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ARTICLE

A Validated Assessment of Off-Shore Wind Energy Potential in Southern Vietnam Using Bias-Corrected ERA5 Data

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ABSTRACT

Vietnam's Power Development Plan 8 (PDP8) identifies offshore wind power as a key pillar for carbon neutrality and long-term energy security. Realizing this potential requires accurate, high-resolution resource assessments to guide strategic planning and de-risk multi-billion-dollar investments. This study delivers the first scientifically validated, bias-corrected estimate of offshore wind energy potential in the strategic maritime region from Vung Tau to Ca Mau. Using the ERA5 reanalysis dataset (2011–2020), we apply a robust, monthly, component-wise regression method calibrated against long-term in-situ observations from two island stations. Raw, unvalidated ERA5 data are shown to grossly overestimate the resource, with mean annual Wind Power Density (WPD) inflated by more than 1.5–2.0 fold. After correction, data quality improves substantially: the overall Mean Bias Error (MBE) is reduced from 3.91 m/s to 0.38 m/s (by 90%), and the Root Mean Square Error (RMSE) drops by 75.0% (from 4.35 m/s to 1.09 m/s). The corrected dataset yields a realistic and conservative mean annual WPD at a 100-meter hub height of 90–290 W/m², compared with an unrealistic 140–460 W/m² from the raw data. These results provide a scientifically grounded baseline for Vietnam's near-shore wind

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resource, clarify the limitations of using coastal-based observations to represent offshore conditions, and underscore the need for future offshore measurement campaigns to further reduce uncertainties and support the sustainable implementation of PDP8.

Keywords: Offshore Wind Energy; Bias Correction Validation; Wind Power Density; Renewable Energy Policy; Power Development Plan 8 (PDP8)

1. Introduction

The global energy paradigm is undergoing an unprecedented transformation, driven by the imperatives of climate change mitigation and rising energy demands [1,2]. Central to this transition is the deployment of renewable technologies, particularly offshore wind, which offers utility-scale power capable of decarbonizing economies [3–5]. While the theoretical potential is vast, the technical realization of offshore projects shares similarities with complex infrastructure and fluid transport systems, where experimental investigation and precise modeling are prerequisites for success. Recent studies in fluid mechanics and infrastructure engineering have demonstrated that rigorous experimental validation is essential to minimize errors in numerical models, whether in water vapor transportation pipelines [6,7] or hydrodynamic performance of intake structures [8]. Similarly, in the context of resource management, accurate data input is critical for optimizing system performance and sustainability [9–12].

Vietnam, with over 3200 km of coastline, is poised to become a significant player in the global offshore wind sector [13]. The National Power Development Plan 8 (PDP8) sets an ambitious target of at least 6 GW of offshore wind capacity by 2030 [13,14]. Major assessments, such as the World Bank's "Offshore Wind Roadmap," estimate Vietnam's technical potential to be among the highest in Southeast Asia [15]. However, translating high-level potential into economically viable projects requires granular, accurate regional data [16].

The maritime region from Vung Tau to Ca Mau is of strategic significance due to its proximity to economic hubs and favorable depth for fixed-bottom turbines [17]. However, relying on unvalidated reanalysis data like ERA5 carries risks of significant bias, a challenge well-documented in both atmospheric and hydrodynamic modeling [18,19]. Just as numerical methods in civil engineering require calibration against physical benchmarks to ensure structural integrity [20], wind resource assessment demands local validation to avoid financial disasters.

Despite the region's importance, a specific, validated assessment remains missing. While national-scale assessments and studies of other regions exist, a high-resolution, validated resource assessment for this specific strategic corridor is absent, creating a critical blind spot for PDP8 implementation. This study addresses this gap by: (1) quantifying biases in ERA5 data using in-situ observations; (2) applying a robust bias correction methodology verified by statistical metrics; and (3) generating realistic WPD maps. By aligning our validation approach with rigorous standards seen in broader infrastructure and engineering fields [21,22], we provide a conservative, scientifically-grounded tool for policymakers.

2. Materials and Methods

2.1. Study Area

The geographical focus of this study is the offshore marine area extending from Vung Tau to Ca Mau in southern Vietnam, delineated by latitudes from 8°0'0"N to 10°6'0"N and longitudes from 103°37'0"E to 106°39'0"E (**Figure 1**). This region forms a critical intersection between the southern part of the South China Sea (East Sea) and the Gulf of Thailand. The area's climate is predominantly governed by the Asian monsoon system, resulting in two distinct seasons: the northeast (winter) monsoon from approximately November to April, characterized by stronger, cooler, and drier winds, and the southwest (summer) monsoon from May to October, which brings warmer, more humid, and generally weaker winds [13]. This pronounced seasonality is a key determinant of the temporal variability of wind resources. The region includes the strategically important archipelagos of Con Dao and Tho Chu. These islands, part of Vietnam's exclusive economic zone, not only influence local wind patterns but also serve as vital locations for meteorological monitoring. The broader sea area is crucial for Vietnam's economy, supporting major shipping lanes, fishing industries, and oil and gas exploration, making it a prime candidate for synergistic development with offshore wind energy [12,23].

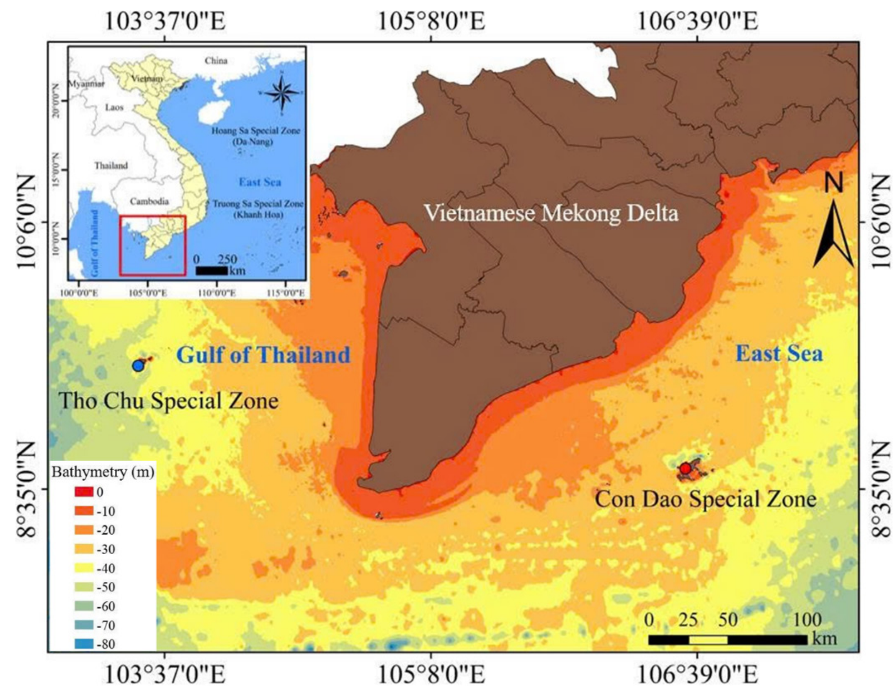


Figure 1. Map of the study area showing the geographical extent from Vung Tau to Ca Mau and the locations of the Con Dao and Tho Chu wind observation stations used for validation.

2.2. Data Sources

ERA5 Reanalysis Data: We utilized hourly time series of 10-meter zonal (U) and meridional (V) wind components from the ERA5 dataset, at a native spatial resolution of 0.25° × 0.25°, for the 10-year period from January 1, 2011, to December 31, 2020.

In-Situ Observational Data: To validate and correct the ERA5 dataset, observational wind data were acquired from two long-term meteorological stations on Con Dao and Tho Chu Islands (**Figure 1**). This data covers the same 10-year period with a 3-hourly temporal resolution and underwent rigorous quality control.

2.3. Bias Correction Methodology

2.3.1. Rationale and Framework

Initial comparisons revealed a significant, systematic overestimation of wind speeds by the raw ERA5 data. To address this, a statistical correction framework based on robust linear regression was developed. A robust linear regression model (M-estimator with a Huber loss function) was chosen over standard Ordinary Least Squares (OLS) due to its reduced sensitivity to outliers, which are common in meteorological observations and can disproportionately influence model parameters [24,25]. The Iteratively Reweighted Least Squares (IRLS) algorithm was used for implementation. Crucially, the correction was applied independently to the zonal (U) and meridional (V) components for each calendar month to preserve the directional integrity of the wind field while accounting for strong seasonality.

Crucially, the correction was applied independently to the zonal (U) and meridional (V) wind components to preserve the directional integrity of the wind field [26]. Furthermore, to account for strong seasonality, a separate set of correction coefficients was derived for each calendar month. The linear model for each month m is:

$$U_{corr} = a_u^{(m)} + b_u^{(m)} u^{ERA5} \quad (1)$$

$$V = a_v^{(m)} + b_v^{(m)} v^{ERA5} + \varepsilon_v \quad (2)$$

2.3.2. Methodological Validation

The efficacy of the framework was rigorously confirmed through a Leave-One-Month-Out (LOMO) cross-validation. This procedure demonstrated a significant improvement in data quality. The overall Mean Bias Error (MBE) was reduced from 3.91 m/s to 0.38 m/s (a 90% reduction). Crucially, the Root Mean Square Error (RMSE) was reduced by 75.0%, dropping from 4.35 m/s to 1.09 m/s. Evaluating the reduction in RMSE is a standard practice in assessing model fidelity, similar to methodologies applied in hydrodynamic performance studies and civil engineering numerical modeling [8,20]. The achieved RMSE of 1.09 m/s indicates a high level of agreement between the corrected dataset and in-situ observations.

2.4. Vertical Extrapolation and Wind Power Density (WPD) Calculation

To assess the wind resource at a typical turbine hub height, the bias-corrected 10-meter wind speeds (WS_corr) were vertically extrapolated to 100 m using the power-law profile [27]:

$$V_{100}(t) = V_{10,corr}(t)\left(\frac{100}{10}\right)^{\alpha_m} \quad (3)$$

where a standard wind shear exponent of $\alpha = 0.3$ was adopted for this offshore study [28]. The Wind Power Density (WPD), representing the available power per unit area, was then calculated using the formula:

$$WPD_m = \frac{1}{2}\overline{\rho(t)V_{100}(t)^3} \approx \frac{1}{2}\rho_0\overline{V_{100}(t)^3} \quad (4)$$

where the overbar denotes the temporal average of the cubed 100-meter wind speed for month m, and ρ_0 is the standard air density, assumed to be 1.225 kg/m^3. This calculation was applied to every grid point in the study area to produce high-resolution maps of the wind resource.

3. Results

3.1. Spatiotemporal Distribution of Corrected Wind Resources

The bias correction resulted in a substantial recalibration of the estimated wind resources. **Figure 2** shows that raw ERA5 data (**Figure 2a,c**) suggests a high-potential resource, with mean annual wind speeds of 5.0 to 7.8 m/s. However, after correction (**Figure 2b,d**), the estimated speeds are substantially lower, falling within a more realistic and conservative range of 4.0 to 6.3 m/s. In the corrected maps, the values near the validation sites of Con Dao and Tho Chu are now grounded in the 2.0–2.5 m/s range. A key feature retained is the clear spatial gradient, indicating that wind speeds generally increase further away from landmasses.

This stark difference translates into a dramatic reduction in the estimated WPD (**Figure 3**). The WPD from raw data is unrealistically high (140–460 W/m^2). In contrast, the bias-corrected WPD is significantly reduced to a more scientifically-grounded and conservative range of 90–290 W/m^2 for the mean annual value. This represents a reduction factor of more than 1.5–2.0 fold, highlighting the profound impact of the bias correction.

3.2. Seasonal Variability of Wind Resources

The corrected wind resource exhibits a distinct seasonal pattern, driven by the regional monsoon climate. **Figure 4** shows the distribution of monthly WPD at 100 m for the Con Dao and Tho Chu station locations. The analysis reveals a clear bimodal distribution. The primary peak occurs during the northeast monsoon, with the highest values observed in December (approximately 320 W/m^2 at Con Dao).

A secondary, lower peak occurs during the southwest monsoon, with WPD values reaching around 208 W/m^2 in July. The inter-monsoon periods (April–May and October) are characterized by much calmer conditions and significantly lower wind power potential.

Table 1 provides a detailed breakdown of the monthly WPD values at several extracted grid points within the study area. The table quantitatively confirms the stark contrast between the raw and robust-corrected estimates across all months and locations. For example, at grid point 1 in December, the raw WPD is 970.6 W/m², which is reduced by a factor of over 1.4 to a mere 700.6 W/m² after correction. This quantitatively proves the severe overestimation of the unvalidated data. The corrected annual mean WPD across these near-shore points is modest, ranging from 245.1 to 273.1 W/m².

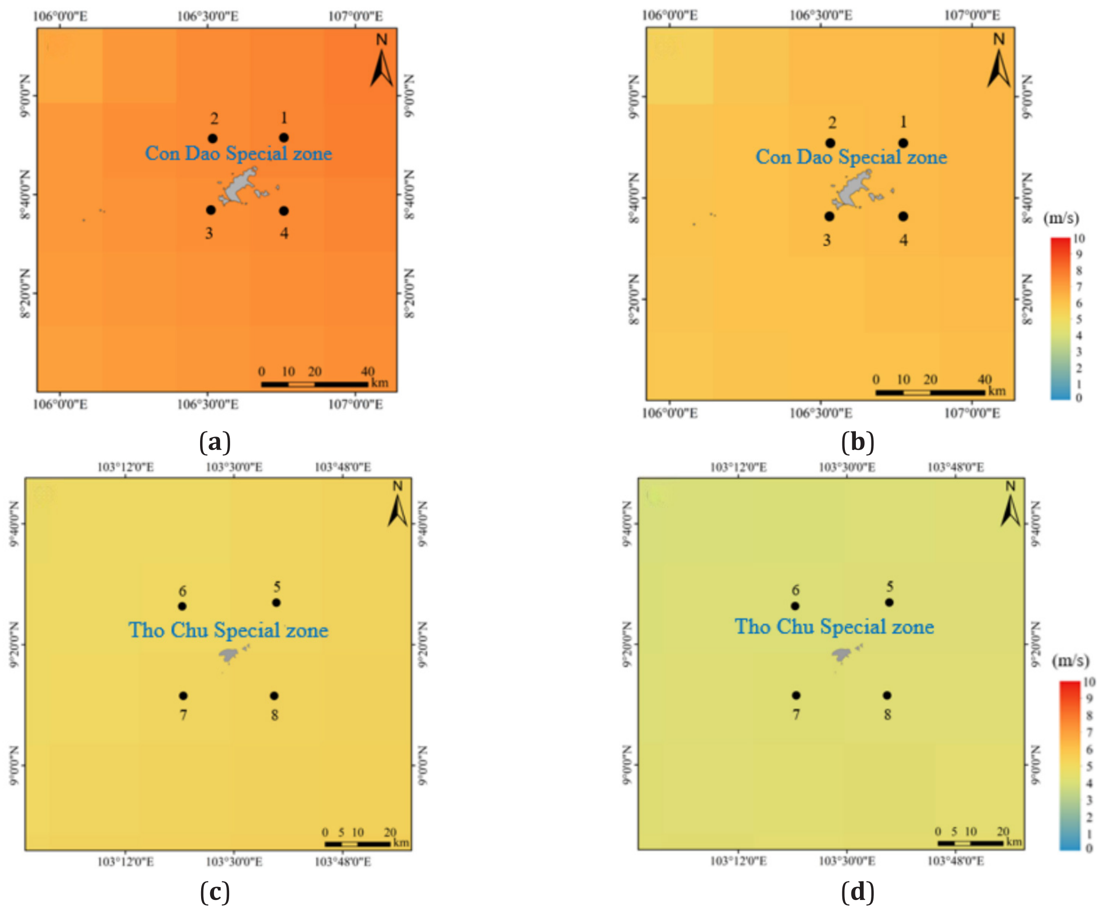


Figure 2. Mean annual wind speed (m/s) at 100 m derived from: (**a**) raw ERA5; (**b**) bias-corrected ERA5 around the Con Dao Islands area; (**c**) raw ERA5; (**d**) bias-corrected ERA5 around the Tho Chu Islands area.

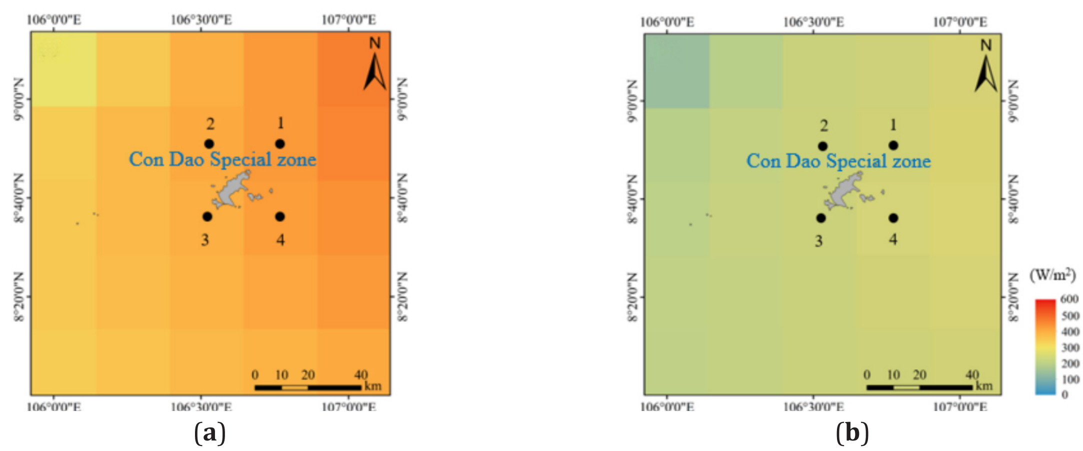
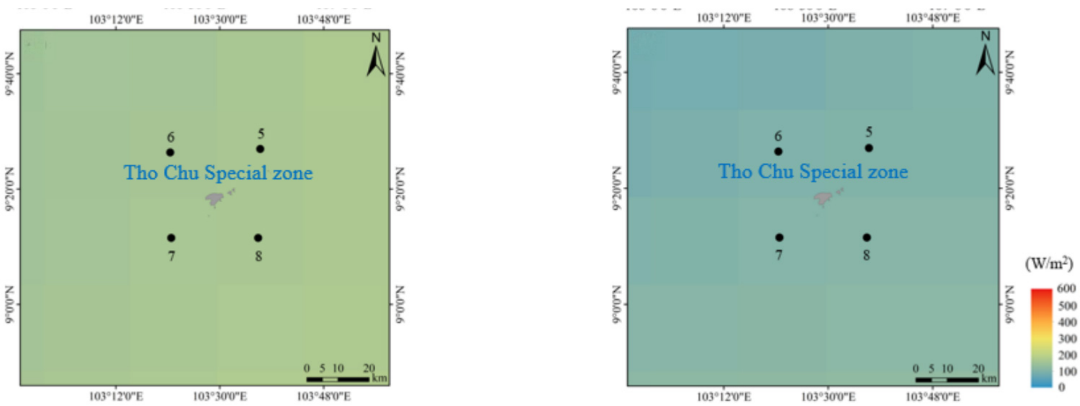
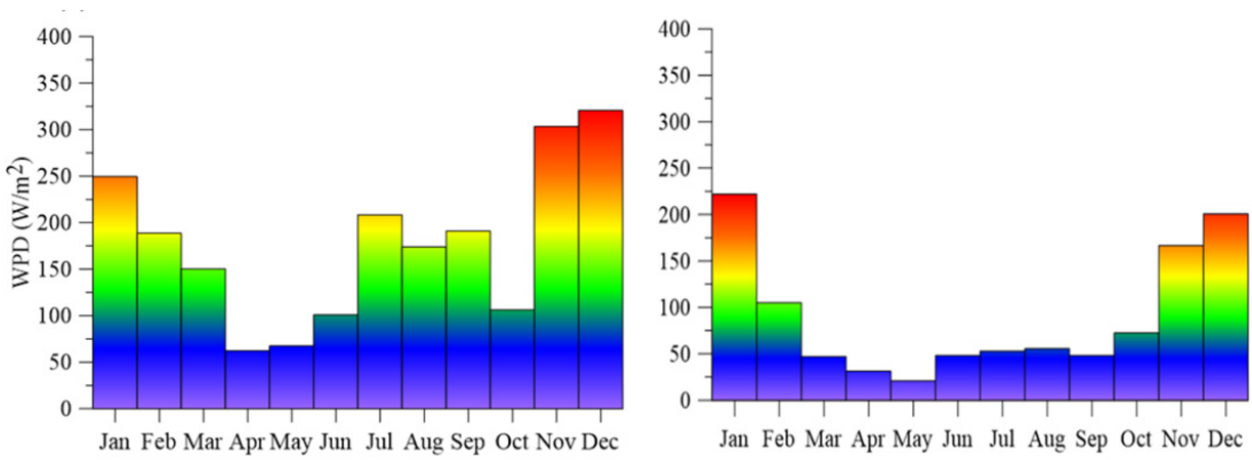


Figure 3. *Cont.*



(c) (d)

Figure 3. Mean annual wind power density (WPD, W/m^2) at 100 m derived from: (**a**) raw ERA5; (**b**) bias-corrected ERA5 around the Con Dao Island area; (**c**) raw ERA5; (**d**) bias-corrected ERA5 around the Tho Chu Island area.



(a) (b)

Figure 4. Distribution of monthly wind power density (WPD) at 100 m for: (**a**) the Con Dao station location; (**b**) the Tho Chu station location, based on the bias-corrected dataset.

Table 1. Distribution of monthly wind power density (W/m^2) at extracted grid points at 100 m, showing a comparison between raw ERA5 and bias-corrected ERA5 values.

ID	WPD	Jan	Fed	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	WPDmrc	573.9	275.0	105.0	39.0	83.2	98.5	236.0	277.8	252.5	88.0	548.0	700.6	273.1
	WPDmr	847.1	408.6	176.2	77.1	150.9	253.1	368.9	653.7	436.7	199.5	780.4	970.6	443.6
2	WPDmrc	538.7	255.8	89.4	34.0	71.0	84.0	199.9	235.5	216.0	71.0	478.9	667.3	245.1
	WPDmr	817.4	388.9	161.6	73.0	138.8	232.0	335.7	593.5	400.8	173.0	757.3	1005.0	423.1
3	WPDmrc	525.6	255.3	93.0	36.2	75.8	85.9	202.6	241.9	218.0	77.3	446.7	514.5	231.1
	WPDmr	774.7	381.8	166.0	76.3	147.5	236.3	338.9	609.5	404.0	187.6	725.6	826.2	406.2
4	WPDmrc	558.1	264.7	94.5	36.0	75.1	88.7	211.3	248.9	228.3	75.1	512.0	716.8	259.1
	WPDmr	855.9	403.6	167.8	75.8	144.0	240.8	348.4	615.9	416.0	179.5	778.4	1043.0	439.1
5	WPDmrc	287.4	187.4	37.7	24.4	19.8	60.4	67.6	63.9	37.3	41.0	102.6	290.9	101.7
	WPDmr	339.5	147.5	68.4	39.5	110.3	138.6	162.0	201.0	230.8	60.6	130.6	346.3	164.6
6	WPDmrc	280.6	189.3	37.4	24.8	19.4	55.4	63.2	62.8	36.3	40.2	104.3	251.6	97.1
	WPDmr	324.8	150.0	67.5	40.1	107.8	126.3	150.8	191.6	223.1	59.4	132.3	328.7	158.5
7	WPDmrc	305.4	196.2	38.8	26.0	19.1	54.2	56.7	56.6	32.1	46.0	117.0	305.9	104.5
	WPDmr	375.6	162.9	70.5	42.3	106.3	123.5	134.1	150.8	195.8	68.8	142.8	349.1	160.2
8	WPDmrc	309.3	196.5	39.6	26.0	19.7	57.9	61.3	58.1	33.5	47.2	115.7	312.1	106.4
	WPDmr	384.7	164.5	72.4	42.2	109.3	132.2	145.2	160.1	204.6	70.6	141.9	352.6	165.0

Note: WPDmrc-wind power density mean_robust corrected; WPDmr-wind power density mean_raw.

4. Discussion

The findings of this study provide a critical, scientifically-grounded recalibration of the near-shore offshore wind potential in Southern Vietnam, with significant implications for policy, planning, and investment.

4.1. The Criticality of Localized Bias Correction

The most striking result is the enormous discrepancy between estimates from raw and bias-corrected data. The reduction in mean annual WPD from the 140–460 W/m² range to 90–290 W/m² is a fundamental re-evaluation. This underscores the significant risks of using unvalidated global reanalysis data for regional planning [29]. An overestimation factor of more than 1.5–2.0 confirms that without localized correction, assessments can be dangerously misleading. Our corrected values present a more conservative, yet far more reliable, baseline for future feasibility studies.

4.2. Detailed Comparison with National Assessments

Our findings can be compared with the 2022 MONRE technical report and the World Bank's "Offshore Wind Roadmap" [30,31]. The MONRE report, based on WRF model simulations, estimates mean wind speeds at 100 m to be 7–10 m/s and WPD between 300–700 W/m² for this region. These figures align remarkably well with our findings from the raw ERA5 data (5.0–7.8 m/s and 140–460 W/m²), suggesting that uncorrected mesoscale and global models may share similar overestimation biases. This detailed comparison underscores our central thesis: while general patterns are captured by various models, localized, in-situ-based bias correction is absolutely essential for obtaining realistic quantitative estimates.

A more direct comparison can be made using the extrapolated observational data presented in the MONRE report for our validation sites. At 100 m, the report's extrapolated observations suggest a mean annual wind speed of approximately 6.5–7.0 m/s for Con Dao and 5.5–6.0 m/s for Tho Chu. These values are significantly higher than our bias-corrected estimates (2.0–2.5 m/s near the sites). This discrepancy likely stems from different methodological approaches: the MONRE report appears to directly extrapolate surface observations, which can propagate measurement uncertainties, whereas our study uses observations to correct a spatially continuous reanalysis field before extrapolation. Our method aims to produce a spatially consistent and validated field rather than a simple point extrapolation.

On a monthly basis, the seasonal patterns are consistent. Both our study and the MONRE report identify a clear peak during the northeast monsoon (December-January) and a secondary peak in the southwest monsoon (July–August). For instance, the MONRE observational data shows a peak wind speed of ~8 m/s in December at Con Dao, while our corrected data yields a peak WPD in the same month. However, the absolute magnitudes differ substantially. The MONRE WRF model indicates WPD values of 600–900 W/m² for this region in winter, whereas our corrected results show a more modest peak of 320 W/m². This detailed comparison underscores our central thesis: while the general patterns are captured by various models, localized, in-situ-based bias correction is absolutely essential for obtaining realistic quantitative estimates of wind power potential.

4.3. Implications for Policy and Grid Integration

Our corrected annual WPD values are modest compared to world-class regions like the North Sea, which can exceed 500 W/m² [32,33]. However, even this modest resource can play a valuable strategic role. The strong seasonality is a crucial piece of information for grid integration. The peak wind resource during the northeast monsoon (December–February) coincides with Vietnam's dry season, when hydropower generation is at its lowest. This complementary relationship suggests offshore wind could be a valuable asset for enhancing energy system stability and reducing reliance on fossil fuels for seasonal balancing [34,35]. These findings have direct implications for PDP8. While the national 6 GW target is ambitious, our results suggest that achieving it cost-effectively may require focusing on zones further offshore where the WPD is higher, or accepting lower capacity factors for near-shore projects. The modest WPD will directly impact project economics, likely leading to a higher Levelized Cost of Energy (LCOE) than previously estimated [36].

4.4. Uncertainties and Limitations

While this study significantly enhances accuracy, it is important to acknowledge remaining uncertainties and contextualize the model performance.

Residual Error and Model Fidelity: The remaining RMSE of 1.09 m/s represents the inherent, non-systematic uncertainty in the model. In the broader context of engineering and infrastructure simulation, achieving an RMSE within this range is often considered acceptable for feasibility studies, though "allowable" thresholds vary by application. As discussed in *Innovative Infrastructure Solutions*, the allowable RMSE serves as a critical benchmark for validating numerical models against experimental data; deviations must be minimized to ensure design reliability [37]. Our reduction of RMSE by 75% aligns with the rigorous validation standards advocated in recent studies on hydrodynamic and offshore structures [8,22], confirming that the bias-corrected dataset is sufficiently robust for strategic planning, even if micro-siting requires further precision.

Spatial Representativeness: The correction coefficients were derived from only two island stations. Their applicability may diminish with increasing distance from the coast. Similar to challenges faced in modeling large-scale water transportation systems where local friction coefficients vary [7], atmospheric dynamics far offshore may differ from coastal observations. The higher wind speeds observed further offshore in our corrected maps should thus be interpreted with caution.

Vertical Extrapolation: The use of a constant wind shear exponent ($\alpha = 0.3$) is a key simplification. In reality, α varies with atmospheric stability [38,39]. A sensitivity analysis suggests that varying α could alter the hub-height WPD by approximately ±15–20%. This highlights the need for advanced profiling, similar to how advanced particle image velocimetry is used to resolve complex flow fields in hydraulic engineering [8].

5. Conclusions

This study has provided the first comprehensive, bias-corrected assessment of the offshore wind resource in the strategic maritime region from Vung Tau to Ca Mau. Our primary finding is that unvalidated ERA5 reanalysis data is profoundly misleading, overestimating the mean annual Wind Power Density by a factor of over 1.5–2.0 fold.

Through rigorous validation, we demonstrated that our bias correction method significantly improves data reliability, reducing the RMSE from 4.35 m/s to 1.09 m/s. This validated dataset presents a realistic and conservative potential: the near-shore mean annual WPD at a 100m hub height is estimated to be in the range of 90–290 W/m^2. While modest, this resource exhibits a strong, beneficial seasonality that complements Vietnam's existing power portfolio.

The path to sustainably harnessing Vietnam's offshore wind potential requires a steadfast commitment to rigorous, data-driven science. Moving beyond optimistic, unvalidated estimates is essential. To address the limitations identified and reduce the residual RMSE further, future work must prioritize targeted offshore measurement campaigns. Specifically, the deployment of floating LiDAR systems is critical to accurately measure vertical wind shear profiles and validate spatial extrapolation [40,41]. By adopting stringent validation standards common in advanced infrastructure and fluid-mechanics experiments [8] and best practices from recent offshore wind-resource assessment studies [42,43], Vietnam can build a robust, de-risked, and successful offshore wind industry under PDP8.

Author Contributions

Conceptualization, H.T.T.M. and T.A.D.; methodology, T.T.N.; software, M.T.B.; validation, T.T.N. and M.T.B.; formal analysis, H.T.T.M.; investigation, H.T.T.M.; writing—original draft preparation, H.T.T.M.; writing—review and editing, T.A.D.; visualization, M.T.B.; supervision, T.A.D. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, Truong An Dang, upon reasonablerequest.

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Conflicts of Interest

The authors declare they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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