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Evaluation of wind energy potential over offshore areas in Vietnam

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ABSTRACT

The study evaluates the technical potential of offshore wind energy in Vietnam based on a 30-year dataset (1991–2020) with a spatial resolution of up to 3 km. The offshore wind energy potential was determined at a height of 100 meters (above sea level) for Vietnam's exclusive economic zone and was classified into shallow waters (depths below 50 meters) and deep waters (50–1000 meters) and by month of the year. The results of the technical wind energy potential calculation differ significantly from some previous studies, particularly from the World Bank's report published in 2022. This difference is due to the expanded spatial coverage of the current study and a larger area with wind speeds greater than or equal to 7 ms^{-1}. Additionally, detailed information on the temporal variability of wind energy density and technical wind energy potential was analyzed, showing large fluctuations between months, with the highest potential occurring in the winter months and the lowest in spring. The results not only contribute to scientific knowledge about renewable energy but also provide reference information for marine spatial planning, with applications in activities related to the development of offshore wind energy in Vietnam.

Keywords: Wind energy, wind energy technical potential, Vietnam, East Vietnam Sea.

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INTRODUCTION

In the context of current climate change, particularly after the Paris Agreement on climate change and the Net-Zero agreement at COP26, renewable energy in general and wind energy in particular are seen as some of the most important solutions to reduce global climate change. Transitioning to clean and renewable energy is a necessary solution to achieve the United Nations Sustainable Development Goals by 2030. At COP26, Vietnam announced its commitment to achieving net-zero emissions by 2050, reducing methane emissions by 30% by 2030, halting the construction of new coal power plants, and phasing out coal power plants by the 2040s, while also committing to reversing and preventing deforestation by 2030. These commitments are reflected in Vietnam's updated Nationally Determined Contributions (NDC) in 2022 (version 3) [1] and Decision No. 896/QĐ-TTg dated July 26, 2022, by the Prime Minister on the National Strategy for Climate Change until 2050 [2]. To achieve these goals, it is necessary to gradually transition from coal power to clean energy sources, reduce the share of fossil fuel sources, and avoid the development of new coal-fired power plants after 2030. Therefore, it is essential to strengthen the implementation of clean energy development solutions, promote energy-saving and efficient energy use, and explore breakthrough technological solutions in the future, while ensuring national energy security.

According to the national electricity development plan (Power Plan VIII) issued on 15 May 2023, a thorough evaluation of the potential for developing renewable energy and new energy sources (such as rooftop solar, large-scale solar, offshore wind, biomass, waste, geothermal, etc.) is a key basis for calculating the development options for power sources and transmission grid capacity for each region and sub-region in Vietnam [3]. According to Clause 5, Article 21 of the Electricity Law promulgated by the National Assembly of the Socialist Republic of Vietnam, number 61/2023/QH 15, dated April 30, 2024, the Ministry of Natural Resources and Environment and the Provincial People's Committees are responsible for managing, publishing, and sharing information on the basic survey of renewable energy resources and new energy sources as per the regulations of the law [4]. Offshore wind energy (OWE) is a renewable energy source with great development potential, with the possibility of installing offshore wind farms in vast ocean areas. The main advantage of offshore wind energy is its higher electricity generation capacity because wind speeds over the ocean are typically more stable and stronger than on land [3, 5]. Additionally, another advantage is that offshore locations are practically unlimited for wind farm deployment and have little to no impact on conflicts with local populations [3–8]. Furthermore, recent advancements in offshore wind technology have helped reduce capital costs, installation, and operational costs [5, 7, 9]. However, one of the current limitations is the lack of data on maritime planning, which makes it impossible to fully assess the technical potential of offshore wind power (OWP) in Vietnam. To date, some related industries for OWP mainly refer to existing research results from the World Bank (WB) [10, 11] and the Danish Energy Agency (DEA) [12]. Therefore, to provide a full basis for national marine spatial planning as well as national power planning, it is necessary to review and comprehensively assess wind energy resources based on the most detailed and reliable data available.

Vietnam has a long coastline of more than 3,260 km from North to South, over 3,000 islands, and maritime areas and continental shelves under its sovereignty, sovereign rights, and national jurisdiction that cover more than 1 million km^2 (three times the area of the land). The country has 28 coastal provinces and cities, which account for 42% of the land area and 45% of the national population. The coastal region of Vietnam has significant potential for wind energy exploitation and plays a crucial role in fulfilling Vietnam's commitments to climate change. Previous studies using observational data from stations and numerical model data have shown very promising results for wind energy potential in Vietnam: Vietnam has low to medium wind energy potential in some inland areas, while the coastal and island regions have greater wind energy potential, with a total wind power potential of approximately 513,360 MW. Particularly, nearly 8% of Vietnam's area is classified as having excellent wind potential, with an average wind speed of 7–8 ms^{-1} at a height of 65 m. Around 1.3% of the country's area has a potential of 26,763 MW, with an average wind speed of over 6 ms^{-1} at a height of 80 m [10, 11, 13]. However, these studies are limited by spatial constraints and the method of extrapolating wind data from grid points to stations, which do not account for the characteristics of the terrain surface.

By using a high-resolution regional model along with observational data from 150 stations, Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHEN) (2019) [14] developed a wind energy map for Vietnam, and the results were quite similar to those of Ta Van Da (2006) [15], Tran Viet Lien (2007) [16], and Doan et al., [17]. These studies all concluded that wind energy potential at 10 m was relatively low but increased at higher altitudes, such as 20–60 m. The highest wind energy potential is primarily concentrated in the coastal and island areas, especially along the coastline of the South Central Coast, Ba Ria-Vung Tau, or the Southwestern region, with the total wind energy throughout the year potentially reaching nearly 1,700 kWh/m². Similar results were obtained in the study by Hiep (2021), using a 2 km resolution WRF model for the Southern region of Vietnam [18].

In addition, there are still debates regarding the assessment of wind energy potential at heights up to 100 m for the offshore area of Vietnam. According to the DEA, the technical potential of OWE in Vietnam's waters, ranging from 5–100 km offshore, is about 160 GW [12]. However, considering only the waters up to 100 km offshore is smaller compared to more recent studies, such as those by the WB (2019, 2022) [10, 11] or Vu Dinh Quang (2020) [19]. WB (2022) [10] updated its estimate of the total technical potential for OWE in Vietnam within a 200 km range from the shore to about 599 GW, with fixed-bottom OWE potential accounting for 261 GW and floating wind energy at 338 GW [10]. This technical potential does not take into account environmental and social constraints and includes all locations with wind speeds of 7 ms^{-1} or higher at a height of 100 m.

Recently, wind energy potential maps for Vietnam, including both coastal and offshore areas, have provided more detailed information on spatial distribution and variability up to a height of 200 m [20–22]. However, to exploit wind energy or assess wind energy potential at a specific location in Vietnam, as well as to build offshore wind farms, further analysis is needed using higher resolution data, and the reliability of the results must be validated. This is also the aim of this study: to use Vietnam's comprehensive meteorological and oceanographic observation station network as a measure to validate the reliability of wind simulation results from a high-resolution regional model with a resolution of up to 3 km. The calculated wind energy potential will provide a reliable reference for marine spatial planning and the development of wind power in the region of Vietnam.

DATASETS AND METHODOLOGIES

Datasets

The wind observation data used to validate the wind field simulation model include:

(1) Wind data from 26 meteorological and oceanographic stations managed by the Vietnam Meteorology Hydrology Administration (VMMHA) and data from the Bach Ho station during the period 1990–2021 (Fig. 1). Since wind observations are primarily intended for basic investigation and disaster prevention, most are conducted at 10 meters above sea level, which is lower than the height at which wind turbines are installed. Therefore, this observation data is mainly used to validate the model's reliability in calculating wind at 10 m above sea level.

(2) Data from several wind power projects. These projects monitor wind at different heights, which is important for validating the wind simulation model at exploitation altitudes such as 40, 50, and 80 m.

(3) Wind data measured by buoys at the sea surface offshore from Nghe An, with coordinates 18°48'N, 105°48'E. The observation

periods are from October 2, 1999, to February 25, 2000, and from June 14, 2000, to November 7, 2000. The buoy was funded by the Norwegian Ministry of Foreign Affairs for the VMMHA in a project to enhance disaster forecasting and warning capacity at sea during 1999–2000. This is considered a valuable data source for assessing wind calculations at the sea surface from the model.

(4) The CCMP wind data set with a high resolution of 0.25 degrees latitude-longitude. This data set is constructed based on the surface wind field from the ERA-Interim data set (European Centre for Medium-Range Weather Forecasts - ECMWF) combined and calibrated with satellite wind data such as SSM/I, SSMIS, AMSR, TMI, WindSat, and GMI, as well as other observations using the Variability Analysis Method (VAM). All wind observations (satellite and buoy) and model analysis fields are referenced to 10 m above sea level. The high-resolution CCMP data set has been available since 1987.

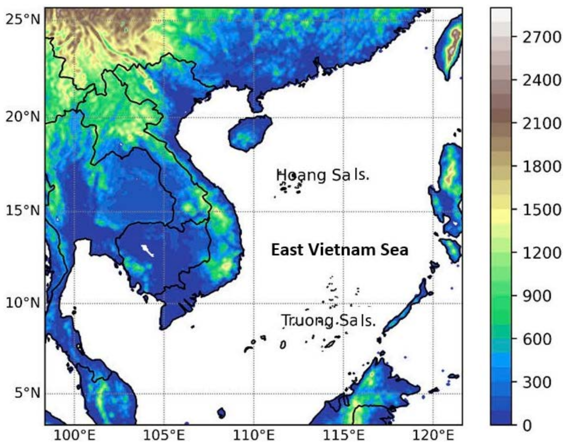


Figure 1. Calculation domain of the regional model WRF

These data sources will be used to assess the reliability of the wind model and to ensure accurate wind energy calculations.

In addition to wind data used for validating the wind speed simulation model, seabed topography data and information about Vietnam's maritime sovereignty areas were collected to assess the technical potential of offshore wind energy in Vietnam.

Methodologies

Calculation of wind and wind energy potential

The Weather Research and Forecasting (WRF) model [23] is used to calculate wind fields and assess the detailed wind energy potential for the region. The model is designed with a horizontal resolution of 9 km and a vertical resolution of 10 m, up to a height of 250 m. The computational domain for the WRF model covers the entire East Vietnam Sea (VES), shown in Figure 1, from 3°N to 26°N, and 98°E to 122°E. The downscaling to a 3 km resolution from a 9 km resolution in the study area was done using the bilinear interpolation method. The simulation period spans 30 years (1991–2020). Before running wind simulations for multiple years, the WRF model is calibrated and validated using observational wind data at various altitudes from the data sources mentioned above. Additionally, ERA5 reanalysis data with a resolution of 0.25° × 0.25° from the ECMWF is used to supplement information in areas where station data is limited.

Instead of using a fixed roughness parameter over a 30-year period for calculations, this study will utilize up-to-date and more detailed surface characteristic data from the annual surface coverage product for Vietnam during the period 1990–2020 from the ALOS/ALOS-2 scientific project of the Japan Aerospace Exploration Agency (JAXA).

This study employs an optimal analysis method, which has been widely applied in establishing initial data fields for numerical weather models. The ERA5 grid data is considered the initial guess in the optimization process, where horizontal interpolation is performed from the observational data of Vietnam's surface stations. Although the grid is set with a horizontal resolution of 1 km × 1 km, due to the limited number of surface stations (both on land and at sea), the calculation will restrict the radius of influence of the raw data (from the observation station) to no more than 8 km in flatland and offshore areas, and no more than 14 km in mountainous regions (areas above 800 m in elevation). For regions with fewer observations, such as those with complex terrain, the calculation will prioritize the ERA5 grid data based on the advantages of re-simulation that ECMWF has implemented.

First, the grid will be calculated in detail for the wind field at a height of 10 m. Then, the new detailed surface characteristic data will be used to extrapolate for higher wind exploitation levels at 50, 100, 150, and 200 m. Additionally, wind direction average maps will also be established. Based on the wind field calculated on the detailed grid, an initial estimate of wind energy potential will be calculated monthly for the entire territory of Vietnam at each specific height.

Information about the wind speed at a specific height is required to estimate the wind energy potential at that altitude. However, in reality, due to a limitation in the number of upper-level observation stations, wind speed in places with no upper-level monitoring measurement needs to be determined indirectly, through a vertical wind distribution function based on the ground wind speed observed at hydro-meteorological stations.

In this project, we will use the logarithmic distribution function, which is both popular and quite suitable for the wind speed in the atmosphere from the surface to an altitude of about 250 m.

Wind speed V_z at the altitude Z is calculated according to the below formula:

$$V_z = V_1 \frac{\ln\left(Z/Z_o\right)}{\ln\left(Z_1/Z_o\right)} \quad (1)$$

where: V_1 is the observed wind speed at the surface; Z_o is the surface roughness; Z_1 is the height of the ground anemometer (Z_1 = 10 m).

Since the requested height is often greater than the height of ground-level wind measurement ($Z > Z_1$), the wind speed at the height of interest is greater than the ground-level wind speed ($V_z > V_1$), meaning that wind speed increases with height. Additionally, the rate at which wind speed increases with height depends on the roughness of the surface (Z_o).

The wind power density (P/A) is calculated from c and k based on the Weibull distribution as follows:

$$\frac{P}{A} = \int_0^\infty \frac{1}{2}\rho v^3 f\left(v\right)dv = \frac{1}{2}\rho c^3 \Gamma\left(\frac{k+3}{k}\right) \quad (2)$$

with Γ is the gamma function and ρ is the air density.

The reliability of the model has been evaluated in studies by Hiep (2021) [18], Nga (2023) [24], when using multi-year observational data from the Bach Ho station, as well as in the "Assessment Report on the Potential of Radiation, Wind, and Waves in Vietnam" published by the Ministry of Natural Resources and Environment in 2022 [20]. This can be considered the most complete and reliable offshore data source available at the moment. The mean error, when compared with various observational data forms, has confirmed the model's capability in simulating wind fields over the sea. A detailed analysis of the model's reliability in simulating wind fields will be gathered and presented in a separate paper.

Calculation of capacity density and offshore wind energy capacity

Capacity density (MDCS) of offshore horizontal axis wind turbine (HAWT) farms is estimated based on the ESMAP's method (2019) at a height of 100 m [12]. Within the scope of this study, MDCS = 3 MW/km^2 is chosen for areas with 7 ms^{-1} ≤ V_{tbn} < 8 ms^{-1} and MDCS = 4 MW/km^2 is chosen for areas with V_{tbn} ≥ 8 ms^{-1}.

The technical potential of OWE is simply estimated based on the total annual wind power capacity over the defined shallow (*BN*) and deep sea (*BS*) areas:

$$TCSDG\text{-}BN\ \left(\mathrm{MW/km^2}\right) = TDT\text{-}BN7*3 + TDT\text{-}BN8*4 \quad (3)$$

where: TCSDG-BN is the amount of wind power capacity in the shallow waters, *TDT-BN*7 is the total area of shallow waters with the annual average wind speed at 100 m (V_{tbn}100) reaching 7–8 ms^{-1}, *TDT-BN*8 is the total area of shallow waters with $V_{tbn}100$ greater than or equal to 8 m/s. Indices "3" and "4" represents MDCS = 3 MW/km^2 and MDCS = 4 MW/km^2:

$$TCSDG\text{-}BS\ \left(\mathrm{MW/km^2}\right) = TDT\text{-}BS7*3 + TDT\text{-}BS8*4 \tag{4}$$

where: TCSDG-BS and *TDT-BS* are the amount of wind power capacity and the amount of deep sea areas, respectively.

The national (or regional) technical potential of wind energy is a sum of the total wind power capacities in the shallow and deep waters.

$$TCSDG\text{-}QG\ \left(\mathrm{MW/km^2}\right) = TCSDG\text{-}BN\ \left(\mathrm{MW/km^2}\right) + TCSDG\text{-}BS\ \left(\mathrm{MW/km^2}\right) \tag{5}$$

in practice: TCSDG is often measured in Gigawatts (GW) (1 GW = 1,000 MW).

RESULTS AND DISCUSSION

Offshore wind power density

In this section, the offshore wind energy potential, or technical potential, is assessed through the distribution of wind power density (WPD) on a monthly scale at two characteristic heights: 10 m, which is the standard observation height for meteorological wind measurements, and 100 m [14]. This is considered theoretical potential, as it does not take into account factors that affect the actual exploitation capacity.

At a height of 10 m

Across the entire VES, WPD at 10 meters is highest during the months of November, December, and January (peak in December), with values ranging from 50–900 W/m², 100–1,200 W/m², and 100–1,000 W/m², respectively. The lowest energy density is observed during the transitional months of April and May, with wind power densities generally below 200 W/m². In particular, in December, the sea areas extending along the northeast-southwest direction from the northern VES to the southeast region of Vietnam show high wind energy potential, ranging from 400–1,200 W/m². Offshore, the highest WPD is found in the northern VES, with a trend of decreasing toward the south. Along the coast, the greatest wind power densities are found in the waters of Binh Dinh–Ninh Thuan and Binh Thuan–Ca Mau, except in April, May, and October, where the largest wind energy potential is in the central Gulf of Tonkin. Notably, the area from Ninh Thuan to Ba Ria-Vung Tau is rich in wind energy potential (Fig. 2).

At a height of 100 m

The wind speed at a height of 100 m is used to assess the offshore wind energy potential. At this height, the distribution of WPD across the entire VES and coastal areas is quite similar to the distribution at 10 m but with significantly higher values and a larger area with high values. The highest amounts occur in November, December, and January, with the WPD ranging from 100–1,600 W/m², 400–1,700 W/m², and 200–1,600 W/m², respectively. The lowest values are observed in May, with the WPD typically below 300 W/m², except for a part of the central Gulf of Tonkin, where the values range from 300–500 W/m² (Fig. 3).

The northern , northern and central Gulf of Tonkin, and the sea area from Ninh Thuan to Ba Ria-Vung Tau have abundant wind energy potential and can be exploited throughout the year. At 100 m, WPD receives the most in winter in the sea area from Ninh Thuan to Ba Ria-Vung Tau, followed by summer and autumn. For the Gulf of Tonkin, the highest WPD occurs in winter, followed by summer and autumn, with the lowest values in spring.

When compared with the results in the "Report on the Assessment of Potential for Solar, Wind, and Wave Energy in Vietnam" published by the MONRE in September 2022 [20], the research results show a similar spatial and temporal distribution of wind energy potential across the VES, but with higher or comparable values. Specifically, the average annual WPD at the center of the Gulf of Tonkin and the sea area from Ninh Thuan to Ba Ria-Vung Tau simulated by WRF-3 km is 500–900 W/m² and 400–600 W/m² at 100 m, while the values published by the MONRE are 500–700 W/m² and 300–500 W/m², respectively.

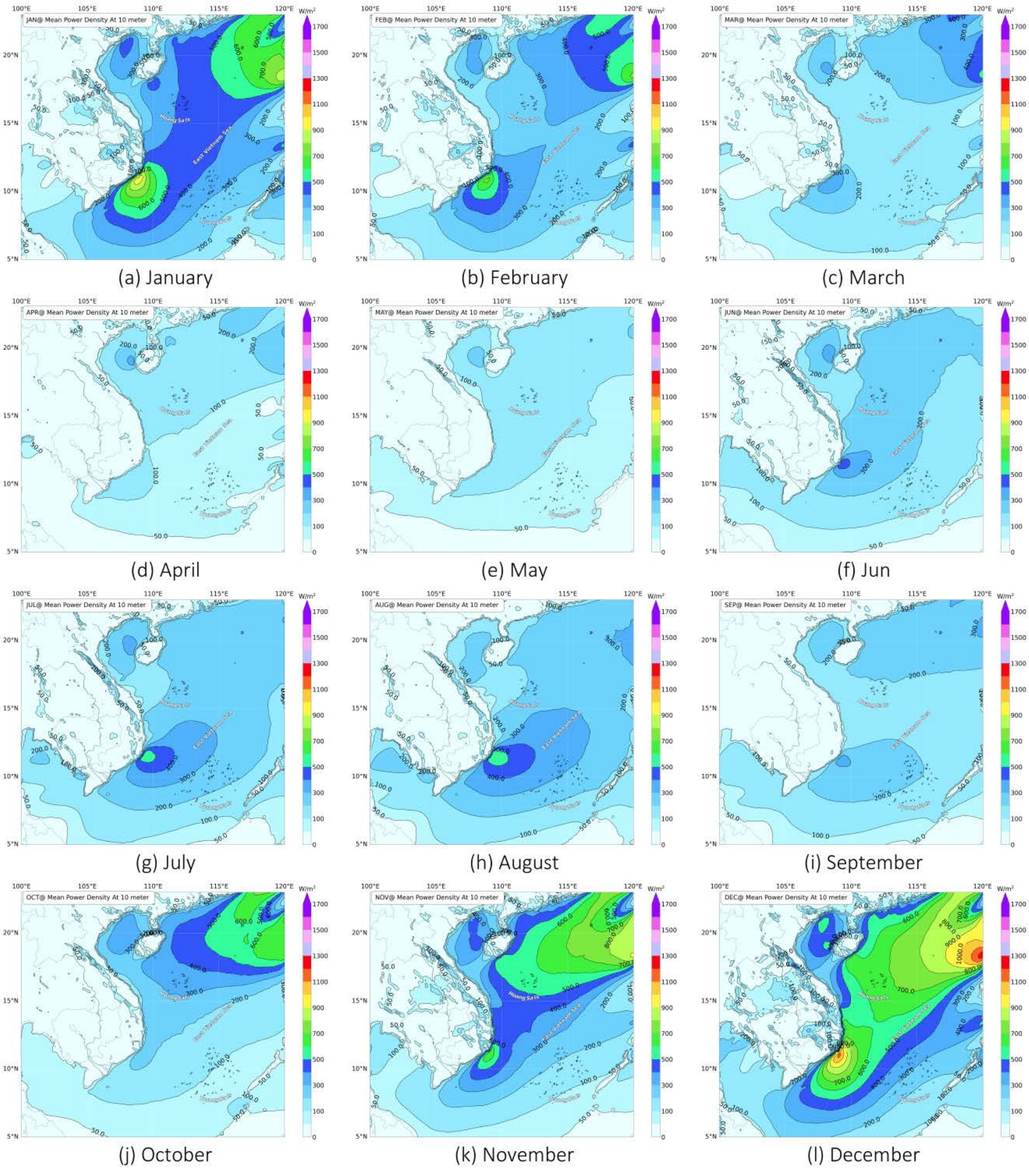


Figure 2. Distribution of wind power density (W/m²) from January to December (a–l) at a height of 10 m in the East Vietnam Sea from WRF-3 km for the period of 1991–2020

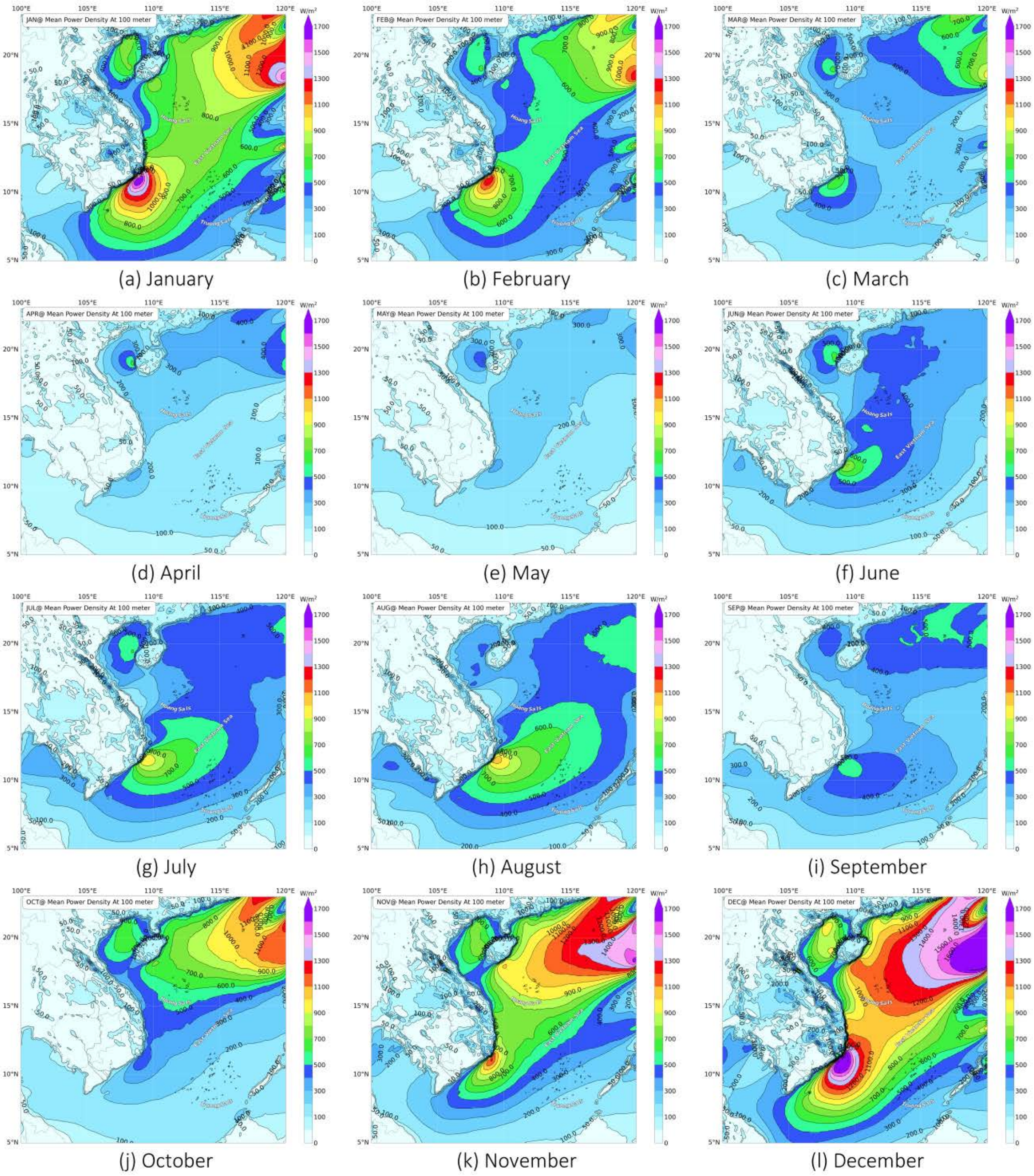


Figure 3. Distribution of wind power density (W/m²) from January to December (a–l) at a height of 100 m in the Vietnam East Sea from WRF-3 km for the period of 1991–2020

Technical potential of offshore wind energy

According to NREL (National Renewable Energy Laboratory) (USA) [25, 26] and ESMAP (Energy Sector Management Assistance Program) (WB) [11, 27], renewable energy potential in general, and wind energy potential in particular, is divided into four main levels: theoretical potential, technical potential, economic potential, and market potential. The technical potential of offshore wind energy is "an estimate of the electricity generation capacity that could be technically feasible, considering only wind speed and water depth"

[13]. This is considered an initial estimate, at a high level, and does not take into account other technical, environmental, social, or economic constraints. To determine the Technical Potential of Offshore Wind Energy, several steps need to be followed in order as outlined below:

i) Identify the study area;

ii) Determine the characteristic height;

iii) Identify the effective wind areas;

iv) Identify the shallow sea areas (where wind turbines are placed directly on the seabed) and deep sea areas where turbines can be placed on floating platforms;

v) Select the capacity density (as analyzed in "*Calculation of capacity density and offshore wind energy capacity*") corresponding to areas with the selected wind speeds;

vi) Exclude sea areas where wind farm development is not allowed or feasible.

In this process, the area for determining technical potential refers to the waters under Vietnam's sovereignty, and the wind speed at 100 m height are used to determine the technical potential of offshore wind energy.

Not all areas at sea can have wind turbines fixed directly to the seabed as is done on land. At a certain depth, this becomes impractical or too expensive. In such cases, wind turbines must be placed on floating platforms. Shallow sea areas are those where wind turbine towers can be fixed directly to the seabed. These are typically nearshore areas where installation technology is well-established, costs are lower, and the towers are securely anchored, offering higher safety and stability. Additionally, the connection to the national power grid is more convenient. This study uses the 50-meter contour as the outer limit of shallow waters, and the deep sea region will lie between the 50-meter and 1,000-meter contours. Furthermore, the area between the coastline and the 30-meter contour is considered shallow water, where fixed and direct turbine installation technology is effective. Therefore, the 30-meter contour is also referenced. The 30-meter, 50-meter, and 1,000-meter contours were extracted from the seabed topography map of the Institute of Geology and Marine Geophysics and are shown in Figure 4.

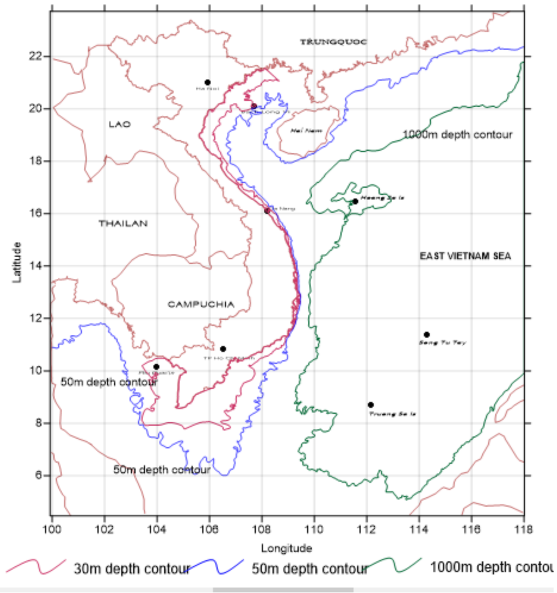


Figure 4. The 30-meter, 50-meter, and 100-meter isodepths in the East Vietnam Sea

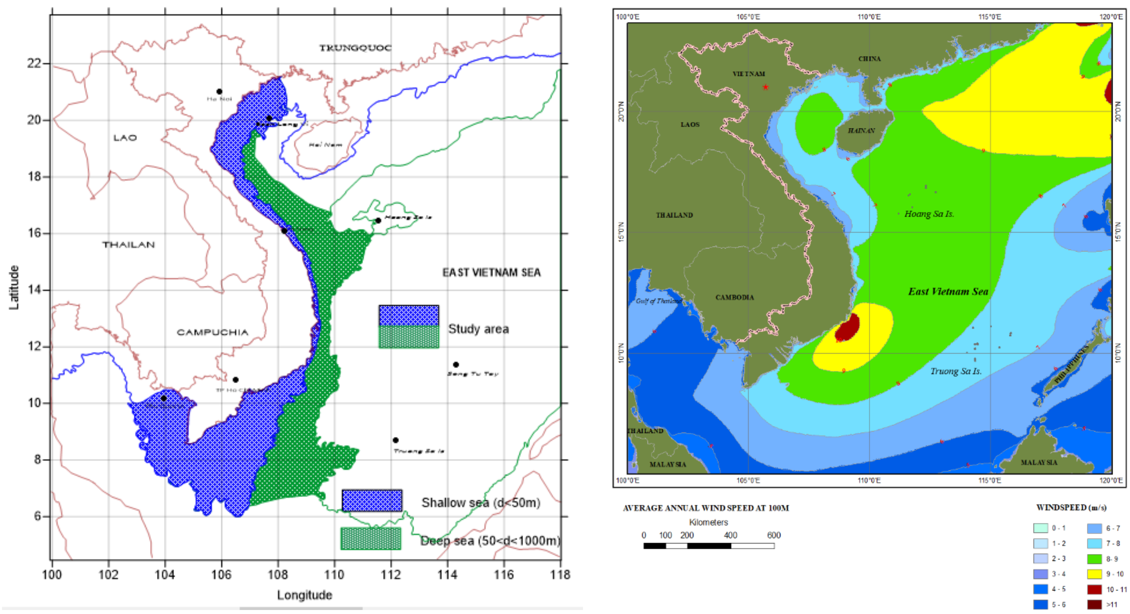
The maritime areas of countries and regions where renewable energy, particularly wind energy, can be exploited are within their Exclusive Economic Zones (EEZ). According to the United Nations Convention on the Law of the Sea (UNCLOS, 1982), the EEZ is the maritime area extending from a country's baseline up to 200 nautical miles (322 km) from that baseline. If the continental shelf extends beyond 200 nautical miles, the EEZ can be extended further, but not beyond 350 nautical miles (563 km). In cases where there are overlapping EEZs between countries, the boundary lines are determined through negotiations between the involved nations.

For Vietnam, some overlapping areas have been resolved through negotiations, but there are still areas under dispute. Therefore, Vietnam's EEZ has not been officially declared for the entire region. To determine the scope of the study for assessing the technical potential of offshore wind energy, certain boundaries have already been defined, such as in the Gulf of Tonkin and the Gulf of Thailand. Other areas are defined based on UNCLOS 1982, using relevant reference materials such as Thanh Nguyen (2019) [28].

The combination of the shallow sea areas, deep sea areas, and the EEZ region, as analyzed above, will define the scope for determining the technical potential of offshore wind energy in Vietnam, as shown in Figure 4, with a total area estimated at approximately 474,600 km^2.

The wind speed field used to assess the technical potential of offshore wind energy is the annual average wind speed at a height of 100 m over the VES in general, and specifically in Vietnam's maritime area, including the area evaluated for technical potential as shown in Figure 5a. Figure 5b displays the map of the average annual wind speed at 100 m above the VES, which is the result of wind speed simulations discussed in "*Datasets and methodologies*".

The wind energy technical potential zoning shown in Figure 6 is the result of overlaying the two maps from Figures 5a and 5b. Table 1 provides detailed results on the total area (km^2) and the total wind power capacity (GW, using the formula in "*Calculation of capacity density and offshore wind energy capacity*") that can be exploited in the sea areas of Vietnam within the 1,000-meter depth contour. The boundaries of the "Northern Sea Area" and the "Southern Sea Area" are represented by the green line in Figure 6, determined according to the marine climate zoning of Vietnam.



(a) (b)

Figure 5. (a) Areas where the technical potential of offshore wind resources estimated, (b) Annual average wind speed at a height of 100 m over the East Vietnam Sea

Table 1. Results of offshore wind energy technical potential in Vietnam

Region	Fixed turbines (shallow waters)	Floating turbines (deep waters)	Total
Available area for wind energy development (km^2)	138,480	167,866	306,346
Northern water	38,843	13,680	52,523
Southern water	99,637	154,185	253,823
Exploitable wind power capacity (GW)	475	593	1,068
Northern water	130	44	174
Southern water	345	549	894

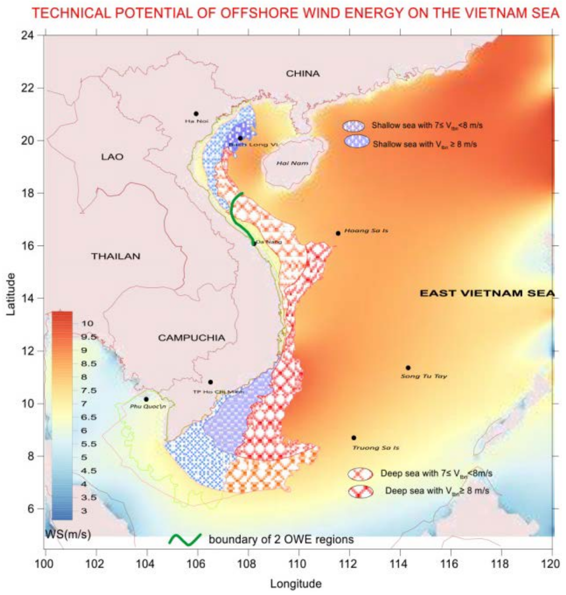


Figure 7. Technical potential of offshore wind energy in Vietnam

The technical potential results for offshore wind energy provide an initial estimate of the total power capacity that could be exploited annually within Vietnam's exclusive economic zone, approximately 1,068 GW. This calculation is based on the annual average wind speed at a height of 100 m, providing a rough estimate of the potential for harnessing this resource for energy development using horizontal-axis wind turbines.

The total wind power capacity estimated in this study is higher than the data published by ESMAP in 2022 (about 600 GW) for two reasons: (1) the area considered for the technical potential in this study, based on the exclusive economic zone of Vietnam as defined by Tran Cong Truc (2023) [29], is broader than the area used in the ESMAP calculation; (2) there is a difference in the scope and distribution of the average wind speed greater than or equal to 7 ms^{-1} between the results of this study and ESMAP.

The distribution of the technical potential of offshore wind energy in Vietnam by month is shown in Figure 7. It can be seen that the technical potential during the winter months (December, January, February) is quite abundant across most of Vietnam's shallow and deep sea areas. Moving into the spring months (March, April, May), significant changes occur. In May, the technical potential significantly decreases in the southern sea areas, with no regions showing an average wind speed greater than or equal to 7 ms^{-1}. Only some areas in the northern and central regions of Vietnam still exhibit higher wind speeds. During the summer months (June, July, August), the technical potential gradually recovers. From June, the wind speeds increase in both the northern and Southern regions. In the south, the Southwest monsoon begins to stabilize and reaches its peak in July. In the northern sea area, in the Gulf of Tonkin, the Southwest monsoon not only changes direction but also gradually weakens, and by August, it becomes almost insignificant. In the autumn months (September, October, November), the technical potential for offshore wind energy decreases, especially in September in the northern sea areas. In October, the Northeast monsoon starts to develop, and the Southwest monsoon decreases sharply, especially in the southern sea areas. The technical potential in the Northern regions increases significantly but decreases in the South. By November, the wind strength increases across the entire Vietnamese maritime region, with the prevailing wind direction being from the Northeast.

Quantitatively, the annual variation of the offshore wind energy potential in Vietnam, as shown in Figure 8, exhibits significant fluctuations throughout the year. This potential is primarily concentrated during the winter months. In just four months from November to February each year, the total offshore wind energy reaches 6063.1 GW, accounting for 50.1% of the total annual potential. December was the highest, followed by January, with corresponding total energy values of 1,650.7 GW (13.64%) and 1,634.7 GW (13.51%). In contrast, May only reaches 147.5 GW, or 1.15% of the year, which is just 8.9% of the value in December. October is higher than May, but still only reaches 670.5 GW, or 5.22% of the total annual potential.

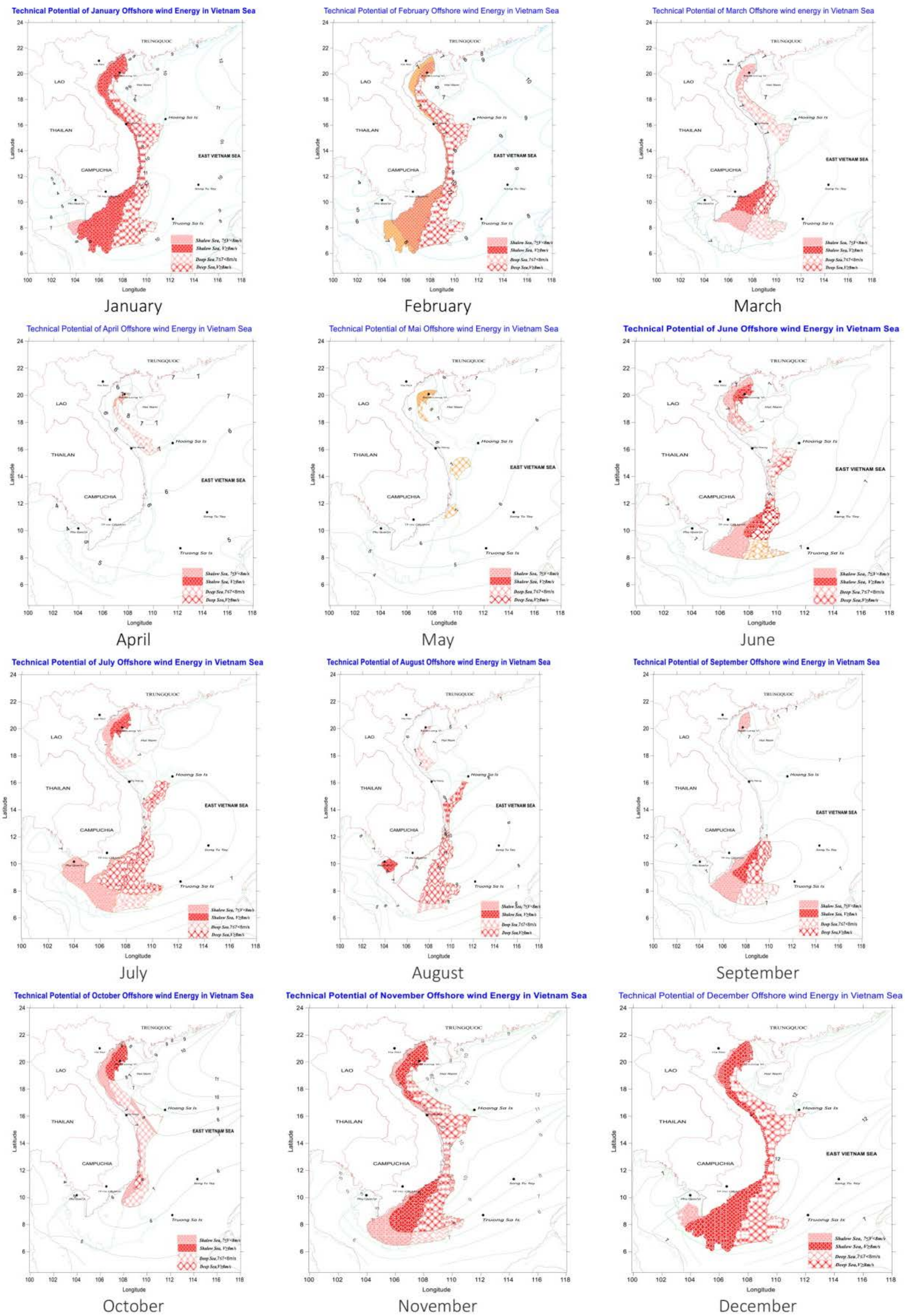


Figure 7. Monthly technical potential of offshore wind energy from January to December in Vietnam

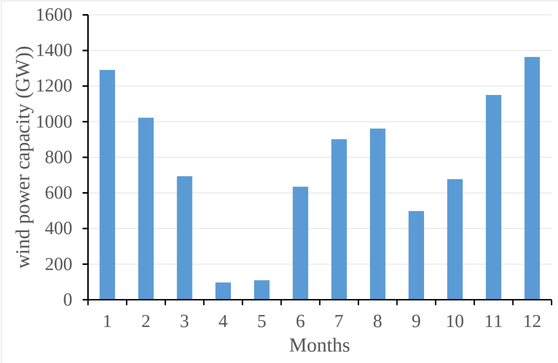


Figure 8. Monthly offshore wind power capacity in Vietnam

The annual variation in wind energy potential across different regions, such as the Northern shallow seas, southern shallow seas, Northern deep seas, and Southern deep seas, is more complex and not uniform across these areas (Fig. 9). For the Northern shallow and deep sea areas, the potential for offshore wind energy is mostly concentrated during the Autumn-Winter period (October–January). From late spring to early autumn, the technical potential is relatively low and mainly confined to shallow sea areas (June–July). For the Southern sea areas, the technical potential during the summer and winter periods is nearly the same. The contribution from the winter months (December and January) in all these regions reaches the highest proportions, between 12–14%.

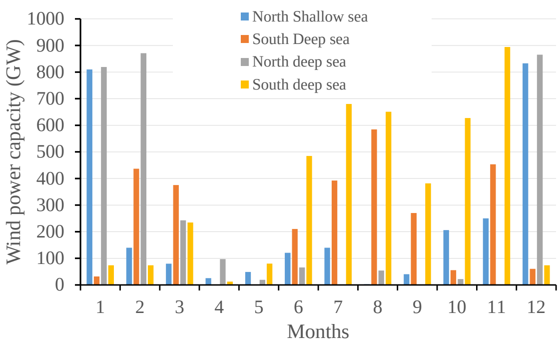


Figure 9. Monthly offshore wind power capacity according to different regions in Vietnam

The calculation results for offshore wind energy above do not take into account restricted or prohibited areas for offshore wind energy development, such as marine conservation areas, areas with high traffic density, tourist zones, and other areas with development restrictions, as mentioned previously. Typically, these areas are considered and published in the National Marine Spatial Plan. However, despite the National Marine Spatial Plan being published, the spatial planning for marine industries and sectors has not been widely disclosed. Therefore, this is a limitation that requires further research in future studies once information about the planning of marine industries and coastal regions is available.

CONCLUSION

Although there have been numerous research studies in Vietnam on the assessment of wind energy resources, they have primarily focused on the land areas. Some of these studies, which solely rely on wind observation data from meteorological stations for assessment, are not entirely reasonable. The marine area is considered to have a much greater energy potential compared to the land, so evaluating the wind energy potential, including both theoretical potential and technical potential for the marine region, is of particular importance. In this study, the technical potential of offshore wind energy is determined at a height of 100 m (above sea level) for Vietnam's sovereign marine areas. The areas are classified into shallow seas (depths 0–50 m) and deep seas (50–1,000 m) and are categorized by month of the year. The wind energy density (theoretical potential) and the technical potential of offshore wind energy in Vietnam are determined based on a 30-year wind simulation dataset (1991–2020) with a resolution of 3 km. The key results of the study are summarized as follows:

The regions with the best wind energy potential are the North VES, the northern and central areas of the Gulf of Tonkin, Binh Dinh–Ninh Thuan, and Binh Thuan–Ca Mau, with the average annual wind energy density ranging from 400–900 W/m², 300–600 W/m², 400–700 W/m², and 300–900 W/m², respectively. Specifically, the wind potential reaches good to excellent levels in the area from Ninh Thuan to Ba Ria-Vung Tau (500–900 W/m²).

The total area (in km²) of shallow and deep waters suitable for wind energy exploitation is approximately 306,346 km², with the areas designated for exploitation in shallow and deep seas being 138,480 km² and 167,866 km², respectively. The total potential wind power that can be harnessed annually in Vietnam's exclusive economic zone is around 1,068 GW, with approximately 475 GW in shallow seas and 593 GW in deep seas. The total wind power capacity calculated in this study is higher than the data published by ESMAP in 2022, due to the larger area of Vietnam's exclusive economic zone considered in the TNKT calculation and the greater distribution range of average wind speeds > 7 m/s in the ESMAP data.

The technical potential of offshore wind energy in Vietnam varies significantly throughout the year. This potential is primarily concentrated in the winter months and is lowest in the spring. Meanwhile, the technical potential in northern shallow seas, southern shallow seas, northern deep seas, and southern deep seas exhibit more complexity and do not follow a uniform pattern. For the northern shallow and deep seas, the offshore wind energy potential is mostly concentrated in the winter period. From late spring to early autumn, the technical potential is relatively low and primarily found in the shallow seas. In the southern seas, the technical potential in the summer and winter periods are quite similar. The contribution of the peak winter months (December and January) in all regions reaches the highest ratio of 12–14%.

The nearshore marine areas play a significant role in the development of wind energy because they are directly connected to the land and share the same technologies currently used on land for the adjacent marine areas. Therefore, a detailed assessment of the wind energy technical potential for the nearshore marine region will be published in subsequent studies.

In addition, it is necessary to continue enhancing and refining the dataset on the basic wind speed fields for Vietnam (both on land and in marine areas) with the highest possible resolution and reliability. This should include achieving a resolution of 1 × 1 km using WRF and higher resolutions for areas with significant potential and islands using micro-scale models like WAsP, while also strengthening experimental observational datasets, including both at sea level and at altitudes of 10–300 m for validation. Moreover, updating information and data on Vietnam's exclusive economic zone, along with areas permitted for wind energy development in the National Marine Spatial Plan, is essential for further improving the assessment results. This will ensure the most effective support for the country's planning as well as for investors involved in the development of offshore wind energy in Vietnam.

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