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Wind Potential Assessment for Songkhla, Thailand

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ABSTRACT

The analysis and evaluation of wind energy projects are important to understand their economic and environmental suitability for installation and operation. Using wind data from the Meteorological Department, Used WAsP software for calculating, simulating, and analyzing the Annual Energy Production (AEP) and then applied it to calculate the Levelized Cost of Electricity (LCOE) of wind turbines installed in the Songkhla province area. The selected areas are suitable for all three models of wind turbines in the simulation. From the wind data analysis, wind direct was found that in the east sector (sector 4), there is the highest wind frequency at the wind station. The simulation results from Laem son-on area and Hua khao area show suitable mean wind speeds for wind farm installations. In the wind turbine simulation, three models were compared: Bonus 300 kW MkIII, Bonus 1.3 MW, and PowerWind 56 900 kW. At the Songkhla cape area, the positions with the highest AEP were 132.485 MWh, 344.419 MWh, and 332.597 MWh, respectively. Hua Khao area, the positions with the highest AEP were 225.284 MWh, 586.303 MWh, and 540.045 MWh, respectively. In the LCOE calculations for all model of wind turbines, at both Laem Son- On and Hua Khao locations, the most cost-effective wind turbine is the Bonus 300 kW. It has an LCOE of $142.43/MWh and $83.76/MWh, respectively. Therefore, the most cost-effective location is Hua Khao.

1. Introduction

Nowadays, it is an era where humans must recognize the importance of nature and the environment as the foundation, whether it is global disasters or resource shortages. In addition to natural disasters, some are the result of human activity. Therefore, researchers and academics in many countries are looking for ways to cope with the resulting impacts and try to improve them. For example, suggesting reforestation, taking care of wildlife in reserves, inventing alternative energy devices, monitoring and controlling the amount of carbon dioxide released from factories, and so on. In the current energy sector, there has been significant development in technology and convenience. However, to ensure the sustainability of nature for a long time, we humans must utilize the resources available on Earth to achieve maximum benefit.

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That is, we must use various forms of energy from alternative sources. In the natural aspect, such as wind, sunlight, geothermal resources, and biomass, and in the chemical aspect, by synthesizing energy through technology. This is because some types of energy are limited, such as petroleum and coal. Although these energy sources are widely used and provide high energy, they are also running out on the earth. Researchers focus on developing sustainable and reliable alternative energy sources that are clean to help reduce global warming issues and increase energy production in countries that may face shortages in the future. Wind energy is one of the clean energy sources that has been used in practice and accepted worldwide for its ability to efficiently convert to electricity. It has a high potential and can help produce more electricity in various countries. Humans have made efforts to use wind as a source of energy. The starting point of the idea of applying wind power is believed to have originated in ancient Babylonia. In the 17th century BC, various types of windmills were developed by the Persians [1]. These windmills had vertical-axis characteristics, while those used by Europeans had horizontal-axis features. Both types served as prototypes for the development of wind turbines in various sizes and shapes in the subsequent years. They were adapted for installation in different countries or geographical locations according to their suitability. In the 19th century, the era of wind turbines for electricity generation began. The first wind turbine designed specifically for electricity generation was constructed in 1887 by the Scottish engineer James Blyth in his garden [2]. In 1891, a large-scale electricity-generating wind turbine was built in Denmark, featuring a rotor with a diameter of 17 meters [3]. Subsequently, large-scale wind turbines, driven by gearbox systems, were established in Ohio, operating at a capacity of 12 megawatts for over 20 years. Since then, wind turbine technology has continued to develop, resulting in smaller, more efficient turbines that are better suited for different environments and have greater potential for electricity production.

The influence of wind power generation has entered Thailand over the past century, beginning in 1996 when the Electricity Generating Authority of Thailand (EGAT) selected the cape of Promthep in Phuket province as the site for installing a wind turbine to generate 150 kW of electricity [4]. Afterwards, wind turbine stations were installed in many other provinces throughout Thailand. The trend towards renewable energy has been rapidly developing, leading to increased use of renewable energy sources in the country. The Ministry of Energy has developed the Alternative Energy Development Plan (AEDP2018) [5] with the aim of increasing the proportion of renewable and alternative energy in the form of electricity, heat, and biofuels to reach a final energy consumption of 30% by the year 2037. The plan sets a target for total energy used to generate electricity at 2,989 MW, ranking third in the country's total renewable and alternative energy production. As of the year 2021, wind power has a capacity of 1,546.32 MW [5]. Furthermore, it is necessary to determine the coordinates for the construction of additional wind power stations to meet the targets set. In Thailand, researchers are interested in analyzing and calculating the potential of the country's topography, wind directions, and their economic feasibility. They have a particular interest in the southern region, where there are high mountains and flat coastal areas that are exposed to the prevailing southeast winds, creating a wind flow with sufficient speed for analysis and feasibility calculations. In order to achieve the set goals, it is necessary to determine the coordinates for the construction of new wind turbines. In Thailand, researchers are interested in analyzing and calculating the possibilities in terms of topography, wind direction and economic feasibility. They are particularly interested in the southern region, which has high mountains and coastal plains with winds blowing from the southeast, creating winds strong enough to be analyzed and calculated [6-8].

The province of Songkhla is suitable for the installation of wind power generators. Some of these generators were installed in the Sathing Phra District. In 2009, the project began with wind power generators capable of producing 1.5 megawatts of electricity, with a height of 80 meters and threebladed turbines measuring 37 meters in length [9]. This was the second such project in Thailand, and it was completed in 2011 with the goal of providing sufficient electricity to the community, utilizing natural energy sources to benefit the community and reduce environmental pollution. However, this research discusses the analysis to find suitable locations for wind turbine installations in Songkhla Province, which have the potential for economically viable wind energy production. This analysis is based on AEP (Annual Energy Production) and LCOE (Levelized Cost of Energy). Therefore, researchers have selected Songkhla Province to analyze the possibility of wind energy production and promote the goal of increasing wind energy according to the AEDP (Alternative Energy Development Plan) for the year 2018. This data can be used for future development purposes. History of wind energy is summarized in Table 1, and a comparison of the economics of wind energy from various research areas is shown in Table 2.

Table 1
History of Wind Energy

Year	Event	Ref.
200 B.C.	Peruvians use wind turbines to grind grains, which are vertical axis wind turbines with blades attached to wooden or stone paddles that are fixed vertically and have blades attached to the paddles. The wind turbine model described has blades that are approximately 5-9 meters long.	Glenn [10]
1105 A.D.	France adapts wind turbines for grinding grain	Ragheb [11]
1191 A.D.	England adapts wind turbines to grinding grain	Ragheb [11]
13th century	Wind turbines are popular for grinding grain in Europe.	Ragheb [11]
17th century	Wind turbines have been released in the United States.	Golding [1]
1779	Adriaan de Boois received permission from the city of Haarlem, Netherland to build a windmill. Adriaan built his windmill on top of the old Goê Vrouw tower.	Ragheb [11]
18th century	Multi blade wind turbines are being built in the United States.	Gipe and Möllerström [2]
1887	Scottish engineer James Blyth built the first electricity-generating wind turbine in his garden.	Gipe and Möllerström [2]
1891	The first wind generator was built in Denmark.	Vestergaard *et al.,* [3]
1899	the Danish scientist Poul la Cour improved the wind turbine when he discovered that building it with a small number of rotor blades gave better results and increased the production of electricity.	Righter [12]
1925	Wind turbines are commercially available in the United States.	Gipe and Möllerström [2]
1931	A vertical-axis wind turbine design called the Darrieus wind turbine is patented by Georges Jean Marie Darrieus, a French aeronautical engineer. This type of wind turbine is still used today, but for more niche applications like on boats, not nearly as widely as horizontal-axis wind turbines. A horizontal-axis wind turbine similar to the ones we use today is built in Yalta. The wind turbine has 100 kW of capacity, a 32-meter-high tower, and a 32% load factor	Shahan [13]
1941	A 1,250-kW wind turbine is installed in Vermont, USA.	Shahan [13]
1957	Johannes Juul, a former student of Poul la Cour, builds a horizontal-axis wind turbine with a diameter of 24 meters and 3 blades very similar in design to wind turbines still used today. The wind turbine has a capacity of 200 kW and it employs a new invention, emergency aerodynamic tip breaks, which is still used in wind turbines today.	Shahan [13]
1975	NASA has developed wind turbines to generate electricity.	Shahan [13]
1975	The first US wind farm is put online, producing enough power for up to 4,149 homes.	Shahan [13]

1979	The first commercial-scale wind farm was built in California, USA.	Shahan [13]
1981	A second wind farm goes up in the US. Total US installed wind power capacity is now approximately 10 megawatts, enough for approximately 8,575 homes.	Shahan [13]
1987	NASA's MOD-5B wind turbine is a two-blade wind turbine and has the largest installed capacity of 3.2 MW.	Shahan [13]
1991	The world's first offshore wind farm was installed in Denmark. It includes 11 wind turbines manufactured by Bonus Energy, each with a capacity of 450 kW.	Shahan [13]
1996	the Electricity Generating Authority of Thailand (EGAT) selected the cape of Promthep in Phuket province as the site for installing a wind turbine to generate 150 kW of electricity.	EGAT [4]
1998	China-based Goldwind is formed to manufacture wind turbines.	Shahan [13]
2000	149 wind farms are online in the US, providing enough power for up to 1.1 million homes.	Shahan [13]
2002	The world's largest offshore wind farm at the time, the 80 MW Horns Rev wind farm, was installed in Denmark.	Vattenfall's Power Plant [14]
2009	A deep-sea offshore wind farm using floating wind turbine technology has been installed in the North Sea of Norway.	NBC News [15]
2010	The world's largest offshore wind farm at the time, the 300 MW Thanet wind farm, was installed in the UK.	CNN Wire Staff [16]
2013	2,000-kilowatt wind turbine off the coast of Fukushima Prefecture began trial operations. Two more turbines of 7,000 kilowatts each will be installed this year, creating the world’s largest floating offshore wind farm. The project is an important part of the prefecture’s effort to revive its economy following the March 11, 2011, earthquake and tsunami.	Takaaki [17]
2019	The world's largest offshore wind farm, the 1.2 GW Hornsea One wind farm, was commissioned off the coast of England.	Ziady [18]

Table 2
Comparison of Economics of wind energy from various area of research

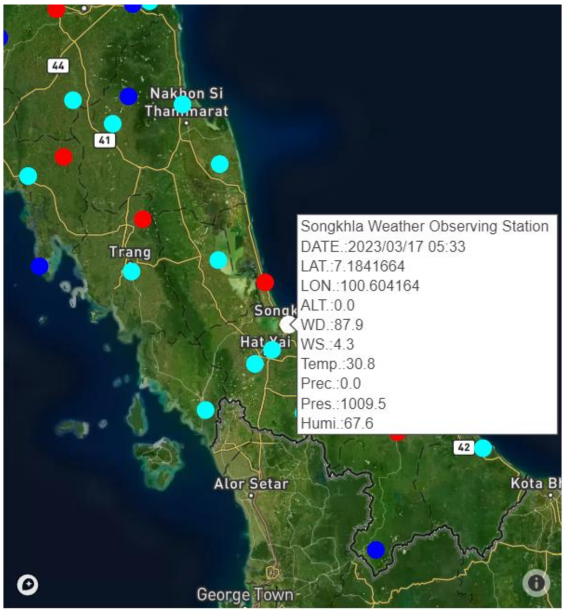
Country	Size	Economics of wind energy	Result	Ref.
This study examined the potential of wind energy in 22 regions in eastern Iran.	Mapna 2.5 MW and Vestas V100–1.8 MW 60 turbines	the lowest cost is 0.015 USD/kWh at the Khaf site and with the Mapna 2.5 MW turbine. The highest wind power is 0.085 USD/kWh at the Dashtebayaz site and with the S47-660 turbine (Sabaniroo).	the largest annual energy production is 11.98 GWh in Khaf and is obtained from a Mapna 2.5 MW turbine. Mapna 2.5 MW and Vestas V100–1.8 MW 60 Hz VCS turbines have a better performance than the two other turbine models.	Mohamadi *et al.,* [19]
Ratchaburi (S1), Pathum Thani (S2), and Saraburi (S3)	which are VestasTM: V47 660 kW (T1), V60 850 kW (T2), and V82 1650 kW (T3)	T1 and T3 cannot gain many benefits over costs. T2 can gain profits of 66 US$/kW, 562 US$/kW and 1655 US$/kW at sites S1, S2, and S3, respectively. The payback period of 7 years.	VestasTM V60 850 kW, the corresponding annual energy productions are determined as 601 MWh, 735 MWh, and 1030 MWh at heights of 120 m. Site S3 has the highest potential of wind energy generation among all sites.	Quan and Leephakpreeda [20]
Prince of Songkla University (PSU) Hatyai Campus, KhorHong district,			Annual average of wind power density is 81 W/m2, Weibull’s shape parameter (k) is 1.83 and Scale parameter (C) is 4.4 m/s. The Wind rose showed	Luankaeo and Tirawanichakul [21]

Songkhla province			that the wind direction mostly come from NE (North-East) at 15% and N (North) 15%.	
The offshore wind resource and an offshore wind power plant optimization in the Gulf of Thailand (GoT).	ranging from the lower size turbines (3.3 MW), to the larger size turbines (8 MW), and including a medium size turbine (5 MW).	AEP: short-term planning (Zone I), between 5 and 8 PWh per annum; medium-term planning (Zones II, III and IV), an additional 23 to 33 PWh per year; long-term planning (Zones V and VI), an additional 25 to 36 PWh per year.	The GoT could have a total installed capacity of 6,000 to 8,000 MW, would generate between 50 and 75 PWh of energy per year, while avoiding emissions of 30 to 40 million tons CO_2eq per year. The economic viability of projects is possible without the additional revenues from eventual CO_2eq emission taxations or trading.	Chancham *et al.,* [22]
Ko Yai in southern Thailand	Wind turbine 20 MW	Finally, the optimized, 20 MW (10 2 MW WTG) wind power plant in Ko Yai, Thailand could have an annual energy production of 33 GW h/year, corresponding to a capacity factor of 21%. The levelized cost of energy (LCOE) is estimated at 8.7 US cents/kWh.	the proposed 20 MW wind power plant is not viable under the current financial incentives of the electricity authority of Thailand (Provincial Electricity Authority, PEA).	Waewsak *et al.,* [8]
Huasai district, Southern Thailand	both a wind turbine size matrix with integer elements between 1 and 8 representing turbine power rating from 225 kW to 3000 kW	BPSO-TVAC renders a lower cost of energy (COE) ranging between 13.41 (1250 kW, 7D) to 15.25 (3000 kW, 4D) cent/kWh. The lowest COE layout with 13.41 cent/kW h installing 6 turbines sizing 2600 kW, produces AEP of 20.58 GWh giving annual operating income of 1.78 M$.	the maximum operating income layout shows a higher of COE of 14.19 cent/kW h than 13.14 cent/kW h at the lowest COE layout, but an AEP increase from 20.58 to 46.01 GW h/year overwhelm the higher COE	Pookpunt and Ongsakul [7]
The Andaman coast consists of 6 provinces, namely Ranong, Phangnga, Phuket, Krabi, Trang and Satun	Generated by a 10 MW wind power plant (Very Small Power Producer (VSPP) for Thailand)	Thungkhangok has the highest potential for wind power plant development, with an annual mean wind speed of 8.14 m/s. In this area, the AEP and the capacity factor (CF) of a 10 MW wind power plant are 51 GWh/y and 58%, respectively.	Some areas as well as the Wangprachan and Khuandon districts in Satun province. Wind power development, using 10 MW VSPP, would attain capacity factors of over 25% for all sites of interest. The annual energy production for these provinces is 23 GWh/year, 48 GWh/year, 51 GWh/year, 26 GWh/year, and 32 GWh/year, respectively.	Niyomtham *et al.,* [6]

2. Material and Method

2.1 Study Area

Songkhla Province is one of the southern provinces of Thailand. It has a population of over 1.4 million people and covers an area of 7,394 square kilometers. The annual energy consumption of Songkhla Province depends on various factors. Being an economically significant province with industries and exports, there is a high energy demand. Industrial energy consumption accounts for up to 55.57% of the total energy usage, and this demand continues to increase each year. Therefore, the Ministry of Energy needs to promote sustainable energy innovations to replace and supplement conventional energy sources throughout the country. This study focuses on analyzing the wind potential in the area of Songkhla Province, using various variables such as wind speed, wind direction, temperature, humidity, pressure, and precipitation. The research utilized three years of historical data from the meteorological stations in Songkhla Province. The data has a granularity of wind information recorded every 10 minutes each day, spanning from January 1, 2020, to December 31, 2022. The central coordinate for wind measurement in Songkhla Province allowed for a rough analysis of the wind data. The data was collected from C-Band met masts with a coverage radius of 240 kilometers, covering the entire study area. This data was then used in Wind Atlas Analysis and Program (WAsP). The various stations are shown in the Figure 1.



Songkhla Weather Observing Station
DATE.:2023/03/17 05:33
LAT.:7.1841664
LON.:100.604164
ALT.:0.0
WD.:87.9
WS.:4.3
Temp.:30.8
Prec.:0.0
Pres.:1009.5
Humi.:67.6

Fig. 1. Songkhla Station (TMD AWS, 2023) [23]

2.2 Wind Potential Analysis

Data from the Meteorological Department's wind measurements were used in the weather and wind analysis WAsP program. The wind data from each station for every year were combined using Python. Then, the wind that was measured was represented by a reference point with a height of at least 3 m/s for effective operation. Afterward, testing was conducted to determine the optimal height for wind turbines. The preliminary evaluation of wind speeds in Songkhla Province, using the Global Wind Atlas, found that at heights greater than 50 meters, there was sufficient wind speed, and at heights of 80 meters and above, several types of wind turbines were suitable. Therefore, in selecting sites, different types of turbines were compared at each simulated location for weather and wind analysis to generate energy density data. The Weibull distribution was used to calculate shape and scale parameters for site selection criteria.

In this study, the mean wind speed was analyzed using WAsP Climate Analysis 3.1, a function tool in the WAsP program. Specific locations were specified for each station as data input into the program. Data measured at a height of 10 meters above ground level was collected every 10 minutes each day for 3 years using data from AWS observation reports, as shown in Figure 2. The data from each station were then combined by grouping them into 365-day periods or 1 year. Importantly, the wind speed unit needed to be converted from knots to m/s before the combined wind data was imported into Climate Analysis. The results of the analysis, which were ultimately calculated for each station, included mean wind speed, mean wind direction, power density, Weibull A-parameter, Weibull k-parameter, and a wind rose as shown in Table 4 and Figure 2. An example of data obtained from the Meteorological Department is shown in Table 3.

Table 3

Wind data report (0052.Songkhla Weather Observing Station) [23]

Time (MM/DD hh:mm)	Wind Speed (knot)	Wind Dir (Deg)	Temp. (°C)	Prec. (mm)	Pres. (hPa)	QFF. (hPa)	Humi. (%)	Vis. (m)	Weather. (Identifies)
01/01 00:30	6.6	69	27.3	0.0	1012.6	1012.6	77.2	18727	00
01/01 00:40	4.9	75	27.5	0.0	1012.7	1012.7	78.3	18173	00
01/01 00:50	6.0	75	27.5	0.0	1012.9	1012.9	76.5	18201	00
01/01 01:00	4.3	96	27.8	0.0	1013.1	1013.1	77.4	19299	00
01/01 01:10	3.3	89	28.0	0.0	1013.1	1013.1	74.5	18997	00
01/01 01:20	4.5	101	28.1	0.0	1013.2	1013.2	74.2	17297	00
01/01 01:30	5.1	86	28.4	0.0	1013.3	1013.3	74.3	18323	00
01/01 01:40	5.2	91	29.0	0.0	1013.3	1013.3	71.2	18360	00
01/01 01:50	6.8	96	29.0	0.0	1013.4	1013.4	72.6	18729	00
01/01 02:00	7.2	92	29.5	0.0	1013.4	1013.4	71.0	16311	00

Table 4
Mean wind speed, mean wind direction, power density, Weibull A-parameter, Weibull k-parameter in WAsP program

Sector		Wind climate				Power (at 1.225 kg/m^3)
number	angle (°)	frequency (%)	Weibull-A (m/s)	Weibull-k	mean speed (m/s)	Power density (W/m^2)
1	0	0.7	0.7	1.31	0.63	1
2	30	3.8	2.2	2.92	1.98	7
3	60	17.9	2.5	3.19	2.23	9
4	90	21.0	1.9	2.29	1.71	5
5	120	4.8	1.0	1.54	0.89	1
6	150	3.9	0.9	1.37	0.83	1
7	180	6.2	1.0	1.32	0.92	2
8	210	13.3	1.1	1.40	0.98	2
9	240	20.3	2.1	1.76	1.88	9
10	270	5.2	2.1	1.83	1.89	9
11	300	1.7	1.0	1.22	0.93	2
12	330	1.3	1.1	1.27	0.98	2
All (emergent)					1.61	6
Source data					1.56	6

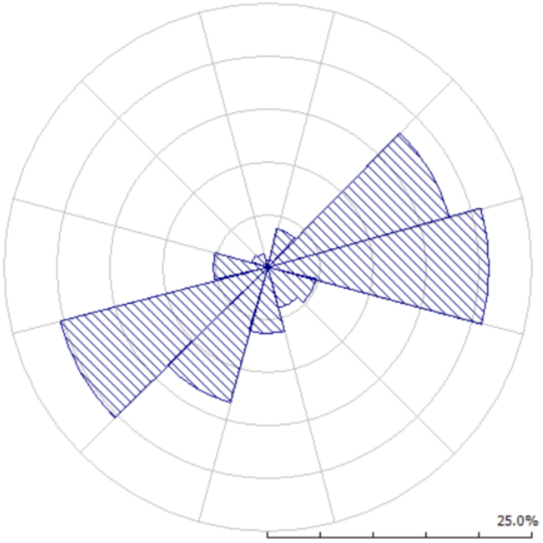


Fig. 2. Wind rose in WAsP program

2.3 Convert/Transform from: lat-lon in Decimal Degrees to UTM/USNG

A case study in Songkhla, Thailand latitude and longitude
7°11'03.0"N 100°36'15.0"E
7.1841664,100.604164

To use the WAsP program, it is necessary to first convert/transform from latitude-longitude in decimal degrees to UTM/USNG for Songkhla Province or the study location, as shown in Table 5.

Table 5
Convert/Transform from: lat-lon in decimal degrees to UTM/USNG

Lat-Lon-Height	UTM/USNG
Latitude	Zone 47
N07° 11′ 02.99904″	Northing (m) or Y co-ordinate
N071102.99904	794418.072
7.1841664000	Easting (m) or X co-ordinate
Longitude	677133.756
E100° 36′ 14.99040″	Convergence (dms)
E1003614.99040	00 12 02.40
100.6041640000	Scale factor
Ellipsoid Height ()	0.99998834
Not given	Combined factor
	N/A
	USNG
	47NPH7713494418

2.4 Surface Elevation and Roughness Maps

The elevation and vector maps of Songkhla Province are important data for use in the WAsP program. Therefore, the WAsP Map Editor tool in the WAsP program was used to prepare elevation and wind speed maps. The Universal Transverse Mercator coordinate system, Zone 47, along with the WGS-1984 datum, was used for the mapping process. The maps are in the form of a Digital Elevation Model (DEM), and they look like the one in Figure 3.

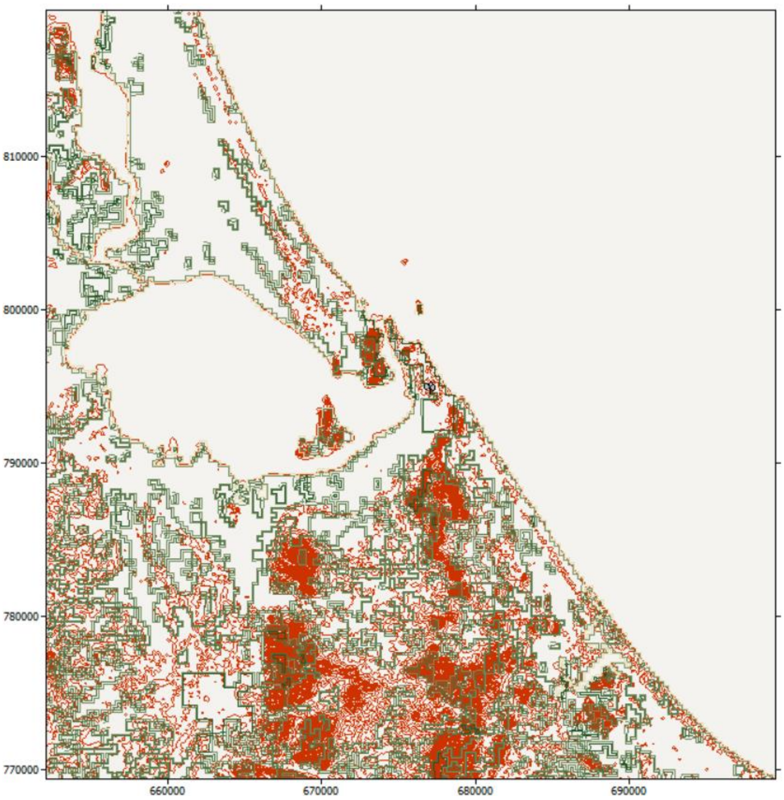


Fig. 3. The elevation and vector maps of Songkhla Province

The data of Elevation and Roughness Maps were both imported from the Global Wind Atlas (GWA) warehouse map server, roughness maps as showed the surface roughness in Songkhla province can be characterized into seven types: water bodies, bare areas, grassland, croplands, flooded forest, urban areas and forests as shown in Figure 4.

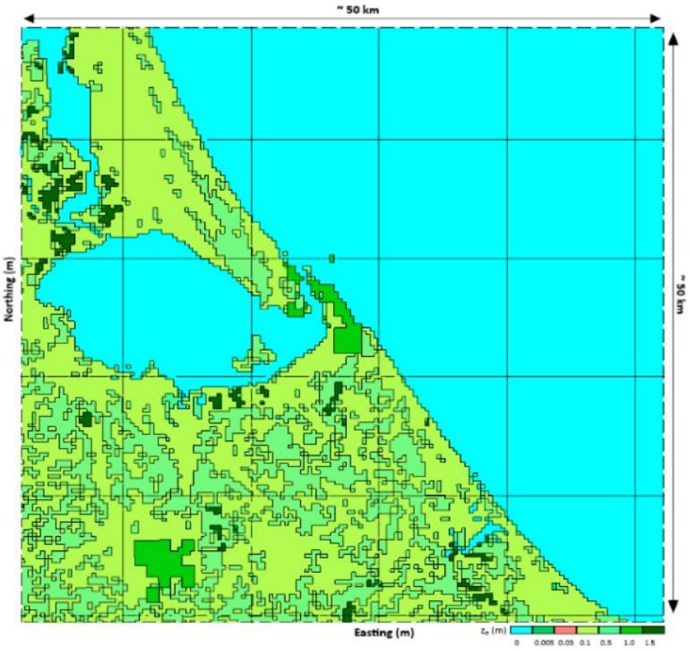


Fig. 4. Roughness maps

2.5 Sitting Wind Assessment and Analysis

In this study, each test location will be tested with different types of wind turbines, and positions with wind speeds exceeding 3 m/s will be selected, with three turbines of each type, to examine the differences. The Annual Energy Production (AEP) is analyzed using the WAsP program, and the efficiency of the wind turbines is shown in the power curve as depicted in the Figure 5 to Figure 7.

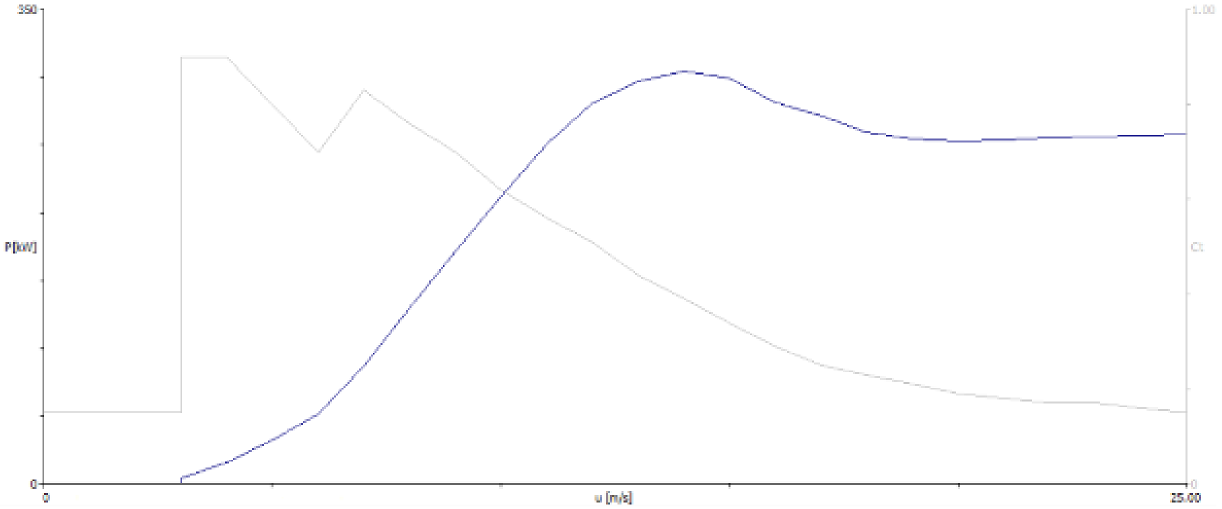


Fig. 5. Bonus 300 kW MkIII power curve

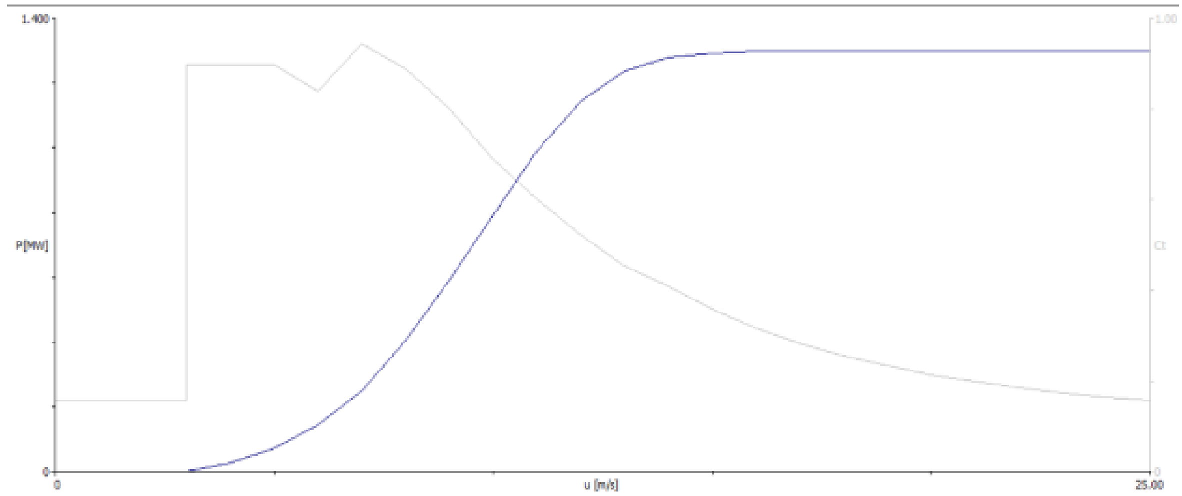


Fig. 6. Bonus 1.3 MW power curve

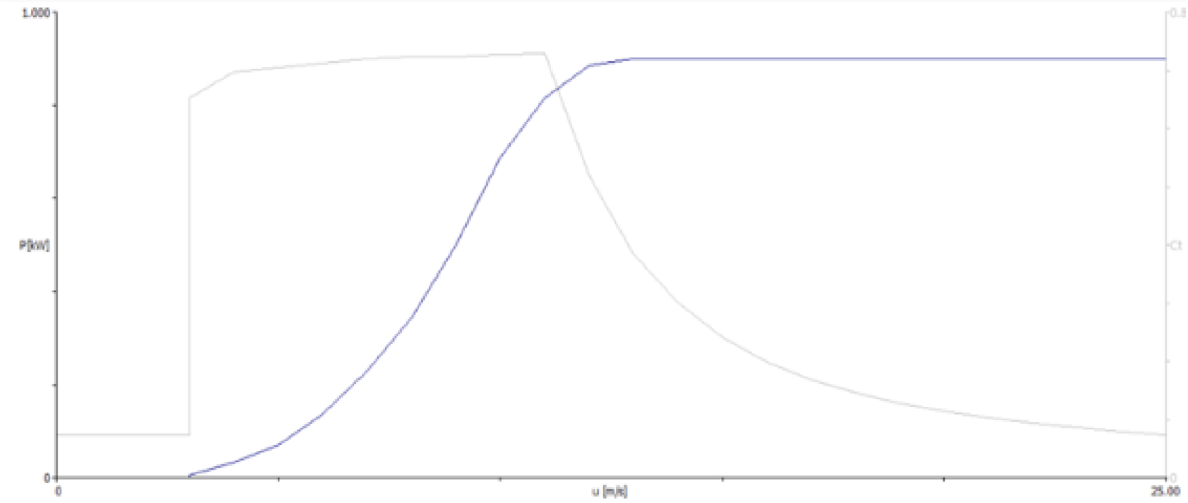


Fig. 7. PowerWind 56 900kW power curve

The wind potential assessment will use basic weather data at a 10-meter height. Wind speeds at various heights can be calculated from Eq. (1).

$$V = V_0 (\frac{h}{h_0})^{\propto} \quad (1)$$

where, *V* is the wind speed *(*m/s*)*, V_0 is measured at h_0=10 m, h is the height *(*m*).* α refers to the surface roughness coefficient value [24].

The design of wind turbines for electricity generation involves an equation used to analyze and describe wind speed variations, which is the Weibull distribution equation. This equation is included in the WAsP program, allowing us to simulate wind speeds in various areas and at different heights. A suitable design enables us to make rough estimates of investments, specifically the minimum electricity production costs. The analysis of data to determine the electricity output from wind turbines involves the popular Weibull distribution for wind data analysis. The parameters of the Weibull distribution include the shape parameter (k), which characterizes the data's distribution, with lower values indicating that lower wind speeds are more frequent than higher wind speeds. The scale parameter (c) is related to the average wind speed, with higher values when the average wind speed is high. The relationship between wind speed and the Weibull distribution is expressed in Eq. (2):

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right](k > 0, V > 0, c > 1) \tag{2}$$

The Weibull distribution has a related cumulative probability function, as shown in Eq. (3).

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right](k > 0, V > 0, c > 1) \tag{3}$$

From the above equation, $F(v)$ is the cumulative distribution function of observing wind speed (v), $f(v)$ is the probability of witnessing wind speed (v), c represents the scale parameter, and k denotes the dimensionless shape factor of the distribution.

2.6 Economic Analysis

In the planning or simulation of energy-related constructions, such as wind turbines that simulate energy generation, there are methods or indicators used to assess the cost-effectiveness of wind turbine installation investments. This indicator is known as LCOE, which stands for Levelized Cost of Energy. It represents the net present value of the cost per unit of electricity production over the asset's lifetime. It is often used as a substitute for the average price that the asset must receive in the market to break even throughout its operational life. The analysis of LCOE takes into consideration the expenses spread over the project's operational life to provide a highly accurate financial picture. If you require a straightforward cost per watt calculation, which is often used in the industry, LCOE calculates the actual cost, measured in U.S. dollars per kWh or U.S. dollars per MWh of energy produced. It is calculated using the following Eq. (5).

$$LCOE = \frac{Sum\ of\ costs\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime} \tag{4}$$

$$LCOE = \left(\frac{TIC \times r}{1-(1+r)}/Q\right) + LVC \tag{5}$$

TIC stands for Total Investment Cost, which includes construction costs, land, and wind turbines, depending on the wind turbine's capacity size. Here, r represents the discount rate, Q is the energy produced by the wind turbine, and LVC is the variable construction cost.

3. Results and Discussion

3.1 Analyze the Effect of Wind Direction Frequency

Figure 8 shows the wind rose, a graph of wind frequency in sector 4 directions, which correlates with Table 6. The data presented includes wind direction frequency at 10 m from all directions.

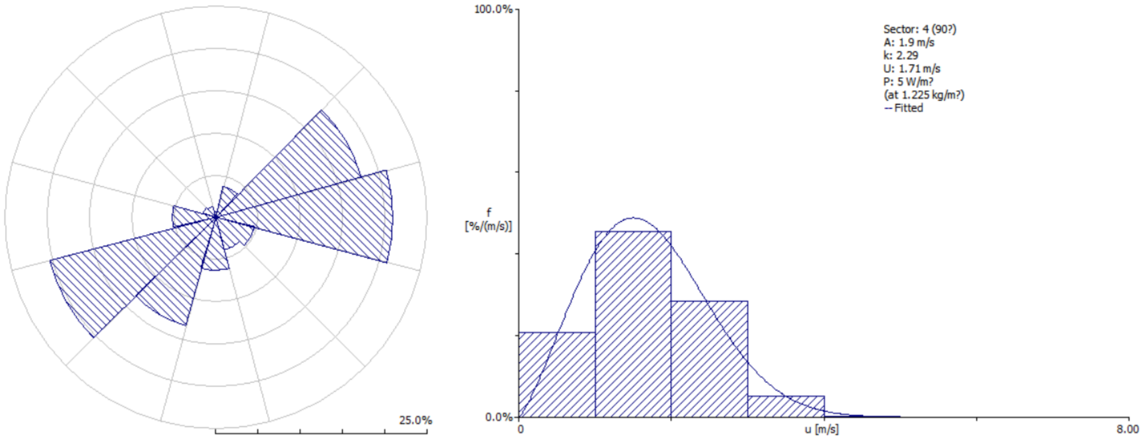


Fig. 8. Wind rose and wind direction frequency

Table 6
Wind direction frequency at 10 m

Sector		Wind climate				Power at 1.225 kg/m^3
number	Angle (°)	Frequency (%)	Weibull-A (m/s)	Weibull-k (m/s)	Mean speed (m/s)	Power density W/m^2
1	0	0.7	0.7	1.31	0.63	1
2	30	3.8	2.2	2.92	1.98	7
3	60	17.9	2.5	3.19	2.23	9
4	90	21.0	1.9	2.29	1.71	5
5	120	4.8	1.0	1.54	0.89	1
6	150	3.9	0.9	1.37	0.83	1
7	180	6.2	1.0	1.32	0.92	2
8	210	13.3	1.1	1.40	0.98	2
9	240	20.3	2.1	1.76	1.88	9
10	270	5.2	2.1	1.83	1.89	9
11	300	1.7	1.0	1.22	0.93	2
12	330	1.3	1.1	1.27	0.98	2

From the monthly wind data over three years in Figure 9, it was found that the highest average wind speed at a height of 10 meters occurred in February, reaching 2.36 m/s. Subsequently, the average wind speed remained relatively constant at around 1.2-1.8 m/s. Analyzing the wind frequency and wind rose in Figure 10 with the WAsP program revealed that the direction with the highest wind frequency was the southeast (sector 4, 90 degrees), with a frequency of 21% and a power density of 5 W/m^2. Another nearby direction was the south-southwest (sector *9*, 240 degrees), with a frequency of 20.3% and a power density of 9 W/m^2. In terms of the direction of the highest average wind speed, it is the east-northeast (sector 3, 60 degrees), with Weibull-A max 2.5 m/s, Weibull-k max 3.19 m/s, and a mean wind speed max of 2.23 m/s.

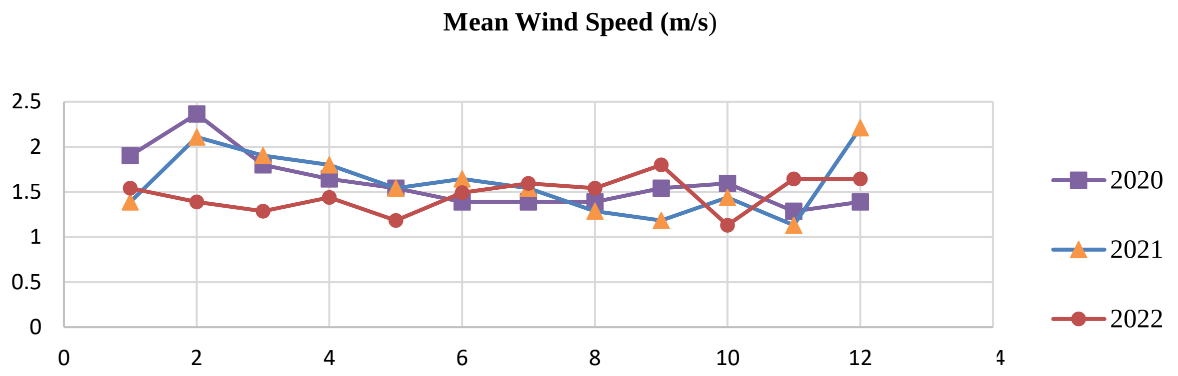


Fig. 9. Graph displaying the monthly average mean wind speed from 2020 to 2022

3.2 Wind Assessment Analysis for Selected Sites

Through analysis and calculations in the WAsP program, suitable positions can be found based on the mean wind speed map. Three different turbine models were simulated, each with three turbines to more accurately determine the positions with the highest wind speeds. The tested turbine models include the Bonus 300 kW MkIII wind turbine, Bonus 1.3 MW wind turbine, and PowerWind 56 900 kW wind turbine. These tests were conducted in both the Laem Son-On and Hua Khao areas.

3.2.1 Wind turbine power curve

Wind turbines of different sizes have varying capacities for electricity generation. Table 7 arranges and compares data from three types of wind turbine models.

Table 7
Three different turbine models specifications from power curve Figure 5 to Figure 7

Turbine models	Rotor Diameter	Cut-in speed	Cut-out speed	Rated Power	Rated wind speed
Bonus 300 kW MkIII	33.4 m	3 m/s	25 m/s	305 kW	14 m/s
Bonus 1.3 MW	62 m	3 m/s	25 m/s	1.3 MW	17 m/s
PowerWind 56 900 kW	56 m	3 m/s	25 m/s	900 kW	13 m/s

3.2.2 Calculate net annual energy production (*AEP*)

Table 8 shows the results obtained from simulating all three wind turbine models. Figure 10 and Figure 11 display the mean wind speed map from the simulation program at Laem Son On and the actual map from satellite images at Laem Son On, respectively. Each model provided important calculated results as follows

i. For the Bonus 300 kW MkIII wind turbine: Net AEP (Annual Energy Production) is 132.485 MWh. Proportional wake loss is 0.10%. Capacity factor is 5.0%. The maximum assessed mean wind speed is 3.02 m/s. Air density is 1.144 $\mathrm{kg/m^3}$. Power density is as high as 40 $\mathrm{W/m^2}$.
ii. For the Bonus 1.3 MW wind turbine: Net AEP is 344.419 MWh. Proportional wake loss is 0.62%. Capacity factor is 3.0%. The maximum assessed mean wind speed is 3.11 m/s. Air density is 1.148 $\mathrm{kg/m^3}$. Power density is as high as 41 $\mathrm{W/m^2}$.
iii. For the PowerWind 56 900 kW wind turbine: Net AEP is 332.597 MWh. Proportional wake loss is 0.02%. Capacity factor is 4.2%. The maximum assessed mean wind speed is 3.11 m/s. Air density is 1.142 $\mathrm{kg/m^3}$. Power density is as high as 41 $\mathrm{W/m^2}$.

Table 8
AEP at Laem Son On

Variable	Bonus 300 kW MkIII	Bonus 1.3 MW	PowerWind 56 900kW
Total gross AEP (MWh)	132.496	346.563	332.652
Total net AEP (MWh)	132.485	344.419	332.597
Proportional wake loss (%)	0.10	0.62	0.02
Capacity factor (%)	5.0	3.0	4.2
Mean speed (m/s)	3.02	3.11	3.11
Air density (kg/$\mathbf{m^3}$)	1.144	1.148	1.142
Power density (W/$\mathbf{m^2}$)	40	41	41

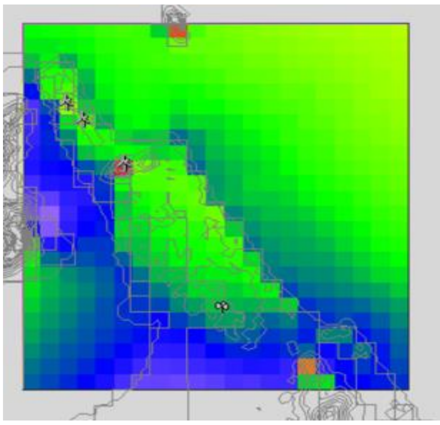


Fig. 10. Mean speed map at Laem Son On

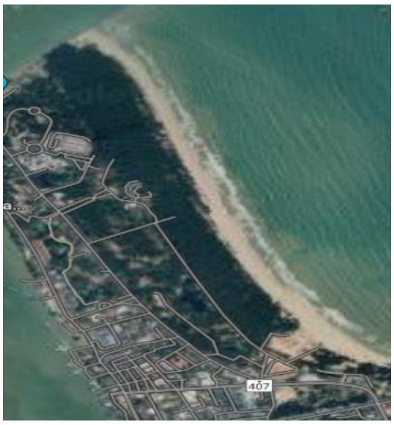


Fig. 11. Laem Son On from Google map

Table 9 shows the results obtained from simulating all three wind turbine models. Figure 12 and Figure 13 display the mean wind speed map from the simulation program at Hua Khao and the actual map from satellite images at Hua Khao, respectively. Each model provided important calculated results as follows

i. For the Bonus 300 kW MkIII wind turbine: Net AEP (Annual Energy Production) is 225.284 MWh. Proportional wake loss is 0.38%. Capacity factor is 8.4%. The maximum assessed mean wind speed is 3.64 m/s. Air density is 1.140 kg/m^3. Power density is as high as 68 W/m^2.
ii. For the Bonus 1.3 MW wind turbine: Net AEP is 588.361 MWh. Proportional wake loss is 1.75%. Capacity factor is 5.1%. The maximum assessed mean wind speed is 3.58 m/s. Air density is 1.137 kg/m^3. Power density is as high as 64 W/m^2.
iii. For the PowerWind 56 900 kW wind turbine: Net AEP is 540.045 MWh. Proportional wake loss is 0.78%. Capacity factor is 6.8%. The maximum assessed mean wind speed is 3.58 m/s. Air density is 1.138 kg/m^3. Power density is as high as 63 W/m^2.

Table 9
AEP at Hua Khao

Variable	Bonus 300 kW MkIII	Bonus 1.3 MW	PowerWind 56 900kW
Total gross AEP (MWh)	225.569	588.361	540.109
Total net AEP (MWh)	225.284	586.303	540.045
Proportional wake loss (%)	0.38	1.75	0.78
Capacity factor (%)	8.4	5.1	6.8
Mean speed (m/s)	3.64	3.58	3.58
Air density (kg/$\mathbf{m^3}$)	1.140	1.137	1.138
Power density (W/$\mathbf{m^2}$)	68	64	63

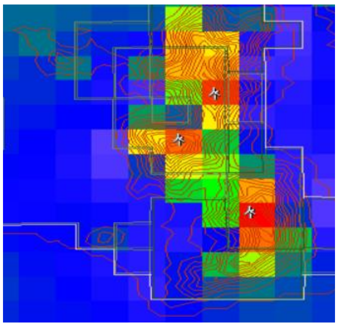


Fig. 12. Mean speed map at Hua Khao

Fig. 13. Hua Khao from Google map

3.3 Levelized Cost of Energy

In calculating the LCOE, we assume that TIC (Total Installed Cost) is the lowest cost, estimated at around $1000/kW, and WACCs (r) for new projects stood at 2.6-5.0% in Europe and the United States in 2019 (in nominal terms after tax), 4.4-5.4% in China, and 8.8-10.0% in India. The wind turbines modeled have an operational lifespan (t) of up to 25 years, and the Levelized Variable Cost (LVC) increases proportionally with the turbine size and the energy produced per year, which is obtained from the AEP calculated in the simulation. Various values are shown in the Table 10 and Table 11.

Table 10
LCOE at Laem Son On

Wind turbine model	Bonus 300 kW MkIII	Bonus 1.3 MW	PowerWind 56 900kW
AEP MWh/year	132.485	344.419	332.597
Total Investment Cost ($)	300000	1300000	900000
Levelized Variable Cost ($)	31492	123877	85761
LCOE ($/MWh)	142.43	237.41	170.21

Table 11
LCOE at Hua Khao

Wind turbine model	Bonus 300 kW MkIII	Bonus 1.3 MW	PowerWind 56 900kW
AEP MWh/year	225.284	586.303	540.045
Total Investment Cost ($)	300000	1300000	900000
Levelized Variable Cost ($)	31492	123877	85761
LCOE ($/MWh)	83.76	139.47	104.82

4. Conclusions

The study concludes that wind turbines should be installed facing east, as the highest wind frequency was recorded from wind measurements by the Thai Meteorological Department in Songkhla Province and the simulation results. The analyzed energy output of the three turbine models at Laem Son On, shows that the Bonus 1.3 MW turbine has the highest net AEP at 344.419 MWh with a proportional wake loss of around 3.8%, capacity factor between 3% and 5%, and a maximum measured wind speed of 3.11 m/s, air density ranging from 1.142 to 1.144 $\mathrm{kg/m^3}$, and power density between 40 and 41 $\mathrm{W/m^2}$.

In the case of the turbines installed at Hua Khao, the Bonus 1.3 MW turbine has the highest AEP at 586.303 MWh with a proportional wake loss of approximately 1.75%, capacity factor between 5.1% and 8.4%, a maximum measured wind speed of 3.58 m/s, air density between 1.137 and 1.140 $\mathrm{kg/m^3}$, and power density ranging from 63 to 68 $\mathrm{W/m^2}$.

The LCOE calculations indicate that the most cost-effective wind turbine for installation is the Bonus 300 kW Mk III, with an LCOE of approximately $83.76/MWh. Thus, the most suitable location for installation is the headland. It's important to note that this simulation is just a preliminary part of the analysis and modeling of wind turbines, and researchers hope it will contribute to future energy production in the country. The electricity power calculations obtained from the WAsP program are beneficial in making decisions for selecting suitable locations or countries for planning wind turbine installations. It is cost-effective for investment decisions. Additionally, it can accurately determine coordinates when compared to actual maps. The conclusions from this research can be extended by defining other parameters or adjusting to more suitable types of wind turbines in the future.

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