Assessing the wind energy potential of Hai Phong's offshore area

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Abstract
While offshore wind farms are a global reality, Vietnam remains untapped in this renewable energy sector. Hai Phong, a city experiencing rapid economic growth, faces increasing electricity demands. This study assessed the wind energy potential of Hai Phong's offshore area by calculating wind energy density at 10 meters and extrapolating to 100 meters using meteorological data and semi-empirical formulas. Results indicate significantly higher average wind energy density offshore compared to coastal areas (1.36 times at 10 meters). At 100 meters, average wind energy density fluctuates substantially (2,927 to 22,108 W/m²) with a notable difference between monsoon seasons (2.04 times higher in the Southwest monsoon than the Northeast one). This preliminary investigation seeks to evaluate the potential of Hai Phong's sea wind as a resource, laying the groundwork for comprehensive research initiatives in the future.

Keywords**:** *Offshore wind energy, clean energy source, wind resources, Hai Phong city.*
JEL Classifications: *O13, P18, P48.*
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1. INTRODUCTION

Wind energy has become a global phenomenon, with over 130 countries harnessing its power. The industry has experienced rapid growth, with global capacity nearly doubling from 2011 to 2020, reaching 733 GW. China and India have been key drivers of this expansion, accounting for over half of the new installations in the past decade *(WB, 2021)*.

Offshore wind energy is rapidly emerging as a promising clean energy source. The UK led the global offshore wind (WE) industry in 2016 with the largest installed capacity (8.5 GW) and lowest costs. By September 2019, global offshore wind capacity had expanded to approximately 25 GW, representing annual investments of around $26 billion. Historically, offshore wind was significantly more expensive than onshore, with 2015 levelized costs of electricity (LCOE) ranging from $150 to $200/MWh. However, a dramatic shift occurred between 2016 and 2017, as European competition drove levelized cost of energy (LCOE) below $100/MWh. This trend culminated in subsidy-free offshore wind projects in the Netherlands. The US and UK further accelerated cost reductions, with bids falling to $65/MWh and £39.65/MWh, respectively, by late 2019. Global offshore wind capacity grew by 4.8 GW in 2018, with Europe contributing 60% and China emerging as Asia's leader. Forecasts predict annual installations of 7-11 GW from 2019-2024, rising to 15-21 GW from 2025-2030. By 2030, cumulative capacity is expected to reach 190 GW, backed by $700 billion in investments. While Europe will maintain steady growth, Asia is projected to dominate installations over the next decade, with the United States capturing approximately 10% of the global market (*Du Van Toan et al., 2020*).

Vietnam boasts abundant offshore wind resources strategically located near densely populated areas. This prime positioning presents a significant opportunity to harness wind power, potentially contributing nearly 30% of the nation's electricity demand by 2050 *(WB, 2019)*. The industry is poised for substantial growth in the coming years. Offshore wind power is crucial for sustainably meeting Vietnam's rapidly increasing electricity needs, with the potential to supply 12% of the country's power by 2035. Estimates indicate a colossal offshore wind potential of up to 609 GW across 3,000 km of coastline and 150,000 km² of sea area, considering depths of up to 50m and a distance of 70 km from shore *(Teske et al., 2019)*. This study also delineates potential wind energy zones and influencing factors on power output. While Vietnam has successfully developed onshore and nearshore wind power, offshore wind remains nascent. Despite variations in wind power potential assessments due to differing scales and methodologies, studies consistently highlight Vietnam's immense wind energy prospects *(Van Khiem Mai, 2024)*.

Hai Phong city is one of the provinces and cities with important industrial clusters, the 2nd largest port in the country, with a population of over 2 million people. With these characteristics, the demand for electricity is increasing. To further clarify the picture of the wind potential of Hai Phong waters. The paper used the method of calculating the wind energy density of the 10m floor according to the observation data of the meteorological measuring column and used a semi-experimental formula to extrapolate the wind speed of the 100m floor. The paper focuses on evaluating the reliability of existing data sources and testing the calculation of wind energy density, making policy recommendations for offshore wind power development in Hai Phong.

2. MATERIALS AND METHODS

2.1. Materials

Wind data was collected from two level, fixed base hydrometeorological stations (Hon Dau and Bach Long Vi) located along the coastal and island regions. These stations, equipped with 10-meter wind measuring poles, adhere to Level I station standards for wind data collection. Data was recorded every six hours from 1980 to 2020. Prior to analysis, raw data underwent preprocessing in Excel to remove outliers and filter maximum monthly wind speeds.

2.2. Methods

a) Calculation of wind energy density (Ministry of Natural Resources and Environment, 2022):

The average wind energy density E (W/m^2) at a specific location over a given period (year, season, month, etc.) is calculated using the following formula:

$$E = (1/2\rho)(1/N)\sum_{i=1}^{n} v_i^3 \qquad (1)$$

Where: ρ represents the air density, assumed constant at 1.225 kg/m^3, v_i is the instantaneous wind speed (m/s), N is the sample capacity.

b) Calculation of wind distribution (Ministry of Natural Resources and Environment, 2022):

$$V_z = V_1 \frac{\ln(z/z_0)}{\ln(z_1/z_0)} \qquad (2)$$

Where: V_z is the wind speed at the desired altitude, Z. For comparison, V_1 is the ground-level wind speed measured at an altitude of Z_1 = 10m. , Z_0 is the roughness of the cushion, and Z_1 is the altitude of the ground anemometer (Z_1 = 10m). Because the altitude to be calculated is usually greater than the ground wind measurement altitude ($Z > Z_1$), $V_z > V_1$ or wind speed increases with altitude. In addition, the degree of increase in wind speed with altitude depends on the roughness of the cushion (Z_0). The greater the roughness of the cushion, the faster the wind speed at the required altitude (V_z) increases.

c) Method of building wind energy density diagram

This study employed a Geographic Information System (GIS) to construct foundational data layers essential for generating wind energy density diagrams. The Inverse Distance Weighted (IDW) interpolation method, a GIS-based technique, was utilized in this process.

3. RESULTS AND DISCUSSIONS

3.1. Hai Phong coastal wind regime

Analysis of coastal wind patterns from 1980 to 2020 reveals distinct seasonal variations. Predominant wind directions shift between the rainy and dry seasons. Southerly, southeasterly, and southwesterly winds characterize the rainy season, while northeasterly, northerly, and easterly winds dominate the dry period. Easterly winds are most frequent, comprising approximately 26.93% of all observations. Southeast and north winds follow, accounting for 15.44% and 12.94%, respectively. Northeast and south winds are less common at 9.2% and 9% (Table 1).

Wind patterns in the region exhibit pronounced seasonal variability. Annually, winds typically range from 0.5 to 2.1 m/s, accounting for nearly half (47.9%) of total wind velocity. The next most common wind speeds, 3.6 to 5.7 m/s, comprise about 24% of the total (Table 1). Stronger winds exceeding 5.7 m/s occur less frequently (11.7%) and predominantly originate from easterly, southerly, south-easterly, and north-easterly directions. Notably, extreme wind events surpassing 15 m/s are concentrated between May and October, coinciding with the region's stormy season.

During the dry season, easterly winds dominate (39.5%), followed by northerly (18.2%) and north-easterly (12%) winds. Wind speeds between 0.5 and 2.1 m/s account for slightly more than half (50.3%) of the total, with 3.6-5.7 m/s winds comprising about 23.1%. High-speed winds (over 5.7 m/s) are relatively uncommon (10.3%) and primarily originate from easterly, northerly, north-easterly, and south-easterly directions.

In contrast, the rainy season is characterized by south-easterly winds as the predominant direction (20.4%), followed by northerly (17.2%) and easterly (12.1%) winds. Wind speeds in the 0.5-2.1 m/s range constitute approximately 47.4% of the total, while those between 3.6 and 5.7 m/s reach around 23.2%. Stronger winds (over 5.7 m/s) are more common during the rainy season (16%) and primarily originate from easterly, southerly, and south-easterly directions.

3.2. The sea breeze regime in Hai Phong

Hai Phong's wind regime is primarily influenced by the Gulf of Tonkin. The region experiences two distinct monsoon seasons: a northeast monsoon from October to February, characterized by cold, dry weather, and a southwest monsoon from April to August,

Table 1. Average wind frequency for years (1980 - 2020) in Hon Dau

Direction	Velocity (m/s)						Sum
	0.5 - 2.1	2.1 - 3.6	3.6 - 5.7	5.7 - 8.8	8.8 - 11.1	>11.1	
North	8.24	1.71	1.93	0.95	0.07	0.04	12.94
Northeast-North	1.44	0.46	0.39	0.06	0.01	0.00	2.37
Northeast	5.90	1.29	1.34	0.59	0.02	0.01	9.16
East-Northeast	1.09	0.32	0.48	0.24	0.01	0.02	2.16
East	10.52	4.52	7.99	3.77	0.09	0.05	26.93
East Southeast	1.50	1.11	1.55	0.53	0.01	0.02	4.73
Southeast	6.38	2.83	4.81	1.34	0.02	0.05	15.44
South Southeast	1.16	0.90	1.45	0.72	0.09	0.00	4.32
South	3.13	0.99	2.43	2.11	0.31	0.02	8.99
South-Southwest	0.53	0.12	0.32	0.54	0.05	0.01	1.56
Southwest	0.66	0.26	0.55	0.61	0.06	0.01	2.15
West-Southwest	0.16	0.01	0.04	0.01	0.01	0.00	0.23
West	0.65	0.09	0.07	0.04	0.00	0.00	0.84
West Northwest	0.26	0.04	0.01	0.02	0.00	0.00	0.33
Northwest	4.08	0.46	0.28	0.07	0.01	0.01	4.92
North Northwest	2.22	0.24	0.32	0.11	0.01	0.00	2.91
Sum	47.90	15.40	24.00	11.70	0.80	0.30	100

(Source: National Centre for Hydro-Meteorological Network - NCN)

associated with hot, humid conditions and abundant rainfall. March and September are transitional months with variable wind directions, often shifting clockwise. Over a 20-year period (1982-2002), the average wind speed was 3.3 m/s. Calm conditions occurred 3.49% of the time, while wind speeds ranged from 0.5 to 2.1 m/s (33.6%), 2.1 to 3.6 m/s (17.4%), 3.6 to 5.7 m/s (33.4%), 5.7 to 8.8 m/s (11.2%), 8.8 to 11.1 m/s (0.8%), and above 11.1 m/s (0.1%).

From October to February, east and northeast winds dominate, with average speeds reaching 6.5-8.2 m/s. Wind speeds are particularly high from October to January, often exceeding 9.0 m/s. December experiences the highest frequency of these wind directions (99%), while other months see around 67%. Although northeast winds are less frequent than east winds, they are generally stronger.

The southwest monsoon, occurring from April to August, brings average wind speeds of 5.5 m/s, increasing to 7.0 m/s in June. Southerly and southwesterly winds prevail due to the development of the Indian low-pressure system over the Gulf of Tonkin. April is characterized by southeast winds averaging 6.0 m/s, while south and southwest winds dominate from June to August, especially in July (67%). Southwest wind intensity decreases in August. March and September are transitional months with unstable wind directions and speeds. Northeast winds are most frequent in March (17%), while southwest winds peak in September (12%). Average wind speeds during these months are around 5.0 m/s.

Average monthly wind speeds have varied over time. The highest values were recorded in the 1990s (8.2 m/s), followed by 2011-2020 (7.4 m/s), 1980-1989 (7.3 m/s), and 2000-2010 (7.0 m/s). However, all periods experienced average monthly wind speeds exceeding 5 m/s, with peak values occurring in summer or winter (Table 2, Table 3).

Table 2. Monthly average wind speed (m/s) at Bach Long Vi station over a ten-year period

Periods	Months											
	1	2	3	4	5	6	7	8	9	10	11	12
1980-1989	7.28	7.07	6.73	5.73	6.13	6.65	7.3	5.42	5.57	6.98	7.00	7.01
1990-1999	7.12	6.74	6.46	5.95	6.04	7.23	8.19	5.84	5.00	6.73	7.27	7.54
2000-2010	6.57	6.15	5.54	5.75	5.49	6.15	6.43	4.66	5.26	6.15	6.72	6.97
2011-2020	5.67	5.37	4.51	4.84	5.72	6.46	6.03	4.90	4.66	5.78	6.28	7.38

(Source: National Centre for Hydro-Meteorological Network - NCN)

A comparative analysis of average and maximum wind speeds over multiple years in the study area reveals a consistent trend of decreasing wind speeds from the open sea towards the coastline. When comparing the open sea area of Hai Phong to the northwestern coastal islands (Co To), the coast (Hon Dau), the inland region (Phu Lien), and the coast of the Gulf of Tonkin's mouth (Con Co), it is evident that the open sea consistently exhibits the highest average and maximum wind speeds across all months (Table 3). This data highlights the substantial potential for offshore wind power generation in Hai Phong's waters.

Bach Long Vi island, located in the research area's offshore zone, successfully commissioned its first wind power station in 2004 with a capacity of 858 kW. This achievement followed a three-year construction period aided by the expertise of Spanish companies Made (equipment) and Tucme (consultancy) (*Tran Anh Tu, 2014*). Initial testing over three months conclusively demonstrated the island's abundant wind resources, capable of consistently powering the station. A detailed analysis of wind speed data from October 1st to 25th, 2004, revealed a regular station output of 600-800 kW/h, corresponding to wind speeds of 10-16 m/s. Long-term wind monitoring (1980-2010) at an altitude of 10 meters recorded an average annual wind speed of approximately 7 m/s. Calm conditions (≤ 1.0 m/s) occurred 5.56% of the time, while wind speeds exceeding 7.0 m/s constituted 29.41% of the dataset (*Tran Duc Thanh. 2013*).

Table 3. Comparison of average and maximum monthly wind speeds (m/s) in the open sea (Bach Long Vi) and the stations on the west coast of the Gulf of Tonkin in the period of 1980-2020

Station	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Bach Long Vi	19.1	18.9	18.5	17.9	18.3	18.2	21.5	23.4	21.5	21.9	20.3	19.6
Co To	15.3	15.1	14.7	14.9	14.6	18.1	21.0	19.2	18	17	15.9	15.8
Hon Dau	13.5	13.5	13.0	14.6	16.3	16.3	19.7	17.6	17.2	15.2	13.0	12.3
Phu Lien	10.2	11.0	11.5	15.0	15.9	16.6	20.3	18.3	15.8	13.6	11.7	11.3
Con Co	13.1	12.1	11.9	13.0	13.0	12.1	12.2	14.5	14.3	18.3	15.0	14.0

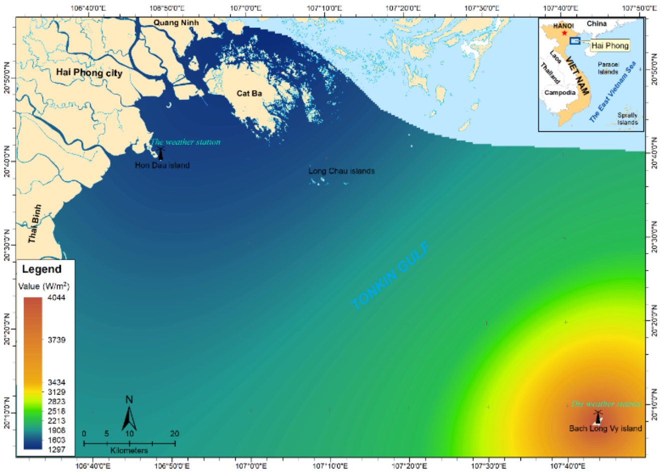
(Source: National Centre for Hydro-Meteorological Network - NCN)

Table 4. The highest average monthly wind energy density, E (W/m²), during the period 1980-2020 in coastal waters (Hon Dau) and open seas (Bach Long Vi)

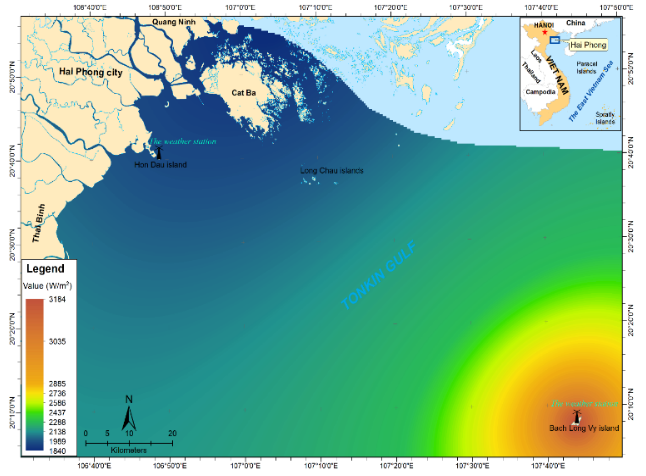
Month/ Station	Bach Long Vi		Hon Dau		Month/Station	Bach Long Vi		Hon Dau	
height	10m	100m	10m	100m	height	10m	100m	10m	100m
1	4378	9103	1483	3084	7	9291	19315	7778	16171
2	4520	9398	1607	3341	8	10635	22108	5057	10514
3	4133	8593	1408	2927	9	8577	17830	4554	9467
4	3578	7439	2042	4245	10	8576	17829	3043	6326
5	4297	9833	2800	5821	11	5764	15662	1400	2911
6	5272	10960	3970	8253	12	5049	10497	1166	2425

3.3. Wind energy density distribution of the study area

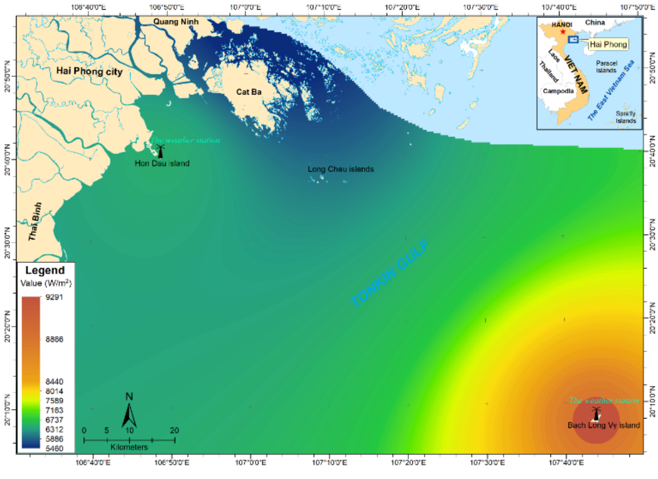
a) Wind energy density at 10m



▲ *February*



▲ *April*



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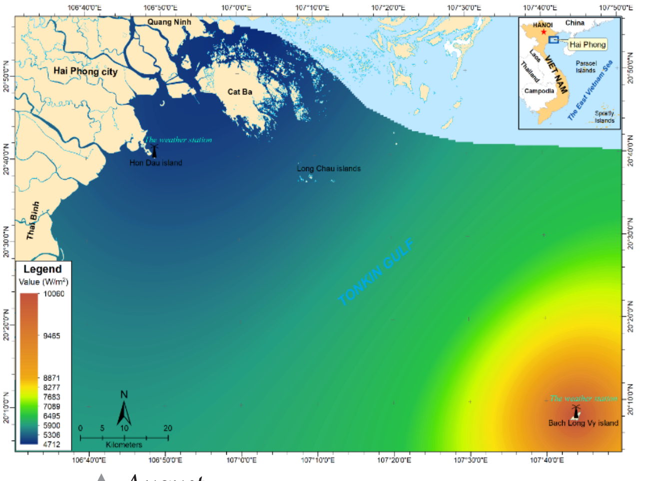
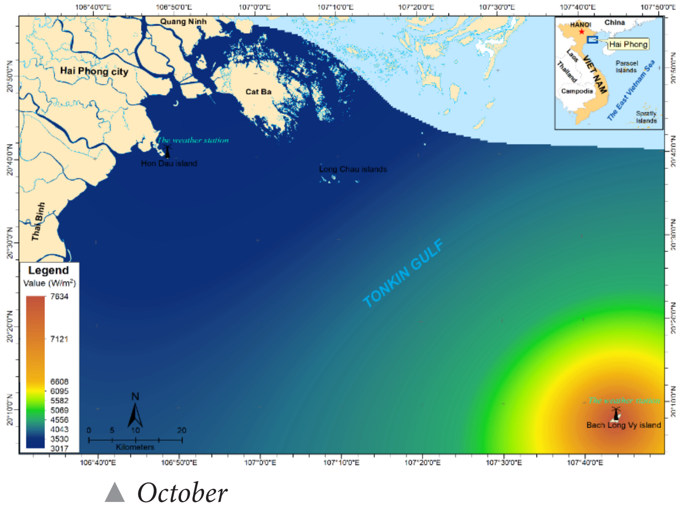
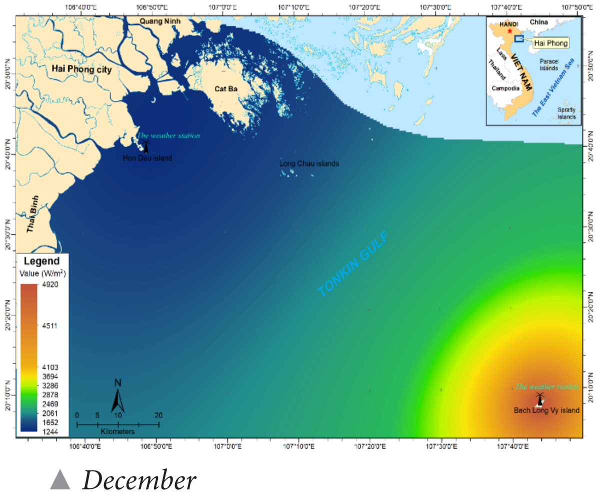


▲ *August*



▲ *October*



▲ *December*

▲ *Figure 1. Average wind energy density E (W/m²) of the maximum value Hai Phong sea at an altitude of 10m (period 1980-2020)*

Wind energy density in Hai Phong exhibits significant seasonal and spatial variability. Offshore Hai Phong boasts an average monthly wind energy density ranging from 3,578 to 10,635 W/m², with a pronounced monsoon influence. Southwest monsoon months (July to September) consistently exceed 8,000 W/m², doubling the energy density of Northeast monsoon months (below 5,000 W/m²) (Table 4, Figure 1). In contrast, the coastal area experiences a lower average monthly wind energy density between 1,166 and 7,778 W/m². While still influenced by the monsoon cycle, with Southwest monsoon months surpassing 4,000 W/m² and outperforming Northeast monsoon months by a factor of 4-5, the overall energy potential is markedly lower (Table 4). Importantly, the maximum monthly wind energy density offshore is 36% higher than that of the coastal area (Table 4).

b) Wind energy density at 100m

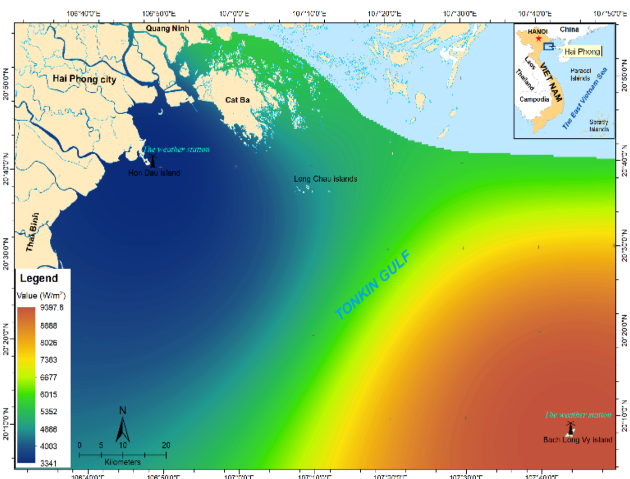
Hai Phong sea at an altitude of 100m (period 1980-2020)

At the 100-meter level, the coastal area of Hai Phong exhibits monthly average wind power density ranging from 2,927 to 22,108 W/m². The open sea consistently surpasses 7,000 W/m² year-round, with values in the southwest monsoon (July-September) averaging 2.04 times those of the northeast monsoon (December-February). The coastal maximum drops to 2,425-16,171 W/m², yet southwest monsoon months still exceed 9,000 W/m², five times the northeast (Table 4, Figure 2). Offshore wind energy density is 2.1 times greater than coastal (Table 4).

Hai Phong boasts one of Vietnam's two most promising offshore wind energy areas (Ministry of Natural Resources and Environment, 2022). Vietnam, overall, leads Southeast Asia in wind energy resources, with a total potential of 513,360 MW (medium to large global density) (Pham Anh Tuan, 2007). Approximately 40% of Vietnam enjoys strong winds (7-9 m/s at 65 meters), ideal for large-scale wind farms (Vu Manh Ha, 2007). This underscores Hai Phong's offshore wind potential as a cornerstone of Vietnam's future renewable energy landscape.

To harness this potential, Hai Phong should:

+ Prioritize wind power development through city resolutions, replacing thermal power gradually. Offer incentives to wind energy investors (tax breaks, legal support, land clearance).



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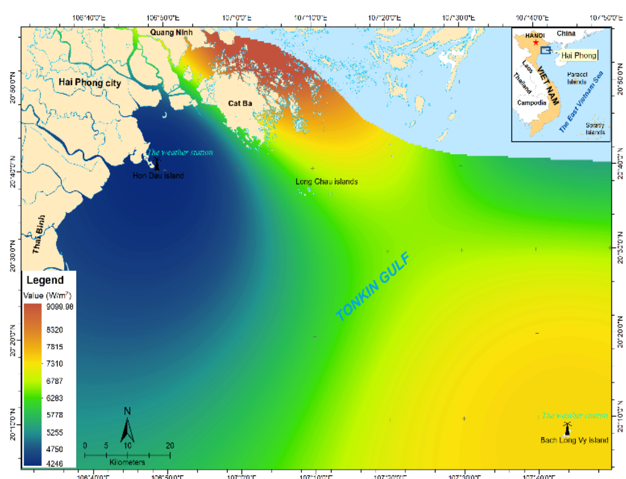

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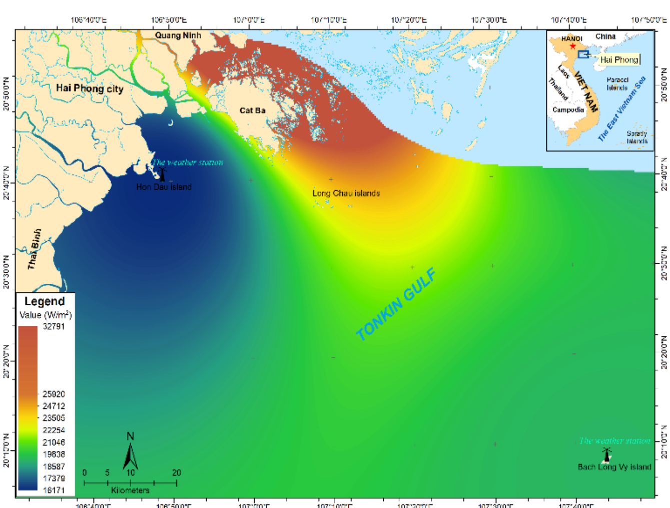

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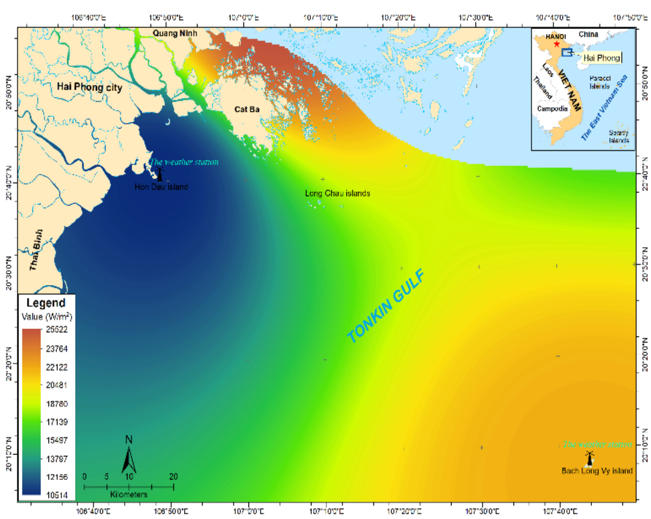
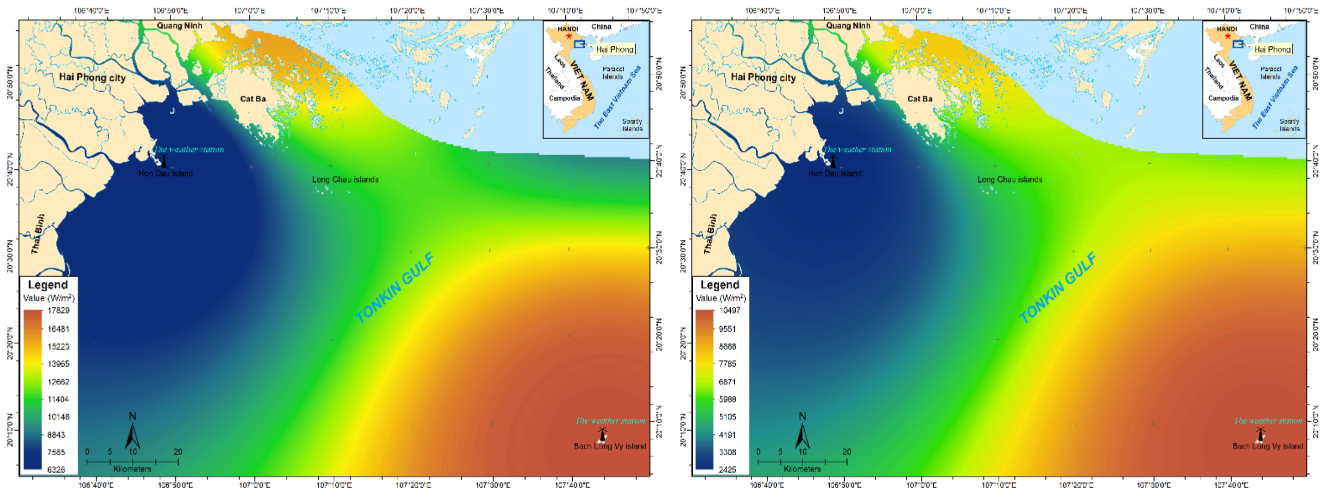


▲ *August*



▲ October ▲ December

▲ *Figure 2. Average wind energy density E (W/m²) of the maximum value Hai Phong sea at an altitude of 100m (period 1980-2020*

+ Establish a renewable energy steering committee led by a vice mayor, with industry, trade, and coastal district representatives.

+ Conduct comprehensive wind resource assessments for coastal and offshore areas, informing detailed land and sea use planning for renewable energy. Pilot small-scale projects to gain practical experience.

+ Enhance the professional capabilities of city officials managing renewable energy through domestic and international training.

+ Foster international collaboration on marine science and technology, specializing in renewable energy. Develop local research and application programs for sustainable coastal and offshore resource management.

4. CONCLUSION

The research findings illuminate Hai Phong's offshore wind energy potential for developing offshore wind power projects. However, the study's scope is limited by its reliance on data from 1980 to 2020, necessitating an update to 2023 for enhanced reference and timeliness. Moreover, this initial assessment of Hai Phong's offshore wind potential on a monthly basis lays the groundwork for more detailed investigations to support specific project development goals.

Marine management agencies, electricity, and offshore wind power companies can utilize this research as a foundation for further, in-depth studies aligned with Vietnam's 2050 net-zero target.

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