Study on Offshore Wind Energy Potential in the Gulf of Thailand

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Abstract- Thailand's Alternative Energy Development Plan (AEDP) aims to reduce electric power generation from fossil fuels by generating electricity from wind. In this study, the purpsoe is to determine a good place for a wind farm installation. The wind potential of the Gulf of Thailand (GoT) was monitored every 10 minutes for four years (2017-2020) at 10 m agl of 10 meteorological masts and analyzed using the Wind Atlas Analysis and Application Program (WAsP). Stations with average wind speeds greater than 3 m/s were provided to Multi Criteria Decision Analysis (MCDA) in order to find a viable offshore wind farm in GoT. Furthermore, the Annual Energy Product (AEP) was calculated and analyzed using 28 Vestas V112-3.0 MW Offshore in this study. The results revealed that Prachuap Khiri Khan and Narathiwat are two MCDA-selected stations. Prachuap Khiri Khan had a mean wind speed of 4.1 m/s and a power density of 121 W/m^2, while Narathiwat had a mean wind speed of 4.5 m/s and a power density of 181 W/m^2. Prachuap Khiri Khan's total net AEP was 226.7 GWh/year, with a capacity factor of 33.1%. Narathiwat's total net AEP was 270.8 GWh/year, with a capacity factor of 37%. In terms of economics, Narathiwat has a lower cost per unit than Prachuap Khiri Khan, at \$0.14/kWh and \$0.17 kWh, respectively. A suitable wind farm in the Gulf of Thailand allows wind energy to be used to generate electricity, which benefits the investor or people interested in offshore windfarm.

Keywords Wind resource assessment, Gulf of Thailand, Offshore Windfarm, WAsP, Site Selection

1. Introduction

Today, the increase in the world population is affecting energy consumption, resulting in decreased sources of natural energy such as coal or fossil fuels, and increased pollution. Therefore, to reduce the depletion of fossil fuels and pollution from coal emissions, investment in renewable energy should be the world's main concern [1,2]. The consumption of energy resources has risen in 2008-2018. Coal and natural gas increased from 2,103,391 to 2,864,881 ktoe and 423,361 to 677,561 ktoe respectively [3]. The rise in energy consumption could be a warning sign to mankind to be aware of lacking energy sources. Renewable energy should provide a suitable power solution for the location, with low capital costs and a high internal rate of return [4,5]. In Thailand, there are aims to generate electricity from renewable energy, according to the AEDP2015 plan. Of the total electricity consumption, electricity produced by renewable energy is counted as around 20 %. According to fuel or coal ratios in electricity generation in Thailand in the Power Development Plan 2015-2036 (PDP2015), the ratio of renewable energy should be 15-20 % within 2036 [6].

The wind resource assessment and atlas are critical data sources for enhancing wind power systems that generate electricity while lowering CO_2 emissions. For the past decade, wind energy has been rapidly producing electricity. Wind energy performance improves feasibility and efficiency depending on weather conditions [7]. There were many winds assessments study in Chukk state [8], on-site anemometry observation [9] and on Kadavu Island and Suva Peninsula. To create a wind map with high resolution, is microscale and mesoscale [10] that are used to analyse the year's resource assessment. The Wind Atlas Analysis and Application Program (WAsP) is an analysis data tool, and it is used to perform wind climate predictions, wind resources, and power generators of wind turbines [11] to determine the wind conditions at a weather station [12]. In some studies, a future wind farm assessment was used to collect wind data and population density for more than 1 year [13] or 10-year period to derived monthly seasonal and annual wind characteristics from high-resolution satellite observations [14]. The models contain vertical extrapolation of wind data to compensate for obstacles, surface roughness changes and terrain height variations [15]. This process is predicted by source data of regional wind climatology and geostrophic wind speed distributions for 12 directions in each sector [16].

Wind power systems were the major trend in many nations as demand grew. To utilize wind energy, it is necessary to investigate the wind potential in the area in order to determine the appropriate scale size of wind turbine. Small wind turbines have a high potential in the Sultanate of Oman for home, community, and irrigation usage [17]. Offshore wind, like freshly developed onshore wind, is predicted to increase significantly. Deploying turbines at water takes advantage of greater wind resources than on land. In a cost-benefit analysis of wind power plant electricity output, the results demonstrate that offshore wind farms produced more than onshore wind farms in terms of levelized cost of energy [18]. Therefore, new offshore turbines are able to achieve significantly achieve more full-load hours, depending on resource availability [19]. In Thailand there are researches on offshore wind resources in Andaman or western Thailand [20].

In this study, a wind resource assessment in the Gulf of Thailand was focused on by collecting meteorological raw data for four years from 2017 to 2020 along the east coast lines of Thailand to predict mean wind speed, wind power distribution, wind frequency distribution, Weibull parameters, and analyzing a wind map using WAsP. A Multi-Criteria Decision Analysis was also used to locate a good location for an offshore windfarm. Rather than ranking windfarm potential sites, the optimal wind power potential was estimated in this technique [21]. Furthermore, the power study for this site was performed by a Vestas112-3MW offshore turbine [22]. This study's contributions include:

• Using wind energy potential data and wind profile distribution in the Gulf of Thailand with recently updated data for further study and development.

• Providing an appropriate offshore windfarm with Annual Energy Productive (AEP) data to evaluate and enhance in the future.

2. Material and Method

2.1. Study site and wind potential analysis

The Gulf of Thailand (GoT) borders are on the South China Sea, with two under-water ridges aligned along the North-South barrier. The Gulf of Thailand has around 270,000 km^2 of total area. The topography at the bottom of the Gulf of Thailand is a basin. [23] The boundary of the upper Gulf of Thailand contacts the low land of Chao Phraya and the eastern coastline, and the westside contacts the southern coast of Thailand. The east side is bordered by the territorial waters of Cambodia and Vietnam, and the south is sided by Malaysia. In this study, the east and south-east sides of 10 Department by Automatic Weather System, as shown in Thailand, were focused. The wind data was carried out from the meteorological (met) mast of Thai Meteorological Figure 1, which can be separated into 3 and 7 met masts in the Eastern and Southern-Eastern regions, respectively. In the eastern region of Thailand, there are Khlong Yai, Phliu and Rayong met stations. These stations are located near the middle region and the eastern coastline. In the southeast of Thailand, there are 7 stations: Prachuap Khiri Khan, Chumphon, Koh Samui, Nakhon Si Thammarat, Songkhla, Pattani and Narathiwat. These stations are located on the east side of the southern region of Thailand. The raw wind data at 10 m was collected by AWS data. Collected The wind data along the east and southeast of Thailand was collected by ASL height and carried out every 10 minutes for 4 years from 2017-2020.

Fig. 1. Overview of the Gulf of Thailand along with 10 AWS Thai Meteorological Station.

To provide the mean wind speed data for each station, Wind Climate Analysis was used as a tool in WAsP to display the average wind speed, and then to filter out the stations where the mean wind speed was below 3 m/s because of the minimum wind speed for cut-in speed of Vestas V112-3MW offshore turbines.

The Vestas V112 – 3.0 MW Offshore turbine was designed by Vestas Wind System A/S, a manufacturer from Denmark. Table 1 presents the specifications of Vestas V112-3.0 MW Offshore turbine specifications [22] and the power curve turbine in Figure 2. In the vertical extrapolation, wind speed equations were applied to wind speed at various heights. The available wind speed was necessary to measure the wind turbines' hub height [24].

Since the wind assessment is based on the met mast that is 10 m height, the wind speed at various heights was calculated by Equation (1).

$$V = V_0 \left(\frac{h}{10}\right)^{\alpha} \quad (1)$$

where, V is the wind speed (m/s) at height h, and V_0 is measured at 10 m, h is the height (m) corresponding to V (m/s). α refers to the surface roughness coefficient value, which is chosen as 0.12 for a smooth sea surface as the terrain area data for offshore sites [21].

Table 1. Vestas V112-3.0 MW Offshore turbine specifications [22]

Rotor Diameter	Hub Height	Cut-in speed	Cut-out speed	Nominal revolutions	Rated Power	Rated wind speed
112 m	84 m	3 m/s	25 m/s	13.8 rpm	3 MW	12.5 m/s

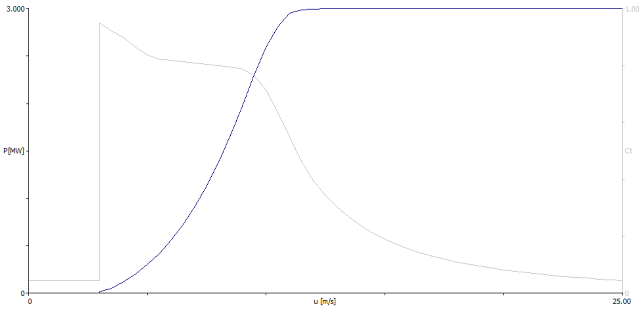

Figure 2 Vestas V112-3.0 MW power curve turbine

The wind speed at 50 m of height was classified into types of wind power, and the wind speed at 84 m of height represented the potential of wind speed at turbine hub height. In the chosen stations, the wind data analysis is the key to assess wind potential of wind systems [25]. Wind Climate Analysis tool in WAsP was used to generate the power density data, and Weibull distribution was applied for shape and scale parameters. The Weibull probability distribution modelled as:

The Probability density function of the Weibull Equation (2)

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

The corresponding cumulative probability function of Weibull distribution is Equations (3)

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

where *f(v)* is the probability of observing wind speed *(v)*, *F(v)* is the cumulative distribution function of observing wind speed *(v)*, and *c* represents the scale parameter while k represents the dimensionless shape factor of the distribution.

k and *c* can be calculated by Equation (4) and (5)

$$k = \left(\frac{\sigma}{v_{avg}}\right)^{-1.086} \quad (4)$$

$$c = \frac{v_{avg}}{\tau(1-1/k)} \quad (5)$$

Where v_{avg} and σ are the average and variance of wind speed. τ is the Gamma function, which is expressed in Equation (6).

$$\tau(x) = \int_0^\infty e^{-u} u^{x-1} du \quad (6)$$

The effective wind power density (EWPD) for wind turbines can be calculated by Equation (7).

$$\text{EWPD} = \frac{1}{2}\int_{v_1}^{v_2} \rho v^3 f'(v) dv \quad (7)$$

where v_1 is the starting speed, v_2 is the cutting speed and ρ is the air density.

To provide a suitable station for offshore wind turbines, the site selection criteria was the selective in this study with the Multi-Criteria Decision Analysis.

2.2. Criteria wind farm and site selection

Multi-Criteria Decision Analysis (MCDA) is the main stream to select the wind farm concerning both of technical data as the wind assessment in selecting area and in social restriction as a military area or a civil area. Therefore, to perform offshore wind farm within high and sustainable value before investment, the multi-criteria decision was necessary. There were many MCDA methods selected in this study. For offshore site selection, the Analytical Hierarchy Process (AHP) [26] approach was utilized. The main applicable decision criteria in this selection in Figure 3. includes following section:

2.2.1 Territorial water

The territorial water is the sea border area to the shore of a state in international law [27]. The law of the sea of 1982 (Art.3) mentions that it is around 22 km from the shore or 12 NM.

2.2.2 Military areas

In this section, a military area includes navy or onshore training areas in Thailand that are located far away from the civil population with restricted zones and are unusable for wind farm purposes. This will affect the expansion of wind farm sites in the future.

2.2.3 Aircraft route

Because of the rapidly growing aviation business, a lot of new airports have been established to support a number of aircraft and new airlines. The aircraft routes needed to be increased to decrease flight density. Site selection should be considered regarding routes of aircraft in terms of take-off and landing processes. A certain distance from shores may be imposed to prevent new routes that may occur in the future.

2.2.4 Pipelines and Cables

Under the Gulf of Thailand, there are natural gas pipelines and underground cables along the ocean [28] that should be avoided when selecting a wind farm in order to prevent damage that may occur during the installation process or maintenance.

2.2.5 Social Impact

Visual impacts and noise should be concerned if a selected place is a residential area or a tourist attraction. This problem can be reduced by locating wind farms around 1km away from the shore. to reduce turbine noise and visual impacts. [29]

2.2.6 Environment Impact

These impacts were concerned about preventing some animals, such as birds or bats, from colliding with wind turbines because the installed location was on the routes or forced to change wind directions. The vibration of turbine blades and noise can also disturb the habitats of some species of marine animals from migration routes in some species.

2.2.7 Sea depth

The installation of offshore turbines should be concerned about soil property and the sea depth affected by some types of turbine installation. The sea depth of the monopole type started from 0-30 m and the sea depth of the Tripod was 50 m However, in the future, the Floating Structure in this study could be used for over 50 m up to 300 m of water depth [30].

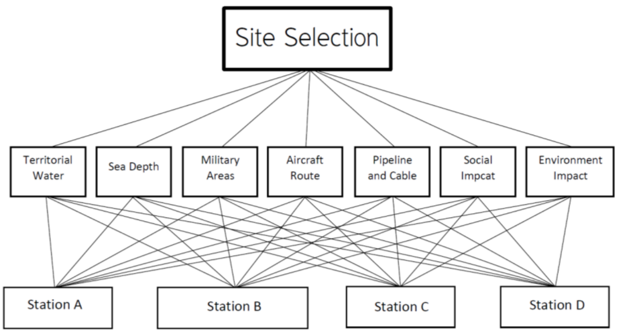

Fig. 3. Wind farm Site Criteria Decision Chart

2.3 Sitting wind assessment and analysis

In this study, 28 wind turbines of Vestas V112-3.0 MW were used, and their mean maximum generating power was 84 MW., and Annual Energy Productivity (AEP) was analysed by the WAsP program. The wind turbine site was located with space to reduce wake turbulence at 560 m It was 5 times the turbine diameter, or 5D in each row and 10D in each column.

In addition, after the offshore wind farm was selected, Annual Energy Productive (AEP) and Capacity Factor (C.F.) were calculated. The annual energy production can be calculated to find annual turbine efficiency and production as a wind turbine generator in Equation (8). [31]

$$\text{AEP} = \frac{C.F. \times Area \times WM \times 8760}{1000} \quad (8)$$

Where AEP is the annual energy output in kWh/year, C.F. is the capacity factor or efficiency factor of the wind turbines, area is the rotor area in m^2, WM is the wind power density in W/m^2, and 8,760 is hours/year.

To perform an economic study of an investment. The selected site resulted in the use of economic evaluation. This study's source offered costs from wind turbine pricing, construction costs, grid connection costs, and other costs (O&M). In Equation (9), the Net Present Value (NPV) is the present value of net cash flow to represent the capital budgeting and investment profitability analysis. Benefit-Cost The ratios in this study will be based on the cost and cash outflow of a comparable total investment cost in Equation (10). In a discount flow analysis, the internal rate of return (IRR) is a discount rate used to get the NPV to zero. In this study, the interest rate will be 4% and the investment period will be 20 years. The Levelized Cost of Energy (LCOE) reported in Thailand's Development Plan's Feed-in Tariff (FiT) report [32] was 0.202 $ per unit.

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} \quad (9)$$

$$B/C = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}} \quad (10)$$

Where, B_t is Cash inflows of investment over the time period, C_t is cash outflows of investment over the time period, i = Loan rate of the investment and t = Time period of investment. If the values of B/C < 1 investment result in losses, B/C = 1 investment is neither profitable nor profitable, and B/C > 1 investment is profitable. [33]

3. Results

3.1. Wind Potential Analysis of the Gulf of Thailand (GoT)

The raw wind data analysis results to offer wind potential in each station were addressed in this part. Table 2 displays the average wind speed and power density. The data revealed that there were three stations where the mean wind speed was greater than 3 m/s at 10 m. Rayong, Prachuap, Songkhla, and Narathiwat had wind speeds of 3.45 m/s, 3.24 m/s, 3.10 m/s, and 3.60 m/s, respectively, with power densities of 67 W/m^2, 54 W/m^2, 44 W/m^2, and 82 W/m^2.

The monthly mean wind speed in an average of 4 years was shown in Figure 4 and 5. In these figures, it displays that almost all of the wind data was insufficient to provide power in some months, but the average wind data was interesting at Rayong, Prachuap, Songkhla, and Narathiwat stations, and these stations should be in the site selection process.

3.2 Site Selection for Offshore wind farm

The wind stations were selected at above 3 m/s of the mean wind speed. In this section, criteria decisions were followed up, and the Analytic hierarchy process (AHP) method was used to score and find the suitable site for the wind farm. The result of the criteria was discussed as follows:

3.2.1 Territorial Water

As indicated in Figure 6, the Gulf of Thailand is separated into five zones from shore: Internal Waters, Territorial Waters, Contiguous Zone, and Exclusive Economic Zones, totaling 202,676.20 km^2. [34] Internal and territorial water are represented by the green and yellow portions, respectively. This study evaluated regions that were no more than 12 nautical miles apart.

Table 2. Hourly mean wind speed of Gulf of Thailand (GoT) at 10 m 4 years 2017-2020.

Station	Location		Universal Transverse Mercator (UTM) Zone	Elevation (m)	Mean Wind speed (m/s)	Power density (W/m²)
	Latitude (m E)	Longitude (m N)				
1.Khlong Yai	268778.00	1303101.00	48 P	-55	2.65	22
2.Phliu	191987.00	1379095.00	48 P	6	2.06	18
3.Rayong	755965.00	1397770.00	47 P	273	3.45	67
4.Prachuap	588262.00	1308436.00	47 P	458	3.24	54
5.Chumphon	520634.00	1167949.00	47 P	-1	2.51	30
6.Koh Samui	613412.00	1044830.00	47 P	-1	2.60	30
7.Nakhon Si Thammarat	603387.00	944796.00	47 P	19	2.31	28
8.Songkhla	677136.00	794418.00	47 P	16	3.10	44
9.Pattani	737631.00	750324.00	47 P	13	2.21	25
10.Narathiwat	811600.00	710120.00	47 P	9	3.63	82

Fig. 4. Annual wind speed patterns for the 5 AWS site along the coast line of the GoT at 10 m

Fig. 5. Annual wind speed patterns for the 5 AWS site along the coast line of the GoT at 10 m

3.2.2 Military Areas

There were 2 sites in conflict. In Prachuap Khiri Khan, there was a military zone located in the south of the bay, and it was also a restricted zone. However, there were still some available usable areas around the upper side of the station. Songkhla was in the same condition as Prachuap because the site was located around the flying unit of the Royal Thai Air Force.

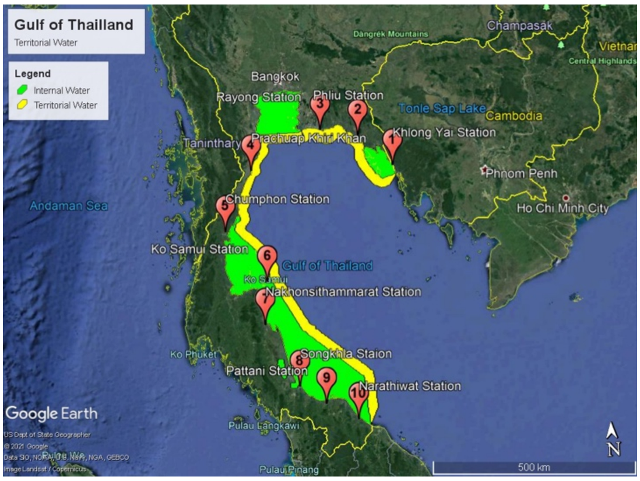

Fig. 6. Overview Territorial Water in Gulf of Thailand

3.2.3 Aircraft Routh

Aircraft routes continued to affect this criterion, according to Civil Aviation. Songkhla Airport, or Hat Yai International Airport, is located in the Royal Thai Air Force area, which is used for take-off and landing aircraft. Therefore, the Songkhla site was not suitable for an offshore wind farm.

3.2.4 Pipeline and Cables

In the Gulf of Thailand, there are natural gas pipelines that distribute gas energy as a source of electricity in the country. The path of pipelines and cables that lie aligned at the bottom of the sea. There are 2 sites that are the main hubs of this pipeline, Rayong and Songkhla. As a result, these sites were unselected.

3.2.5 Social Impact

People who live in a coastal area could be impacted by noise and other visual effects. On other sites, except Rayong, it could be possible to install wind turbine farms far away from the shore. In Rayong, there are some small islands around this site, including Samet Island. That is, there are always many tourists at the site, so a wind farm could impact on the scenery and the number of tourists coming to this site. As a consequence, it could not be a good turbine site.

3.2.6 Environment Impact

There was a marine migration report of Indo-Pacific Bottlenose dolphins, Finless porpoises, Indo-Pacific Humpback dolphins, Irrawaddy dolphins, Bryde's whales and Omura's whales around the Prachuap Khiri Khan shore. [35] This topic needs to be further studied in order to be concerned about the impacts on marine life around this shore. However, this could be a minor effect on site selection.

3.2.7 Sea Depth

Although the deepest part of GoT is 80 m, the average depth is around 50 m The sites that were used in this study were around 10-20 m deep, so they were not considered an effective site to be selected. After the criteria of selection were discussed, the results are shown in Table 4 with the mean wind speed at 50 and 84 m from Equation (1) and the AHP Process was completed and defined, the data values with the matrix calculator showed that there were two selected sites: Narathiwat and Prachuap Khiri Khan.

3.3 Wind assessment analysis for selected sites

There were two suitable sites in Table 3 to analyse wind power for wind farms. Prachuap Khiri Khan is located in the upper part of the south of Thailand and is in contact with the middle part of the Gulf of Thailand. According to the results from WAsP, the mean wind speed, wind power density, wind direction and Weibull distribution were found as shown in Figure 7. And Table 4. mean wind speed and power density at 84 height m are 4.1 m/s and 121 W/m^2, respectively, with most wind frequency distribution coming from 240° or the South South-West (SSW) side.

Table 3. Analysis suitable location for offshore wind farm with criteria decision (✓ Suitable, × Unsuitable, * Partially suitable)

Station	Mean Wind Speed (m/s)		Territorial Water	Military Areas	Aviation Route	Pipeline and cable	Social Impact	Environ ment Impact	Sea Depth
	at 50 m	at 84 m							
Rayong	4.18	4.45	✓	✓	*	×	*	✓	✓
Prachuap	3.93	4.18	✓	*	✓	✓	✓	*	✓
Songkhla	3.78	4	✓	*	×	×	✓	✓	✓
Narathiwat	4.4	4.69	✓	✓	*	✓	✓	✓	✓

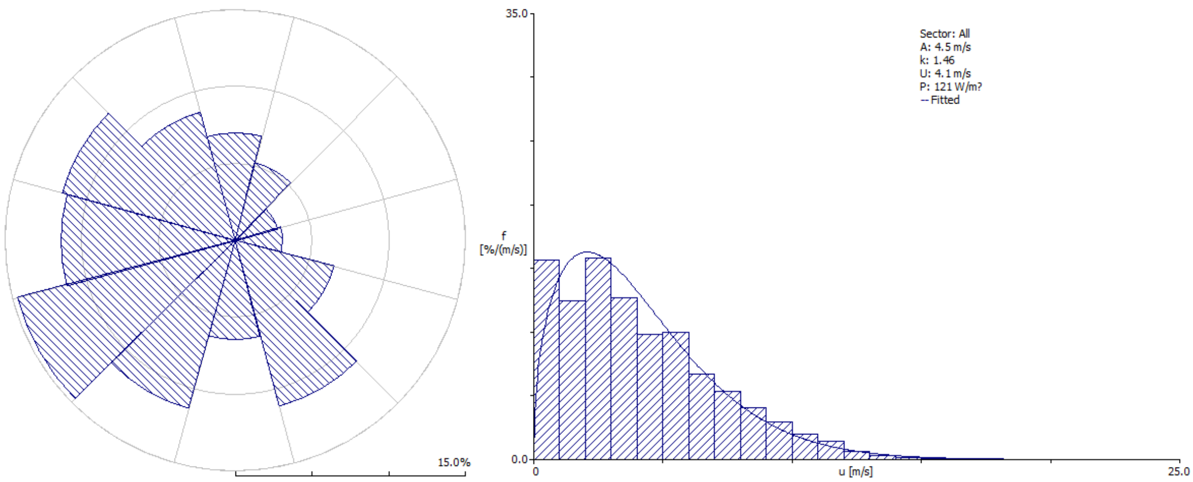

Fig. 7. Wind Rose and Weibull distribution at 84 m agl of Prachuap Khiri Khan site.

Table 4. Prachuap Khiri Khan distribution sector site statistic

Angle°	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
Frequency (%)	7.1	5.4	3	3.2	6.7	11.2	6.5	11.3	14.4	11.1	11.5	8.5
Weibull-A (m/s)	6.3	6.8	5.4	4.5	5.5	7.4	4.5	4.1	4.5	3.8	2.7	2.8
Weibull-k	2.04	2.16	1.77	1.5	1.78	2.32	1.41	1.82	1.72	1.45	1.59	1.22
Mean speed (m/s)	5.61	6.01	4.81	4.1	4.93	6.6	4.07	3.64	4.02	3.49	2.38	2.64
Power density (W/m^2)	202	236	149	114	159	294	123	62	90	75	21	43

The wind farm installation, the row and the column of the wind farms in the selected areas were different from the nature of the coast. There were 28 suitable wind turbines organized into 4 rows and 7 columns at the Prachuap Khiri Khan site. The spacing of turbines was 560 m per row and 1120 m per column at 112 m of the hub diameter. The statistical results of the wind farms are shown in Table 5. For the Prachuap wind farm site at 84 m of wind turbine height, the Wake Loss was 6.86%, which means the total net of AEP was missing from the gross AEP of 16.7 GWh. That is, the mean percent of wind farm efficiency at this site was 93.4%.

200 high resolutions of the wind maps of Prachuap Khiri Khan at 84 m of height and 50 × 50 km^2 were provided, including the mean wind speed, the power density and the AEP map area as shown in Figure 8-10. The interior details of the wind farm were discussed later. Along the shore, the wind farms with wind directions were provided by Google Earth Pro as shown in Figure 11.

Table 5. The statistical results of Prachuap Khiri Khan wind farm site

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	243.41	8.69	8.36	8.88
Total net AEP [GWh]	226.7	8.1	7.88	8.43
Proportional wake loss [%]	6.86	-	3.43	9.07
Capacity factor [%]	33.1	-	31.8	33.7
Mean speed [m/s]	-	6.67	6.51	6.77
Mean speed (Wake-Reduced) [m/s]	-	6.46	6.37	6.61
Air density [kg/m^2]	-	1.15	1.15	1.15
Power density [W/m^2]	-	405	373	428

Fig. 8. Mean wind speed map of Prachuap Khiri Khan at 84 m agl

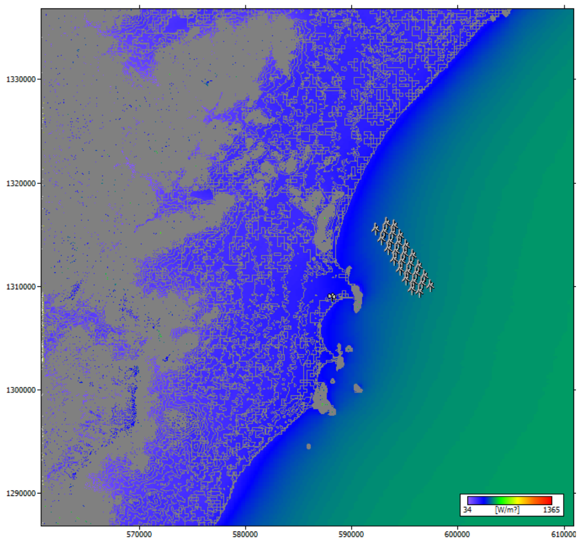

Fig. 9. Wind power density map of Prachuap Khiri Khan at 84 m agl

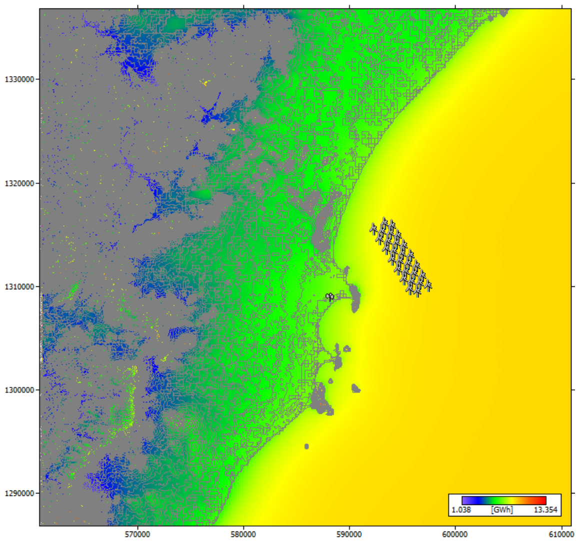

Fig. 10. AEP map of Prachuap Khiri Khan at 84 m agl

The Narathiwat site was located on the south border of Thailand. Its territorial water contacts with Malaysia's border. At 84 m of height, there was a mean wind speed and wind power density of 4.5 m/s and 181 W/m^2, respectively. The main wind direction was from 240° or the South South-West (SSW) side, as shown in Figure 12. and Table 6.

Fig. 11. The wind farm selected site and Wind direction from South South-West (SSW) at Prachuap Khiri Khan Site (The source map from Google Earth Pro)

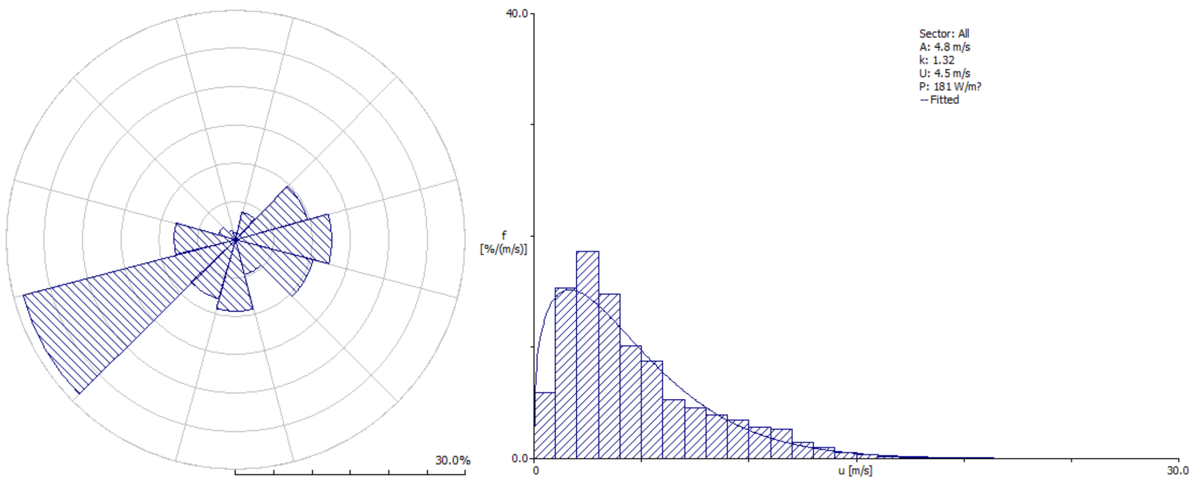

Fig. 12. Wind Rose and Weibull distribution at 84 m agl of Narathiwat site

Table 6. Narathiwat distribution sector site statistic

Angle°	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
Frequency (%)	0.9	3.8	9.8	12.6	10.5	4.7	9.3	8.1	28.7	8	2.3	1.3
Weibull-A (m/s)	4.5	6	8.3	9.7	7.8	3.8	3	2.6	3.8	3.2	3.3	4.3
Weibull-k	1.73	2.59	2.7	2.88	2.02	1.49	1.45	1.5	1.87	1.46	1.38	1.59
Mean speed (m/s)	4.04	5.34	7.35	8.68	6.88	3.47	2.72	2.38	3.34	2.87	3	3.87
Power density (W/m^2)	91	143	363	575	378	70	35	23	47	41	51	88

Table 7. represents the results of the Narathiwat site. Since the wind farm location was aligned along the shore, and fewer rows were free from some of the criteria, the wake loss at this site was 2.37%, so the efficiency site of Narathiwat was 97.6%. The high resolution of the wind map of this site is shown in Figure 13-15. It consists of a mean wind speed map, a power density map and an Annual Energy Production (AEP) map for the 50 × 50 km^2 area of the Narathiwat site with 200 resolutions. The wind directions, the wind farm site and the area map were sourced from Google Earth Pro as shown in Figure 16.

Table 7. The statistical results of Narathiwat wind farm site

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	277.37	9.91	9.68	10.09
Total net AEP [GWh]	270.8	9.67	9.48	9.87
Proportional wake loss [%]	2.37	-	0.87	2.73
Capacity factor [%]	37.7	-	36.8	38.4
Mean speed [m/s]	-	7.27	7.18	7.35
Mean speed (Wake-Reduced) [m/s]	-	7.18	7.11	7.26
Air density [kg/m^2]	-	1.15	1.15	1.15
Power density [W/m^2]	-	510	499	518

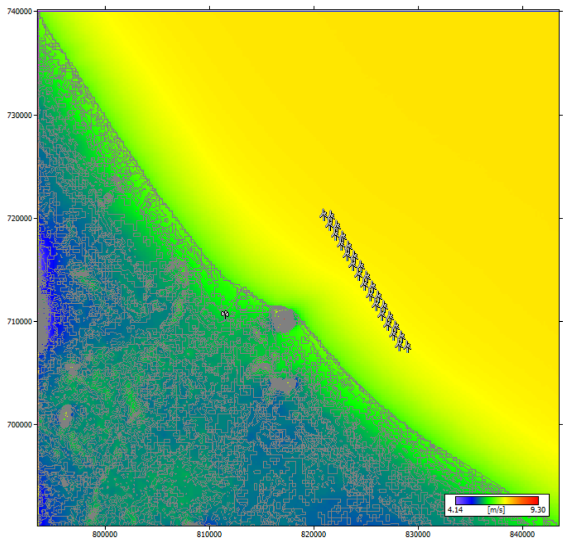

Fig. 13. Mean wind speed map of Narathiwat at 84 m agl

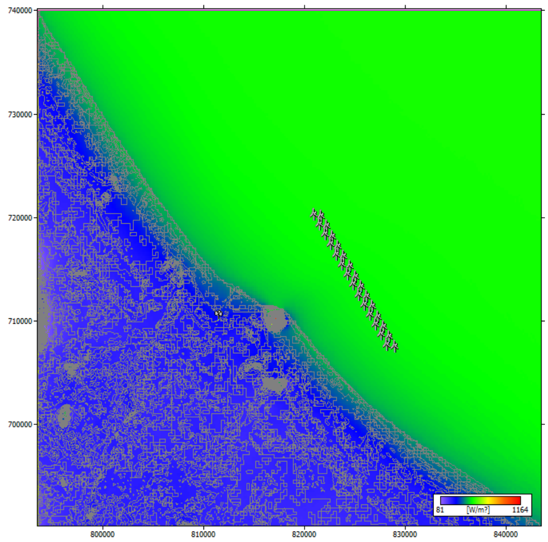

Fig. 14. Wind power density map of Narathiwat at 84 m agl

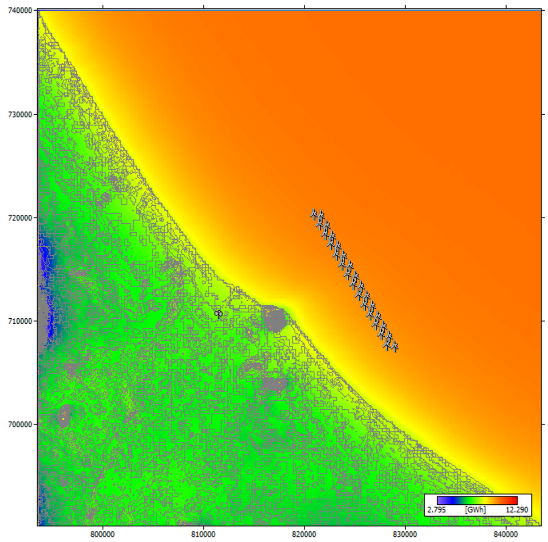

Fig. 15. AEP map of Narathiwat at 84 m agl

Fig. 16. The wind farm selected site and Wind direction from South South-West (SSW) at Narathiwat Site (The source map from Google Earth Pro)

At these two selection sites, the frequency of wind distribution in Narathiwat site the most frequency distribution is 28.7% of wind distribution in 240° was more constant than Prachuap that frequency distribution is 14.4% in 240°, and it affected the wind speed measurement and analysis that provide wind speed at Narathiwat is 4.5 m/s and 4.1 m/s in Prachuap Khiri Khan. However, the expansion of larger wind farm scale of Prachuap site should be concerned about limitations of the restriction zone, economy impacts and other impacts on marine imitation from the MCDA. Therefore, Narathiwat site could be a better choice with higher wind potential and the Total net AEP, but there were some criteria to concern. Due to the deepest sea, this wind farm site could not be installed far away from the coarse line. A further study was needed in other criteria concerns.

In the economic analysis, the selected wind farm is established in the identical conditions as before, with the exception of the net AEP that was calculated. Table 8 shows the investment cost for an offshore wind farm at $3300/kWh [36] based on a 4% interest rate and a 20-year investment period. The results show that in Prachuap Khiri Khan, the benefit-cost ratio and IRR were 1.12 and 4%, respectively, with an LCOE cost of $0.17/kWh, and in Narathiwat, the benefit-cost ratio and IRR were 1.34 and 10%, respectively, with an LCOE cost of $0.14/kWh. Thus, Narathiwat is the preferable place for economic investment, with an IRR greater than the interest rate.

Table 8. Selected Offshore windfarm economic analysis.

Wind farm	Prachuap Khiri Khan	Narathiwat
AEP (GWh)	226.7	270.8
Turbine Initial Cost ($)	110,880,000	110,880,000
Construction Cost ($)	41,580,000	41,580,000
Grid Connection Cost ($)	69,300,000	69,300,300
O&M and Other Cost ($)	55,440,000	55,440,000
Total Investment Cost ($)	277,200,000	277,200,000
B/C Ratio	1.12	1.34
NPV ($)	69,732,910	181,838,341.62
IRR (%)	4	10
LCOE ($/kWh)	0.17	0.14

4. Conclusions

This study incorporates uncertainly sourced data from wind resource and energy production, as well as calibration of observation sensors and the position of meteorological masts. This can result in an inaccuracy in the data obtained or in the measurement of wind energy, particularly in the AEP. The uncertainty analysis should be used to reduce the cost of energy or to improve the efficiency of wind farm procurement in the future study.

The wind resource assessment and offshore wind farm site selection in the Gulf of Thailand were separate into 10 site stations at 10 m of height in every 10 minutes for 4 years (2017-2020).

There were four sites with mean wind speeds greater than 3 m/s, which was deemed a minimum for cut-in wind turbines. Furthermore, MCDA was utilized to determine the best offshore wind farms. The chosen places were Prachuap Khiri Khan and Narathiwat, both of which had some conflicts. The mean wind speed was 4.1 m/s and 4.5 m/s, the wind power density was 121 W/m^2 and 181 W/m^2, and the net Annual Energy Productive (AEP) of 28×V112 turbines was 226.71 GWh and 270.79 GWh, respectively, at 84 m of turbine height at Prachuap Khiri Khan and Narathiwat locations. The wind is blowing from 240° South South-West (SSW) in both locations, but slightly more in Narathiwat. The net AEP values at the Narathiwat location were relatively high. The turbine alignment at the Narathiwat site was in two rows and fourteen columns, however at the Prachuap Khiri Khan location, it was in four rows and seven columns, with more wake loss turbulence, which can help to lessen by separating wind turbine space in rows with 5D and 10D in column. The 200 m high resolution wind map with a 50×50 km^2 area revealed that there was more wind power value energy in all assessments, including wind power, power density, and AEP, implying that the further the distance from the shore, the better the wind values. However, the economics of long-distance installation and sea depth need be investigated further. For the investor, Narathiwat is a better station than Prachuap Khiri Khan. According to the economic evaluation results, Narathiwat's LCOE was $0.14/kWh, which was less than $0.17/kWh in Prachuap Khiri Khan.

Wind observation was utilized in this study to measure from onshore for greater accuracy and less tolerance, while wind data at offshore wind should be measured by observation. Due to a shortage of research data that may result in unsuitable wind farm sites, a further investigation in some part of the criteria or some places is proposed to produce more certain decision outcomes in the criteria data. Because offshore windfarm is such a new trend and technology, the true price and cost were questionable for more accurate numbers for economic analysis.

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