung Tau, and (4) Ho Chi Minh city to Kien Giang. The LEANWIND 8 MW was chosen as the reference turbine for estimating wind energy potential. An assessment of offshore wind power resource and infrastructures was presented based on the following set of criteria: temporal variation in temperature, synchronous power sources and power transmission, major sea ports, and the spatial and temporal variation of offshore wind power and density. The following conclusions were drawn:

- The CCMP dataset is reliable as their wind speed probability distribution was in good agreement with that of the measurement data.

- The largest and average wind speeds were about 12 and 11 m/s at Phu Quy island (Zone 3) in January. The ranges of wind speed in Bach Long Vi (Zone 1) and Ly Son (Zone 2) were from 3.578- 9.682 m/s and 2.91-9.275 m/s, respectively. The wind speed/during this period in Phu Quoc (Zone 4) was the lowest, ranging from 2.765 to 7.347 m/s.

- The major ports with channel depths greater than 10 m and capable of accepting vessels up to 30,000 DWT are located in Zone 1, the southern part of Zone 2, Zone 3, and Zone 4. Especially, the Van Phong port in Zone 3 has a depth range of

15-20 m and expects to accept a vessel of up to 120,000 DWT.

- The highest density of energy occurred during the winter months and autumn was the second largest. Zone 3 contained the highest wind energy potential during the four seasons, where the annual accumulated wind energy density was about 80 GWh/km^2.

- The CFs over the five-year span 2007-2011 at Phu Quy, Bach Long Vi, Ly Son, and Phu Quoc were 54.5, 40.4, 25.2, and 17.8%, respectively. The considerable temporal variations inter-annually are important input to designing energy storage systems, grids, and synchronous power sources, as well as for energy demand management.

- Zone 3 (particularly Binh Thuan and Ninh Thuan sea), the southern part of Zone 2, and Ba Ria - Vung Tau in Zone 4 were the most suitable to offshore wind energy development, owing to high capacity factors and a power density with moderate variation, the fact that the resource was not far from shore, and their excellent port facilities.

- Given the high demand for energy and good port capacity, but the potential resource is further offshore, Zone 1 and Zone 4 are recommended for future development when far offshore wind farms become more cost-effective.

- Future studies to obtain measurement data for wind profiles at turbine hub heights, and to consider biology, metocean, and seabed topography and geology, are recommended before planning such marine spaces.

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