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Preliminary Wind Resource Assessment of Songkhla, Thailand using WAsP Simulation

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ABSTRACT

This study presents a preliminary wind resource assessment at specific sites in southwestern Thailand for the deployment of onshore wind power for the future deployment. The primary objective of this research is to estimate wind power potential by using the near-surface wind observations over a period of 10-year (2013-2022) acquired from four weather observation stations. WAsP simulations were conducted to analyse prevailing wind direction, wind speed and power density. The Bonus 300kW Mk III wind turbine was selected to estimate energy production at each site at 30 meters above ground level (AGL). The findings identify four sites Sadao, Hat Yai, Kho Hong and Songkhla that demonstrate strong potential for prospective wind farm development. The WAsP analysis indicates mean wind speeds of 2.40 m/s for Sadao, 5.83 m/s for Hat Yai, 3.84 m/s for Kho Hong and 3.41 m/s for Songkhla. The estimated power densities for Sadao, Hat Yai, Kho Hong and Songkhla are 86 W/m², 74 W/m², 259 W/m² and 74 W/m², respectively. The mean net annual energy production values calculated for Sadao, Hat Yai, Kho Hong and Songkhla are 171.401 MWh, 629.079 MWh, 351.292 MWh and 217.072 MWh, respectively.

1. Introduction

Wind energy is gaining increasing global prominence and significance. It is a clean and renewable source of energy. Among all green energy technologies, wind energy is one of the fastest growing and is seen as a reliable solution for sustainable energy development [39]. Many countries have invested in wind power projects over the last ten years. Wind energy is not only environmentally friendly but also offers long-term benefits, such as reducing fuel imports and greenhouse gas emissions. Therefore, many countries are working to increase wind energy to reach their energy goals [31].

Thailand continues to rely predominantly on fossil fuels for electricity generation. In 2018, around 57% of the electricity came from conventional power plants and 18% came from coal and lignite

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power plants [36]. This shows that Thailand still uses natural gas, coal and lignite as its main sources of electricity. In 2019, the Electricity Generating Authority of Thailand (EGAT) reported a total electricity capacity of 45,298 MW, with 75% of this capacity from non-renewables [10]. By 2037, this capacity is expected to reach 77,211 MW. To reduce fossil fuel use, Thailand's Power Development Plan (PDP) aims to increase renewable energy use to 37% by 2037 [35].

In southern Thailand, electricity demand is growing by 5–6% every year due to tourism and development in the service sector [9]. Southern Thailand is a popular destination for tourists and has a high population density. The region spans approximately 20,116 km² and is home to over 2.3 million people. Songkhla province, located in this region, is shown in Figure 1. The topography includes mountain ranges and coastal areas next to the Andaman Sea. The region has a tropical climate with two main seasons: a rainy season from April to October and a hot season from November to March [28].

Wind energy potential has been studied in many parts of the world. For example, Adaramola *et al.,* [1] studied wind patterns in coastal Ghana and suggested wind turbines with cut-in speeds below 3 m/s. Boudia *et al.,* [3] used the WAsP program to study three coastal sites in Algeria. They estimated wind speed, energy output and cost using different turbines. Wang *et al.,* [38] examined wind data from four locations in China. Mohammadi *et al.,* [21] applied various methods to calculate wind power in Alberta, Canada. Sharma *et al.,* [32] used WAsP to estimate wind energy in Fiji, finding AEP values between 400–650 MWh. Dayal *et al.,* [8] studied 30 locations in Fiji using WAsP and identified the best ones for wind farms using a 275-kW wind turbine model.

Several studies have also explored wind energy in Thailand. In Songkhla province, Luankaeo *et al.,* [18] studied wind energy at Prince of Songkhla University, Hat Yai campus. They used wind speed data and WAsP at 30 meters height and found an average wind speed of 4.4 m/s and a wind power density of 81 W/m². This result supports the potential for small-scale wind projects.

Kamdar *et al.,* [13] deliberated Hat Yai and used wind data from 2017 to 2019. They also used WAsP and found an annual mean wind speed of 3.5 m/s at 10 meters and an estimated energy output of 2,731.28 MWh with an 80-kW turbine. They concluded that wind power could be useful for small-scale energy generation in the area.

Other studies in Thailand also show the country's wind potential. Niyomtham *et al.,* [24] used mesoscale and microscale models along the Andaman Coast and identified five potential wind sites with energy production between 18–36 GWh/year. These sites could reduce CO_2 emissions by over 80k tons per year. Waewsak *et al.,* [37] assessed offshore wind in the Gulf of Thailand. They found that the Gulf has a power potential of about 7,000 MW and could produce up to 15 TWh/year of electricity. Chancham *et al.,* [5] focused on the Bay of Bangkok and found that offshore wind projects could reach 924 MW in the short term, with even higher capacity in the future. These projects could help reduce millions of tons of CO_2. Chancham *et al.,* [6] used WAsP and other methods to study two offshore sites in Prachuap Khiri Khan and Narathiwat. They found average wind speeds of 4.1 and 4.5 m/s, with potential AEP of over 226 GWh/year at each site. These sites can support 84 MW wind farms.

These studies demonstrate that Thailand possesses significant wind energy potential in both onshore and offshore areas. However, more detailed studies are still needed in the southwest region, especially in Songkhla province. Only a few studies have focused on wind energy in south-western Thailand [27]. There is a gap in the data and knowledge in this region. Chen *et al.,* [7] also pointed out that accurate data is very important to avoid incorrect wind energy predictions. The WAsP program is a useful tool for this purpose. It uses Weibull distribution and can estimate wind climate and energy output using real wind turbine models.

This study fills the gap by using WAsP to assess wind energy potential in south-western Thailand. Wind speed and direction are analysed and the program is used to calculate wind speed, power density and energy output. The Bonus 300 kW Mk III wind turbine is used to estimate the annual energy production at selected sites. This work is especially important at a time when the world is moving toward cleaner energy and wind energy can play a key role in that future.

Figure 1 presents the location of weather observation stations in Songkhla province, Thailand. These stations are operated by the Thai Meteorological Department (TMD) [34] and are used in this study to collect wind data. The map highlights the Songkhla province in blue and the rest of Thailand in light yellow. Red dots indicate the TMD weather stations used for analysis.

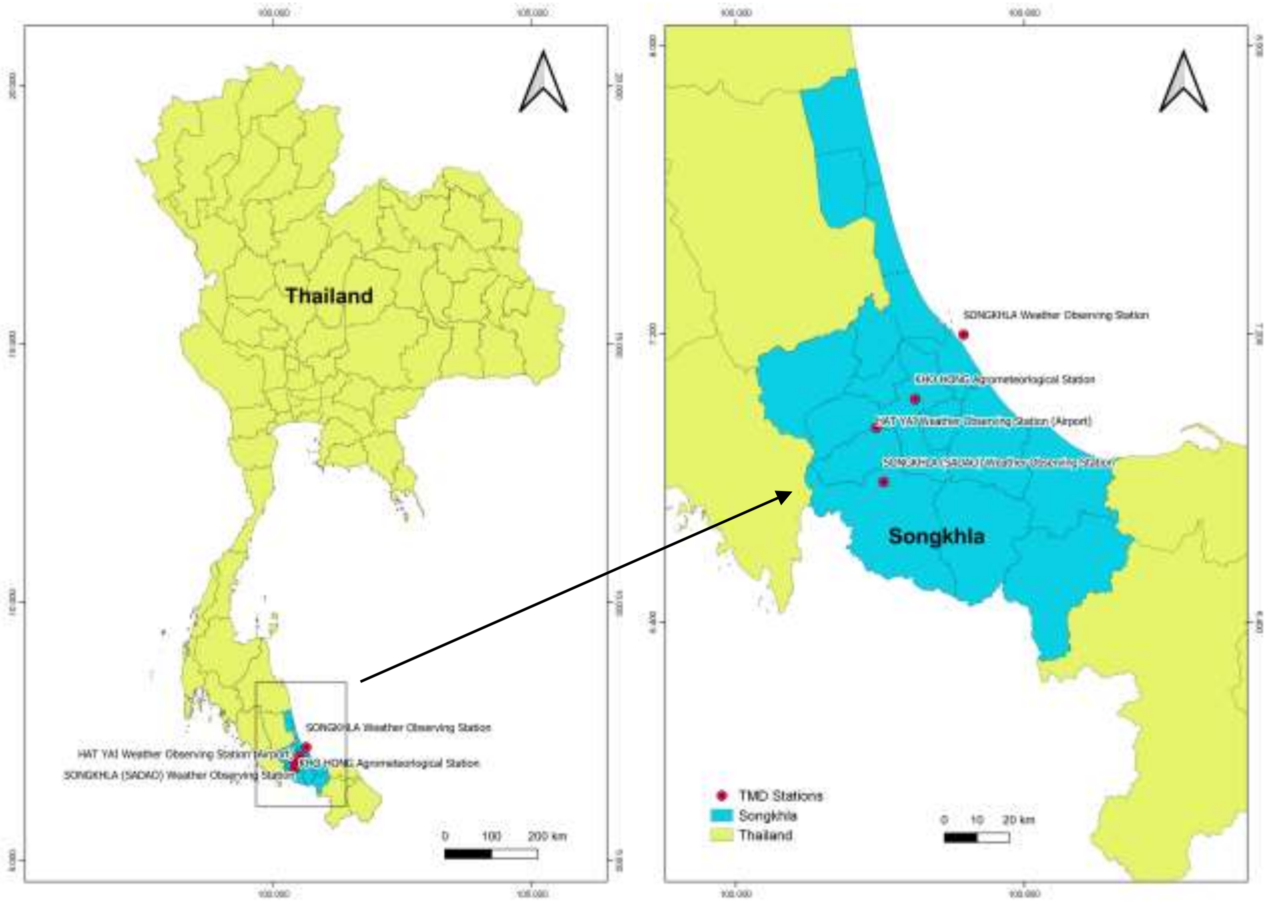


Fig. 1. Study area showing the position of four met mast stations in Songkhla [13,14]

This study uses wind data collected over a period of four years from the following four TMD stations:

i. Songkhla Weather Observing Station
ii. Kho Hong Agrometeorological Station
iii. Hat Yai Weather Observing Station (Airport)
iv. Sadao (Songkhla) Weather Observing Station

Each station's geographic coordinates will be listed in Table 1 for reference. These stations are distributed across different parts of Songkhla, providing useful coverage for assessing the regional wind energy potential.

2. Methodology
2.1 Onsite Wind Measurement

This study analyses wind data collected over the past four years from four weather observation stations operated by the TMD [34]. All stations record wind data at 10 meters above ground level (AGL). These stations are equipped with instruments such as anemometers, wind vanes, barometers and thermometers, which are mounted on meteorological mast towers and connected to data loggers for automated recording. The anemometer records wind speed in the range 0 -75 m/s with an accuracy of ±2%. Wind direction is measured using a wind vane, which operates within a range of 0° to 360°. The barometer records atmospheric pressure with values ranging from 800 hPa to 1100 hPa and a resolution of 0.1 hPa. The thermometer measures temperature ranging from -40°C to 50°C [15].

Table 1 provides details for each station, including geographical coordinates, measurement period, measurement height and the percentage of valid data recorded. The data for all stations are recorded at 10-minute average intervals, which is considered as an international standard. All sites have data availability exceeding 85%, except for Phang Nga, which has 78% availability.

Table 1
Details four met mast stations in Songkhla, Thailand [34]

Station name	Latitude (°)	Longitude (°)	Height (m)	Measurement duration
Songkhla	7.198	100.632	10	2013-2022
Kho Hong	7.019	100.49	10	2013-2022
Hat Yai	6.940	100.389	10	2013-2022
Sadao	6.789	100.410	10	2013-2022

Missing wind speed data in Thailand can be attributed to several factors, including data collection methods, geographic coverage and technical limitations. Technical issues with instruments and data loggers, such as sensor failures due to harsh environmental conditions, power interruptions or equipment malfunctions, also contribute to data loss. Wind speed sensors and data loggers can fail or produce invalid readings due to harsh environmental conditions, power supply interruptions or equipment malfunctions. For example, sensors installed at multiple heights (10m to 30m or higher) require stable operation and any failure can result in missing data at specific measurement heights [16,25]. To manage missing values, a gap-filling protocol was applied using linear interpolation for short-term gaps (≤6 hours), consistent with IEC standards. In cases where interpolation was not appropriate, a conservative replacement threshold (0.1–0.5 m/s) was applied to prevent bias in wind resource estimation [12,22,23].

2.2 The Weibull Distribution Function

The Weibull distribution, a lifetime distribution frequently used in reliability engineering which is a two-parameters probability distribution. It is often used in calculations to define the wind speed histogram. WAsP uses Weibull probability distribution to study the characteristics of wind [4,30]. The probability distribution function (PDF) used in wind speed analysis can be expressed by Eq. (1) [20]:

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

Where, $f(v)$ and v represent PDF and observing wind speed, respectively, A defines the Weibull scale parameter in m/s while k indicates the dimensionless Weibull shape parameter. The Weibull shape parameter k takes values between 1 and 3 and describes the behavior of wind in accordance with its speed and shows variations of wind variables as k is small, while large values of k indicate a rather constant wind speed [19,30].

2.3 Simulation Models

This study utilizes near-surface wind observations as input data for the WAsP software. The WAsP Climate Analyst 3.1 is used to analyse wind data. Elevation and surface roughness maps are prepared using the WAsP Map Editor 12.3. Then, Subsequently, WAsP 12.6 is employed to simulate wind speed, power density, annual energy production (AEP) and capacity factor (CF) for each study site.

WAsP is a computer-based simulation program developed by the Technical University of Denmark (DTU). It is widely used for wind atlas development, wind resource assessment and site selection for wind farms [11]. WAsP generates wind maps and models wind distribution across a region using observed wind data [12,22,23].

WAsP Climate Analyst 3.1 is a tool within the WAsP package. In this study, it processes raw wind data from four weather stations provided by the TMD [34]. The tool processes this data to generate wind climatological outputs, including Weibull distribution parameters and wind rose diagrams.

WAsP Map Editor 12.3 is also part of the WAsP package. It is used to generate elevation and surface roughness maps. These maps are based on data from the Global Wind Atlas (GWA) Map Warehouse. The elevation maps employ a 3-arcsecond resolution (~90 meters), while the roughness maps use a 10-arcsecond resolution (~300 meters).

WAsP 12.6 is subsequently used to simulate wind conditions at the selected sites. It estimates wind speed and power density and applies the Bonus 300 kW Mk III wind turbine model to calculate Annual Energy Production (AEP), incorporating minimal wake losses by using WAsP's wake model [22,26]. The technical specifications for the Bonus 300 kW Mk III turbine including a cut-in wind speed of 4 m/s, rated wind speed of 13 m/s and cut-out wind speed of 25 m/s along with its power curve (Figure 2), are referenced from the manufacturer's datasheet [2].

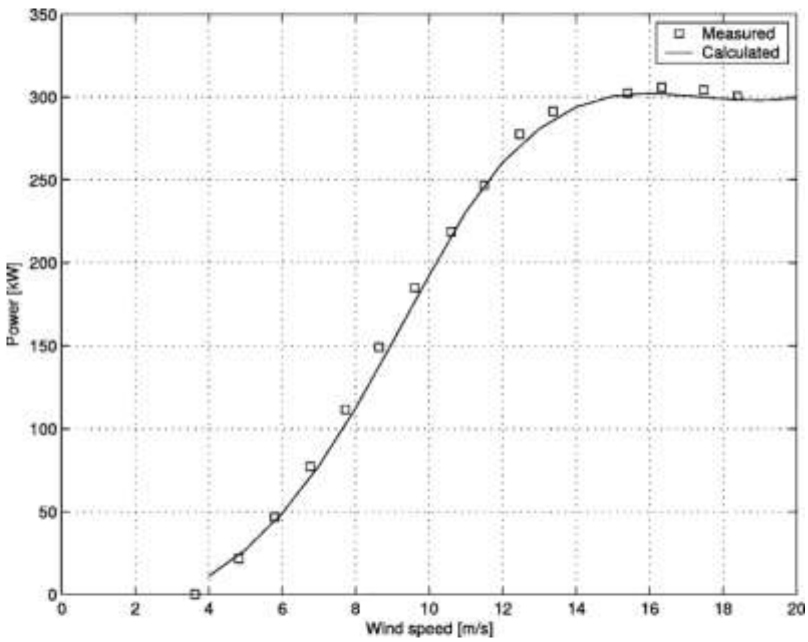
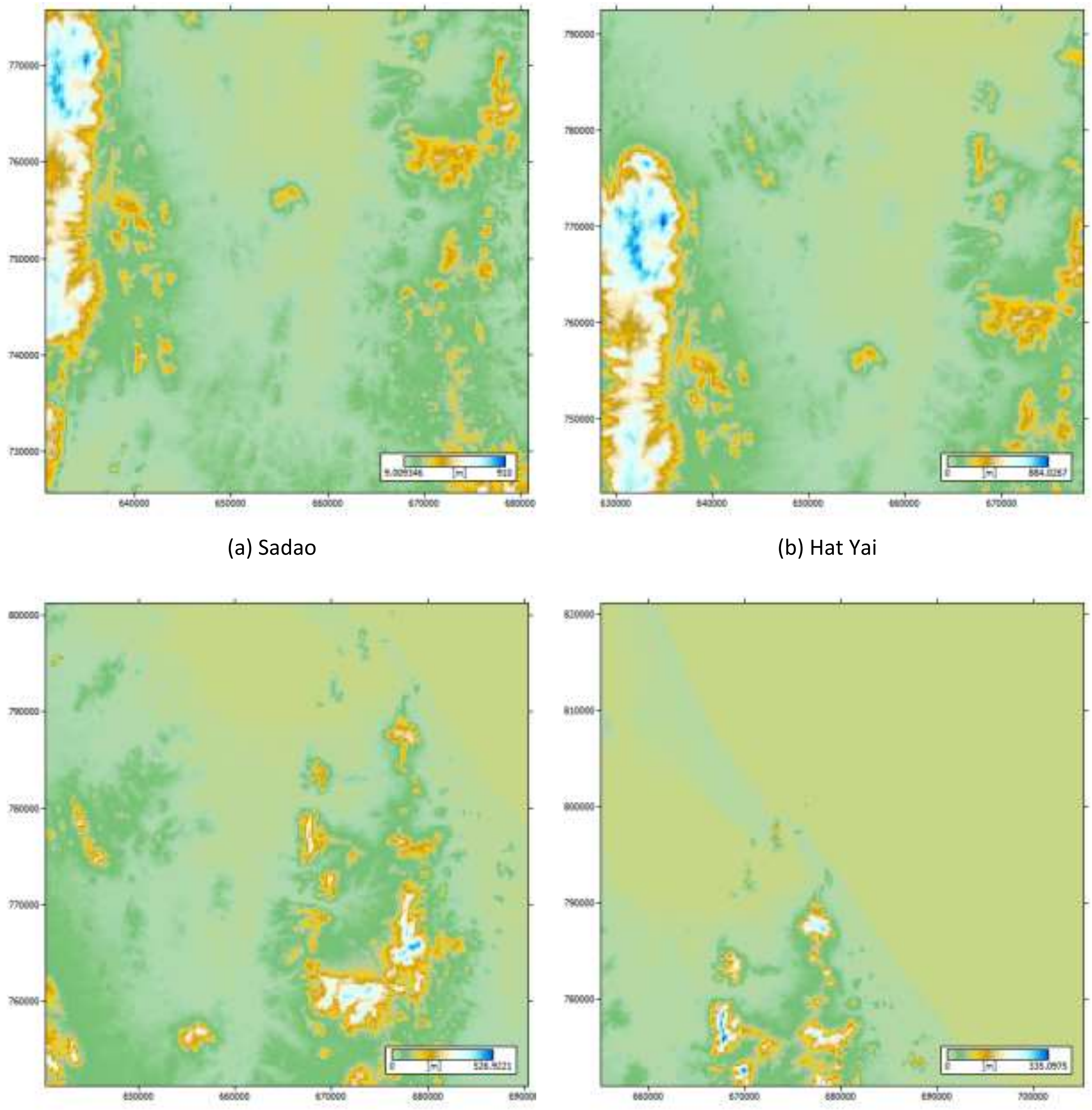


Fig. 2. Power curve of the Bonus 300 kW wind turbine [40]

This turbine model has been shown to be reliable during tropical cyclones and strong wind events [8]. The elevation and surface roughness maps of the study area are shown in Figure 3 and Figure 4, respectively.

A resource grid within the WAsP domain is used to create wind maps at the four weather stations. Three important parameters are used to assess wind energy potential: wind speed, power density and AEP. Wind speed shows if the wind is strong enough to operate a wind turbine. Power density shows how much wind energy is available at a location. AEP estimates the total energy that can be produced by a wind turbine each year at that site.



(a) Sadao

(b) Hat Yai

(c) Kho Hong

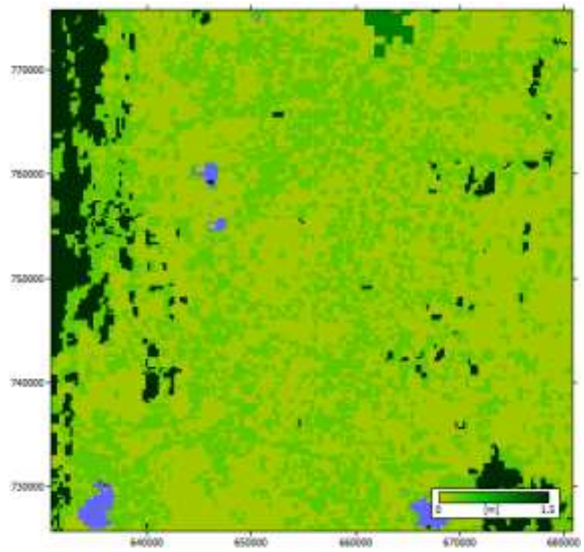
(d) Songkhla

Fig. 3. Elevation maps of the study area: (a) Sadao (b) Hat Yai (c) Kho Hong and (d) Songkhla

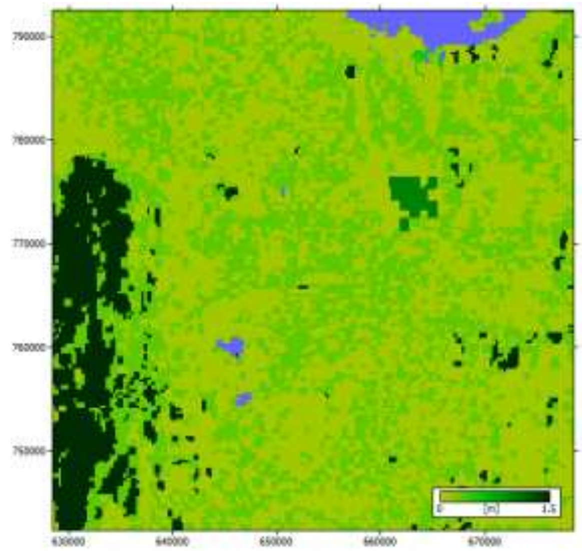
Elevation maps of the selected weather stations in Songkhla province:

i. Sadao
ii. Hat Yai
iii. Kho Hong
iv. Songkhla.

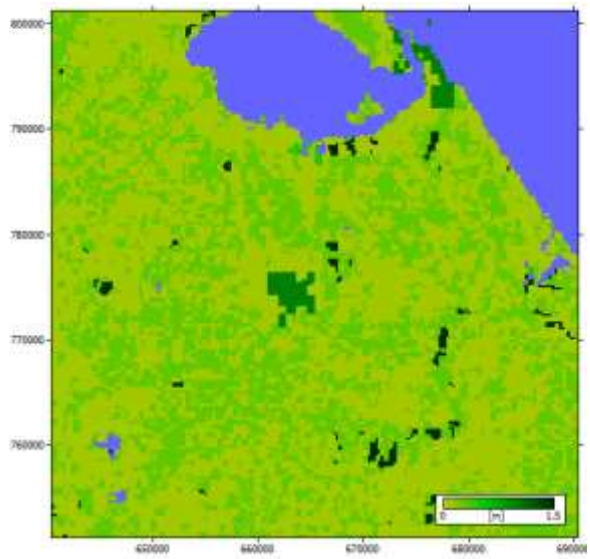
These maps use colour shading to show the height of land. Green areas show lower elevation, while yellow orange and blue/white areas show higher ground. Each map uses a different elevation scale, which may make comparison difficult. The colour bar legends are small and hard to read. Using the same scale and larger legends would help improve clarity. Also, coastlines are not shown in these maps due to the zoomed-in view, unlike in Figure 4. Clear subplot labels (a) to (d) on the images are recommended to guide the reader.



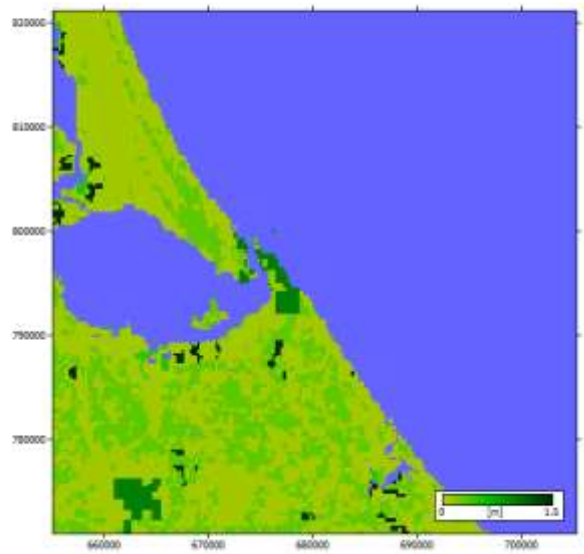
(a) Sadao



(b) Hat Yai



(c) Kho Hong



(d) Songkhla

Fig. 4. Surface roughness maps of the study area (a) Sadao (b) Hat Yai (c) Kho Hong (d) Songkhla

Surface roughness maps of the selected weather stations in Songkhla province:

i. Sadao
ii. Hat Yai
iii. Kho Hong
iv. Songkhla.

These maps show surface types that affect wind flow, such as forests, cities and open areas. Lighter colours often show smoother surfaces like water or open land, while darker or more textured colours show rougher areas like buildings or trees. These surface roughness maps help understand how the terrain affects wind speed and direction.

2.4 Wind Resource Assessment and Simulation Procedure

Wind speed data measured at 10 meters above ground level were extrapolated to the chosen hub height of 30 meters using the logarithmic wind profile equation. This method uses the surface roughness length of the surrounding area to estimate wind speed at higher elevations. It is commonly used in wind energy studies [8,17]. The surface roughness values were obtained from the WAsP Map Editor, using the Global Wind Atlas database.

The extrapolation was done using the following logarithmic wind profile law in Eq. (2),

$$V(z) = V(z_0)\frac{\ln(z/z_r)}{ln(z_0/z_r)} \tag{2}$$

Where, $V(z)$ is the wind speed at the desired height z, $V(z_0)$ is the wind speed at the reference height (10 m) and z_r is the roughness length. The roughness lengths were derived from the surface roughness maps created in WAsP Map Editor 12.3.

A hub height of 30 meters was selected because it is the minimum operational hub height for the Bonus B33/300 wind turbine used in the simulation. Although a 40-meter hub height is available, the 30-meter option was selected to reduce construction costs and minimize extrapolation error. Future studies could explore the benefit of higher hub heights in capturing stronger wind speeds.

The extrapolated wind speed data at 30 meters were input into WAsP 12.6 to calculate wind power density and Annual Energy Production (AEP) at each site. WAsP first analyses wind speed data using its Climate Analyst 3.1 tool, fitting it to a Weibull distribution, which describes the probability of different wind speeds occurring at a location [17].

WAsP then matches this distribution with the power curve of the Bonus B33/300 turbine, which has Rated power: 300 kW; cut-in speed: 3 m/s; rated wind speed: 13 m/s; cut-out speed: 25 m/s; rotor diameter: 33.4 m; swept area: 877 m^2 [2].

Using this data, WAsP calculates the expected energy output from the turbine at each location. The software also considers wind direction frequency, terrain effects and surface roughness by dividing the wind into different directional sectors. WAsP applies a flow model to estimate how wind behaves over complex terrain, including speed-up effects, sheltering and roughness changes. Although the raw wind data were recorded at 10-minute intervals, WAsP uses these as frequency distributions rather than time series.

This simulation method allows for detailed analysis of wind potential at the study sites in Songkhla province and helps assess the suitability of wind energy technologies in the region.

3. Results

This section presents a detailed analysis of the resource maps of four weather observation stations along with the potential for deployment of onshore wind energy in future.

3.1 Statistical Analysis of Wind Speed and Direction

Figure 5 to Figure 8 illustrate the Weibull distribution in terms of wind rose and wind speed frequency distribution for four met mast stations in omni-directional format. In order to harness more wind energy, the turbine must be arranged in perpendicular position to the wind direction. For this purpose, Weibull distribution in terms of wind rose and wind speed frequency must be known. The statistical analysis shows that north-east winds are most frequent in Songkhla province.

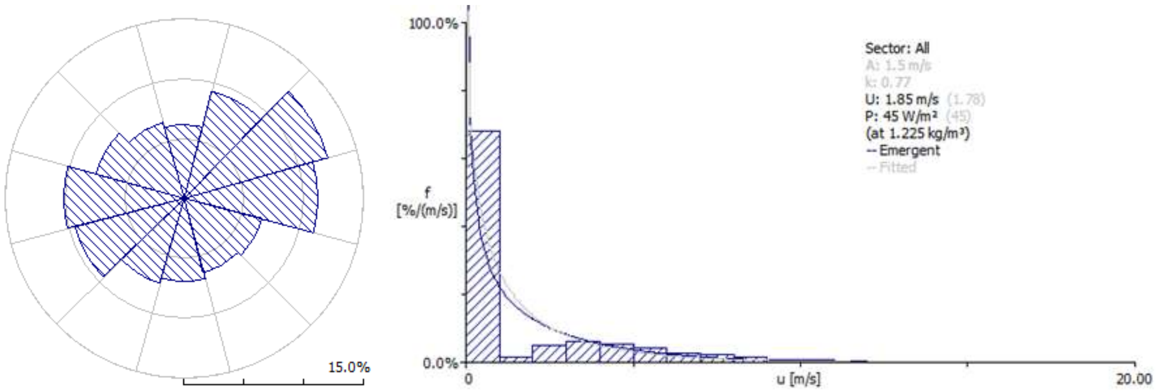


Fig. 5. Wind rose and speed frequency histogram for Sadao

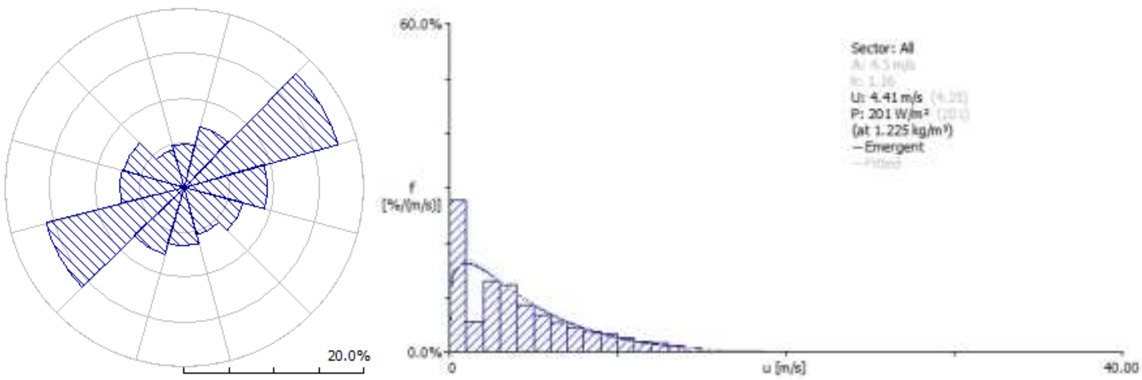


Fig. 6. Wind rose and speed frequency histogram for Hat Yai

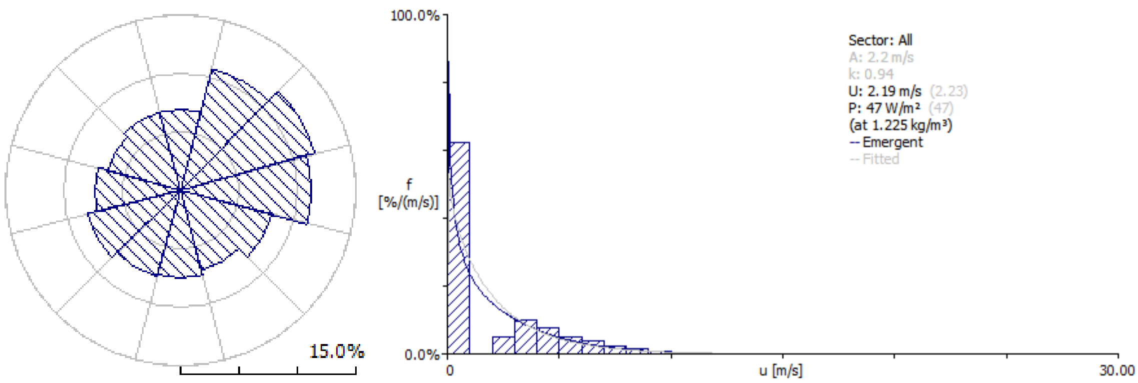


Fig. 7. Wind rose and speed frequency histogram for Kho Hong

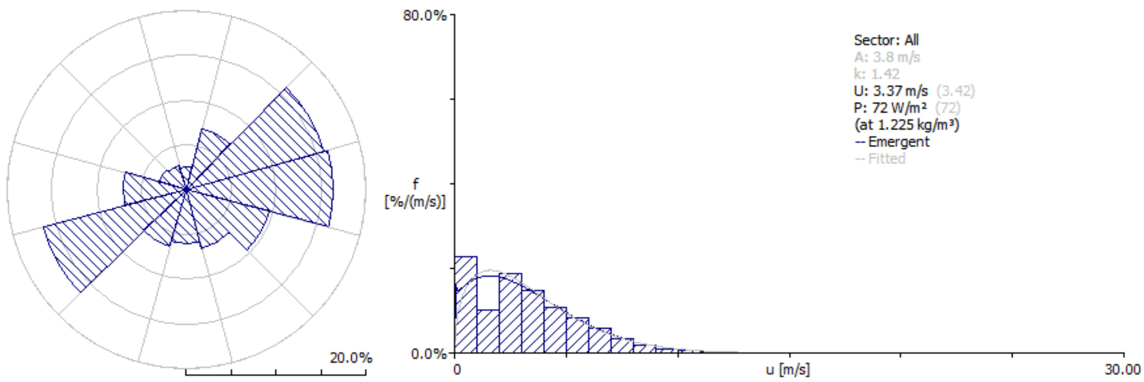


Fig. 8. Wind rose and speed frequency histogram for Songkhla

Table 2 shows the wind potential at 10 meters above ground for four stations in southern Thailand. Among the sites, Hat Yai has the highest average wind speed (4.41 m/s) and power density (201 W/m²), indicating better wind energy potential. Songkhla also shows moderate potential with a wind speed of 3.37 m/s and power density of 72 W/m². In contrast, Sadao and Kho Hong have lower wind speeds (1.85 m/s and 2.19 m/s) and low power densities, suggesting that these locations may not be suitable for efficient wind energy generation at this height. The Weibull parameters (c and k) help describe the wind speed distribution, with Songkhla showing more consistent wind patterns due to a higher k value (1.42).

Table 2
Summary of wind potential at 10 meters above ground

Station	Sadao	Hat Yai	Kho Hong	Songkhla
c is the Weibull scale parameter [m/s]	1.5	1.45	2.2	3.8
k is the Weibull shape parameter (dimensionless)	0.77	1.16	0.94	1.42
U is the average wind speed [m/s]	1.85	4.41	2.19	3.37
P is the power density [W/m^2]	45	201	47	72

3.2 Resources for Potential Locations

This section describes the wind energy resource mapping at selected sites in south-western Thailand which meet the criteria for utility-scale wind power generation. Simulated data using the Bonus 300kW Mk III wind turbine at 30 m hub height AGL is used to estimate wind speed, power density and AEP for 4 sites (Sadao, Hat Yai, Kho Hong and Songkhla) as shown in Table 3 and Figure 9 and Figure 10.

Table 3
Wind Resource Estimates by 4 sites (Sadao, Hat Yai, Kho Hong and Songkhla)

Station	Mean wind speed [M/S]		Wind power density [W/M^2]		Annual energy production [MWh]	
	Min	Max	Min	Max	Min	Max
Sadao	1.73	3.72	32	343	76.200	341.888
Hat Yai	3.49	9.16	125	1832	284.588	942.404
Kho Hong	2.47	6.17	82	1076	149.158	606.002
Songkhla	2.22	4.33	20	167	60.564	384.252

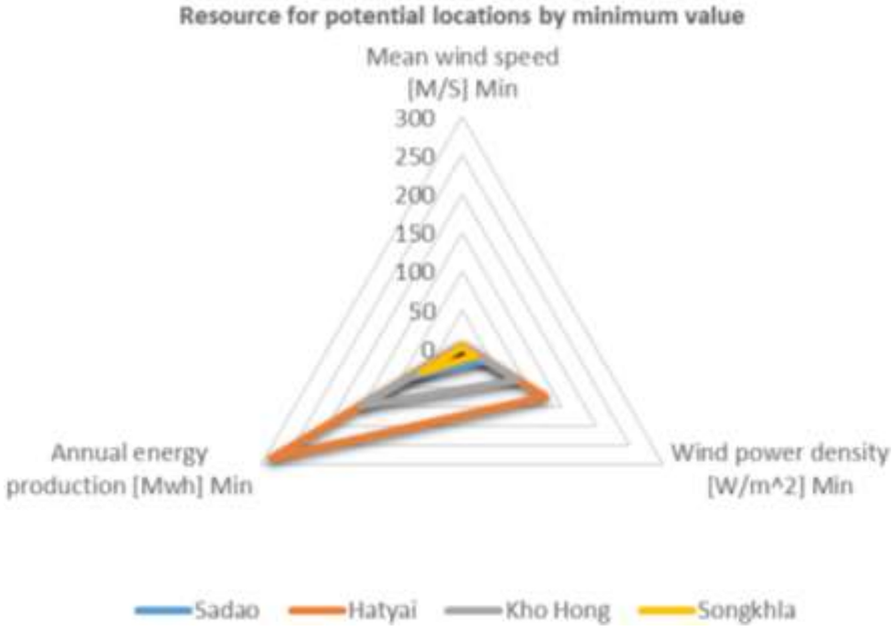


Fig. 9. Resource for potential locations by minimum value

Figure 9 and Figure 10 illustrate the minimum and maximum values of wind energy indicators across the four study locations. Among them, Hat Yai consistently has the highest minimum and maximum values for mean wind speed, wind power density and annual energy production, indicating strong and reliable wind conditions even during less favourable periods. Kho Hong follows with moderate potential, while Sadao and Songkhla display significantly lower values, especially in wind power density and energy production. These results suggest that Hat Yai is the most promising location for consistent wind energy generation based on minimum and maximum performance.

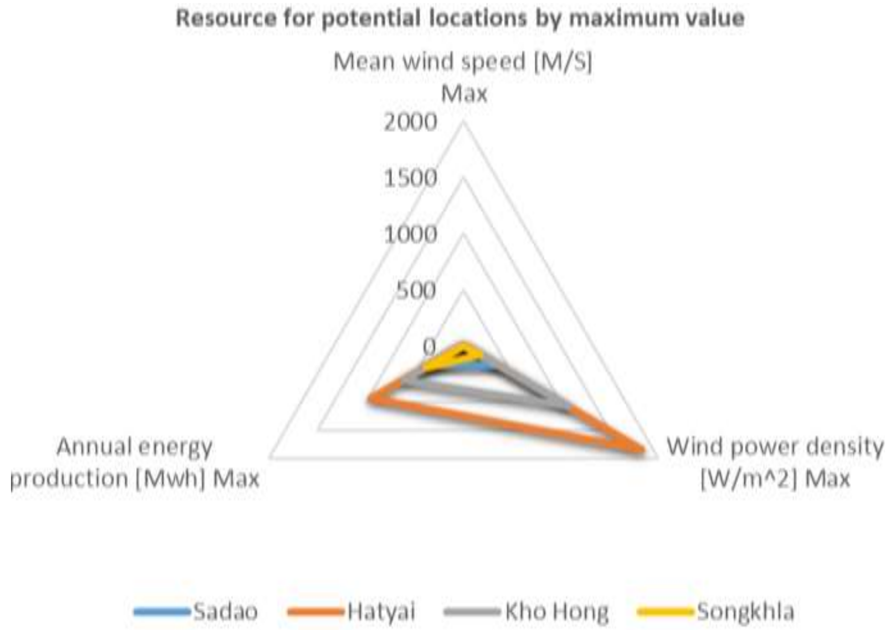


Fig. 10. Resource for potential locations by maximum value

The average wind speeds for Sadao, Hat Yai, Kho Hong and Songkhla are 2.40 m/s, 5.83 m/s, 3.84 m/s and 3.41 m/s, respectively. Comparing these average mean wind speed values with the wind speed class at 30 m height [33].

Similarly, the average wind power density for Sadao, Hat Yai, Kho Hong and Songkhla values up to 86 W/m², 74 W/m², 259 W/m², 74 W/m², respectively. Comparing the average wind power density values with the wind power density class at 30 m height [33].

For power analysis, Bonus 300kW Mk III turbine's power curve and wind characteristics of each site in Sadao, Hat Yai, Kho Hong and Songkhla determine average AEP of 171.401 MWh, 629.079 MWh, 351.292 MWh, 217.072 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 four stations is given in Table 4.

Table 4
Yearly statistical analysis of the selected sites

Station	Sadao	Hat Yai	Kho Hong	Songkhla
Mean net AEP [MWh]	171.401	629.079	351.292	217.072
Total proportional wake loss [%]	0.12	0.25	0.14	0.09
Mean wind speed [m/s]	2.40	5.83	3.84	3.41
Mean power density [W/m²]	86	74	259	74
Total capacity factor [%]	6.4	23.5	13.1	8.1

In this study, the maximum wind speed, wind power density and AEP are identified at four sites i.e. Sadao, Hat Yai, Kho Hong and Songkhla. These four sites show minimum to maximum net AEP that range from 76.200 MWh to 341.888 MWh, 1125 MWh to 1832 MWh, 82 MWh to 1076 MWh and 60.56 MWh to 384.252 MWh, respectively. The minimum to maximum wind speed values for Sadao, Hat Yai, Kho Hong and Songkhla are in the range of 1.73-3.72m/s, 3.49-9.16 m/s, 2.47-6.17 m/s and 2.22-4.33 m/s, respectively. Similarly, the minimum to maximum wind power density values for Sadao, Hat Yai, Kho Hong and Songkhla are in the range of 32-343 W/m², 125-1832 W/m², 82-1076 W/m² and 20-167 W/m², respectively.

The total capacity factor presented in Table 4 indicates how efficiently wind turbines at each site convert wind into electricity over a year. It is calculated by comparing the actual annual energy production (AEP) with the energy the turbine would produce if it worked at full capacity all the time.

Capacity factor is influenced by wind speed, wind consistency, turbine type and local site conditions. In this study, capacity factors ranged from 6.4% at Sadao to 23.5% at Hat Yai. These are low values compared to typical capacity factors for onshore wind turbines, which usually range from 25% to 40% [29]. A capacity factor below 20% is considered too low for economic large-scale power generation.

These low values can be explained by the mean wind speeds and power densities. For example, Sadao has a mean wind speed of 2.40 m/s and a power density of 86 W/m², which are not high enough for efficient wind energy production. As a result, the capacity factor is only 6.4%. Hat Yai has a higher wind speed of 5.83 m/s and shows a better capacity factor of 23.5%, but it still falls below typical industry expectations.

In addition, the wake loss percentages at all sites (ranging from 0.09% to 0.25%, as shown in Table 4) are very low, so wake effects are not the main reason for the low-capacity factors. Instead, the quality of the wind resource is the main limiting factor.

4. Conclusions

This study investigates wind power potential in south-western Thailand, where electricity demand continues to rise. Using WAsP software, wind resource assessments were conducted at four selected sites: Sadao, Hat Yai, Kho Hong and Songkhla.

The results show a range of wind characteristics and production outcomes. Among the sites, Hat Yai had the highest mean wind speed (5.83 m/s) and the highest average energy production (629.079 MWh), while Sadao had the lowest wind speed (2.40 m/s) and lowest capacity factor. These findings suggest that not all locations are equally suited for wind energy generation.

The study also analysed wind directions, revealing patterns such as the dominance of north-east winds in Songkhla. This information is valuable for correct turbine alignment, which affects performance. The capacity factors which measure effectively wind energy is converted into electricity, ranged from 6.4% to 23.5%, all below the global average for onshore wind turbines [29].

These findings suggest that most sites may not be viable for large-scale wind projects unless improved turbine technology, better site selection or seasonal wind analysis is applied. Locations with higher capacity factors should be prioritized for investment to ensure efficient use of resources and support the shift toward sustainable energy.

5. Implications

The low-capacity factors observed in this study suggest that these sites may not be optimal for large-scale wind energy generation. For example, Sadao's 6.4% capacity factor, combined with its lower wind speed and power density, indicates a less favourable environment for wind energy production. Even Hat Yai, with a capacity factor of 23.5%, falls below the typical industry standards for onshore turbines, which generally fall between 25% and 40% [29].

This suggests that further exploration is needed to optimize wind energy production at these sites. Possible improvements could include exploring more efficient turbine technologies, optimizing turbine placement or considering other factors such as local terrain or seasonal wind patterns.

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