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A Study on Wind-Wind Energy for Electric Vehicles Charging Station on the Southern Highway of Thailand

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ABSTRACT

This comprehensive research delves into the energy landscape of Southern Thailand. Leveraging sophisticated tools such as WAsP, the study conducts an exhaustive examination of the wind energy potential, taking into account the intricate geographical and climatic conditions of the region. The research meticulously fulfils its objectives, encompassing the assessment of wind potential based on multifaceted criteria, the development of a comprehensive wind atlas and an intricate simulation of annual energy production. Moving beyond the technical realm, the study extends its scope to scrutinize the proposed electric vehicle charging stations from an economic perspective. This facet of the research aligns with global sustainability initiatives, adding a practical and applicable dimension to the findings. A notable outcome of the study is the strategic identification of five charging stations in the southern provinces of Thailand, namely Songkhla, Prachuap Khiri Khan, Surat Thani, Chumphon and Narathiwat. This strategic placement is poised to play a pivotal role in supporting the escalating prevalence of electric vehicles in the region. The research pioneering in its nature, contributing significantly to the ongoing global transition towards renewable energy sources. The findings furnish foundational insights that contribute to both academic discourse and practical applications, not only in southern Thailand but also as a valuable reference for similar endeavours globally. In terms of specific values, the study conducts a detailed analysis of the average mean wind speed, wind power density and other critical parameters. For instance, the average mean wind speed values for Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani are reported as 2.88 m/s, 4.18 m/s, 3.21 m/s, 5.43 m/s and 2.16 m/s, respectively. Similarly, the average wind power density values for the mentioned locations are 77 W/m², 225 W/m², 139 W/m², 370 W/m² and 31 W/m², respectively. These metrics, along with other detailed statistical analyses, contribute to a nuanced understanding of the hybrid energy potential in southern Thailand.

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1. Introduction

Energy is a linchpin for societal progress, impacting economic, cultural and political aspects by meeting various needs. However, the growing demand for energy and the environmental consequences of traditional sources requires a shift towards sustainability. Thailand, which mainly depends on natural gas, follows this global trend with initiatives such as the Renewable Energy Development Plan (AEDP) 2015 [29], which includes wind power targets. In 2018, the AEDP was updated to increase wind power targets to 1,485 MW. Despite these efforts, the country's limited renewable energy potential remains a significant challenge. Thailand aims to replace 30% of fossil fuel use by 2036 and wind power capacity has expanded from 507.00 MW in 2016 to 627.80 MW in 2017 and 1,102.82 MW in 2018 [8].

Various researchers have investigated wind energy potential in specific locations. Adaramola *et al.,* [1] analysed Weibull parameters related to seasonal and annual wind speeds at a height of 12 meters in Ghana's coastal regions, finding wind speeds ranging from 3.88 to 5.30 m/s, which suggests that wind turbines with a cut-in speed below 3 m/s and rated wind speeds between 9 to 11 m/s are suitable for wind farms. Boudia *et al.,* [7] assessed wind power potential along Algeria's northwest coast using the Wind Atlas Analysis and Application Program (WAsP), analysing wind speed, annual energy production (AEP) and cost estimates for different wind turbine models. Their study at a 10-meter height found that Oran had an annual mean wind speed of 4.2 m/s and a power density of 129 W/m², with AEP estimates ranging from 2.822 GWh at Site 3 using the Nordex N50 model to 12.425 GWh at Site 2 with the Vestas V90 turbine, identifying Site 2 as the most promising location with an electricity cost of $0.0181 per kWh and a capacity factor of 51.36%. Wang *et al.,* [30] studied wind statistics and power potential at four locations in China, analysing wind speed data from 2003 to 2012, which showed consistent wind conditions for stable wind farm operations, with mean wind speeds recorded at 7.2495 m/s, 7.2336 m/s, 7.7769 m/s and 8.0943 m/s at 10 meters. Mohammadi *et al.,* [23] compared six methods—graphical (GP), empirical Justus (EMJ), empirical Lysen (EML), energy pattern factor (EPF), maximum likelihood (ML) and modified maximum likelihood (MML)—for determining Weibull parameters and daily power density in southern Alberta, Canada, finding that the EMJ, EML, EPF and ML methods provided the most accurate estimates. Sharma *et al.,* [27] assessed wind resources in Fiji's southern island, estimating AEP values for different locations, where Suva recorded a maximum wind speed of 6.38 m/s at 34 meters above sea level (ASL), while Kadavu recorded 3.88 m/s at the same height and power analysis with the Vestas V27 225 kW turbine suggested a payback period of 9.12 years and a capacity factor of 22.77%. Dayal *et al.,* [12] identified optimal locations for utility-scale wind farms in Fiji using the WAsP program with the Vergnet 275-kW turbine model, showing net AEP values of 43 GWh for Rakiraki, 42 GWh for Nabouwalu and 37 GWh for Udu, with capacity factors between 0.42 and 0.48 and wind farm efficiencies of 97–98%. Chaitammachok *et al.,* [9] conducted a wind potential assessment in Songkhla, Thailand, using the WAsP program with the Bonus 300 kW MkIII, Bonus 1.3 MW and PowerWind 56 900 kW turbine models, revealing that Laem Son-On had the highest AEP at 132.485 MWh, 344.419 MWh and 332.597 MWh for the three turbines, while Hua Khao exhibited even higher values of 225.284 MWh, 586.303 MWh and 540.045 MWh. Economic analysis identified the Bonus 300 kW turbine as the most cost-effective option, with a Levelized Cost of Electricity (LCOE) of $142.43/MWh at Laem Son-On and $83.76/MWh at Hua Khao, positioning Hua Khao as the most viable site for wind farm installations.

This research focuses on southern Thailand, a region offering a unique confluence of geographical and climatic conditions conducive to hybrid energy solutions, specifically the integration of wind [2,6,17,18] and another energy source. Despite the worldwide surge in renewable energy adoption, there exists a research gap concerning the hybrid energy potential in Southern Thailand. This study aims to address this void by employing advanced tools such as WAsP and GIS to comprehensively analyse wind resources [3,9,19,20]. The research objectives span from evaluating hybrid potential based on land suitability and economic viability to creating a Hybrid Atlas using sophisticated mapping tools. Additionally, the study seeks to simulate annual energy production, providing insights into the performance of selected sites. The significance of this research lies in its contribution to understanding the unique conditions and potential of hybrid energy in Southern Thailand. The study provides a comprehensive framework for data collection, analysis, simulation and graphical representation, offering foundational insights for both research bodies and practical applications in the region. Moreover, given the increasing prevalence of electric vehicles in Southern Thailand, identifying suitable and economical charging station sites becomes imperative. This novel study pioneers a detailed examination of the hybrid energy potential in the region, filling a critical gap in existing literature and contributing to the global transition towards sustainable and renewable energy sources.

Furthermore, as part of the evolving energy landscape in Southern Thailand, it follows the main routes by car from central to Southern Thailand (using Highway No. 4,41,42 and 43) Click or tap here to enter text. via routes in 5 provinces. These charging stations, namely Songkhla, Prachuap Khiri Khan, Surat Thani, Chumphon and Narathiwat (Figure 1), will play a crucial role in supporting the increasing prevalence of electric vehicles in the region. By strategically locating these charging stations, the aim is to provide convenient and accessible infrastructure for electric vehicle users, fostering a more sustainable and environmentally friendly transportation system. This addition aligns with the broader goals of the research, extending its impact beyond the realm of energy production and into the practical facilitation of green transportation alternatives in Southern Thailand.

While limited research on wind energy resources has been conducted in selected locations in Thailand [10,25], the country has not fully tapped into its wind power potential. Chen *et al.,* [11] emphasized the importance of avoiding inaccurate data to prevent misleading potential estimates during wind resource assessment. The WAsP program emerges as a powerful tool for wind energy modelling and simulation, employing the Weibull distribution for resource assessment and analysis.

Notably, a gap in the literature exists concerning wind energy potential in southwestern Thailand. This study addresses this gap by utilizing the WAsP program to comprehensively assess wind energy potential through an in-depth investigation of local wind resources. The study conducts statistical analyses of wind speed and direction and applies the WAsP program to calculate wind speed and wind power density. Finally, the Bonus 300kW Mk III wind turbine is employed to estimate annual energy production suitable for the installation of charging stations for electric vehicles.

Fig. 1. Map Showing the main routes by car from central to Southern Thailand (using Highway No. 4,41,42 and 43) [4,5]

2. Methodology

2.1 On-Site Wind Measurement

This study examines wind data collected over four years from five weather observation stations operated by the Thai Meteorological Department (TMD) [28]. These stations consistently measure wind parameters at a height of 10 meters above ground level (AGL) using precision instruments such as anemometers, wind vanes, barometers and thermometers. The instruments are mounted on meteorological mast towers and record data through automated data loggers, ensuring high accuracy and reliability. The specifications of these measurement tools, obtained from the TMD, are detailed in Table 1 [20].

Table 1
Tool specifications obtained from the Thai Meteorological Department [20]

Equipment	Sensor Type	Instrument Range	Accuracy	Height (AGL)
Anemometer	Ultrasonic sensor	0–75 m/s	±2%	10 m
Wind vane	Ultrasonic sensor	0–360°	±2%	
Thermometer	Platinum resistance element	−40 °C to 50 °C	±0.3 °C	
Barometer	Digital	800–1100 hPa	±0.2	
Relative humidity	Thin film	0–100% RH	±2% RH	
Rain gauge	Tumbling cup	0–100 mm/h	2%	

2.2 Measurement Locations

Five sites were strategically selected for wind measurements based on geographical and climatic conditions favourable for wind energy development.

Each site was evaluated for its wind energy potential, considering land suitability, proximity to infrastructure and prevailing wind conditions. Table 2 provides specific details for each weather observation station, including geographical coordinates, measurement period and the total amount of accepted data. The data for all stations are captured at 10-minute intervals, adhering to the international standard. Notably, all sites have data availability exceeding 85%.

Table 2
Details four met mast stations in Songkhla, Thailand [28]

Station name	Latitude (°)	Longitude (°)	UTM Easting	UTM Northing	UTM Zone	Roughness Length/RL(m)
Chumphon	10.6	99.1	510938.85	1171753.58	47P	0.2
Prachuap Khiri Khan	11.6	99.6	565411.28	1282391.91	47P	1.5
Surat Thani	9.1	99.1	510988.37	1005909.45	47P	0.2
Songkhla	6.94	100.410	655771.12	767347.71	47N	0.1
Narathiwat	6.4	101.8	809762.11	708265.97	47N	0.3

Note: Elevation and roughness data were imported, compared with the Global Wind Atlas (GWA) [14] and created using coordinates in WAsP Map Editor 12 [16,24]

2.3 Wind Data Collection

To accurately assess wind energy potential, comprehensive data collection and analysis were conducted. The following sections outline the key aspects of wind data acquisition, including measurement duration and recorded parameters.

2.3.1 Measurement duration

Wind data were collected over a five-year period (2018–2022) using data from the TMD [28]. According to the coordinates in Table 2, The data was recorded at 10-minute intervals, ensuring high temporal resolution for analysis. All wind measurements were taken at a standardized height of 10 meters above ground level (AGL) to maintain consistency across all locations. By systematically organizing and analysing wind data, this study aims to provide a robust foundation for assessing wind energy potential in Southern Thailand.

2.3.2 Recorded parameters from Thai Meteorological Department (TMD)

This study recorded multiple meteorological parameters crucial for wind energy assessment, including timestamp (time of data recording), wind speed (m/s) at 10 meters, wind direction (°) at 10 meters, temperature (°C), precipitation (mm), atmospheric pressure (hPa) and humidity (%). These parameters collectively provide a detailed dataset for evaluating wind characteristics and assessing the feasibility of wind power generation, ensuring accurate analysis for potential energy production and site suitability.

2.4 The Weibull Distribution Function

In the realm of reliability engineering, a commonly employed lifetime distribution is the Weibull distribution, characterized by two parameters. This probability distribution is extensively utilized in calculations to delineate the wind speed histogram. Notably, the Weibull probability distribution finds prominent application in the analysis of wind characteristics, with tools such as WAsP leveraging its features for in-depth studies [26]. The probability distribution function (PDF) used in wind speed analysis can be determined by Eq. (1) [22]:

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^{k}}, k > 0, v > 0, A > 1 \quad (1)$$

The notation used in the context of the Weibull distribution involves the probability density function (PDF) denoted as $f(v)$, where 'v' represents the observed wind speed. In this representation, 'A' is employed to signify the Weibull scale parameter, measured in meters per second (m/s) and 'k' denotes the dimensionless Weibull shape parameter.

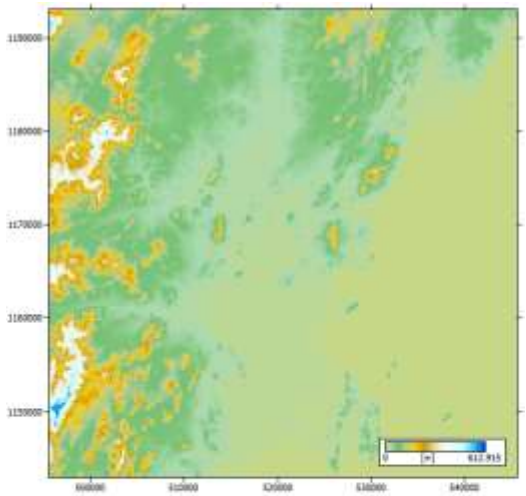
The Weibull shape parameter 'k' assumes values within the range of 1 to 3. This parameter plays a crucial role in characterizing wind behaviour based on speed. When 'k' is small, it indicates significant variations in wind speed, reflecting a more erratic pattern. Conversely, larger values of 'k' suggest a more consistent and stable wind speed, highlighting a relatively uniform behaviour in wind variables [21,26].

2.5 Simulation Models

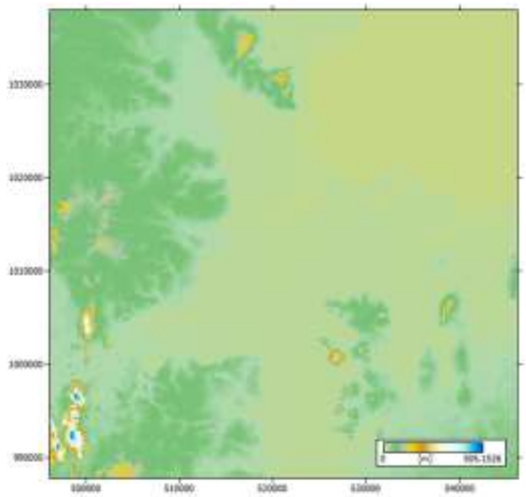
In this research, near-surface wind observations serve as input for WAsP Climate Analyst 3.1. Elevation and surface roughness maps were created using WAsP Map Editor 12.3. Subsequently, WAsP 12.6 was employed to calculate wind speed, power density, annual energy production (AEP) and capacity factor (CF) for each study site [19].

WAsP, a computer-based simulation program developed at Denmark Technical University (DTU), is a widely employed tool for conducting systematic investigations related to regional wind atlas development, wind resource assessment and optimal site selection. This software plays a crucial role in the analysis and understanding of wind patterns, making it instrumental in various applications within the field of wind energy [15]. It creates wind resource maps and estimates the spatial distribution patterns of wind by utilizing wind data Click or tap here to enter text.

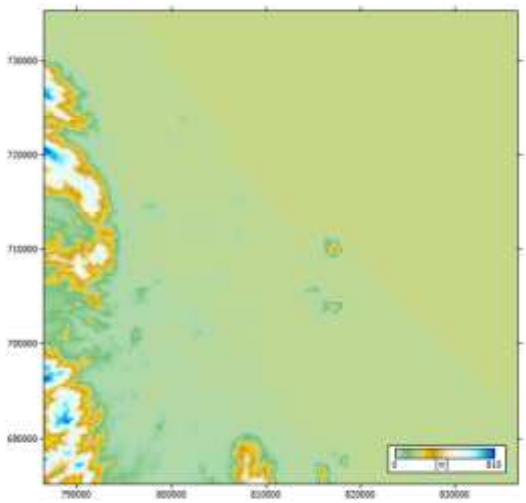
The WAsP Climate Analyst 3.1 is a separate tool found in WAsP. In this study, it analyses the raw wind data of five met mast stations obtained from TMD to estimate the wind climatology in the form of Weibull distribution function and wind rose. Similarly, WAsP Map Editor 12.3 is separate program inside WAsP package. It creates elevation and surface roughness maps by utilizing the Databases of Global Wind Atlas (GWA) Map Warehouse. WAsP 12.6 simulation estimates the wind speed and power density. For power analysis, Bonus 300kW Mk III is used to calculate the AEP. This wind turbine model has been found secured in tropical cyclone especially in extreme wind conditions [12]. The elevation and surface roughness maps of the study area are displayed in Figure 2 and Figure 3.



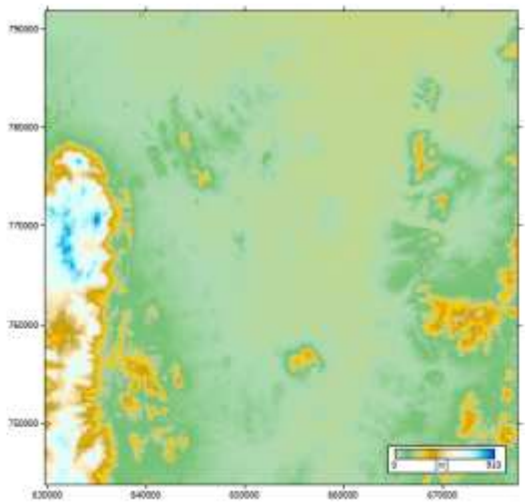
(a) Surat Thani



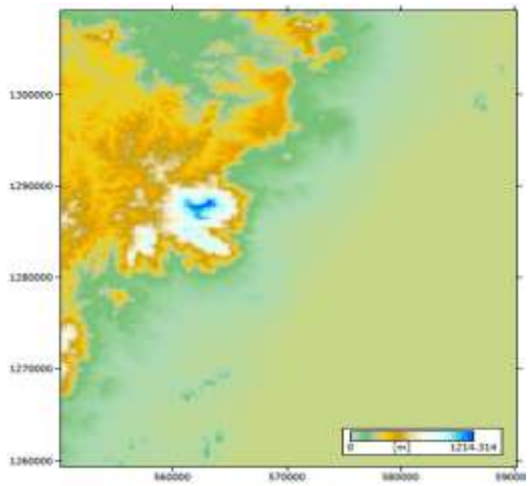
(b) Narathiwat



(c) Songkhla



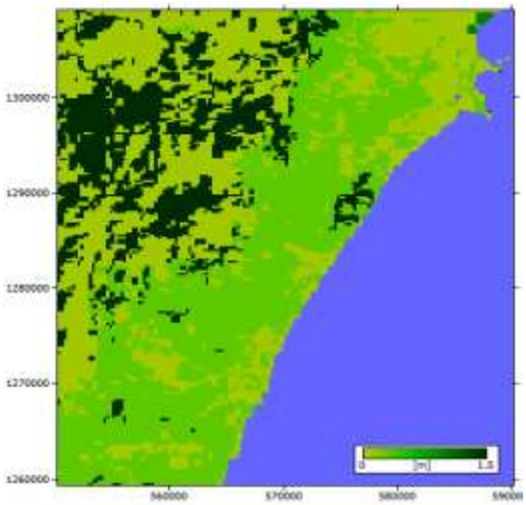
(d) Chumphon



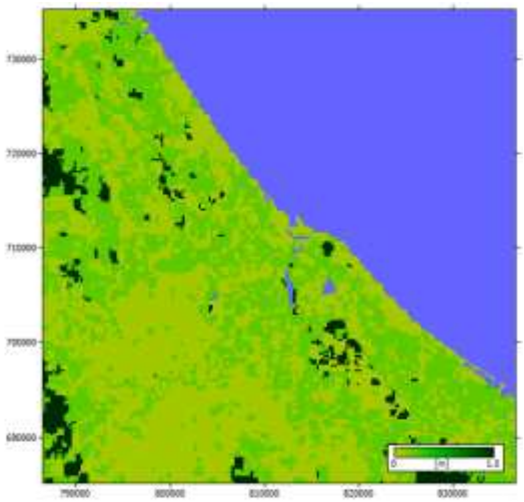
(e) Prachuap Khiri Khan

Fig. 2. Elevation maps of the study area (a) Surat Thani (b) Narathiwat (c) Songkhla (d) Chumphon (e) Prachuap Khiri Khan

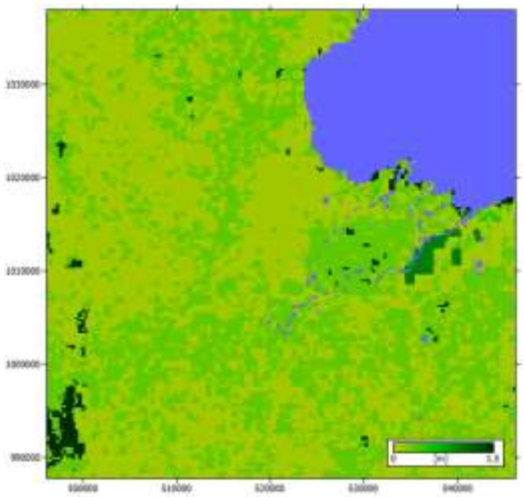
The resource grid within the WAsP domain facilitates the generation of wind maps for the five weather observing stations. In evaluating wind energy potential, three key parameters hold significance: wind speed, power density and annual energy production (AEP). Wind speed, for example, serves as a crucial determinant in assessing whether the speed at a specific site is sufficient to drive the selected wind generator for electricity generation. Wind power density indicates the potential power available in the wind resource, while annual energy production quantifies the wind energy potential at a specific site for a selected wind generator within the resource grid domain. Together, these parameters provide a comprehensive understanding of the potential for harnessing wind energy at the analysed sites.



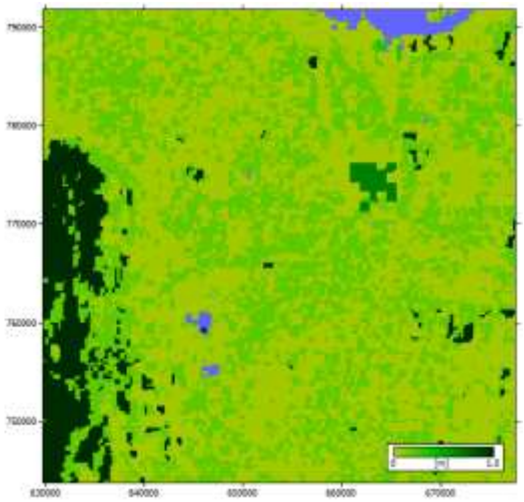
(a) Surat Thani



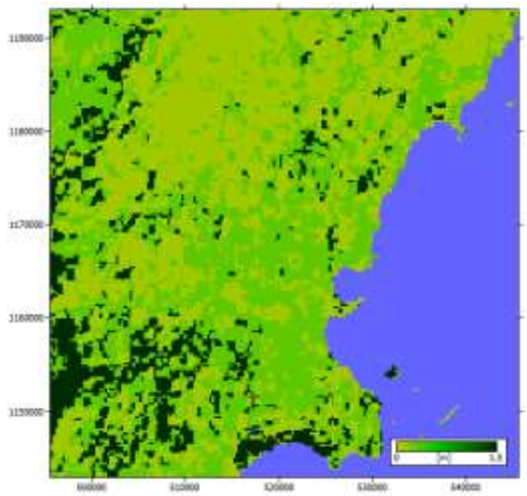
(b) Narathiwat



(c) Songkhla



(d) Chumphon



(e) Prachuap Khiri Khan

Fig. 3. Surface roughness maps of the study area (a) Surat Thani (b) Narathiwat (c) Songkhla (d) Chumphon (e) Prachuap Khiri Khan

2.6 Statistical Analysis of Wind Energy Potential in Southern Thailand

To evaluate the differences in wind energy potential across the five locations (Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani), a one-way Analysis of Variance (ANOVA) was employed. The ANOVA test assessed whether the mean values of key wind energy metrics (Wind Speed) significantly varied between locations.

Figure 4 illustrates the Analysis of Variance (ANOVA) method [13]. ANOVA can be implemented using either one-way or two-way methods. One-way ANOVA is applicable to a single independent variable, while two-way ANOVA can handle two or more independent variables. In this study, we employ one-way ANOVA, considering only one independent variable, "Day," for analysing monthly data variance. This independent variable applies to both:

i. between the months, where variance is observed on different days
ii. comparisons within month, where variance is observed on the same days/repeated days.

The implementation involves three steps, as described below.

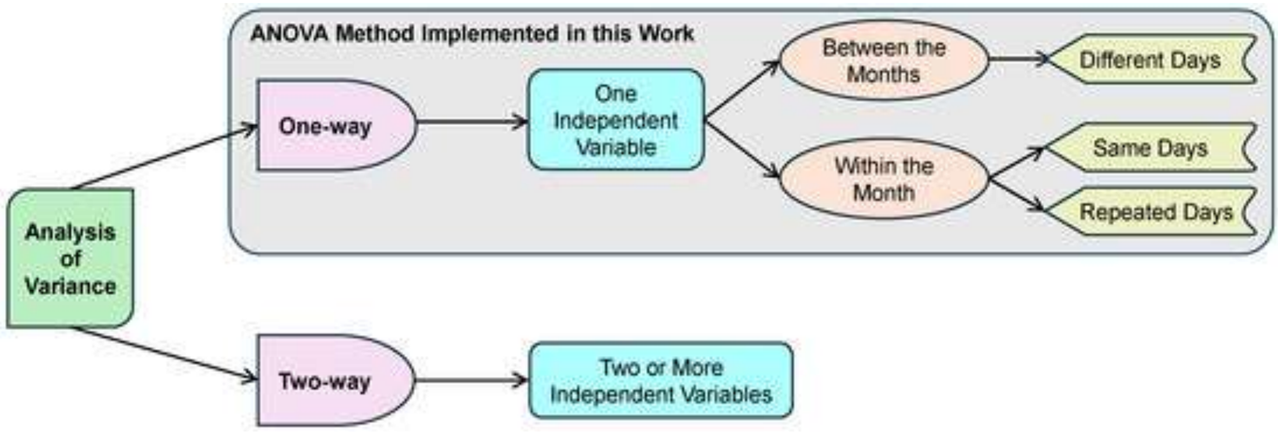


Fig. 4. Types of ANOVA [13]

2.7 ANOVA Approach

The one-way ANOVA was applied using "Site" as the single independent variable. The focus was primarily on the wind speed parameter due to its critical role in wind energy assessment. The methodology comprised three major steps:

i. Step 1: Finding the Variance:
The process begins by creating a dataset from the provided table and loading it into a Data Frame for easy analysis. Basic statistics for each metric are calculated to understand the data distribution. Next, simulated data is generated based on the means and assumed standard deviations for each metric. This involves creating multiple samples per site to simulate real-world observations. The generated data is then grouped by site and one-way ANOVA is performed to find the variance in the data. The F-statistics and p-value are calculated to determine if there are significant differences between the groups.
ii. Step 2: Extracting F and p Values:
In this step, the F-test and p-value are extracted from the ANOVA results. The F-test measures the ratio of variances between the groups, while the p-value indicates the statistical significance of the results. A p-value of less than 0.05 suggests that there is a significant difference between the groups [13].
iii. Step 3: Tukey HSD Post Hoc Test
If the ANOVA results indicate a significant difference, a Tukey Honest Significant Difference (HSD) post hoc test is performed to identify which specific groups differ from each other. The Tukey HSD test compares all possible pairs of group means and reduces the likelihood of incorrectly identifying significant differences [13].

These steps outline the methodology for performing variance analysis using one-way ANOVA and subsequent post hoc testing to identify significant differences between groups.

3. Results

This section presents a detailed analysis of the resource maps from five weather observation stations and examines the potential for future deployment of onshore wind energy.

3.1 Statistical Analysis of Wind Speed and Direction

Figure 5 to Figure 9 illustrate the Weibull distribution using wind rose diagrams and wind speed frequency distributions for the five meteorological mast stations, presented in an omni-directional format. Understanding the Weibull distribution in terms of wind rose and wind speed frequency is crucial for optimizing wind energy harnessing. To maximize wind energy capture, it is essential to orient the turbine in a perpendicular position to the prevailing wind direction. Therefore, understanding the Weibull distribution, as illustrated in these figures, is crucial for effective turbine placement and energy production planning.

The statistical analysis of the data reveals that north-east winds are the most frequent in Songkhla province, underscoring the importance of considering directional wind patterns for optimal wind energy utilization in the region.

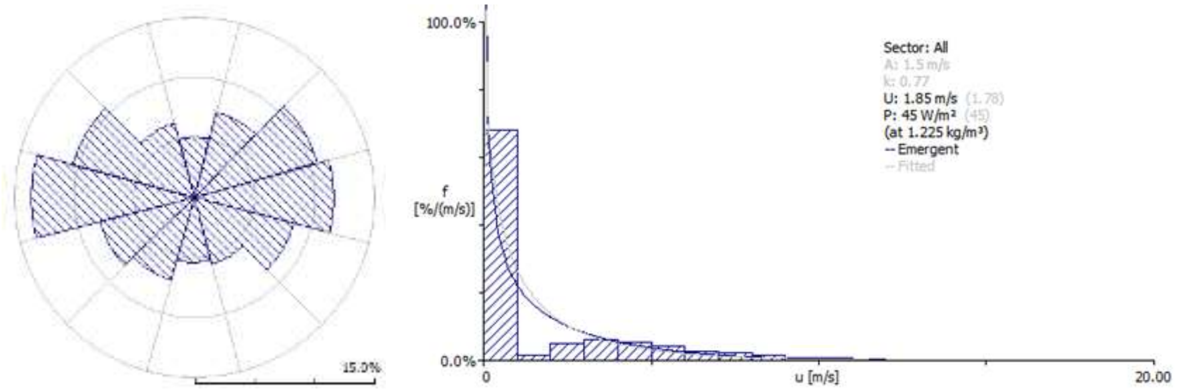


Fig. 5. Wind rose and speed frequency histogram for Chumphon

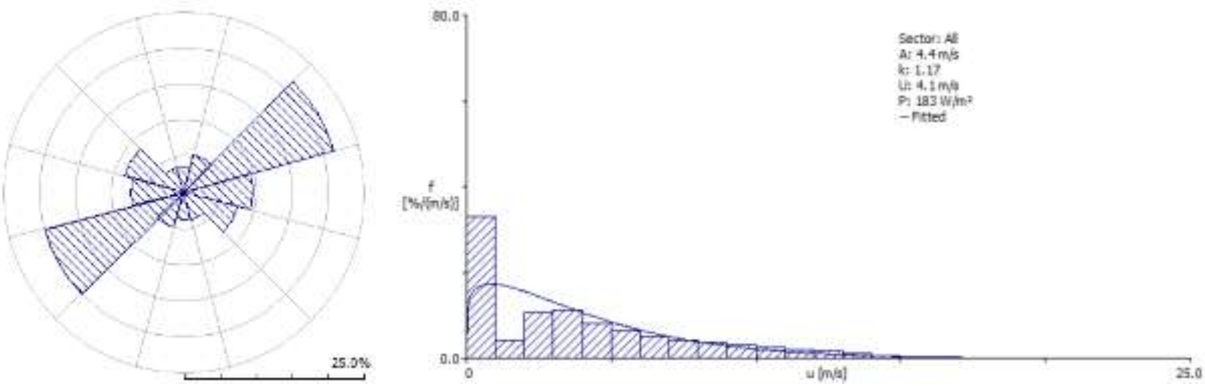


Fig. 6. Wind rose and speed frequency histogram for Songkhla

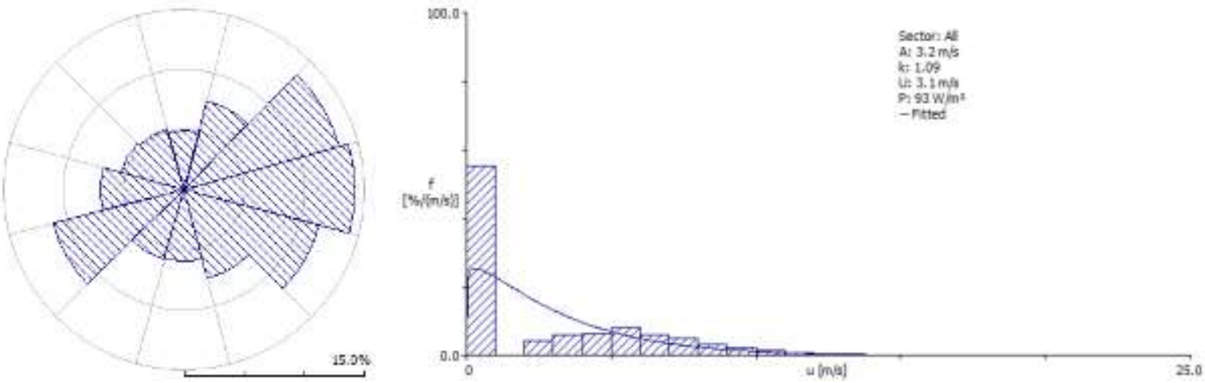


Fig. 7. Wind rose and speed frequency histogram for Narathiwat

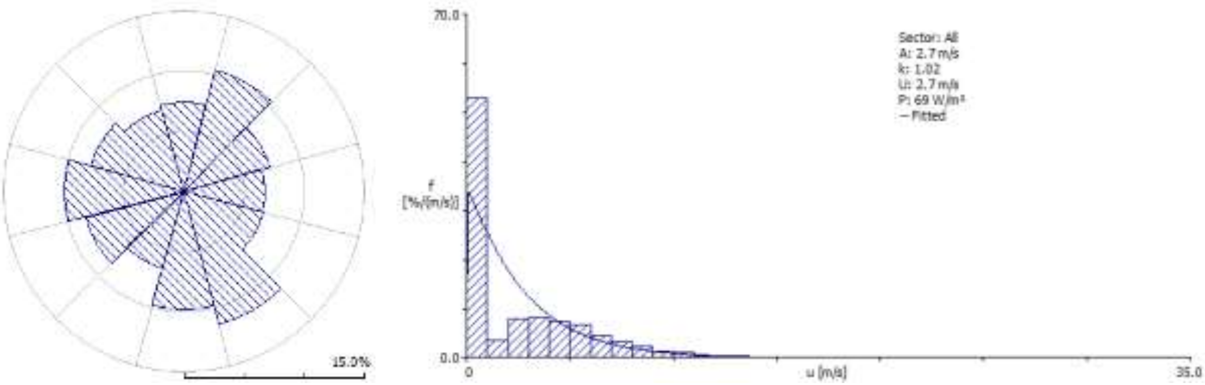


Fig. 8. Wind rose and speed frequency histogram for Prachuap Khiri Khan

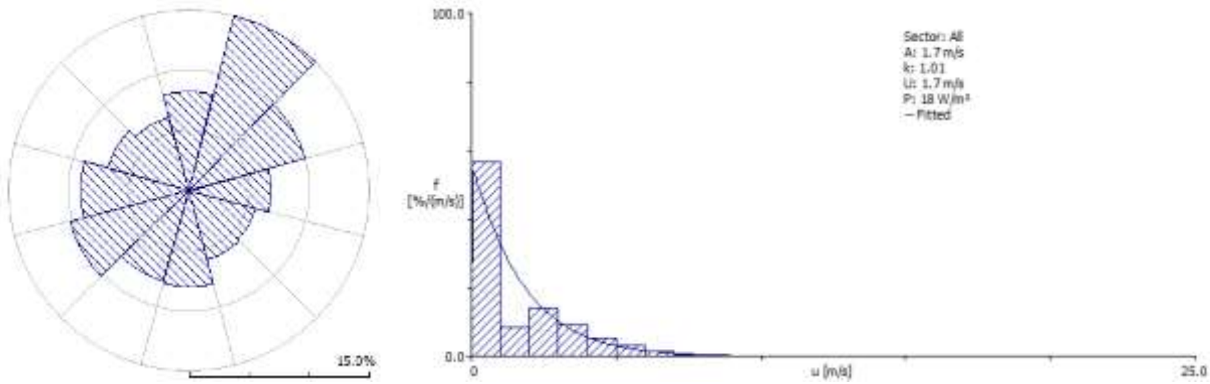


Fig. 9. Wind rose and speed frequency histogram for Surat Thani

The wind potential analysis at 10 meters above ground reveals that Songkhla exhibits the highest wind energy potential, with the greatest scale parameter (c = 4.4 m/s), average wind speed (U = 4.1 m/s) and power density (P = 183 W/m²), indicating strong and consistent wind resources. Narathiwat follows with moderate wind potential, while Prachuap Khiri Khan also shows viable characteristics. In contrast, Chumphon and Surat Thani have the lowest wind energy potential, characterized by lower scale parameters, wind speeds and especially low power densities, making them less suitable for efficient wind energy development at this height.

Table 3
Summarize wind potential at 10 meters above ground

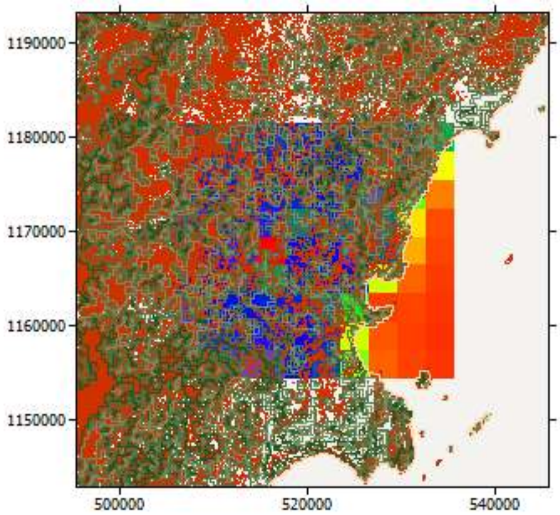
Station	Chumphon	Narathiwat	Prachuap Khiri Khan	Songkhla	Surat Thani
c is the Weibull scale parameter [m/s]	1.5	3.2	2.7	4.4	1.7
k is the Weibull shape parameter (dimensionless)	0.77	1.09	1.02	1.17	1.01
U is the average wind speed [m/s]	1.85	3.1	2.7	4.1	1.7
P is the power density [W/m^2]	45	93	69	183	18

3.2 Resource Mapping of Potential Locations

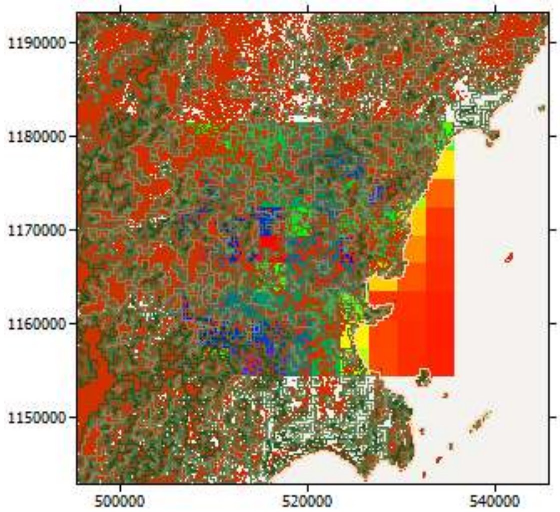
This section describes the wind energy resource mapping at selected sites in Southern highway route of Thailand which fulfil the criteria for prospective wind power generation at utility scale.

3.2.1 Chumphon

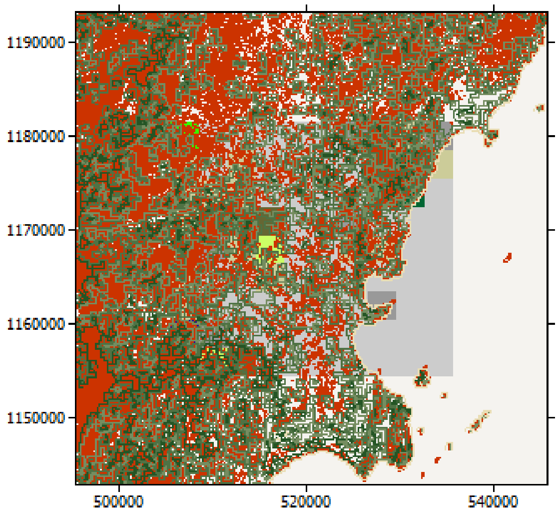
The wind turbine Bonus 300kW Mk III at 30 m hub height AGL is used to estimate wind speed, power density and AEP for Chumphon site as shown in Figure 10(a), 10(b) and 10(c).



(a) Mean wind speed



(b) Wind power density

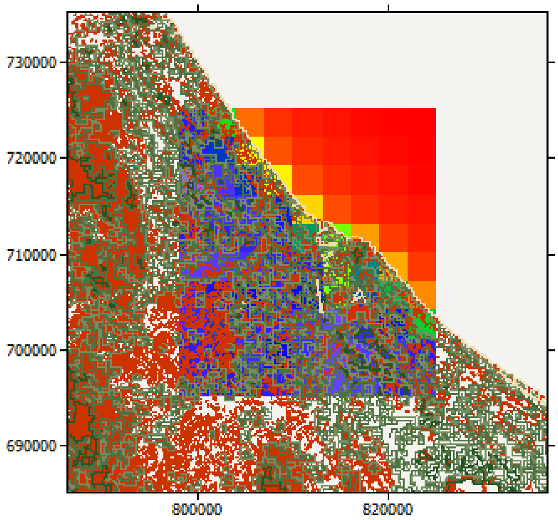


(c) Annual energy production

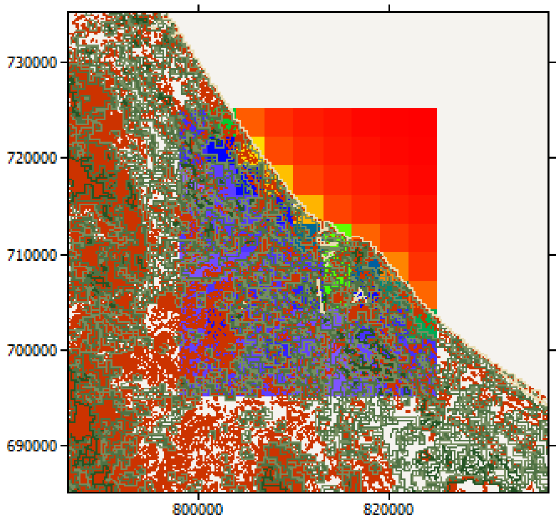
Fig. 10. (a) to (c) Mean wind speed, wind power density and annual energy production map of Chumphon

3.2.2 Narathiwat

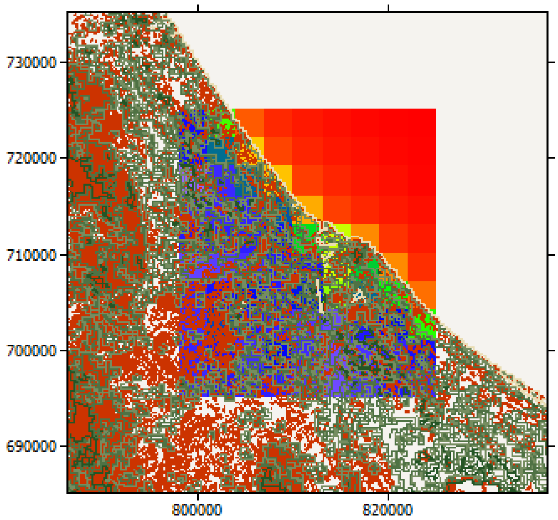
The wind turbine Bonus 300kW Mk III at 30 m hub height AGL is used to estimate wind speed, power density and AEP for Narathiwat site as shown in Figure 11(a), 11(b) and 11(c).



(a) Mean wind speed



(b) Wind power density

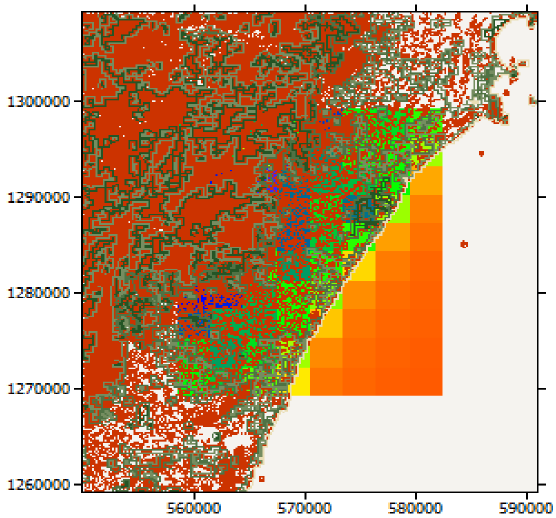


(c) Annual energy production

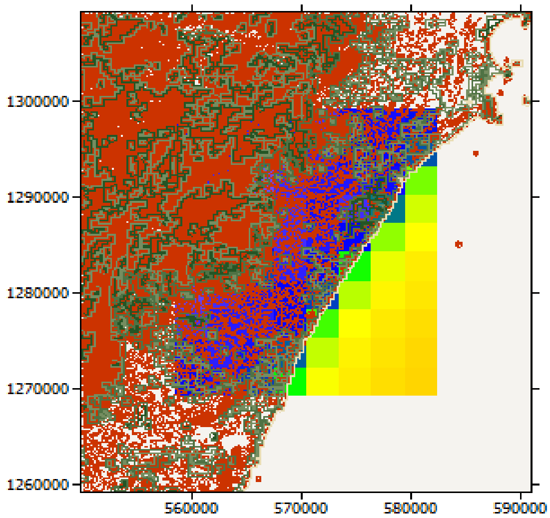
Fig. 11. (a) to (c) Mean wind speed, wind power density and annual energy production maps of Narathiwat

3.2.3 Prachuap Khiri Khan

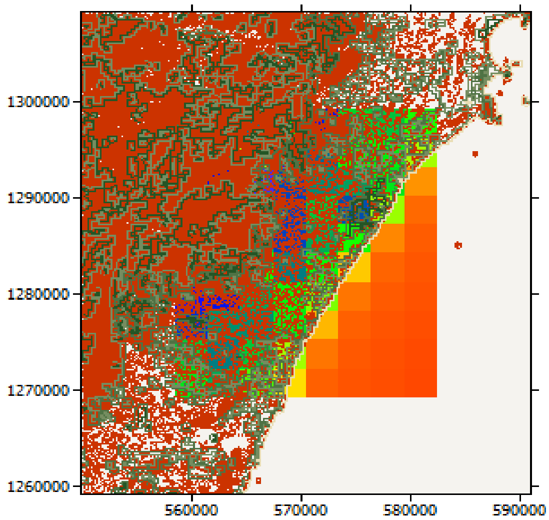
The wind turbine Bonus 300kW Mk III at 30 m hub height AGL is used to estimate wind speed, power density and AEP for Prachuap Khiri Khan site as shown in Figure 12(a), 12(b) and 12(c).



(a) Mean wind speed



(b) Wind power density



(c) Annual energy production

Fig. 12. (a) to (c) Mean wind speed, wind power density and annual energy production maps of Prachuap Khiri Khan

3.2.4 Songkhla

The wind turbine Bonus 300kW Mk III at 30 m hub height AGL is used to estimate the mean wind speed, power density and AEP for Songkhla site as shown in Figure 13(a), 13(b) and 13(c).

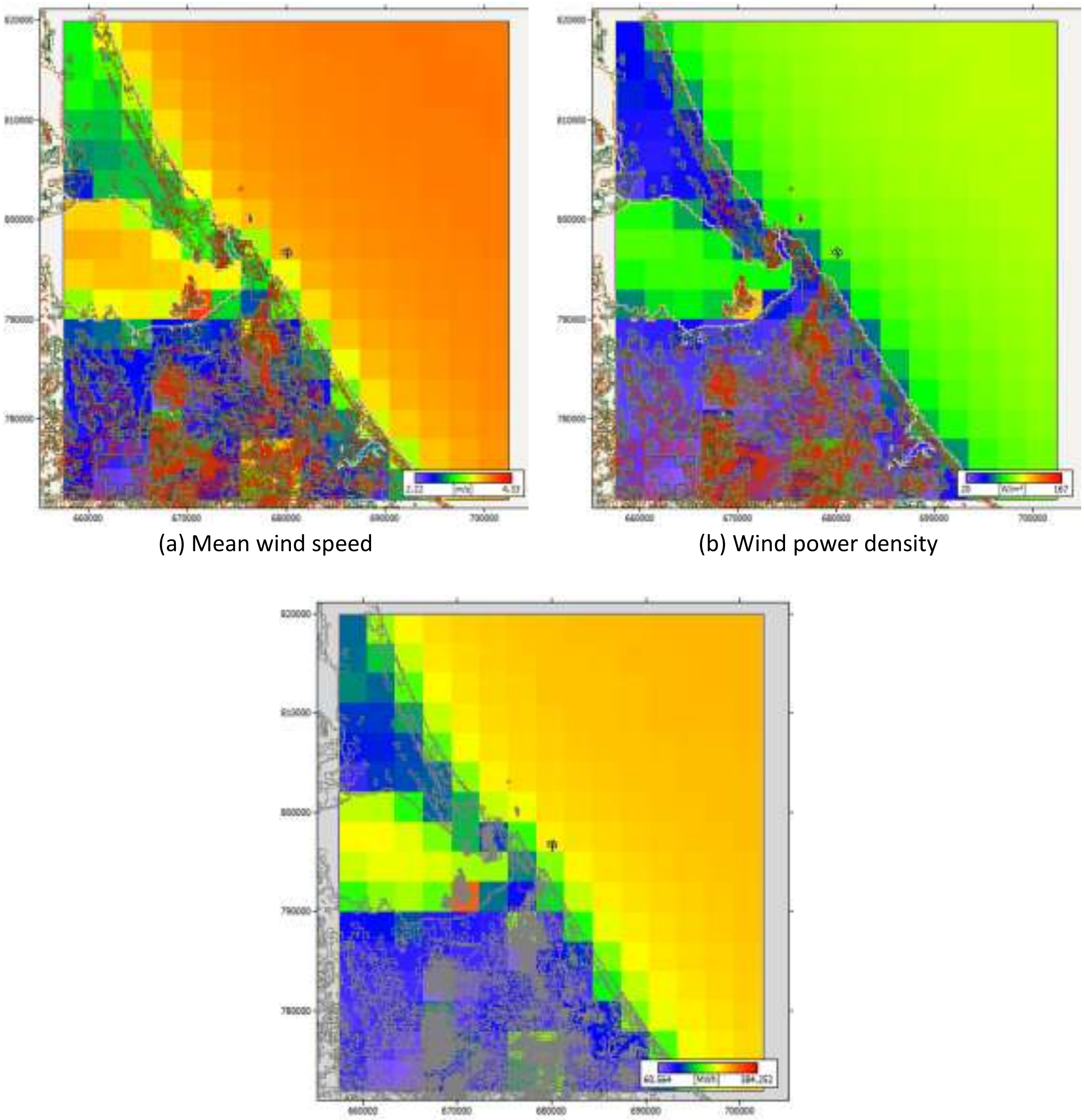
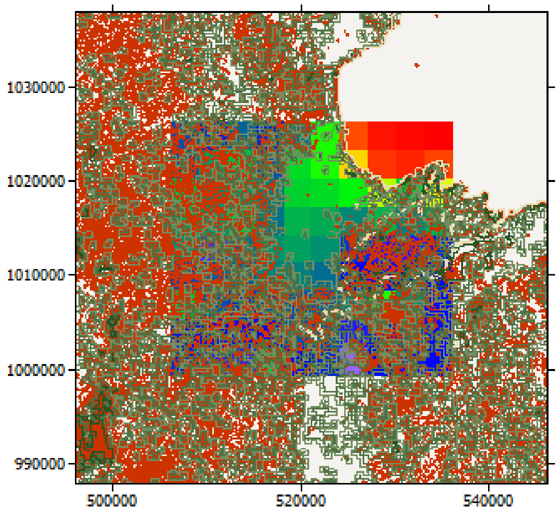

(a) Mean wind speed
(b) Wind power density
(c) Annual energy production

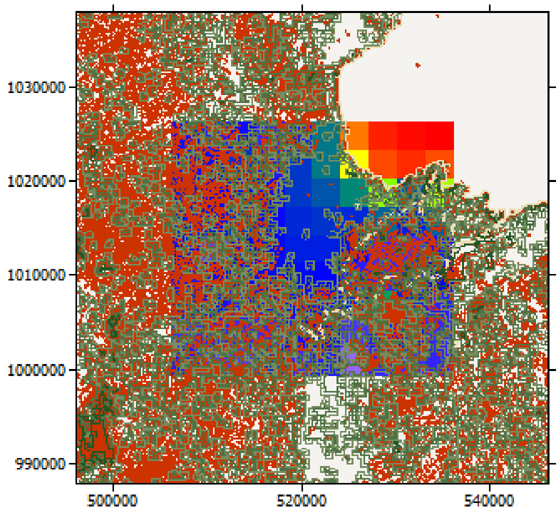
Fig. 13. (a) to (c) Mean wind speed, wind power density and annual energy production maps of Songkhla

3.2.5 Surat Thani

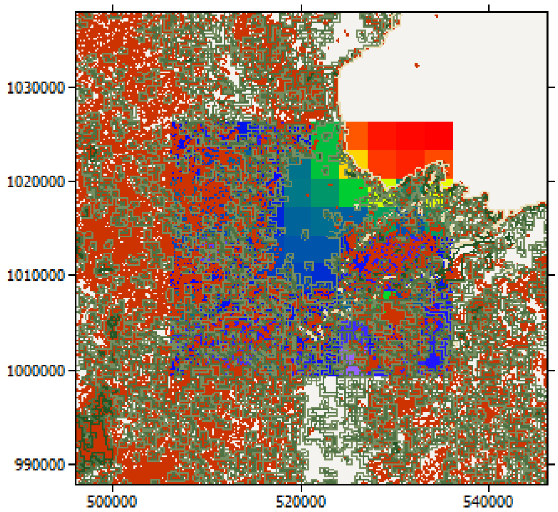
The wind turbine Bonus 300kW Mk III at 30 m hub height AGL is used to estimate the mean wind speed, power density and AEP for Surat Thani site as shown in Figure 14(a), 14(b) and 14(c).



(a) Mean wind speed



(b) Wind power density



(c) Annual energy production

Fig. 14. (a) to (c) Mean wind speed, wind power density and annual energy production maps of Surat Thani

The average wind speeds for Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani are 2.88 m/s, 4.18 m/s, 3.21 m/s, 5.43 m/s and 2.16 m/s, respectively. These average wind speed values were compared with the wind speed classification at 30 m height, as defined in the reference.

Similarly, the average wind power density for Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani values up to 77W/m², 225 W/m², 139 W/m², 370 W/m², 31 W/m²· respectively.

For power analysis, Bonus 300kW Mk III turbine's power curve and wind characteristics of each site in Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani determine average AEP of 192.889 MWh, 438.474 MWh, 237.811 MWh, 594.103 MWh, 91.878 MWh respectively.

The WAsP simulation for assessment of wind energy potential is performed at 30 m AGL. The summary of the statistical analysis performed by WAsP for five stations is given in Table 4.

Table 4
Yearly statistical analysis of the selected sites

Station	Chumphon	Narathiwat	Prachuap Khiri Khan	Songkhla	Surat Thani
Mean net AEP [MWh]	192.889	438.474	237.811	594.103	91.878
Mean wind speed [m/s]	2.88	4.18	3.21	5.43	2.16
Mean power density [W/m^2]	77	225	139	370	31
Total capacity factor [%]	7.2	16.4	8.9	22.2	3.4

In this study, the analysis of maximum wind speed, wind power density and Annual Energy Production (AEP) has identified noteworthy values at five distinct sites: Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani. The net AEP across these sites exhibits a range from 72.735 MWh to 291.691 MWh for Chumphon, 291.61 MWh to 631.640 MWh for Narathiwat, 484.858 MWh to 851.509 MWh for Prachuap Khiri Khan and 54.442 MWh to 186.209 MWh for Surat Thani.

The wind speed values, spanning from minimum to maximum, for Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani, are within the ranges of 1.99 - 3.86 m/s, 3.35 - 5.35 m/s, 1.74 - 4.71 m/s, 4.78 - 7.78 m/s and 1.82 - 2.84 m/s, respectively.

Similarly, the wind power density values, ranging from minimum to maximum, for Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani, fall within the intervals of 25 - 167 W/m^2, 109 - 406 W/m^2, 19 - 406 W/m^2, 245 - 1059 W/m^2 and 19 - 70 W/m^2, respectively. These comprehensive findings provide a detailed overview of the wind energy potential and related parameters at each of the specified locations.

3.3 Results of Statistical Analysis of Wind Energy Potential in Southern Thailand

To evaluate the differences in wind energy potential across the five locations (Chumphon, Narathiwat, Prachuap Khiri Khan, Songkhla and Surat Thani), an Analysis of Variance (ANOVA) can be applied. The ANOVA test helps determine whether the mean values of key parameters significantly differ among the five sites is given in Table 5.

Table 5
Descriptive statistics and wind speed distribution per 5 Sites

Site	Chumphon	Narathiwat	Prachuap Khiri Khan	Songkhla	Surat Thani
Number of Observations	14,598	14,593	14,598	14,597	14,599
Mean (m/s)	1.65	2.72	2.34	3.82	1.49
Standard Deviation (m/s)	2.22	3.38	3.01	3.79	1.88
Minimum (m/s)	0	0	0	0	0
Maximum (m/s)	14	22	33	22	25
Range (m/s)	14	22	33	22	25
Coefficient of Variation (%)	134.25%	124.63%	128.60%	99.25%	126.26%

3.3.1 Descriptive statistics and wind speed distribution

A detailed analysis of wind speed characteristics at the five locations revealed distinct distribution patterns:

i. Songkhla had the highest average wind speed (3.82 m/s) and the most consistent winds (lowest CV: 99.25%), with a high median and large interquartile range.
ii. Narathiwat followed with 2.72 m/s average wind speed, though it exhibited greater variability and frequent strong gusts.

iii. Prachuap Khiri Khan showed a highly skewed distribution with a lower mean (2.34 m/s) but the highest recorded wind speed (33 m/s).
iv. Chumphon and Surat Thani displayed the lowest mean speeds (1.65 and 1.49 m/s, respectively), with Surat Thani being the most stable but also featuring an extreme outlier at 25 m/s.

These findings suggest significant microclimatic differences across the sites, influenced by local topography and coastal conditions.

3.3.2 One-way ANOVA

The one-way ANOVA test returned the following results:

i. F-statistic: 1482.77
ii. p-value: 0.0000

The F-statistic and p-value indicate that the differences in wind speed across the locations are highly statistically significant.

Table 6
One-way ANOVA results (using Python library/package *statsmodels.formula.api*)

Source	df	Sum of Squares	Mean Square	F	p-value
Site (Groups)	4.0	51,376.27	12,844.07	1,482.77	0.0000
Residual	72,980.0	632,166.32	8.66		

The one-way ANOVA results clearly indicate significant variation in wind speeds among the five locations. With a very high F-statistic (1,482.77) and a p-value of 0.0000, the analysis confirms that the differences in mean wind speeds are not due to random chance. The large sum of squares between groups (51,376.27) relative to the residual variance further supports the conclusion that site location has a substantial effect on wind speed. These findings justify the need for location-specific planning in wind energy development across southern Thailand.

3.3.3 Tukey HSD post hoc test results

All ten pairwise comparisons between the five stations were statistically significant ($p < 0.05$). Notable differences include:

i. Songkhla vs Surat Thani: 2.33 m/s
ii. Chumphon vs Songkhla: 2.17 m/s
iii. Narathiwat vs Surat Thani: 1.23 m/s

Even the smallest difference (Chumphon vs Surat Thani: 0.16 m/s) was statistically significant due to the large sample size (The data was recorded at 10-minute intervals and using data five-year period (2018–2022)).

Table 7
Multiple comparison of means - Tukey HSD, FWER=0.05

group1 WS m/s at 10m	group2 WS m/s at 10m	meandiff	p-adj	95% CI lower	95% CI upper	reject
Chumphon	Narathiwat	1.0648	0.0	0.9708	1.1588	True
Chumphon	Prachuap Khiri Khan	0.6887	0.0	0.5948	0.7827	True
Chumphon	Songkhla	2.1707	0.0	2.0767	2.2647	True
Chumphon	Suratthani	-0.1642	0.0	-0.2582	-0.0703	True
Narathiwat	Prachuap Khiri Khan	-0.376	0.0	-0.4700	-0.2821	True
Narathiwat	Songkhla	1.1059	0.0	1.0119	1.1999	True
Narathiwat	Suratthani	-1.229	0.0	-1.3230	-1.1350	True
Prachuap Khiri Khan	Songkhla	1.4820	0.0	1.3880	1.5759	True
Prachuap Khiri Khan	Suratthani	-0.853	0.0	-0.9469	-0.7590	True
Songkhla	Suratthani	-2.3349	0.0	-2.4289	-2.2410	True

4. Conclusions

This research presents a comprehensive investigation aimed at addressing a critical knowledge gap regarding wind energy potential in Southern Thailand. The central focus of the study is the integration of wind energy assessment with regional geographical and climatic characteristics. By employing advanced tools such as the Wind Atlas Analysis and Application Program (WAsP), this study provides a robust, data-driven evaluation of wind energy viability across four strategic locations. The methodological framework integrates high-resolution wind analysis, geographic and topographic data and rigorous statistical techniques, including Weibull distribution modelling and ANOVA testing, to yield actionable insights for future wind energy development.

The results reveal considerable spatial variability in wind resources, with Hat Yai and Narathiwat emerging as the most promising locations due to their elevated average wind speeds, power densities and annual energy production. Conversely, locations such as Sadao and Surat Thani exhibit relatively lower wind resource potential, indicating limited feasibility for utility-scale wind energy infrastructure without further technical or environmental enhancements.

Importantly, these findings are benchmarked against international performance standards. The International Renewable Energy Agency (IRENA) defines a minimum capacity factor of 20% as the threshold for economically viable wind energy projects. This metric serves as a critical benchmark in project planning and investment evaluation:

i. Why a 20% Capacity Factor?
- Economic Viability: A capacity factor of 20% ensures sufficient electricity generation to recover costs and yield a viable return on investment.
- Resource Assessment: This threshold serves as a screening tool for site feasibility; locations below this value are typically unsuitable for large-scale development.

ii. Implications
- Project Planning: Developers can use this benchmark to prioritize high-performing sites such as Hat Yai and Narathiwat.
- Investment Decisions: Policymakers and stakeholders may use capacity factor data to assess long-term viability and financial bankability of wind energy projects.

Beyond technical evaluation, this study contributes to the broader sustainability agenda by integrating an economic assessment of Electric Vehicle Charging Stations (EVCS). This element supports Thailand’s Alternative Energy Development Plan and aligns with global efforts to decarbonize transportation systems. The identification of five optimal EVCS sites across the southern corridor underscores the strategic convergence of renewable energy deployment and sustainable mobility infrastructure.

Furthermore, the study provides a replicable framework for regional wind energy assessment. It emphasizes the necessity of location-specific planning, the role of microclimatic influences on wind yield and the potential for integrating renewable energy systems into transportation networks.

5. Implications and Future Outlook

i. Wind Resource Planning: Prioritize investment in Hat Yai and Narathiwat to capitalize high-yield wind resources.
ii. Infrastructure Resilience: Account for extreme wind events in areas such as Prachuap Khiri Khan and Surat Thani during turbine and infrastructure design.
iii. Refined Modelling: Promote the adoption of high-resolution spatial and temporal wind models to enhance site selection and energy forecasting.
iv. Policy Alignment: Align wind energy development with national decarbonization goals by integrating findings into EV infrastructure planning and energy security strategies.

6. Final Remark

This research offers a foundational reference for both academic investigation and practical implementation of wind energy solutions in Southern Thailand. Its interdisciplinary scope, empirical rigor and contextual relevance position it to inform energy policy, guide infrastructure development and advance the global transition toward a sustainable, low-carbon future.

This pioneering research serves as a foundational reference for both academic inquiry and practical implementation of wind energy solutions in Southern Thailand. Its interdisciplinary scope and evidence-based findings aim to influence energy policy, guide infrastructure development and promote a sustainable energy future not only regionally but as part of a broader global movement.

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