Analysis of the Turbulence Intensity for Selecting Wind Turbines on Vietnamese Islands: The Case of the Coto Island

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ARTICLE INFO

Article history:
Received: 15 August 2024
Revised: 18 October 2024
Accepted: 21 December 2024
Online: 15 May 2026

Keywords:
Wind conditions
Turbulence intensity
Terrain complexity
Coto Island
Vietnam

ABSTRACT

Wind energy is currently considered a sustainable energy source globally, including on both large and small scales. Controlling turbulence due to complex environments is still an urgent issue in the production of wind power today, particularly for wind turbines near mountains, forests, or urban areas. The small islands off the coast, like Coto Island, are a good example of this. With a favorable location, Coto Island (Vietnam) has great potential in exploiting and using renewable energy sources such as wind, solar, and biomass, especially wind energy. However, due to the island's terrain complexity, wind turbines here may be negatively affected by local turbulence conditions. In this study, the authors have therefore analyzed and evaluated turbulence characteristics at some selected sites on this island. Based on the analysis results, wind turbines selected for low-hilly areas should be classed as Class C, while those near residential areas should be classified as Class A.

1. INTRODUCTION

Today, the need to transition to low-carbon energy sources is growing worldwide. This is attributed to the ongoing global energy crisis and its significant impact on energy communities [1, 2]. The current energy crisis involves most fossil fuel sources and occurs in many countries around the world. The entire world economy is interconnected and thus further magnifies the impact of this crisis. Europe is facing gas restrictions in both production and consumption, while a series of factories in China are having to reduce output or close due to the lack of gas supply. In other economies (including emerging, developing and developing economies), rising prices have impacted most sectors of society, and caused significant economic, socially and political strains.

The energy crisis has impacted energy policies and priorities in most countries. Many schemes to accelerate the deployment of sustainable renewable energy such as wind and solar have been issued, in addition to initiatives to develop energy efficiency [3, 4]. This increasing use of renewable energy sources leads to the need for accompanying technical solutions, including wind power and its generation systems (turbines) [5–8]. Normally, most wind turbines are designed to deliver as much energy as possible in a cost-effectively and the best locations for them are usually places with high wind speeds, flat terrain, and little turbulence. However, wind turbines are also affected by electrical and environmental conditions that have the directly and indirectly impact on their loading, durability, and operation. Electrical conditions refer to the conditions of the power grid that is connected to the wind turbine system, while environmental conditions include wind conditions and other external conditions. In the above conditions, wind conditions are considered a prerequisite to ensure the integrity of the wind turbine system structure and decide to deploy this system. The wind conditions consist of a constant mean flow combined with turbulence, where turbulence is a random variation in wind speed from a 10-minute average.

In fact, wind turbines are often affected by turbulences due to the complex nature of the surrounding environment, especially when located near obstacles like hills and forests, or high buildings, see Fig. 1 [9, 10]. In these environments, air flows are affected by rough terrain structures along with obstacles of varying heights. As a result, the boundary layer flow behaves differently compared to in homogeneous environments. The average wind speed is typically low, but the turbulence intensity is much higher. This could have a major impact on the structure of wind turbines here because they must withstand greater fatigue loads [5, 11]. In cases where wind turbines cannot withstand harsh conditions, they may fail and result in serious, unforeseen accidents.

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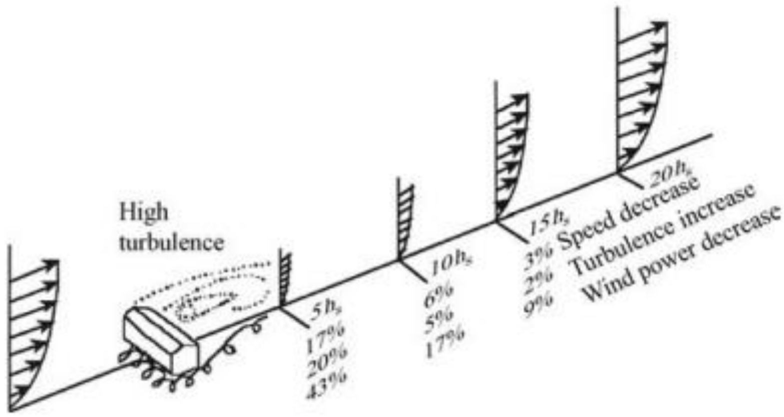


Fig. 1. Illustration of the turbulence effects by terrain complexity.

Wind turbines are affected by the environmental conditions around them, especially wind conditions near the turbine site [5, 11]. Unfortunately, winds do not move continuously and evenly, they can gust and hit wind turbines from different directions. This phenomenon is also known as turbulence, characterized by rapid changes in both wind speed and direction. Turbulence is a major factor affecting both the annual wind power output and the technical performance of wind turbines. Therefore, understanding turbulence intensity is crucial before starting any wind power projects.

The criteria for wind conditions have been introduced in the IEC 61400-1 (2005) standard [12] and its amendment IEC 61400-1 (2010) [13] on Wind turbines - Design requirements. According to these standards, the selected wind turbine must safely withstand specific wind conditions which typically include a constant average flow combined with turbulence. In normal turbulence models, the representative value of turbulence intensity is determined by the relationship between the standard deviation and the corresponding 10-minute average wind speed.

The Wind Atlas Analysis and Application Program (WAsP) is used to calculate wind conditions. It's a linear extrapolation tool for analyzing both horizontal and vertical wind data [14, 15]. WAsP includes a comprehensive suite of models that can calculate wind conditions in complex terrains. The input data comprises an analysis of raw wind data, including speed and direction, along with topographic data for a specific area. The resulting wind map can then help identify the most suitable type of wind turbine and its optimal site.

Literature [16, 17] mentions the possibility of identifying wind resources in complex terrain by modeling wind data at a specific site through wind tunnel tests or Computational Fluid Dynamics (CFD) software. These tools are increasingly popular today due to the increasing demand for accuracy in wind energy exploitation.

Up to now, there are very few studies on the offshore turbulence intensity in Vietnam [18]. Most wind power projects nationwide are focused on onshore or near shore areas. The surveys in [19] examined the technical feasibility of a wind power project in the Southeast region of Vietnam using WAsP software, focusing on selecting installation locations for wind turbines within the same wind power plant to obtain the maximum possible technical and economic efficiency. Another investigation in [20] used CFD simulation software and GIS data to determine suitable locations for onshore wind turbines in Ninh Thuan province, Vietnam. The scope of this investigation was for large-scale wind farms with capacities up to 100 MW, where each turbine has a capacity of 4 MW or more.

However, none of the papers above has analyzed offshore wind conditions, especially turbulence characteristics, to exploit this clean energy source in Vietnam's islands.

To address this gap, the present study examines the terrain and wind conditions at two designated sites on Coto Island (Vietnam), followed by an analysis of turbulence intensity at these two sites. The analysis focuses on wind turbines with capacities of 500 kW or less, considering the proximity of these sites to a residential area and the relatively low load demand in the area.

The characteristics of the study area are presented in Section 2. Section 3 describes the methodology and characteristics of the two selected sites, and Section 4 presents the results and accompanying discussions. Section 5 is some conclusions about the surveys of turbulence intensity of wind conditions on Coto Island.

2. STUDY AREAS

Coto Island is the largest island in the Coto - Longchau archipelago in Quang Ninh Province, including Coto, Thanh Lan and Tran islands [21], see Fig. 2. Total natural area of Coto Island is 46.2 km^2 with the continental shelf of over 1,000 km^2. The geographic of this Island coordinates from 20º55'N to 21º15'7"N and from 107º35'E to 108º20'E.

The terrain here is mostly low hills and mountains surrounded by the sea [21]. Hilly areas are about 51% of the natural area, with the highest peak reaching 210 meters on

Thanh Lan island. Flat areas account for 49% of the natural area, alternating between low hills. The island is bordered by coves and sandy beaches, with the land mainly consisting of ferrallitic soil on sandstone. There are 22 km² of wooded land, while agricultural land accounts for 20% of the total area. The island has total 13 small streams, each over 1 km in length.

Coto Island is located in the tropical monsoon climate zone [21]. The annual average temperature is 22.5°C, highest in June with about 36°C and lowest in January with about 5°C. The average humidity reaches 83.6%, the average rainfall is up to 1664 mm/year, and the total sunshine hours a year are around 1820 hours. Northeast monsoon prevails from September to April of the following year. East monsoon prevails from May to August. South monsoon prevails in July. Normally, there are about 2 to 3 storms and tropical depressions from July to September, with the wind speed up to 144km/h. The average temperature of seawater is about 27°C and the high salinity of seawater is up to nearly 4%.

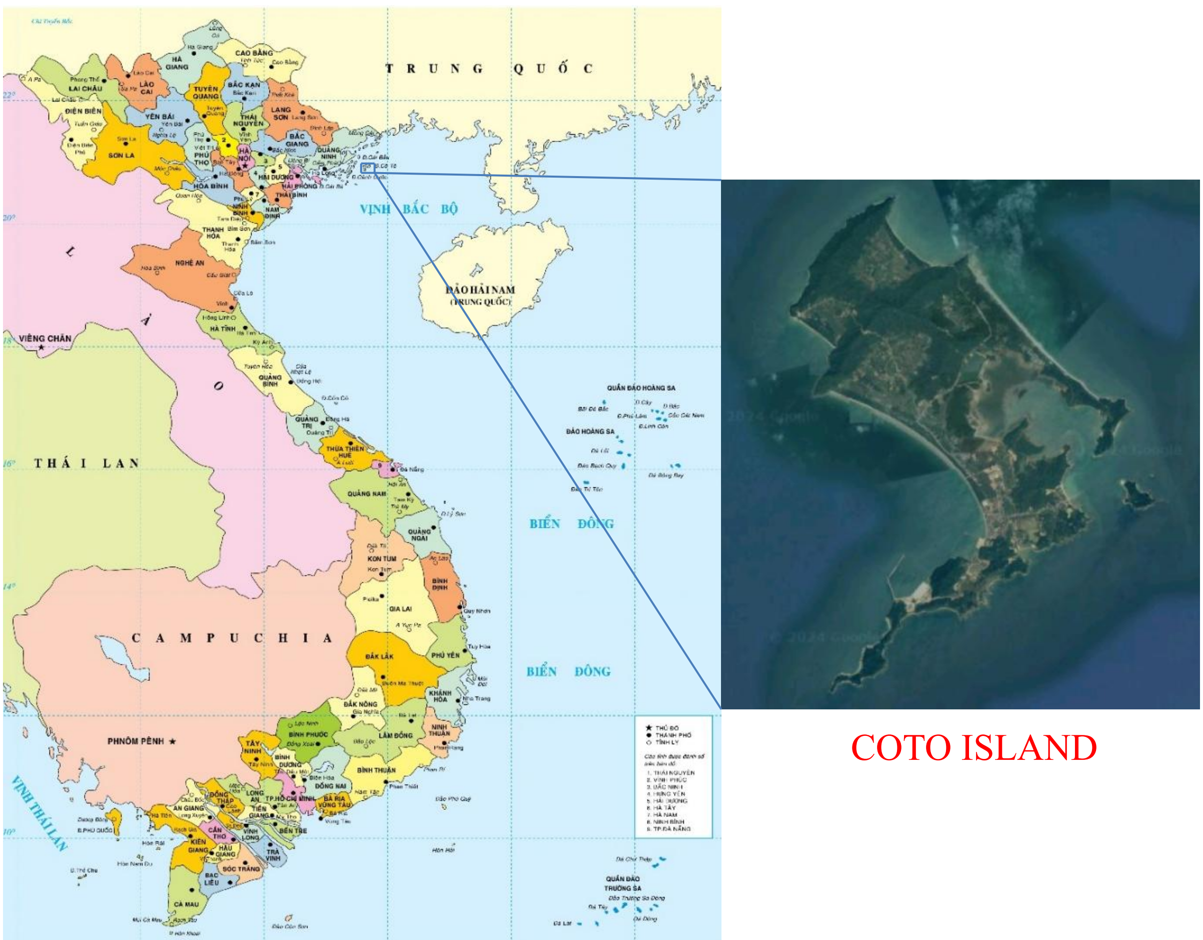


Fig. 2. The map of the Coto Island

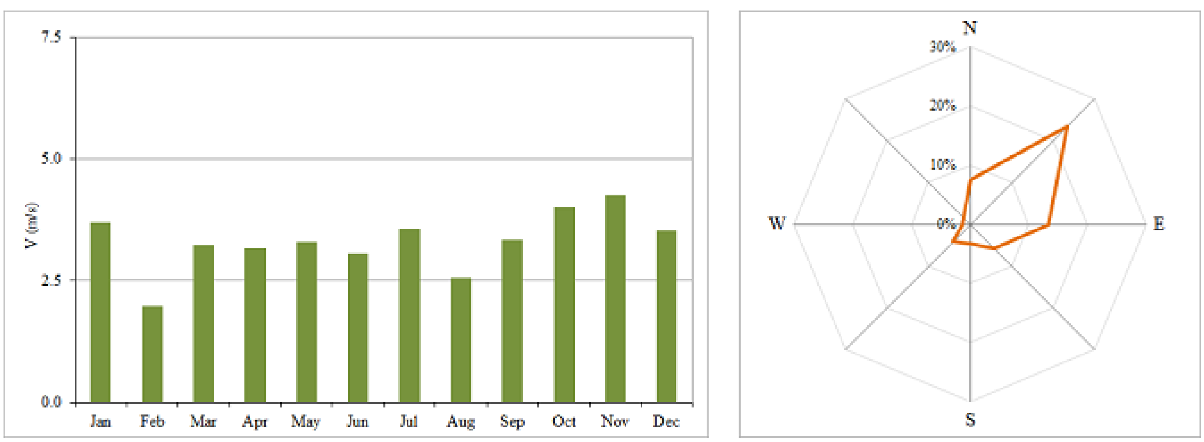
3. MATERIALS AND METHODS

3.1. Materials

The survey and analysis of turbulence intensity were carried out at two locations, one on the mountain (site 1) and one near a residential area (site 2), see Fig. 3. Site 1 was located on a hill spreading around the area, covered with grass and some low trees. Measurements were taken at two heights of 10 m and 35 m on a 50 m high lattice tower placed on top of the hill. Site 2 was located on the edge of the island's central residential area, surrounded by a mix of buildings of varying sizes and some grassed areas. The surrounding buildings are mostly low, and some are up to three stories high. The measurements were performed at a height of 35 m on a 45 m high lattice tower.

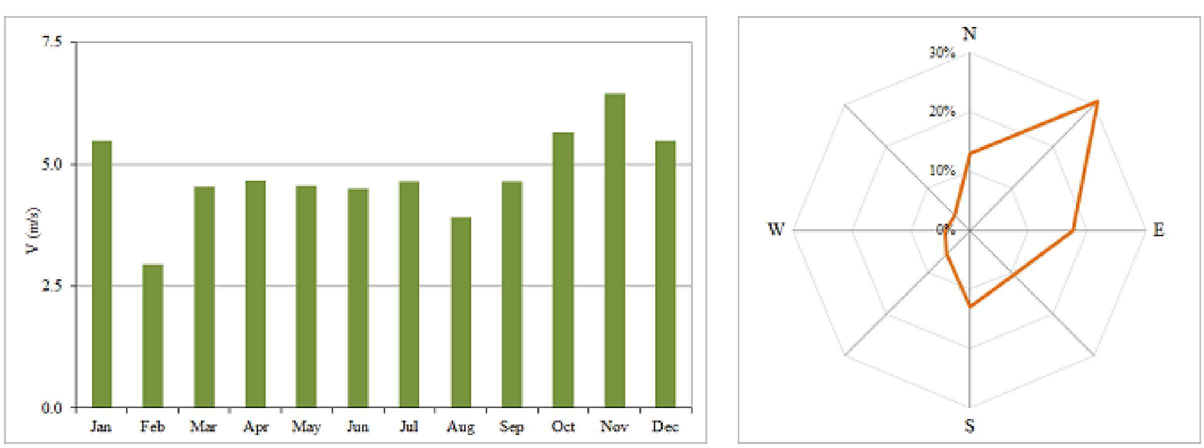
Measurements were performed at the same time for both sites in this study. Data were measured and sampled at an average of 10 minutes over a year, including wind speed and direction as well as standard deviation at three heights above ground level (AGL), see Fig. 4, Fig. 5, and Fig. 6. In particular, site 2 had two prevailing wind directions of Northeast and North with a quiet wind frequency of 0%; while site 1 had one dominant Northeast wind direction and a calm wind frequency of about 0.2%. The average wind speed at site 1 was approximately 5 m/s, while at site 2 it was around 4 m/s.

Fig. 3. Two locations to survey and analyze turbulence intensity on Coto island



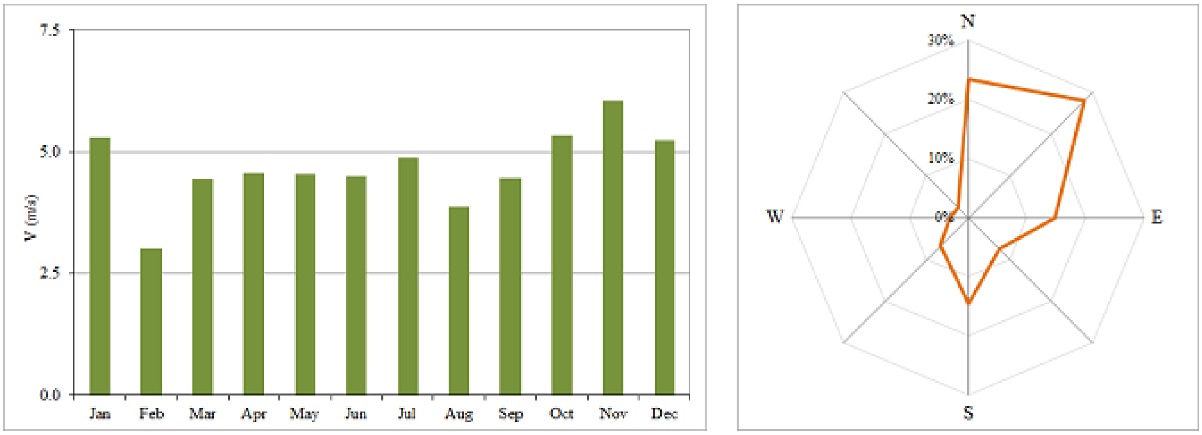
(a) (b)

Fig. 4. Wind speed (a) and rose (b) in Coto island at 10m AGL (site 1)



(a) (b)

Fig. 5. Wind speed (a) and rose (b) in Coto island at 35m AGL (site 1).



(a) (b)

Fig. 6. Wind speed (a) and rose (b) in Coto island at 35m AGL (site 2)

3.2. Methods

As previously mentioned, wind turbines are influenced by environmental conditions, including the topography and wind patterns in their vicinity. Therefore, it is essential to determine the complexity of the terrain at the specific site, followed by an evaluation of the wind patterns at that site.

In this study, the evaluation of the terrain and wind conditions was conducted according to the steps outlined in the flow chart of Fig. 7 below.

According to the flow chart, a preliminary survey of the terrain conditions is necessary to assess the topographic complexity of the selected site. The results obtained would facilitate the subsequent selection of an appropriate model for evaluating the wind conditions in the area.

The wind conditions in this study encompass a mean flow and turbulence, with turbulence representing the random variations in the 10-minute mean wind speed profile. The turbulence intensity profile would be analyzed to determine the turbulence class of the selected site.

3.2.1. Regarding assessing the terrain complexity

The complexity of a site is determined through the criteria of terrain slope and its variations relative to the plane. This criteria is introduced in the IEC 61400-1 (2005) standard [12] and its amendment IEC 61400-1 (2010) [13] on Wind turbines - Design requirements , summarized in

Table 1. Accordingly, the plane in the slope criteria is determined with the corresponding terrain in the specific distance and arc amplitude for all wind directions around the wind turbine and passing through the base of the tower. The terrain variation relative to the fitted plane represents the distance, vertical direction, between this plane and the terrain at points on its surface. The site is considered complex if 15 % of the wind energy comes from areas not meeting these criteria. In cases of less than 5 % of the wind energy from areas failing to conform, the site is seen as homogeneous.

Also according to this standard [12], the terrain slope should be determined within a distance of no more than 20 times the hub height and the complexity of the terrain should be evaluated within a radius of 1.2 times the hub height. In addition, the surface area to assess terrain complexity must not exceed a minimum range of $1.5 * Z_{hub}$ and 100 m.

The WAsP software [14, 15], a wind flow analysis tool developed by Risoe National Laboratory in Denmark shows that the ruggedness index (RIX) is calculated for each radius from the selected site. A flat site usually has an RIX of 0%, and a very complex (sloping) site has an RIX of 30% or more. The index's specific value depends on the area's site under consideration.

Based on the IEC standards [12] and the WAsP software [14, 15] mentioned above, some indexes were selected to determine the complexity of the terrain in this study, that is:

- Index (1) “Maximum slope within 5km radius is equal to or more than 10 degrees”.
- Index (2) “Standard deviation of the topographic cross-section in the upwind part within 5 km radius is equal to or more than 1.5 times of the hub height”.
- Index (3) “Standard deviation of the topographic cross-section in the upwind part within distance of 5, 10 and 20 times of the hub height are more than 0.5, 0.8 and 1.4 times of the hub height, respectively”.
- Index (4) “Speed up ratio caused by local geography is more than 1.2”.
- Index (5) “More 30% of slopes between neighboring contour lines are steeper than 30%”.

Indices (1), (2), (3), and (4) are based on the IEC standards [12], in which: Index (1) is for assessing the possibility of local geographical features influencing the local wind flow; Indices (2) and (3) to determine the terrain complexity around the site; and Index (4) is related to the flow acceleration due to the local geographic feature indicated by index (1). Index (5) is the RIX index in the WAsP software [14, 15].

These indices were conducted for each wind direction, and then the assessment of terrain complexity according to these indicators was carried out as follows.

a) None of (1), (2), (3), (4), (5) are true: Low Complexity

b) At least one of (1), (2), (3), (4) is true, AND (5) is false: Medium Complexity

c) At least one of (1), (2), (3), (4) is true, AND (5) is true: High Complexity

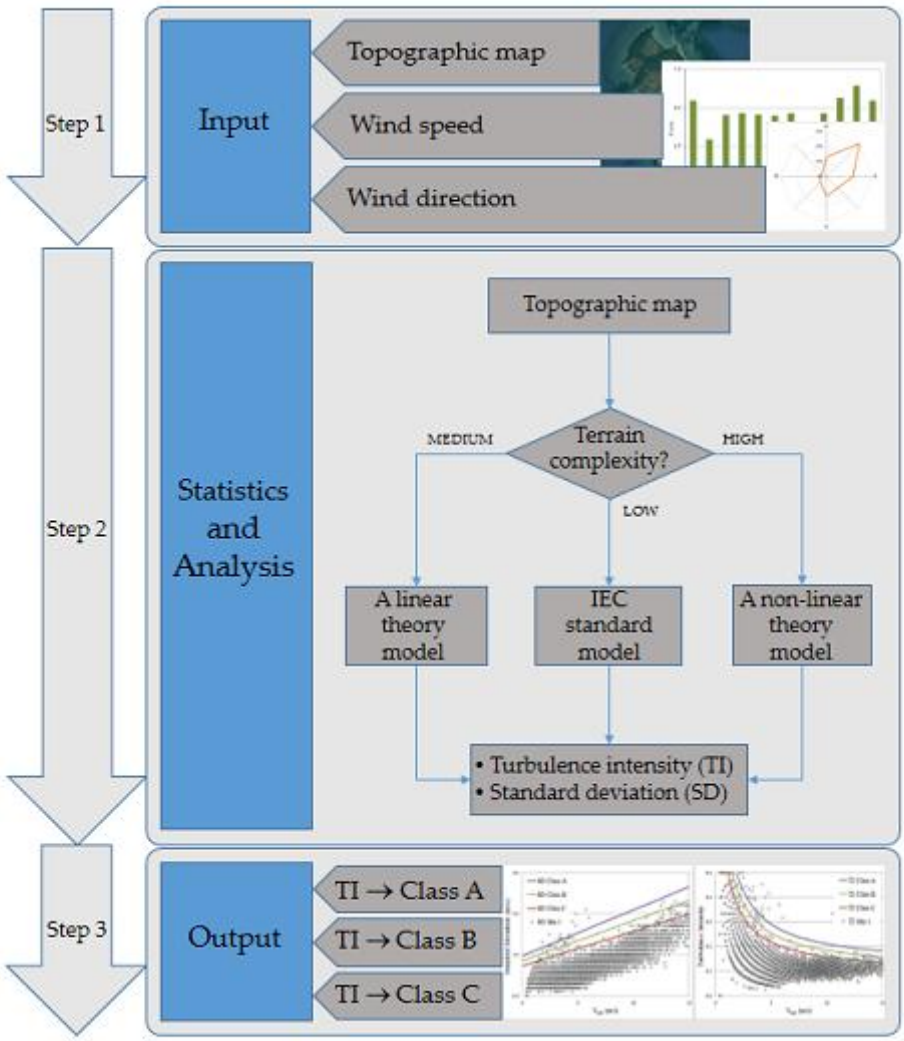


Fig. 7. Flow chart of the proposed approach

Table 1. Criteria for Terrain Complexity in the IEC 61400-1 [12, 13]

Distance range from wind turbine	**Sector amplitude**	**Max. slope of fitted plane**	**Max. terrain variation from wind turbine**
< 5 * Z_{hub}	360º	< 10º	< 0.3 * Z_{hub}
< 10 * Z_{hub}	30º		< 0.6 * Z_{hub}
< 20 * Z_{hub}	30º		< 1.2 * Z_{hub}

Note: Z_{hub} is the Hub Height

3.2.2. Regarding determining the turbulence intensity

According to the IEC 61400-1 standard [12, 13], the turbulence intensity, I, was determined by the turbulence intensity at the non-exceeded level of 90% of corresponding the 10-minute average wind speed and the expected value at the wind speed of 15 m/s, I_{ref}, following the equations below.

$$I = \frac{\sigma}{V_{hub}} \quad (1)$$

$$\sigma = I_{ref}\ (0.75V_{hub} + 5.6) \quad (2)$$

in which, I_{ref} is the expected value of turbulence intensity for a wind speed of 15 m/s; V_{hub} is the 10-minute average wind speed at the hub height, m/s; σ is the standard deviation at the non-exceedance level of 90%, m/s.

The expected value I_{ref} is also classified into 3 turbulence categories of A, B, and C, see Table 2.

Table 2. Wind turbine class in the IEC 61400-1 (2005) [12]

WT class		I	II	III	S
V_{ref} (m/s)		50	42.5	37.5	Values specified by designer
V_{ave} (m/s)		10	8.5	7.5	
I_{ref}	A	0.16			
	B	0.14			
	C	0.12			

The parameter values in Table 2 are at hub height, in which: V_{ref} is the 10-minute average reference extreme wind speed; V_{ave} is the 10-minute average standard annual wind speed; A appoints the category for high turbulence characteristics; B appoints the category for medium turbulence characteristics; C appoints the category for low turbulence characteristics.

In the IEC standard model [12, 13], the assessment of wind conditions allows the selection of wind turbines that meet the on-site conditions and are suitable for safe operation. The meteorological measurements at the site for a year are usually carried out with three main parameters as follows:

(1) Average 10-minute extreme wind speed with a recurrence period of 50 years at hub height.

(2) Expected value of turbulence intensity at a 10-minute average wind speed of 15m/s at hub height (I_{ref}).

(3) Average 10-minute annual wind speed at hub height.

In linear model, its typical model is WasP [14, 15], which is capable of calculating wind conditions at any location in the model domain using elevation maps, surface roughness, and meteorological wind data.

In non-linear model, the assessment of wind conditions is typically conducted through wind tunnel tests or CFD [16, 17]. Boundary conditions are established by nesting and defining ideal flow conditions. In this model, the ideal wind field is computed within a virtual domain and subsequently translated into a realistic wind field.

4. RESULTS AND DISCUSSIONS

4.1. For the terrain complexity

Index (1)

According to survey data, the slope of the fitted plane within a radius of 5 km at site 1 and site 2 was less than 10º, see Table 3. In particular, the maximum slope at site 1 was less than 2.5º, while this value at site 2 was up to 3.5º.

Table 3. Slope of the fitted plane within a radius of 5 km

	Site 1	Site 2
Max. value	2.29º	3.44º
Min. value	0.69º	1.19º

Index (2)

The survey data also showed that in the upwind area within a 5 km radius of the hub, the terrain variation at 2 sites was less than 1.5 times the hub height, see Table 4. In particular, the maximum deviation of the topographic cross-section at site 1 was about 23 m, while this value at site 2 was up to 43 m.

Table 4. Terrain variation in the upwind area of 5 km radius

	Site 1	Site 2
Average value (m)	7.64	9.47
Max. value (m)	23	49
Min. value (m)	0	0
$1.5*Z_{hub}$ (m)	52.5	

Index (3)

According to IEC 61400-1 standards, the terrain variation in this study was determined within a radius of 20 times the hub height, which was 700m. Therefore, the maximum cross-sectional terrain deviation from the hub was 49 m.

In this study, the maximum deviation of the topographic cross-section in the upwind part was surveyed at both sites and both showed values less than 49 m, see Table 5. In which, the maximum deviation at site 1 was up to nearly 48 m, while this value at site 2 was only 20 m.

Table 5. The terrain deviation within radius 700 m

	Site 1	Site 2
Average value (m)	17.6	11.5
Max. value (m)	47.5	20
Min. value (m)	0	0
$20*Z_{hub}$ (m)	700	

Index (4)

The average flow acceleration at both surveyed sites was less than 1.2, see Table 6. The maximum flow acceleration at site 1 was more than double that of site 2. This is expected to be because there were fewer obstacles around.

Table 6. The flow acceleration at site 1 and site 2

	Site 1	Site 2
Average ratio	1.1	1.1
Max. ratio	3.7	1.6
Min. ratio	0.9	0.8

Index (5)

RIX is designed to show the ratio of the slopes steeper than the threshold for generating flow separation, and the threshold value for the judging the possibility of flow separation on slopes is 0.3.

At both sites, site 1 and site 2, the terrain conditions were flat terrain and low hills, so the RIX value for both sites was chosen to be 0%.

Comment:

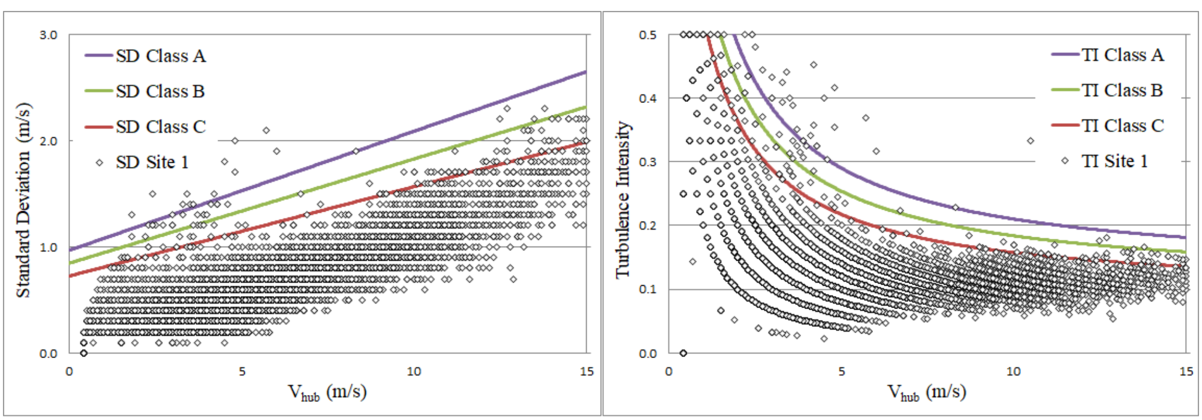
Considering the above index analysis, none of (1), (2), (3), (4) and (5) have been correct for both sites, therefore the terrain complexity in both areas has been determined to be low. Therefore, the determination of turbulence characteristics and standard deviation of wind conditions in the next step could be performed according to the IEC standard wind model.

4.2. For the turbulence characteristics

Based on the results of section 4.1, the IEC standard wind model in [12] was selected to evaluate the standard deviation and turbulence intensity in this study. These indexes were also determined at both locations, see Table 7, Fig. 8, and Fig. 9.

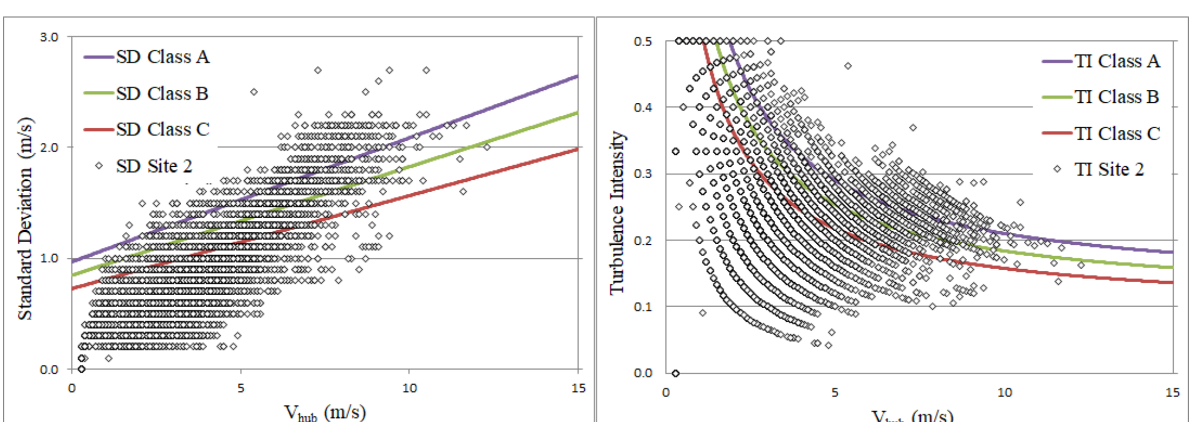
Table 7. Average standard deviation and turbulence intensity

	Site 1	Site 2
σ (m/s)	0.61	0.85
I_{ref}	0.11	0.15



(a) (b)

Fig. 8. Standard deviation (a) and turbulence intensity (b) at site 1.



(a) (b)

Fig. 9. Standard deviation (a) and turbulence intensity (b) at site 2.

The results show the different in wind conditions at locations 1 and 2, even though the distance between them is not too far. Specifically, the average annual wind speed at site 1 was 1.5 times higher than at site 2. The maximum wind speed recorded at site 1 reached up to 16 m/s during this period, while speeds above 10 m/s were rare at site 2. The standard deviation of wind speed at site 2 was quite high, approximately 1.5 times higher than at site 1. A large scatter was observed at site 2 at this hub height, taking both small and large wind speed values. The standard deviation has increased continuously as the wind speed increases, sometimes even reaching nearly 3 m/s when the wind speed here reaches 10 m/s. In contrast, the dispersion at site 1 was relatively small, even at wind speed values of around 10 m/s. This difference is likely due to the varying terrain between the two locations.

Regarding the turbulence characteristics, the two sites exhibit different turbulence intensities, placing them in two different classes. Similar to the standard deviation, a large dispersion is observed at site 2, especially at wind speeds less than 5 m/s. However, observations also recorded many cases when the flow at this site was only slightly disturbed, indicated by several turbulence intensity values of approximately 0.1. In contrast, the turbulence observations at site 1 appear more positive, especially for wind speed values above the threshold of 7 m/s. The scattering level recorded was quite small, especially this scattering at wind speeds above 7 m/s only fluctuating around 0.1. It also means that site 2 has high turbulence characteristics, while turbulence characteristics at site 1 are quite low. This is believed to be due to the difference in terrain conditions at two measuring stations on Coto Island. Site 2 was quite close to a residential area, while location 1 was far from the urban area and on top of a low hill. These obstacles have also been considered one of the causes affecting the wind direction at location 2, increasing the complexity of turbulence intensity here. Turbulence intensity increases with increasing roughness length and decreases with altitude [9, 10]. Additionally, horizontal velocity variances are often found in complex terrain and thus result in higher turbulence intensity.

Despite these differences, these indexes have still been within the acceptable limits of the IEC 61400-1 standard for wind turbine design, with site 1 classified as turbulence Class C and site 2 as Class A. However, the challenging wind and terrain conditions should be carefully considered for wind power production, as these severe turbulence values could affect turbine performance at either location.

5. CONCLUSIONS

This work adds to the existing knowledge of how terrain impacts on offshore wind conditions, specifically the wind conditions on Coto Island in Vietnam. The results show that the complexity of terrain can exacerbate the problems of wind conditions, particularly with regard to standard deviation and turbulence intensity.

Stakeholders may find these Coto Island studies helpful in considering and implementing these models on other islands. The analysis of standard deviation and disturbance intensity in this study also contributes to determining the possibility of wind power production on this island.

The evidence from this study suggests that Coto Island has great potential in exploiting and using wind energy. However, wind energy exploitation here is impacted negatively by turbulent conditions and topographical heterogeneity. However, this study is limited due to the lack of measuring stations at other important locations on the island. The addition of measuring stations and related studies is necessary to provide a comprehensive view of the wind potential on Coto Island.

For this reason, these findings provide valuable information for future research on the wind conditions on Vietnam islands, including areas with higher topographic complexity. Further research on the impact of topographic conditions on wind power production would also be of great benefit in determining the potential for wind power development and expansion in remote areas in Vietnam.

ACKNOWLEDGEMENTS

The authors wish to thank the Institute of Science and Technology for Energy and Environment (ISTEE), Vietnam Academy of Science and Technology (VAST) for supporting to this study.

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