Study on Offshore Wind Energy Potential
in the Gulf of Thailand

Pariyes Sawasklin

A Thesis Submitted in Fulfillment of the Requirements for the
Degree of Master of Engineering in Energy Technology
Prince of Songkla University
2021

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Author	Mr. Pariyes Sawasklin
Major Program	Energy Technology

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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Candidate

ชื่อวิทยานิพนธ์ ศึกษาศักยภาพพลังงานลมนอกชายฝั่งอ่าวไทย
ผู้เขียน นาย ปริเยศ สวาสดิ์กลิ่น
สาขาวิชา วิศวกรรมศาสตรมหาบัณฑิต สาขาวิชาเทคโนโลยีพลังงาน
ปีการศึกษา พ.ศ. 2564

บทคัดย่อ

พลังงานลมเป็นพลังงานทางเลือกที่สามารถนำมาใช้ได้อย่างยั่งยืนจากการที่มีอยู่อย่างไม่จำกัดในธรรมชาติ โดยความเร็วและความหนาแน่นของลมบริเวณนอกชายฝั่งนั้น มีศักยภาพที่สูงเพื่อที่จะนำไปใช้ในการติดตั้งแหล่งฟาร์มของกังหันลมเพื่อผลิตพลังงานไฟฟ้า ในงานศึกษาชิ้นนี้ได้ทำการศึกษาศักยภาพของพลังงานลมตลอดแนวชายฝั่งบริเวณนอกชายฝั่งอ่าวไทยของประเทศไทย โดยมีการเก็บข้อมูลทุกๆ 10 นาที ในระยะเวลา 4 ปี เริ่มจากปี พ.ศ. 2560 - พ.ศ. 2563 จากสถานีวัดลมตลอดแนวชาวฝั่งอ่าวไทย ทั้งหมด 10 สถานี ที่ความสูง 10 เมตร เหนือระดับพื้นดิน ในการจัดหาสถานีที่เหมาะสมในการแหล่งฟาร์มพลังงานลมนั้นจะใช้กระบวนการตัดสินใจแบบหลายหลักเกณฑ์ (Multi-criteria Decision Analysis: MCDA) เข้ามาเป็นเครื่องมือเพื่อช่วยในการตัดสินใจ ข้อมูลของลมนั้นจะใช้โปรแกรมวิเคราะห์ลม (Wind Atlas Analysis and Program: WAsP) ในการคำนวณหาผลลัพธ์ของค่าเฉลี่ยแรงลม (Mean Wind Speed), ความหนาแน่นของพลังงานลม (Wind Power Density), ทิศทางของลม (Wind Power Distribution) และหาค่าพลังงานที่ผลิตได้ในหนึ่งปี (Annual Energy Productive: AEP) ด้วยชนิดกังหันลม Vestas V112-3.0 MW โดยจะนำค่าเฉลี่ยแรงลมในพื้นที่ทีมีค่าเพียงพอในการทำให้กังหันลมทำงาน (Cut-in wind speed) มาวิเคราะห์ในการเลือกแหล่งฟาร์มกังหันลม สุดท้ายนี้จากสถานีที่ได้ทำการเลือกศึกษาทั้งหมด คงเหลือสถานีที่เหมาะสมในการติดตั้งกังหันลมสำหรับฟาร์มพลังงานลม 2 สถานี ได้แก่ พื้นที่สถานีประจวบคีรีขันธ์ และสถานีนราธิวาส ซึ่งมีความเหมาะสมในการติดตั้ง ที่ความสูง 84 เมตร จะมีค่าเฉลี่ยแรงลมอยู่ที่ 4.1 และ 4.5 เมตร/วินาที และค่าความหนาแน่นของพลังงานลมอยู่ที่ 121 และ 181 วัตต์/ตารางเมตร ตามลำดับ โดยที่ทั้ง 2 สถานีนั้นมีทิศทางของลมเฉลี่ยมากที่สุดจากทางทิศใต้และตะวันตกเฉียงใต้ (South South-West: SSW) หรือ 240 องศา และค่าพลังงานทั้งปีที่ผลิตได้จากแหล่งฟาร์มกังหันลมทั้งหมด 84 เมกะวัตต์ จากกังหันลม 28 ต้น ที่พื้นที่สถานีประจวบคีรีขันธ์ และสถานีนราธิวาสจะอยู่ที่ 226.7 และ 270.8 จิกะวัตต์-ชั่วโมง ตามลำดับ พร้อมกับอัตราความสามารถในการผลิตไฟฟ้า (Capacity Factor: C.F.) อยู่ที่ 0.33 กับ 0.38 และประสิทธิภาพของฟาร์มกังหันลมคือ 93.4% กับ 97.63% ตามลำดับ

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Academic Year	2021

Abstract

Wind energy could be an alternative new energy source with free and sustainable power energy. There is high potential of offshore wind speed and power density that are suitable to install a turbine farm for a wind generator. In this study, wind potential data along the east side offshore of Thailand or the Gulf of Thailand were measured in every 10 minutes for 4 years (2017-2020) from 10 meteorological masts at 10 m. high above ground level. The Multi Criteria Decision Analysis (MCDA) was used to find optimal and suitable offshore wind farm stations. The wind data by Wind Atlas Analysis and Program (WAsP) program were analyzed for the results of the mean wind speed, the wind power density, wind distribution and Annual Energy Productive (AEP) with Vestas V112-3.0 MW wind turbines. The wind climates of the sufficient mean wind speed for cut-in wind turbines were also analyzed to select wind farms. Finally, there were 2 selected sites: Prachuap Khiri Khan and Narathiwat sites which were the most optimal at 84 m of height, 4.1 and 4.5 m/s of the mean wind speed, and 121 and 181 W/m^2 the power density, respectively. The most wind direction from the frequency of the distribution was 240° or South South-West (SSW) at both sites. Besides, in this study, the total wind farm capacity is 84 MW with 28 turbines at each site. At Prachuap Khiri Khan and Narathiwat sites, the total net AEP was 226.7 and 270.8 GWh, respectively with 0.33-0.38 of the capacity factor and 93.4-97.63% of wind farm efficiency.

Acknowledgement

I would like to express my sincere thanks to my thesis advisor, Dr. Somchai Saeung and co-advisor, Asst. Prof. Dr. Juntakan Taweekun for invaluable help and constant encouragement throughout the course of this research. I am really most grateful for they teaching and advice, not only the research methodologies but also life management. I would not have achieved this far and this thesis would not have been completed without all the support that I have always received from they.

My sincere thanks also go to my thesis committee: Asst. Prof. Dr. Tianshu Ge, Dr. Kittinan Maliwan and Dr. Thanansak Theppaya.

This research was supported by the grants of Engineering Faculty Graduate Scholarships, Prince of Songkla University, Hat Yai, Songkhla 90112, Thailand. The authors would like to acknowledge Thai Meteorological Department (TMD) sharing valuable wind data and Denmark Technical University (DTU) Wind Energy support and assist WAsP software program.

Finally, I most gratefully acknowledge my parents, my friends and my wife for all their support throughout the period of this research.

Pariyes Sawasklin

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NOMENCLATURE AND ABBREVIATION

AEP	Annual Energy Production
agl	Above Ground Level
AHP	Analytic Hierarchy Process
AWS	Automatic Weather Station
C.F.	Capacity Factor
DEDE	Department of Alternative Energy Development and Efficiency
GDP	Gross Domestic Product
GoT	Gulf of Thailand
GWA	Global Wind Atlas
GWh	Gigawatt-hour
HAWTs	Horizontal-Axis Wind Turbines
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kg	Kilogram
ktoe	Kilotons of oil equivalent
kW	Kilowatt
kWh	Kilowatt-hour
m^2	Square Meters
m	Meter
MCDA	Multi Criteria Decision Analysis
MW	Megawatt
MWh	Megawatt-hour
NM	Nautical Mile
OWC	Observed Wind Climate
P	Power density
PDF	Probability Distribution Function
PWC	Predicted Wind Climate
Rpm	Round per minute
RE	Renewable Energy
s	Second
TMD	Thai Meteorological Department
TPES	Total Primary Energy Supply
TFEC	Total Final Energy Consumption
UTM	Universal Transverse Mercator
V	Voltage
VAWTs	Vertical-Axis Wind Turbines
W	Watt
WAsP	Wind Atlas Analysis and Application Program
WGS	World Geodetic System
WRF	Weather Research and Forecasting
WTG	Wind Turbine Generator

CHAPTER 1
INTRODUCTION

1.1 Significance of the study

Today, increase of mankind population has affected energy consumption, resulting in decreased sources of natural sources energy such as coal or fossil fuel and increased pollution. Therefore, to reduce the depletion of fossil fuel and pollution from coal emission, the investment in renewal energy should be the world's main concern. The consumption of energy resources rose up in 2008-2018. That is consumption coal and natural gas was increased from 2,103,391 to 2,864,881 ktoe and 423,361 to 677,561 ktoe respectively. [23] The rises of energy consumption could be a warning sign to mankind to be aware of lacking energy sources in the near future.

Energy consumption in Southeast Asia was doubled from 1995 to 2015, accounted for the average 3.4% annually. Brunei Darussalam, Cambodia, and Vietnam consumed the most quickly. In 2015, Indonesia, Malaysia, Thailand, and Vietnam used the lion's share of the region's total final energy consumption. (TFEC). That year, the industrial, transportation, and residential sectors consumed about equivalent amounts of energy regionally, but sub-regional discrepancies occurred **(Figure 1.1)**.

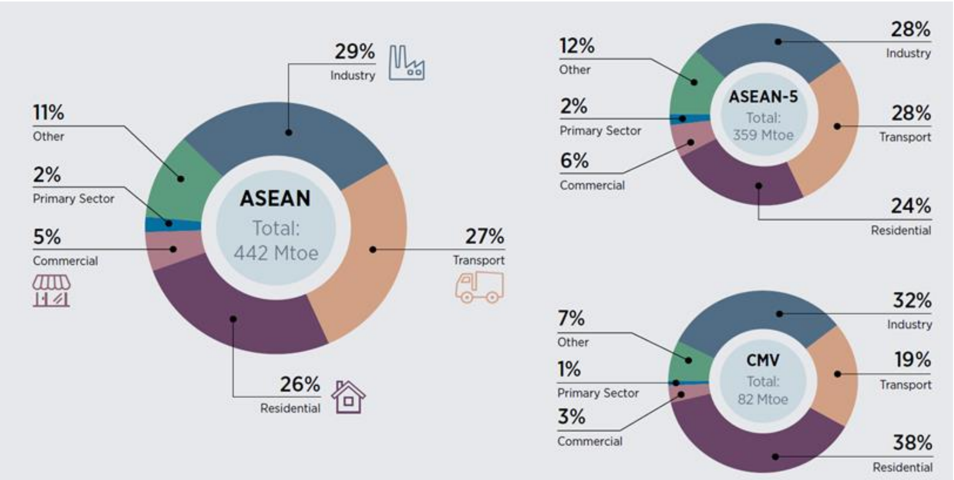


Figure 1.1 Total final Energy consumption by sector in Sotheast Asia,2015
(Source: IEA, 2017)

Industry has historically been the primary source of consumption, accounting for around 12% of total consumption in Myanmar and almost 40% in Vietnam. In instance, oil and natural gas accounted for more than half of the region's energy supply. Crude oil and its derivatives are mostly used in the transportation sector, particularly in locations with considerable increases in fuel demand. While natural gas's proportion of total primary energy supply (TPES) has expanded dramatically over the last two decades, coal's share has climbed the fastest, owing to the addition of new coal-fired power plants since 2000. In 2015, natural gas accounted for the lion's share (41%) of the energy mix, followed by coal (33%) and hydropower (16%). Energy demand is expected to grow at an average annual rate of 4.7 percent from now through 2035, in line with the region's continuous economic growth. The power sector, as illustrated in **Figure 1.2**, will have the biggest growth in energy demand, followed by industry, transportation, and buildings.

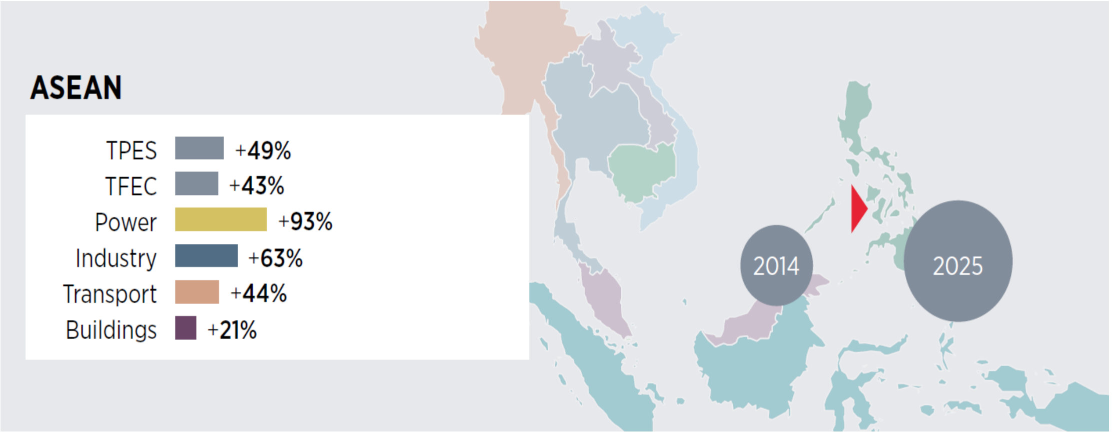


Figure 1.2 Increase in Energy demand from 2014 – 2025
(Source: IRENA, 2018)

In Thailand, there are have been aims to generate electricity by renewable energy, according to AEDP2015 plan. Of the total electricity consumption, electricity produced by renewable energy is counted as around 20 percent. Importantly, according to fuel or coal ratios in electricity generation in Thailand in Power Development Plan 2015-2036 (PDP2015), the ratios of renewable energy should be 15-20 percent within 2036. [1]

Wind energy is one of the best renewable sources of energy because it is completely free, dependable, and ecologically beneficial. Wind energy is essentially the kinetic energy of massive quantities of air moving across the earth's surface. Wind turbine blades collect this kinetic energy, which is subsequently converted to mechanical or electrical energy, depending on the eventual usage. The effectiveness of converting wind to various forms of useable energy is highly dependent on the rotor's interaction with the wind stream. [30]

The wind resource assessment and atlas are the necessary source data to improve wind power technology in order to produce electricity and reduce CO_2 emissions. There were many winds assessments studied in Chukk state [25], on-site anemometry observation [20] and on Kadavu Island and Suva Peninsula. To create a wind map with high resolution, a microscale and a mesoscale [10][49] in Gulf of Thailand include Nakhon Si Thammarat and Songkhla province, Thailand that analyze from the year resource assessment. Microscale models perform high-scale of local area and mesoscale model output to get a small-scale representation of atmosphere motion. The mesoscale wind map including complete data of wind necessary to simulation in microscale. that are used to analyze from the year resource assessment, are consisted. Wind Atlas Analysis and Application Program (WAsP) are an analysis data tool, and it is used to perform wind climate predictions, wind resources, and power generator of wind turbines [37] to determine the wind conditions at a weather station [38]. In some studies, a future wind farm assessment was used to collect wind data and populate density for more than 1 year [41]. The models contain vertical extrapolation of wind data to compensate obstacles, surface roughness changes and terrain height variations [17]. This process predicted by source data of a regional wind climatology and geostrophic as wind speed distributions for 12 directions each sector [26].

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. As a result, depending on resource availability, new offshore turbines can attain much higher full-load hours [5]. In Thailand, studies on offshore wind resources in Andaman or western Thailand have been conducted [31].

Today the energy resources from coal/ignite or natural fossil fuel/gas are being decreased while the population is increasing. That means energy consumption as electricity will grow up rapidly with the new technology that occurs. Herein, to maintain and build up electricity energy, those kinds of renewable energy should be considered and supported as is the alternate ways.

In Thailand, economic growth has been seen over two decades, at the average of 3.9% per year over period. The results showed that the mean GDP of Thailand will increase to 126% in 2036. In addition, the energy consumption demand will increase by 78%, from 142 Mtoe in 2014 to 253 Mtoe by 2036. Demand for fossil fuels will grow up by 65%, followed by 160% of coal, 60% of natural gas, and over 30% of oil products. [23]

According to the growth of GDP and technology in Thailand in the future. Wind assessment and wind data in the Gulf of Thailand should be up-to-date. For site selection of offshore wind farms that need to study in multi-criteria decision. In this study, wind resource assessment in the Gulf of Thailand was focused by collecting meteorological raw data for 4 years from 2017-2020 along the coast lines of the east side of Thailand to predict the mean wind speed, wind power distribution, wind frequency distribution, Weibull parameters and analyze a wind map by using WAsP. Multi-Criteria Decision Analysis was also applied to find places that were suitable for offshore windfarms. In this process, the optimal wind power potential was calculated rather than ranking windfarm possible site [4]. Plus, the power analysis for this site was carried out by Vestas112-3MW offshore turbines [48].

1.2 Objective

1.2.1 To study wind resource assessments of monthly and annually wind speed and wind power density within the up-to-date wind data in the Gulf of Thailand.

1.2.2 To create a wind profile by using Wind Atlas Analysis, Application Program (WAsP) and frequency distribution of wind characteristic.

1.2.3 To select wind farm sites in the Gulf of Thailand by Multi-Criteria Decision Analysis (MCDA).

1.2.4 To calculate net Annual Energy Production (AEP) for the selected wind farm sites.

1.3 The Scopes of the study

1.3.1 In this study, the wind resource assessments were focused on sites in the Gulf of Thailand by using the wind data from Thai Meteorological Department Automatic Weather System.

1.3.2 The period of collection was from 2017-2020 in every 10 minutes.

1.3.3 The wind data were obtained from 10 meteorological mast stations in the East side of Thailand: Khlongyai, Phliu, Rayong, Prachuap Kiri Khan, Chumphon, Koh Samui, Nakhon Si Thammarat, Songkhla, Pattani and Narathiwat.

1.3.4 The wind assessment potential was analyzed by WAsP program and MCDA tool was used to provide the optimal wind farm site from the study areas.

1.3.5 The AEP was analyzed in the suitable sites with 28 wind turbines of Vestas-112 3.0 MW for 84 MW of power generation.

1.4 The Anticipated results

1.4.1 To provide the up-to-date wind assessment data in the Gulf of Thailand.

1.4.2 To provide the wind profile, wind rose and Weibull distribution from at proper stations for further study and development.

1.4.3 To obtain AEP and selected suitable offshore wind farm site from 10 study sites.

1.4.4 To provide the criteria results to evaluate and improve for better selected sites in the future.

1.5 Organization of Thesis

This thesis is divided to 5 chapters in **Figure 1.3** including this chapter - Introduction and other chapters are described below:

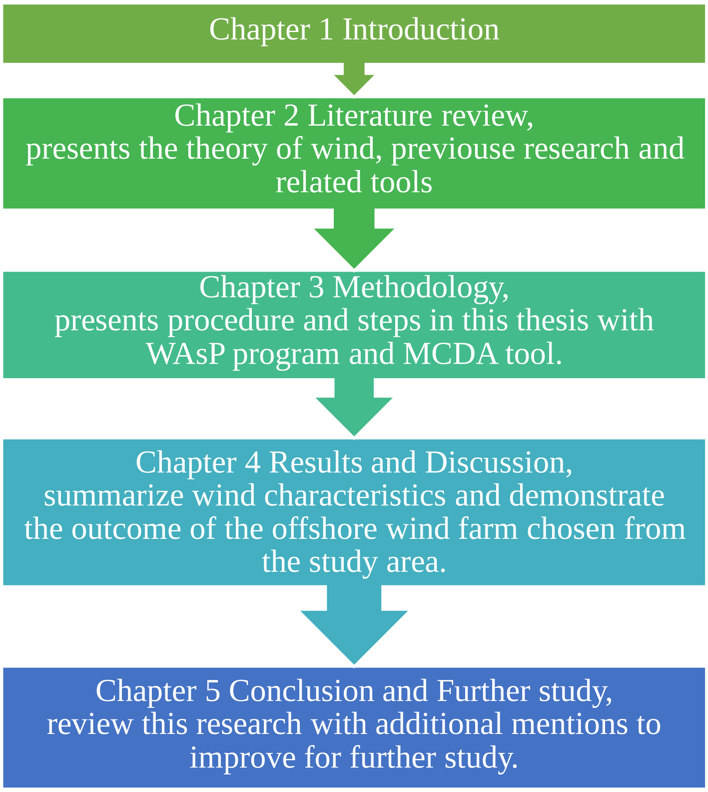


Figure 1.3 The Organization of Thesis Flows

Chapter 2 Literature review, presents the theory of wind, wind characteristics, types of wind turbines and the related theory including the wind potential in Thailand in previous studies. The MCDA tools for decision by AHC tools and the introduction of wind tools analysis of WAsP program are also explained in this chapter.

Chapter 3 Methodology presents the procedures and steps in this study. First, scope the study area and then collect the wind data by using WAsP analysis tools to provide wind assessment results and then filter stations to be optimal for wind farm sites by MCDA tools. Finally, calculate annual energy production from simulation with 28 wind turbines in the selected sites.

Chapter 4 Results and Discussion displayed the wind potential at 10 m above the ground level from 10 study stations. The result and statistics in form of Weibull distribution were analyzed by WAsP. In this chapter, the results of this study revealed the annual mean wind speed, annual power density, annual frequency distribution and annual Weibull distribution at each study site. The selected site from AHC tools of MCDA were also used to provide the annual energy productive from 28 wind turbine offshore installation.

Chapter 5 Conclusion and Further study presents a review of this research and additional ideas to improve the wind data and organizational recommendations for future research and MCDA development.

CHAPTER 2

LITERATURE REVIEW

2.1 Wind Resources

2.1.1 Wind characteristics

Wind has two fundamental properties: direction and speed. The wind vane is an instrument that can be used to determine the direction of the wind. It is also known as a weather vane. Every wind vane is made up of two parts: the front and the back. The shape of an arrow is a popular shape for a wind vane. The point of the arrow represents the ‘front,' and the tail represents the ‘rear.' This is then installed on a vertical column that may move freely when the wind blows. The surface area of the front section is smaller than that of the back.

Because it has a greater surface area, the wind puts more pressure on the rear side of the wind vane in **Figure 2.1** when it blows. As a result, the arrow aligns itself such that its tip points in the wind's direction. The wind vane will be labeled with the following directions: north, south, east, west, and so on. Another typical shape for a wind vane is a rooster. The surface area of the head is less than that of the tail, and it faces the direction of the wind. The wind vane should be set far above ground, away from trees and other objects that might interfere with wind direction, for an accurate reading.

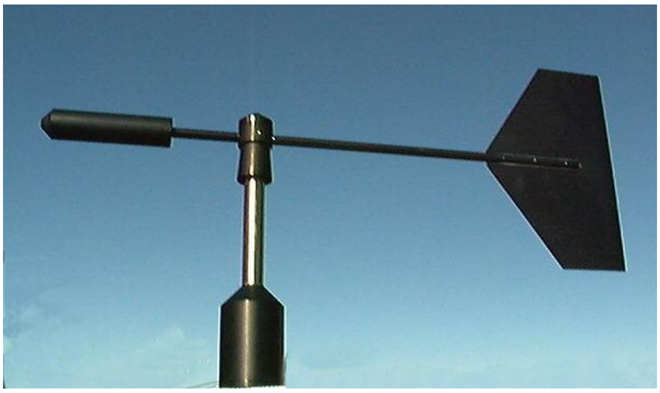


Figure 2.1 Wind direction vane
(Source: http://www.trutrack.com)

An anemometer is commonly used to measure wind speed (anemometer, wind). **Figure 2.2** depicts Cup anemometers are anemometers that have three or four cups symmetrically positioned at right angles to a vertical axis. The wind is stronger on the inside of the cup than on the outside. As a result, the cups begin to spin. The rate of rotation is proportional to the wind speed. As the wind speed increases, the cups rotate faster. Cup anemometers are mostly used by meteorological stations. [3]

Figure 2.2 Cup anemometer to measuring wind speed
(Source: Veerandra AplusTopper, 2020)

2.1.2 Wind energy

Any object that moves possesses kinetic energy, and scientists and engineers are harnessing the kinetic energy of the wind to generate electricity. Wind energy, alternatively referred to as wind power, is generated by utilizing a wind turbine, which is a device that harnesses the wind's strength to generate electricity. [34]

Wind energy is classified into three types:

1. Utility-scale turbines have a capacity range from 100 kilowatts to several megawatts. The electricity is delivered to the power grid and distributed to the end users via electric utilities or power system operators.

2. Distributed or "Small" wind: A single small wind turbine with a capacity of less than 100 kW that is used to power a home, farm, or small business directly without connecting to the grid.

3. Offshore wind turbines: These are wind turbines that are located in vast areas of water, typically on the continental shelf. Offshore wind turbines are far larger and more powerful than those on land. [2]

2.1.3 Wind energy in Thailand

In 2012, Thailand's power usage was 162,668 GWh. The industry sector consumed the most electrical energy, accounting for 82,068 GWh. The commercial, residual, agricultural, transportation, and other sectors utilized 47,210 GWh, 32,097 GWh, 70 GWh, and 930 GWh, respectively.

Thailand generates electricity using a range of sources, including natural gas, coal, and fuel oil, as well as renewable energy sources such as wind, hydroelectricity, and solar energy. Natural gas provides 63.8 percent of Thailand's electricity, followed by coal/lignite at 27.7% and fuel oil and diesel at 1.6%.

Wind energy is a limitless and sustainable source of energy that is also environmentally beneficial, and it is attracting increasing investment. Wind energy generated around 111.7 MW of power in Thailand in 2012. Thailand's government aims to increase alternative electric energy to 25% of fuel usage by 2021, with 1800 MW of wind energy, or 12.9% of all electricity generated by alternative energy in the country. (See **Table 2.1** for more information.) [11]

Table 2.1 Status and target for alternative energy in electricity generation.

Type of Energy	Output in 2010 (MW)	Output in 2011 (MW)	Output in 2012 (MW)	Output in 2021 (MW)
Wind	5.6	7.3	111.7	1800
Solar	48.6	78.7	376.7	3000
Water	58.9	95.7	101.8	324
Biomass	1650.2	1790.2	1959.9	4800
Biogas	103.4	159.2	193.4	3600
Waste	13.1	25.5	42.7	400

Thailand located near equator has moderate wind speed 3-5 m/s. A study wind assessment in Thailand began in 1975. Thailand there are 70 wind measurement station that can separated in 23 stations for 90 meters of height and 47 stations is remain in 40 meters of height and plan to upgrade to 90 meters later. Thailand Maps of Wind Turbine in 2015. (See **Figure 2.3**)

In Thailand, wind characteristics are largely determined by the monsoon, specifically the Southwest Monsoon during the rainy season, which runs from the beginning of May, June, July, August, and September to the beginning of October, and the Northeast Monsoon during the winter season, which runs from the end of October, November, December, and January to the end of February, with March and April serving as a transition period. [14]

2.1.4 Seasonal wind in Thailand

Monsoon winds are one of the most well-known seasonal winds. Monsoons are frequently misidentified as rainstorms when, in fact, they are a seasonal wind. A monsoon is a wind that changes direction periodically between winter and summer in low-latitude areas. Monsoons generally blow from land to water in the winter (during the dry phase because the wind is made up of cold, dry air) and from water to land in the summer. [9]

Thailand's climate may be classified into three seasons based on meteorological data, as follows [44]:

The rainy season, also known as the southwest monsoon season (mid-May to mid-October). Thailand is under the influence of the southwest monsoon, which brings heavy rains. August and September are the wettest months of the year. The exception can be found in Southern Thailand's East Coast, where ample rain continues until the end of the year, is the start of the northeast monsoon, with November being the wettest month.

Winter, also known as the northeast monsoon season (mid-October to mid-February). This is a warm time of year, with temperatures dropping to freezing in December and January in upper Thailand, but there is a lot of rain on the East Coast of Southern Thailand, especially from October to November.

Mid-February through mid-May is the summer or pre-monsoon season. This is the time when the monsoons shift from the northeast to the southwest. The weather warms up, particularly in upper Thailand. The hottest month is April.

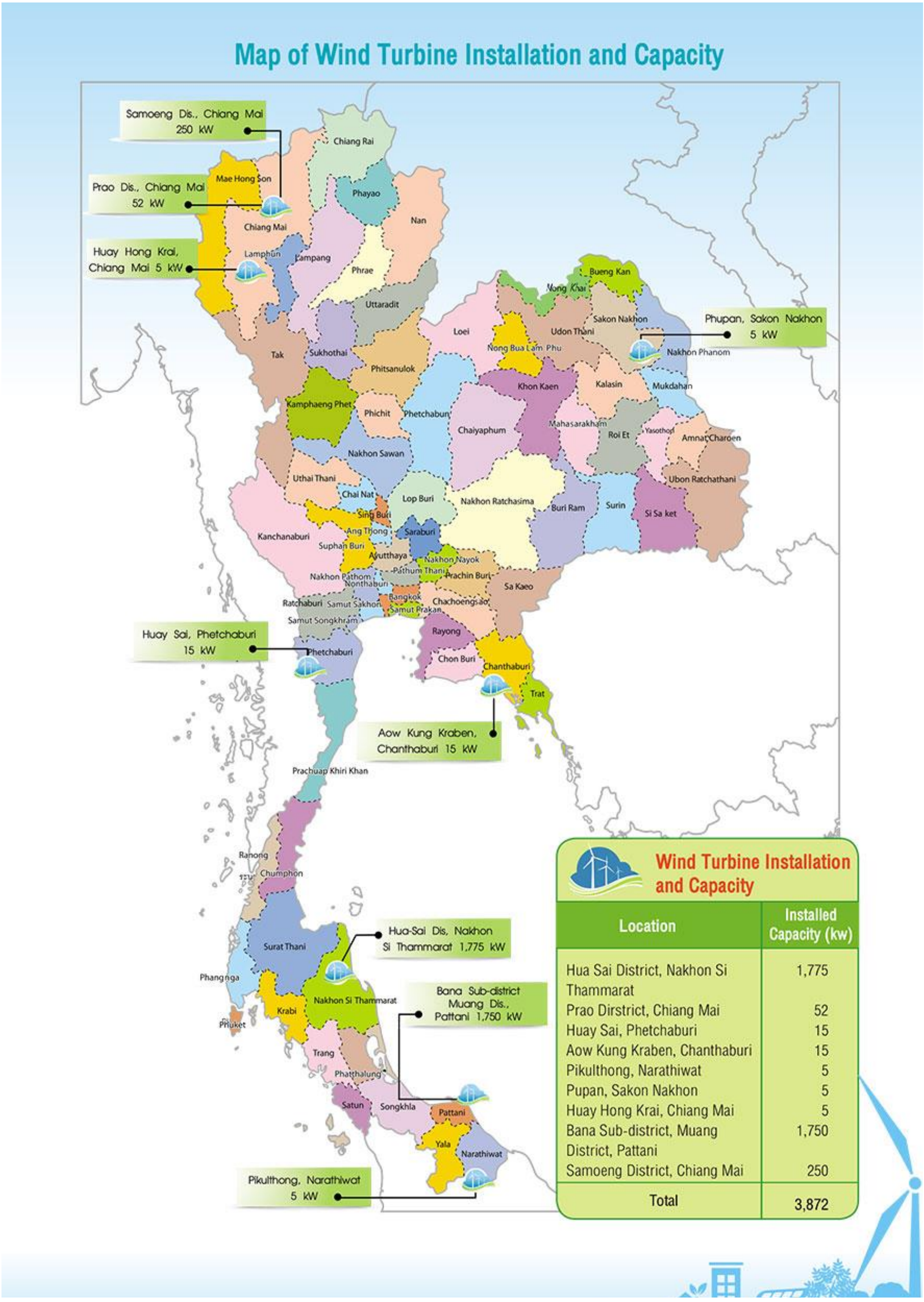


Figure 2.3 Map of Wind Turbine Installation and Capacity 2015
(Source: DEDE Ministry of Energy, 2020)

2.1.5 Wind Assessment

Over the last five years, onshore technology has advanced to maximize energy produced per megawatt capacity installed, allowing more locations with lower wind speeds to be unlocked. Wind turbines have grown in size, with higher hub heights and wider rotor diameters.

Offshore wind is likely to increase rapidly as well. Deploying turbines at water takes advantage of greater wind resources than on land. As a result, depending on resource availability, new offshore turbines can accomplish much higher full-load hours. [22]

Offshore wind resource maps were created in the Gulf of Thailand (GoT) between 2008 and 2012 using the Weather Research and Forecasting (WRF) atmospheric model within the NCEP/NCAR R2 reanalysis climate database and employing 13 met masts built along the GoT coastline. Linearize wind flow in WAsP and CFD models in order to generate a 10x10 km^2 area. Annual mean wind speeds of 5.5-6.5 m/s have been recorded in various regions of the Bay of Bangkok. [10]

2.1.6 The Beaufort Scale

The Beaufort scale is an empirical metric that correlates wind speed with observable sea or land conditions. Its full name is the Beaufort wind force scale, which was invented in 1805 by Royal Navy officer Rear Admiral Sir Francis Beaufort. **Table 2.2** showing wind speed in knots, miles per hour and kilometre per hour or mean speeds average over 10 minutes at meteorological instrument measurement 10 m above ground level. [40]

Table 2.2 Beaufort scale

Wind Force (Scale)	Description	Wind Speed			Specifications
		km/h	mph	knots	
0	Calm	0-1	0-1	0-1	Vertically rising smoke Like a mirror, the sea.
1	Light air	1-5	1-3	1-3	Wind vanes do not reveal direction, but smoke drift does. The sea shook.
2	Light breeze	6-11	4-7	4-6	Wind is felt on the face; leaves rustle; and the wind vane is moved by the wind. Small sea wavelets.
3	Gentle breeze	12-19	8-12	7-10	Leaves and little twigs are constantly moving, and light flags are extended. Large sea wavelets.

Table 2.2 (Contn'd) Beaufort scale

Wind Force (Scale)	Description	Wind Speed			Specifications
		km/h	mph	knots	
4	Moderate breeze	20-28	13-18	11-16	Dust and loose paper are raised, and little branches are displaced. Small waves, a considerable number of white ponies.
5	Fresh breeze	29-38	19-24	17-21	Small leafed trees begin to shake, and crested wavelets emerge on inland waterways. The waves are moderate, and there are a lot of white horses.
6	Strong breeze	38-49	25-31	22-27	Large branches are in motion; telegraph wires are whistling; and umbrellas are being handled with difficulty. Large waves with a lot of foam crests.
7	Near gale	50-61	32-38	28-33	Walking against the wind causes whole trees to move; it is inconvenient. Foam blowing across the sea in streaks.
8	Gale	62-74	39-46	34-40	Twigs break off trees, obstructing progress. Wave crests start to form spindrift.
9	Strong gale	75-88	47-54	41-47	Minor structural damage (chimney pots and slates removed). Wave crests collapse, and spray reduces visibility.
10	Storm	89-102	55-63	48-55	Rarely seen inland; trees uprooted; significant structural damage. The sea surface is mostly white.
11	Violent storm	103-117	64-72	56-63	Extremely unusual; accompanied by widespread devastation. Medium-sized ships have vanished from view behind the waves. The sea was coated in white froth, reducing visibility significantly.
12	Hurricane	>118	>73	>64	Devastation. There is a lot of foam and spray in the air, and there isn't much visibility.

2.1.7 Wind power classification

Classification wind power potential to identification wind height at 10 m and 50 m in the **Table 2.3** [27]

Table 2.3 Wind Power Class at height 10 m and 50 m

Wind Power Class	Resource Potential	At height 10 m		At height 50 m	
		Wind speed (m/s)	Wind Power Density (W/m^2)	Wind speed (m/s)	Wind Power Density (W/m^2)
1	Poor	0-4.4	0-100	0-5.6	0-200
2	Marginal	4.4-5.1	100-150	5.6-6.4	200-300
3	Fair	5.1-5.6	150-200	6.4-7.0	300-400
4	Good	5.6-6.0	200-250	7.0-7.5	400-500
5	Excellent	6.0-6.4	250-300	7.5-8.0	500-600
6	Outstanding	6.4-7.0	300-400	8.0-8.8	600-800
7	Superb	7.0-9.4	400-1000	8.8-11.9	800-2000

2.1.8 Wind Rose Distribution

The wind rose distribution is a technique of visually representing wind conditions, direction, and speed at a particular place over a time period. Average wind direction and wind speed measurements are recorded at a location at short intervals over a period of time to build a wind rose. The wind data is then sorted by wind direction to calculate the percentage of time each direction was blowing. In preparation for displaying a circle graph, wind direction data is often divided into 12 sectors equal 30° arc segments, with the radius of each of the 12 sectors representing the percentage of time of the wind blew from each segment. Wind speed data can be overlaid on each direction segment to illustrate, for example, the average wind speed while the wind was blowing from that direction during the logging period. [35]

Figure 2.4 depicts the annual frequency distribution of wind direction and speed as measured by SODAR at 105 m agl intervals of 10 minutes. The next model analysis focuses on the main wind directions northwest (300°), west (270°), and southeast (135°, where wind direction bins 120° and 150° are represented with similar frequency). [7]

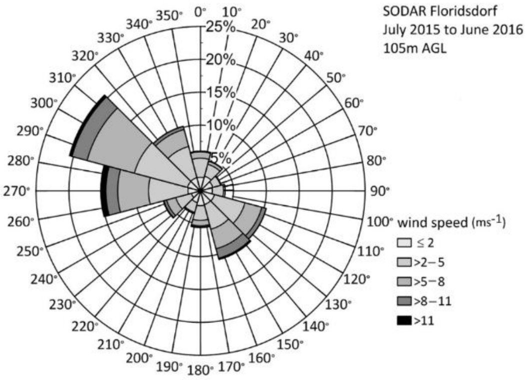


Figure 2.4 Example of Wind Rose Distribution
(Source: Baumann-Stanzer et al, 2020)

2.1.9 Wind Turbine

Wind turbines are classified into two types: horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs) (VAWTs). [18]

The HAWT is the most common type of wind turbine. They frequently have two or three long, thin blades, much like an airplane propeller. The blades are angled to face directly towards the wind. The weight of the blade in **Figure 2.5** necessitates a substantial support for the construction of this sort of turbine.

Figure 2.5 A Horizontal wind turbine for electrical generation
(Source: https://energyeducation.ca)

VAWTs have curved blades that are shorter and wider, similar to electric mixer beaters. Wind direction changes have less of an impact on vertical axis wind turbines. The advantage of mounting the turbine at ground level is that it is easy to maintain and can be positioned in sites such as rooftops. The disadvantages of this turbine arrangement are that the efficiency is decreased due to air drag and the lower wind speeds seen at higher elevations in **Figure 2.6**.

Figure 2.6 A Vertical axis wind turbine for electrical generation
(Source: https://energyeducation.ca)

The sort of foundation used for offshore wind turbines is mostly determined by water depth and sea bed conditions; unlike onshore wind farms, there is no “standard” concrete base. The monopile in **Figure 2.7** is the most commonly used solution.

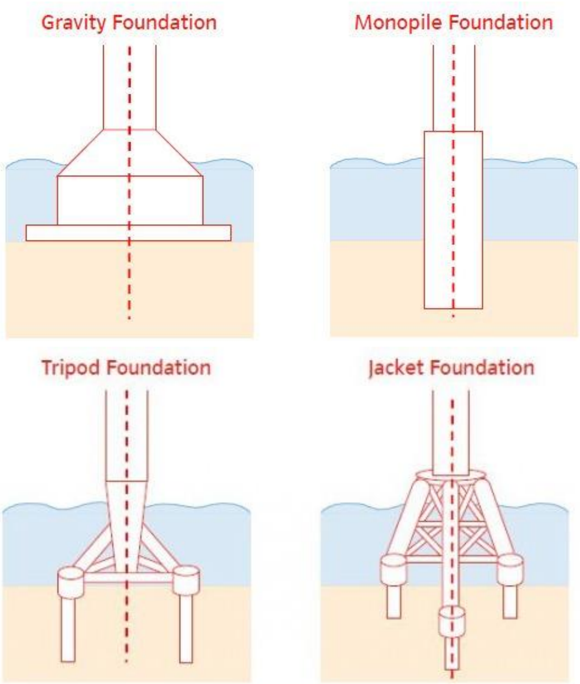


Figure 2.7 Type of wind turbine foundation
(Source: https://www.windfarmbop.com)

Gravity foundations, which are composed of precast concrete and ballasted with sand, gravel, or stones, are utilized primarily in seas with a maximum depth of roughly 30 m.

Monopile foundations are employed in water up to a depth of 25 m. They are made of steel and are hammered into the seabed for roughly 30 meters (similar to the one used to build offshore platforms)

In deeper waters, a tripod is employed (up to 35 m). It's comprised of welded-together sections and is supported on the ground by three steel piles.
If utilized in deep water, wear a life jacket (more than 40 m). It is built of welded steel beams and weighs more than 500 tons.

2.1.10 Offshore Wind farm

To selecting the optimal wind farm that necessary to analyzation in location wind direction and grid connection. Offshore wind power generating has emerged as a significant trend in the field of wind energy development. Denmark has emerged as the global leader in offshore wind power. In 2030, Europe has the capacity to generate up to 3,400 TWh of offshore wind energy within its borders [52]. Offshore wind farms provide a lot of advantages, including the avoidance of land-use disputes, the absence of special geological requirements, high wind speed, abundant wind energy, and so on. The typical unit capacity is at 3 MW, with the larger units having up to 5 MW.

2.2 Related theory

2.2.1 Air density

To predict wind energy potential, it is necessary to assess the air density of the specific area. Air density can calculate as [25]

$$\rho = \frac{\bar{p}}{R\bar{T}}$$

Here, R is the ideal gas constant (= 287 J/kg K), $\bar{p}$ is the monthly average atmospheric pressure, according to the ideal gas law, the air density value is proportional to the atmospheric pressure but inversely proportional to the temperature. and $\bar{T}$ is the absolute temperature (Kelvin).

2.2.2 Wind speed distribution

The Weibull distribution has been used in various studies winds study to determine wind energy quantity with stable accuracy in evaluating actual wind speed data. Furthermore, the WAsP model is more convenient and appropriate for studying wind with limited resources and time. [28]

The Weibull distribution (named after Swedish scientist W. Weibull, who used it in the 1930s to research material strength in tension and fatigue) provides a close approximation to the probability rules of many natural occurrences. For a while, it has been used to represent wind speed distributions for use in wind load investigations. This technique has received the greatest attention in recent years for wind energy applications, not only because of its higher flexibility and simplicity, but also because it can provide a strong fit to experimental data. Wind speed can be expressed using the Weibull distribution function, which is a two-parameter function [29].

The Probability density function of the Weibull Equation (1)

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

Equations represent the Weibull distribution's related cumulative probability function (2)

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

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

Figure 2.8 depicts five Weibull distributions, each with a different Weibull k value and the same average wind speed of 6 m/s. Lower k values, as shown in the graph, correspond to broader wind speed distributions, indicating that winds tend to vary over a wide range of speeds. Higher k values correspond to tighter wind speed distributions, implying that wind speeds tend to be restricted to a narrow range. [21]

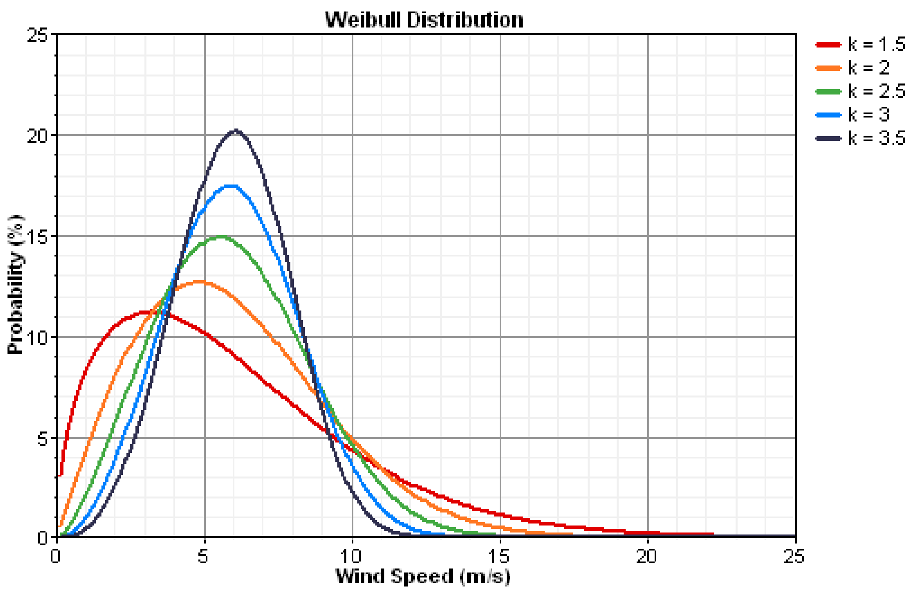


Figure 2.8 Weibull distribution in various k values ($c = 6.0\ m/s$)
(Source: https://www.homerenergy.com)

k and c can be calculated by Equation (3) and (4)

$$k = \left(\frac{\sigma}{v_{avg}}\right)^{-1.086} \tag{3}$$

$$c = \frac{v_{avg}}{\tau(1-1/k)} \tag{4}$$

Where v_{avg} and σ are wind speed average and variation. τ is the Gamma function, which is denoted by Equation (5).

$$\tau(x) = \int_0^\infty e^{-u} u^{x-1} du \tag{5}$$

As a result, Equation can be used to calculate the mean wind speed (MWS) (6).

$$MWS = \int_0^\infty v f(v) dv \tag{6}$$

Equation can be used to calculate the effective wind power density (EWPD) of wind turbines (7).

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

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

$f'(v)$ The probability density function of the effective wind speed is given in Equation (8).

$$f'(v) = \frac{f(v)}{F(v_2 - v_1)} \tag{8}$$

MWS and EWPD are both common indices for assessing wind resources. Equation can also be used to calculate the wind power density (9).

$$\text{WPD} = \frac{1}{2}\int_{0}^{\infty} \rho v^{3} f(v) dv \tag{9}$$

2.2.3 Various height wind speed

The wind speed at height of hub that interested in power application, the available wind speed necessary to measuring at wind turbine hub height. [8] Because of wind assessment are based onshore met mast that height 11 meter. To calculate the wind speed in various height by Equation (10).

$$V = V_0 \left(\frac{h}{h_0}\right)^{\alpha} \tag{10}$$

Where V and V_0 represent the wind speed (m/s) at h and h_0 m, respectively. h is the height (in meters) that corresponds to V (m/s). α refers to the surface roughness coefficient, which has been set at 0.12 for smooth sea surface as terrain area data for offshore sites. [31]

2.2.4 Analysis energy of wind power [53]

A wind turbine's Annual Energy Production (AEP) is the total quantity of electrical energy it produces in a year, measured in kilowatt hours or megawatt hours (kWh or MWh). The power from the power curve for each wind speed is estimated by multiplying the power from the power curve by the wind speed frequency distribution encountered by the wind turbine and the number of hours in a year. The overall AEP of a wind farm may then be computed by aggregating the AEPs of each wind turbine.

The maximum power produced by a wind turbine's generator, measured in kilowatts or megawatts, is referred to as its capacity or rated power (kW or MW). [12]

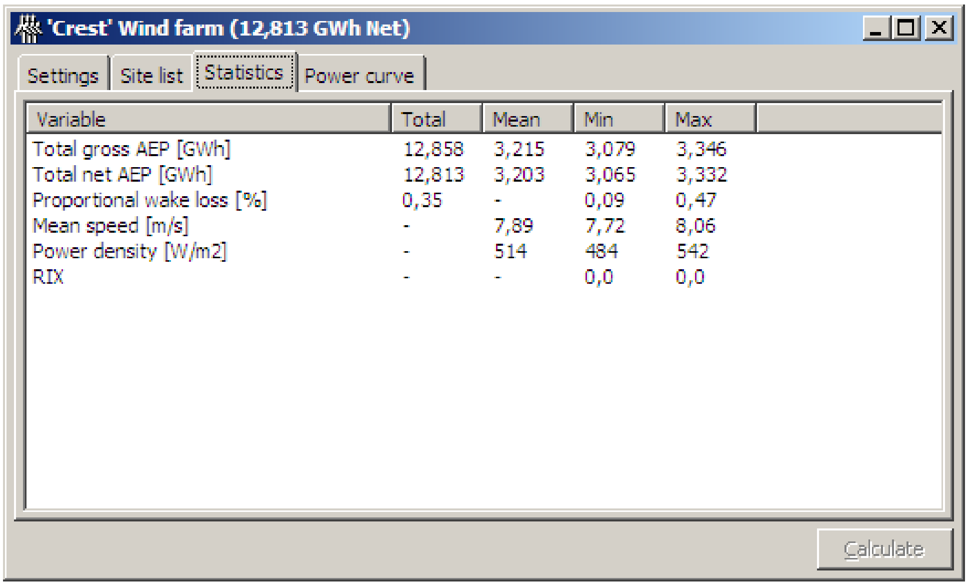
$$AEP = \frac{CF \times Area \times WM \times 8760}{1000} \tag{11}$$

Where, $C.F.$ is Capacity Factor is reduced from 100% to indicate maximum rated power of wind turbine most of the time, WM is the wind power density in W/m^2, and 8,760 is hours per year. The 1,000 converts watts into kilowatts

2.2.5 WAsP Program [50]

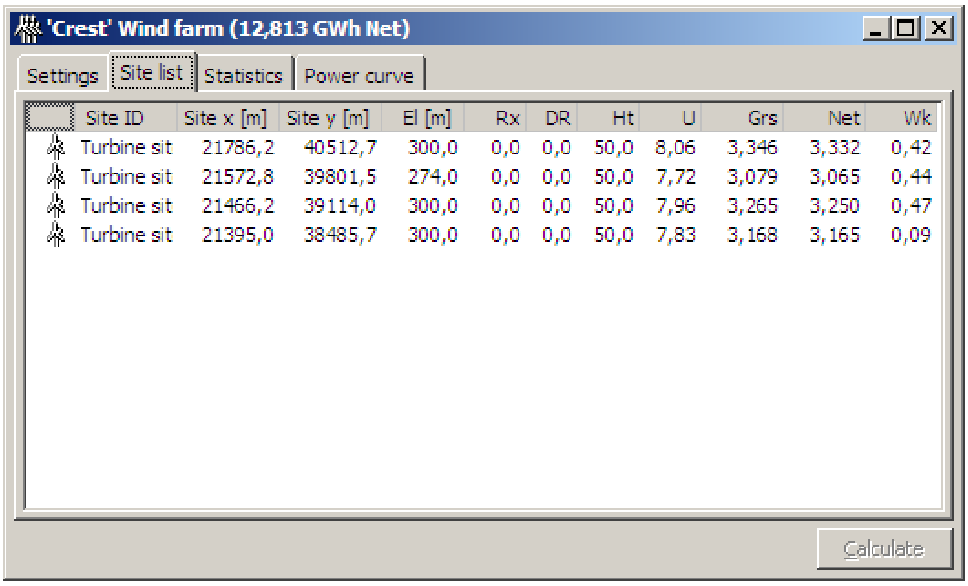
WAsP is a PC software for full data analysis and performed for wind climate predictions, wind resources, and power generator of wind turbine [37] and to determine the wind conditions at the weather station. In some study using WAsP for future wind farm assessment by collected wind data and populated density more than 1 year. [38] And in the WAsP models contain vertical extrapolation of wind data to compensate obstacles, surface roughness changes and terrain height variations. This process predicts by source data of a regional wind climatology and geostrophic as wind speed distributions for 12 directions sector. [17] WAsP program in Offshore is difference from land condition model wind resource by the sea surface is not constant in roughness.

To compute wind farm productivity WAsP, estimate the wake losses for each turbine in the farm and hence the net annual energy production of each wind turbine and the farm as a whole in **Figure 2.9-2.10**



Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	12,858	3,215	3,079	3,346
Total net AEP [GWh]	12,813	3,203	3,065	3,332
Proportional wake loss [%]	0,35	-	0,09	0,47
Mean speed [m/s]	-	7,89	7,72	8,06
Power density [W/m2]	-	514	484	542
RIX	-	-	0,0	0,0

Figure 2.9 Statistics of wind farm production



Site ID	Site x [m]	Site y [m]	El [m]	Rx	DR	Ht	U	Grs	Net	Wk
Turbine sit	21786,2	40512,7	300,0	0,0	0,0	50,0	8,06	3,346	3,332	0,42
Turbine sit	21572,8	39801,5	274,0	0,0	0,0	50,0	7,72	3,079	3,065	0,44
Turbine sit	21466,2	39114,0	300,0	0,0	0,0	50,0	7,96	3,265	3,250	0,47
Turbine sit	21395,0	38485,7	300,0	0,0	0,0	50,0	7,83	3,168	3,165	0,09

Figure 2.10 Site list of wind farm production

WAsP supplied Using Micro Siting as a regional wind climate and a digital map, the wind climate at every site and height on this map may be analyzed in seconds. A 'virtual' wind turbine site can be moved across the terrain using the mouse or by specifying its coordinates, and the wind conditions and estimated electricity production of various sites can be obtained. **Figure 2.11** shows a spatial view of wind climate and digital map.

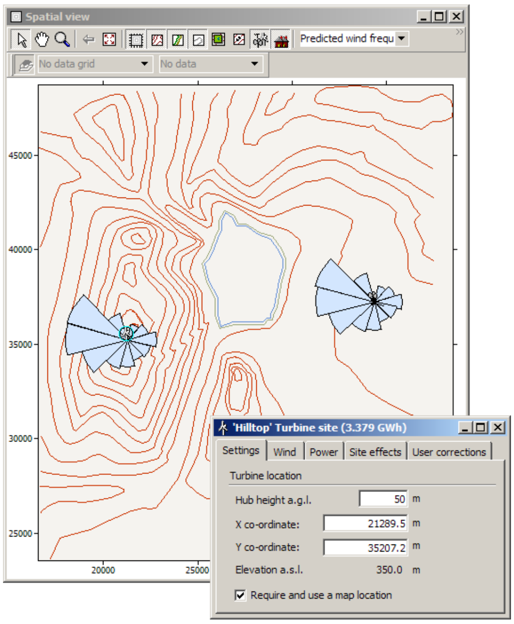
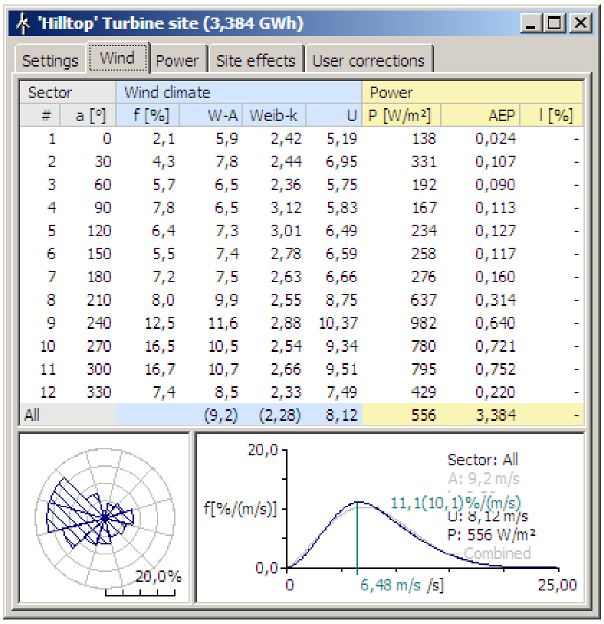


Figure 2.11 Spatial view of wind climate and digital map

Wind Power Potential is calculated by estimating the mean annual energy production (AEP) of a wind turbine and providing WAsP with the wind turbine's power curve in **Figure 2.12**.

predicted wind climate + power curve —> annual energy production (AEP) of wind turbine

If, for example, a 1-MW wind turbine is erected at a given site, the following results are readily obtained:



Sector		Wind climate				Power		
#	a [°]	f [%]	W-A	Weib-k	U	P [W/m²]	AEP	I [%]
1	0	2,1	5,9	2,42	5,19	138	0,024	-
2	30	4,3	7,8	2,44	6,95	331	0,107	-
3	60	5,7	6,5	2,36	5,75	192	0,090	-
4	90	7,8	6,5	3,12	5,83	167	0,113	-
5	120	6,4	7,3	3,01	6,49	234	0,127	-
6	150	5,5	7,4	2,78	6,59	258	0,117	-
7	180	7,2	7,5	2,63	6,66	276	0,160	-
8	210	8,0	9,9	2,55	8,75	637	0,314	-
9	240	12,5	11,6	2,88	10,37	982	0,640	-
10	270	16,5	10,5	2,54	9,34	780	0,721	-
11	300	16,7	10,7	2,66	9,51	795	0,752	-
12	330	7,4	8,5	2,33	7,49	429	0,220	-
All			(9,2)	(2,28)	8,12	556	3,384	-

Figure 2.12 Estimation of Wind Power Potential

2.2.6 Multi Criteria Decision Analysis (MCDA)

Multiple-criteria decision analysis, or multiple criteria decision-making (MDDM) is a subdiscipline of operations research that explicitly considers multiple criteria in decision-making environments.

Analytic Hierarchy Process (AHP) is a multi-criteria decision analysis method which was originally developed by Thomas L. Saaty in 1970s. The AHP analysis method that considers with both qualitative and quantitative information to assess the criteria weightings as the following steps: [32]

Step 1: Identify Potential Alternatives

The AHP method starts with defining the alternatives to be examined. These possibilities could represent the many criteria against which solutions must be evaluated. They could also be different product features that need to be weighted in order to better comprehend the selector's perception. Step 1 requires the completion of a complete list of all accessible choices.

Step 2: Identify the Problem and Criteria

The following step is to model the problem. A problem, according to AHP approach, is a connected set of subproblems. As a result, the AHP technique relies on breaking the problem down into a hierarchy of smaller problems. Criteria for evaluating solutions emerge during the process of breaking down the sub-problem. However, like with root cause analysis, a person can dive deeper and deeper into the problem. In **Figure 2.13**, the decision to stop dividing the problem down into smaller subproblems is a subjective one.

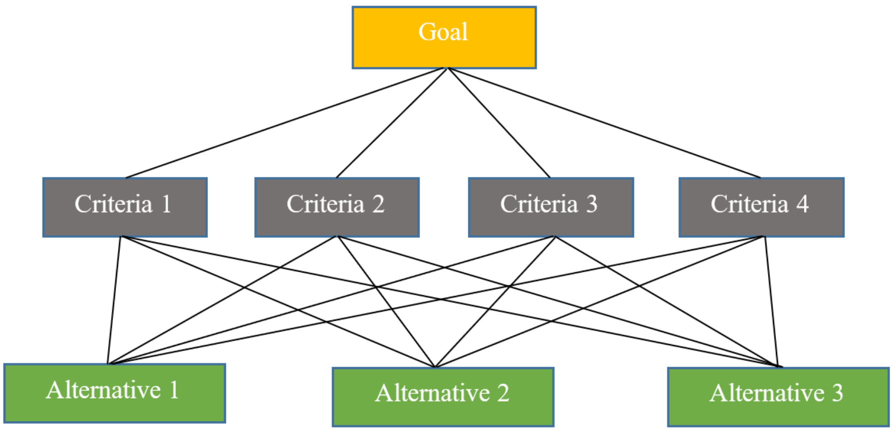


Figure 2.13 Example of a Hierarchy of Criteria

Step 3: Use Pairwise Comparison to Determine Priority Among Criteria [13]

To generate a matrix, the AHP approach employs pairwise comparison. There will be a pairwise comparison of appreciation criteria, and so forth. The specialists will be expected to fill this data in accordance with the expectations of the end selector or the people who will use the process that can distribute in mathematic as follows:

C_i = Main criteria decision where, i = 1, 2, …, n

A_j = Secondary criteria in hierarchy of diagnose where, j = 1, 2, …, n

a_{ij} = Result of pairwise comparison

Where, i = 1, 2, …, n and j = 1, 2, …, n that provide diagnose one by one criteria C_i and A_j

Therefore, the diagnostic will provide in matrix n×n can definition in matrix;

A = [a_{ij}] where, i = 1, 2, …, n and j = 1, 2, …, n

With the rules to bring a_{ij} from pairwise comparison in a couple criteria in matrix are:

1) If $a_{ij} = \alpha$ will make $a_{ij} = 1/\alpha$ by $\alpha \neq 0$
2) If criteria decision C_i was equally to criteria C_j that always provide $a_{ij} = a_{ji} = 1$

So, Matrix A can provide as following:

$$
\begin{array}{ccc}
\text{Criteria} & \begin{array}{cccc} C_1 & C_2 & C_3\ldots & C_n \end{array} & \text{Criteria} \\
A = & \begin{bmatrix} 1 & a_{12} & a_{13} & \ldots a_{1n} \\ 1/\ a_{12} & 1 & a_{23} & \ldots a_{2n} \\ 1/a_{1n} & 1/a_{2n} & 1 & \ldots a_{3n} \\ : & : & : & ::: : \\ 1/\ a_{1n} & 1/\ a_{2n} & 1/\ a_{3n} & \ldots 1 \end{bmatrix} & \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ : \\ A_n \end{array}
\end{array}
$$

Which can be summarize as in **Table 2.4**

Table 2.4 Pairwise Comparison square matrix

Criteria (C)		**Criteria**				
C_1, C_2, C_3, …, C_n		**A_1**	**A_2**	**A_3**	**…**	**A_4**
Criteria	**A_1**	1	a_{12}	a_{12}	…	a_{1n}
	A_2	$1/a_{12}$	1	a_{23}	…	a_{2n}
	A_3	$1/a_{1n}$	$1/a_{2n}$	1	…	a_{3n}
	:	:	:	:	:::	:
	A_4	$1/a_{1n}$	$1/a_{2n}$	$1/a_{3n}$	…	1

The equation that provides to fine number of diagnostics is

$$N = \frac{n^2-2}{2} \qquad (12)$$

when, N = Number of times in comparative diagnosis
n = The number of comparing factor

The most commonly used scale is the relative importance scale between two possibilities. The scale, which assigns values ranging from 1 to 9, determines the relative importance of one possibility when compared to another, as shown in **Table 2.5**.

Table 2.5 Pairwise comparison scale distribution

Importance scale	**Definition**	**Description**
1	Equally preferred	Both criteria affect objective equally.
3	Moderately preferred	One criterion was moderately preferred than other.
5	Strongly preferred	One criterion was strongly preferred than other.
7	Very strongly preferred	One criterion was very strongly preferred than other.
9	Extremely preferred	One criterion was extremely preferred than other.
2, 4, 6, 8	In the middle of upper scale	In the middle of upper scale

Step 4: Finding weight of criteria

When the weight was determining as the number term by expert. Then analyze and calculate the important weight from each hierarchical from top to bottom.

Calculate the hierarchical weight equation as following:

$$Aww = \lambda_{max}w \qquad (13)$$

when, A = Opinion of Expert hierarchical square matrix returns a numeric value adjusted to 1 (Normalized).
w = Relatively important weights for objects belonging to the same hierarchy or below or group that fall under a higher hierarchy.
λ_{max}= Maximum Eigenvalue

Step 5: Identification of Consistency Ratio: C.R.

This is to check the results of the comparisons that have been Made with the reason of consistency by:

Calculate the λ_{max} by taking the sum of the diagnostic values for each criterion in a row multiply by the sum of the horizontal averages for each row then summarize the multiplied result. If the diagnosis in the criteria is completely consistent $\lambda_{max} = n$.

Compute the conformity of Consistency index: C.I. from this equation:

$$\text{C.I.} = \frac{(\lambda_{max} - n)}{(n-1)} \tag{14}$$

Open the Random Consistency Index: R.I. where the R.I. values depend on matrix size from 1×1 until 15×15 as the R.I. result shown in **Table 2.5**

Table 2.6 Random Consistency Index: R.I.

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Compute the Consistency Ratio: C.R. by the comparison ratio between Consistency Index: C.I. and Random Consistency Index: R.I. that can derive into this equation:

$$\text{C.R.} = \text{C.I.}/\text{R.} \tag{15}$$

The acceptance of C.R. is low than or equal to 0.10 vice versa more than 0.10 is unacceptance and should be review the criteria comparison until receive acceptance result.

2.3 Related literature review

Related literature comparison as shown in **Table 2.7** is showing methods and output in each previous research. There were various studies in wind resource assessment in different country and wind data collection. This study will improve previous study in environment impact with MCDA to offshore wind farm site selection. And in this study collect wind various data from Thai meteorological mast and up-to-date data.

2.4 Research gap

In previous study, wind assessment and site selection on onshore and offshore from several study area. The wind data collection is start from 1 year in Kenya [33] until 20 years in Beijing [28]. And in Thailand there were study area from Gulf of Thailand for 5 years, [10] Nakhon Si Thammarat and Songkhla for 2 years. [49] However, previous studies collected wind data that was quite old, so in this study they used wind data from 2017 to 2020 for four years, which differs from previous MCDA methods [41] [4] [24] by using Analytic Hierarchy Process (AHC) tools to analyze wind farms with a number of criteria for optimal wind farm in the Gulf of Thailand.

In this study, the WAsP program was used in most of the studies to analyze the wind data as mean wind speed, power density, and Weibull distribution with an additional method to select the optimal wind farm by Multi Criteria Decision Analysis (MCDA). This study is a further study from the previous Offshore Wind in the Gulf of Thailand study which used the Mesoscale, MC2 method on offshore wind farms in Thailand.

Table 2.7 Related Literature comparison

Reference	Method			Onshore	Offshore	Area	Duration	Results			
	WAsP Program	Mesoscale, MC2	Multi-Criteria Decision					Mean Wind Speed	Annual Energy Productive (AEP)	Weibull Distribution	Site Selection
Ko et al, 2015 [25]	✓			✓		Chuuk State, Micronesia	1 Years (2013)	✓	✓	✓	
González-Longatt et al, 2014 [20]	✓			✓		Venezuela	3 Years (2005-2007)	✓	✓	✓	
Chancham et al, 2017 [10]	✓	✓			✓	Gulf of Thailand, Thailand	5 Years (2008-2012)	✓	✓	✓	✓
Waewsak et al, 2012 [49]		✓		✓		Nakhon Si Thammarat and Songkhla, Thailand	2 Years	✓	✓		
Ramadan H.S., 2017 [37]	✓			✓		Sinai Peninsula, Egypt	2 Years (2002-2003)	✓	✓	✓	
Sharma and Ahmed, 2015 [41]	✓		✓	✓	✓	Fiji Islands: Kadavu Island and Suva Peninsula	1 Year 6 Months (2012-2013)	✓	✓	✓	

Table 2.7 (Cont'd) Related Literature comparison

Reference	**Method**			**Onshore**	**Offshore**	**Area**	**Duration**	**Results**			
	WAsP Program	**Mesoscale, MC2**	**Multi-Criteria Decision**					**Mean Wind Speed**	**Annual Energy Productive (AEP)**	**Weibull Distribution**	**Site Selection**
Argin et al, 2019 [4]	✓		✓		✓	Turkey	6 Years (2008-2013)	✓	✓	✓	✓
Liu et al, 2017 [28]	✓			✓		Beijing, Chaina	20 Years (1991-2011)	✓	✓	✓	
Boudia et al, 2016 [8]				✓		Algeria	5 Years (2006-2010)	✓	✓	✓	
Mukulo et al, 2014 [33]				✓		Mwingi-Kitui plateau, Kenya	1 Year (2010)	✓		✓	
Kim et al, 2017 [24]			✓		✓	Southwest Coast, South Korea	9 Years (2005-2013)				✓
This study	✓		✓		✓	Gulf of Thailand, Thailand	4 Years (2017-2020)	✓	✓	✓	✓

CHAPTER 3

METHODOLOGY

In this study, the data of wind speed, wind directions and temperatures in each concerning station were first collected. The wind speed below 3 m/s, which was considered to be insufficient to distribute for wind power, was filtered. Then the wind data were analyzed by the WAsP program. The results of WAsP could provide monthly and annually wind statistics as the wind speed at each location. The site of the optimal wind farm was selected by AHC tool of multi-criteria decision analysis as shown in the study flow process (**Figure 3.1**).

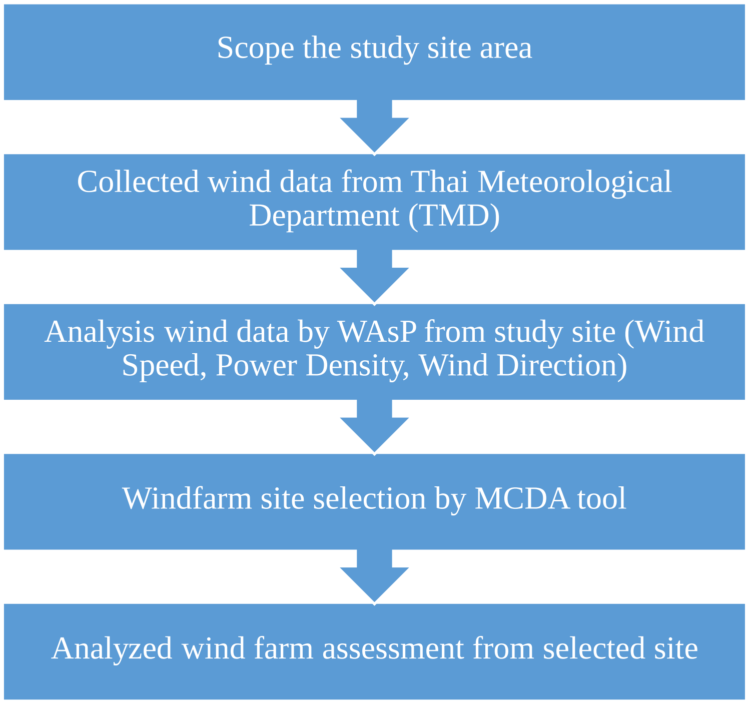


Figure 3.1 Study flow process

3.1 Study site

The Gulf of Thailand (GoT) borders are on the South China Sea, with two under water ridges aligning along the North-South barrier. The Gulf of Thailand covers around 270,000 km^2 of the total area. The topography bottom of the Gulf of Thailand is a basin. [51] The boundary of the upper Gulf of Thailand contacts with the low land of the Chao Phraya River and the eastern coastline, and the west side contacts with the southern coast of Thailand. The east side is bordered by the territorial water of Cambodia, Vietnam, and the South is sided by Malaysia. In this study, the east and south east sides of Thailand were focused. The wind data were carried out from 10 meteorological (met) mast of Thai Meteorological Department by Automatic Weather System, as shown in Figure 1, which can be separated into 3 and 7 met masts in Eastern and Southern-Eastern regions, respectively. In the eastern region of Thailand, there are Khlongyai, 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, Ko Samui, Nakhon Si Thammarat, Songkhla, Pattani and Narathiwat **(Figure 3.2)**. These stations are located at the east side and the southern region of Thailand. The raw wind data at 10 m were collected by AWS data. The wind data along the east and the southeast of Thailand were also collected by ASL height and carried out every 10 minutes' interval for 4 years from 2017-2020.

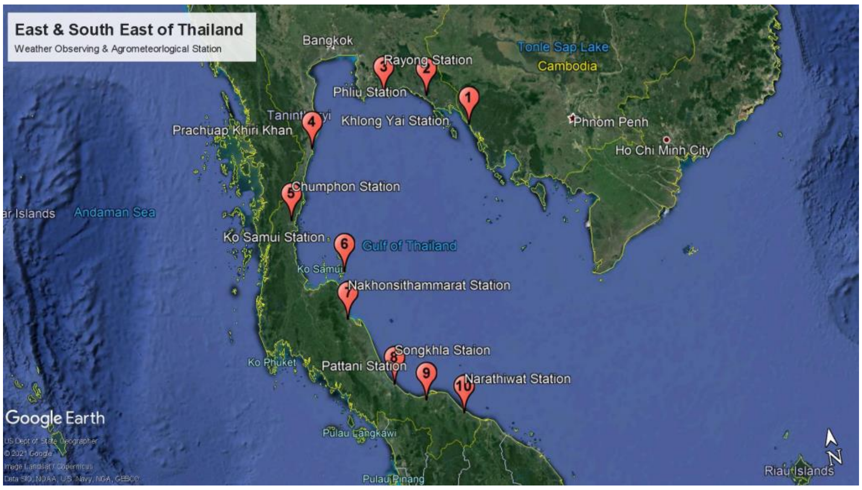


Figure 3.2 Overview of the Gulf of Thailand along with 10 AWS Thai Meteorological Station

1. **Khlong Yai Station** [47]

Khlong Yai Automatical Weather Station (AWS) is located at Trat Meteorology Station in Khlongyai district, Trat province. **Figure 3.3**

Station area	16 m^2
Latitude	N 11°46'48.0"
Longitude	E 102°52'41.2"
Zone	48 P
Elevation	-55 m

Figure 3.3 Khlong Yai AWS
(Source: Trat Meteorological Station Information, 2019)

2. **Phliu Station** [45]

Phliu Automatical Weather Station (AWS) is located at Phlew Agrometeorological Observations Group, Khlung district, Chantaburi province. **(Figure 3.4)**

Station area	16 m^2
Latitude	N 12°27’37.0”
Longitude	E 102°10’00.1”
Zone	48 P
Elevation	6 m

Figure 3.4 Phliu AWS
(Source: Chantaburi Meteorological Station Information, 2019)

3. **Rayong Station** [46]

Rayong Automatical Weather Station (AWS) is located at Rayong meteorology station, Muang district, Rayong province. **(Figure 3.5)**

Station area	15 m^2
Latitude	N 12°38’01.0”
Longitude	E 101°21’23.0”
Zone	47 P
Elevation	273 m

Figure 3.5 Rayong AWS
(Source: Rayong Meteorological Station Information, 2019)

4. Prachuap Station [43]

Prachuap Automatical Weather Station (AWS) is located at Prachuapkhirikhan meteorological station, Prachuapkhirikhan province. **(Figure 3.6)**

Station area	15 m^2
Latitude	N 11°50’06.0”
Longitude	E 99°48’37.0”
Zone	47 P
Elevation	458 m

Figure 3.6 Prachuap AWS
(Source: http://www.aws-observation.tmd.go.th)

5. Chumphon Station [43]

Chumphon Automatical Weather Station (AWS) is located at Chumphon meteorology station, Chumphon province. **(Figure 3.7)**

Station area	15 m^2
Latitude	N 10°33’56.0”
Longitude	E 99°11’19.0”
Zone	47 P
Elevation	-1 m

Figure 3.7 Chumphon AWS
(Source: http://www.aws-observation.tmd.go.th)

6. Koh Samui Station [43]

Samui Automatical Weather Station (AWS) is located at Koh Samui meteorology station, Koh Samui district, Suratthani province. **(Figure 3.8)**

Latitude	N 09°27’02.0”
Longitude	E 100°01’59.0”
Zone	47 P
Elevation	-1 m

Figure 3.8 Koh Samui Meteorological station
(Source: http://www.aws-observation.tmd.go.th)

7. Nakhon Si Thammarat Station [43]

Nakhon Si Thammarat Automatical Weather Station (AWS) is located at Nakhon Si Thammarat meteorology station, Muang district of Nakhon Si Thammarat province. **(Figure 3.9)**

Latitude	N 8°32’46.0”
Longitude	E 99°56’22.0”
Zone	47 P
Elevation	19 m

Figure 3.9 Nakhon Si Thammarat meteorological station
(Source: http://www.aws-observation.tmd.go.th)

8. **Songkhla Station** [42]

Songkhla Automatical Weather Station (AWS) is located at Sothern – East Coast meteorological center in Muang district, Songkhla province. **(Figure 3.10)**

Latitude N 7°11’03.0”
Longitude E 100°36’15.1”
Zone 47 P
Elevation 16 m

Figure 3.10 Songkhla AWS
(Source: http://wwwhttp://www.songkhla.tmd.go.th)

9. **Pattani Station** [43]

Pattani Automatical Weather Station (AWS) is located at Pattani meteorology station, Nongchik district, Pattani province. **(Figure 3.11)**

Latitude N 6°46’60.0”
Longitude E 101°09’00.0”
Zone 47 P
Elevation 13 m

Figure 3.11 Pattani AWS
(Source: http://www.aws-observation.tmd.go.th)

10. Narathiwat Station [43]

Narathiwat Automatical Weather Station (AWS) is located at Narathiwat meteorology station, Muang district, Narathiwat province.

Latitude	N 6°25’00.0”
Longitude	E 101°49’00.1”
Zone	47 P
Elevation	9 m

Figure 3.12 Narathiwat AWS
(Source: http://www.aws-observation.tmd.go.th)

3.2 Wind potential analysis

To provide the mean wind speed data in each station, Wind Climate Analysis was used as a tool in WAsP Then it was used to filter out the station that the mean wind speed was below 3 m/s because of the minimum wind speed for cut-in speed of Vestas112-3MW offshore turbines. In the vertical extrapolation, wind speed equations were applied to wind speed at various height. The available wind speed was necessary to measure the wind turbines’ hub height [8]. Since the wind assessment is based on the met mast that is 10 m high, the wind speed in various height was calculated by assume surface roughness coefficient value, which was chosen as 0.12 for smooth sea surface as the terrain area data for offshore sites [4].

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, Wind Climate Analysis tool was used to generate the power density data, and Weibull distribution was applied for shape and scale parameters. 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.

In this study, the mean wind speed was analyzed by WAsP Climate Analysis 3.1, a function tool in the WAsP program. Locations at each station needed to be specified for the data input into the program before starting the program. Then an instrument at 10 m a.g.l. of height was selected. The data from the AWS observation data reports were collected at 10-minute intervals each day for 4 years, as shown in Figure 3.13. Then the data at each site were combined by separating the data in 365 days or 1 year. Importantly, the unit of speed from knots needed to be changed into m/s before the combine wind data were imported into Climate Analysis (**Figure 3.13**). The results from the analysis, which were finally calculated at each station, were the mean wind speed, the mean wind directions, power density, Weibull A-parameter, and Weibull k-parameter.

Gathering Data by time slot

52. SONGKHLA Weather Observing Station

GMT : 2017-08-18 00:10~24:00 / Interval : 10min

Time	Wind		
	Speed	Dir	
mm/dd hh:mi	kts	Deg	
08/18 00:10	2.5	254	CALM
08/18 00:20	2.5	232	CALM
08/18 00:30	1.4	241	CALM
08/18 00:40	1.8	241	CALM
08/18 00:50	3.2	252	CALM
08/18 01:00	4.3	236	SW
08/18 01:10	4.3	199	SSW
08/18 01:20	6.1	122	ESE
08/18 01:30	6.1	109	ESE
08/18 01:40	7.9	133	SE
08/18 01:50	6.1	115	ESE

Figure 3.13 Wind data report from Thai AWS Observation

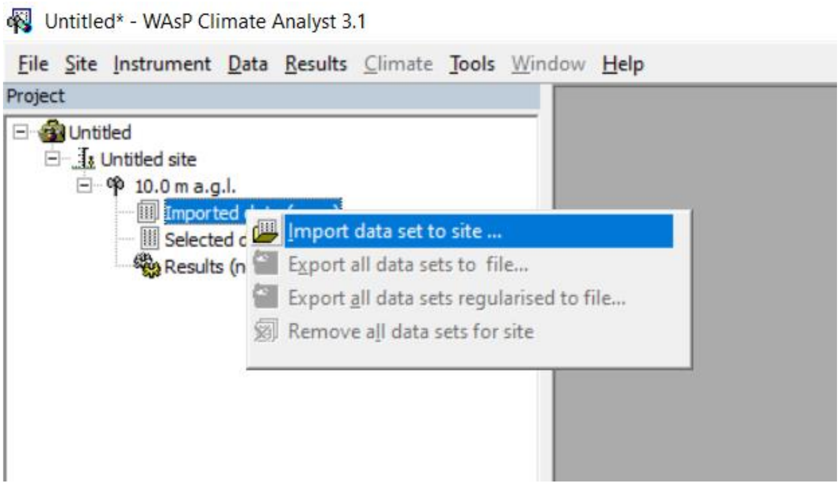


Figure 3.14 Import wind data set in m/s speed unit

3.3 Criteria of wind farm and site selection

Multi-Criteria Decision Analysis (MCDA) is the main stream used to select the wind farm concerning both of the technical data as the wind assessment in selecting areas and in social restrictions as military areas or civil areas. 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.

1. Territorial water

The territorial water is a sea border area to a shore of a state, defined in the international law [39], the law of the sea in 1982 (Art.3) which mentions that it is around 22 kilometers or 12 nautical miles from a shore.

2. Military areas

In this section, military areas include navy or onshore training areas in Thailand that are located far away from civil population with restrict zones and unusable for wind farm purpose that affects expansion wind farm site in future.

3. Aircraft route

Because of rapidly grown aviation business, a lot of new airports were established to support a number of aircrafts and new airlines. The aircraft routes needed to be increased to decrease flight density. Therefore, site selection should be considered regarding routes of aircrafts in phrases of take-off and landing process maybe imposed by certain distance from shores to prevent new routes that may occur in the future.

4. Pipelines and Cable

Under the Gulf of Thailand, there are natural gas pipelines and underground cables along the ocean [36] that should be avoided for site selection as a wind farm in order to prevent damage that may occur during installation process or maintenance.

5. Social Impact

Visual Impacts and noises should be concerned if a selected place is in a resident area or a tourist attraction. This problem can be reduced by locating wind farm around 1km away from a shore to reduce turbine noise and visual impacts. [19]

6. Environment Impact

These impacts were concerned to prevent some animals such as birds or bats to collide 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 habitats of some species of marine animals in terms of migration routes.

7. Sea depth

The installation of offshore turbines should be concerned about soil property and the sea depth which can affect the cost of some types of turbine installation. The sea depth of the monopole type starts from 0-30 m and the sea depth of Tripod is 50 m. However, in the future, the Floating Structure in this study can be used in over 50 m up to 300 m of water depth [6].

3.4 Analytic hierarchy process: AHP

Analytic hierarchy process (AHP) [13] was used for offshore site selection. For the site selection in this study, the main applicable decision criteria included territorial water, sea depth, military areas, aircraft routes, pipelines and cables, social impacts, and environment impacts, shown in **Figure 3.15**.

1. Decision steps and structure chart

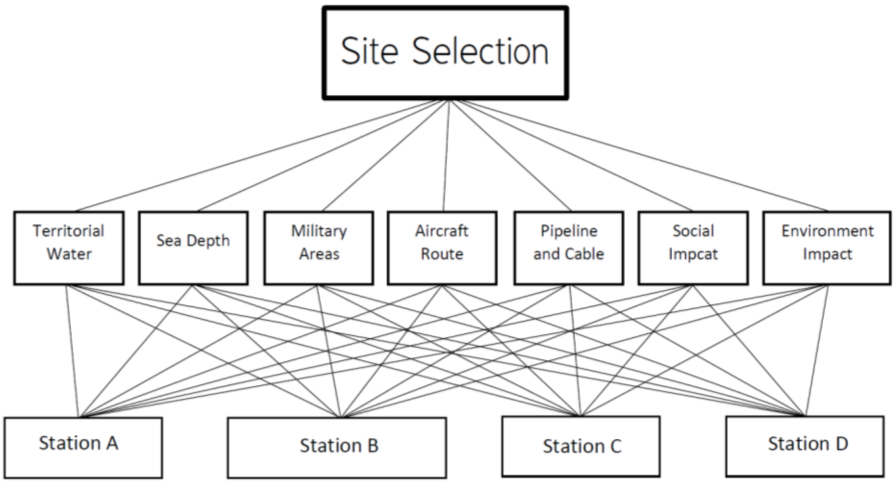


Figure 3.15 Chart of wind farm site decision criteria

2. Criteria of decision comparison matrix

Values of criteria importance in yellow areas in **Table 3.1 – 3.2** were obtained from experts who were advisors in this study. Also, the selection of wind farm sites depended on each criterion.

Table 3.1 Criteria of decision comparison matrix table

Criteria	Territorial Water	Sea Depth	Military Areas	Aircraft Routes	Pipelines and cables	Social Impacts	Environment Impacts
Territorial Water	1	x	x	x	x	x	x
Sea Depth		1	x	x	x	x	x
Military Areas			1	x	x	x	x
Aircraft Routes				1	x	x	x
Pipelines and Cables					1	x	x
Social Impacts						1	x
Environment Impacts							1

Table 3.2 Wind farm site selection

Selection	Station A	Station B	Station C	Station D
Station A	**1**	**x**	**x**	**x**
Station B		**1**	**x**	**x**
Station C			**1**	**x**
Station D				**1**

3.5 Sitting wind assessment and analysis

3.5.1 Selected wind farm sites and Annul Energy Productive

In this study, in each wind farm, 28 wind turbines of Vestas V112-3.0 MW were used, and their mean maximum to generate power was 84 MW., and Annual Energy Productive (AEP) was analyzed by the WAsP program. The wind turbine sites were located with space to reduce wake turbulence at 560 m It was 5 times of the turbine diameter or 5D in each row and 10D in each column. **Table 3.3** presents the specifications of Vestas V112-3.0 MW Offshore turbine and **Figure 3.16** shows the power curve of selected turbines.

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 rotor function.

Table 3.3 specifications of Vestas V112-3.0 MW Offshore turbine

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

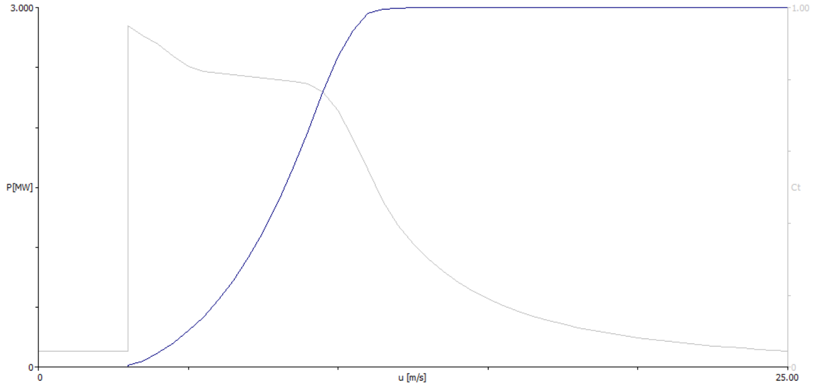


Figure 3.16 Vestas V112-3.0 MW power curve

3.5.2 Simulation of selected sites and wind maps

Wind resource maps were necessary to provide Vector maps, derived from Elevation Maps **(Figure 3.17)** and Roughness Maps **(Figure 3.18)** in the WAsP Map Editor tool.

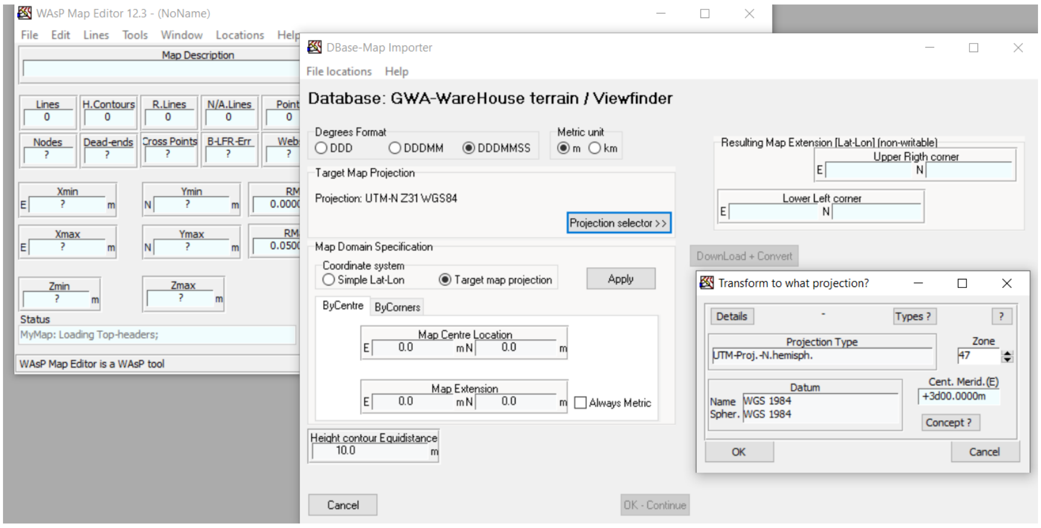


Figure 3.17 Data input generation from Elevation maps

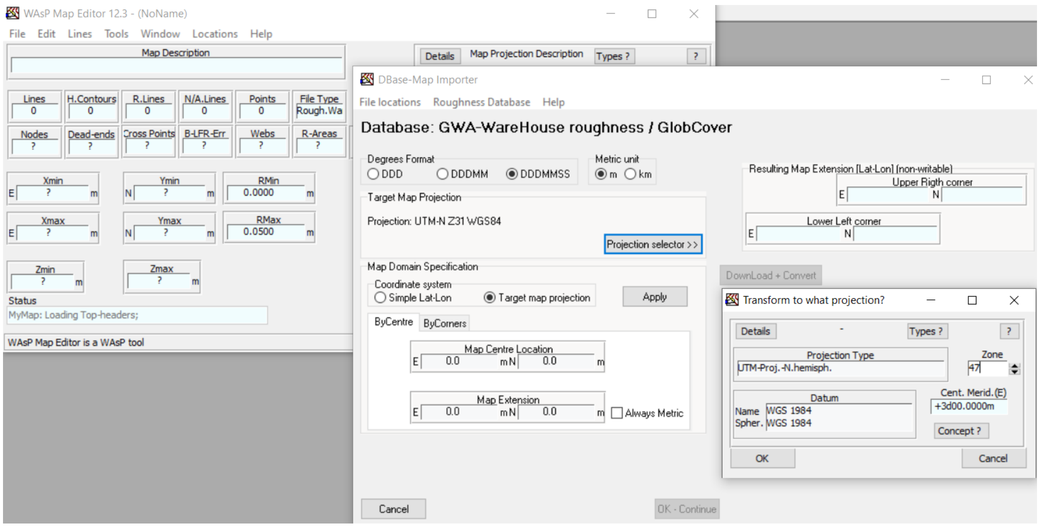


Figure 3.18 Data input generation from Roughness Maps

The data of Elevation and Roughness Maps were both imported from the Global Wind Atlas (GWA) warehouse map server and Google Earth maps in order to classify lands and roughness length including the sea surface at normally 0. However, in this study, 0.12 of roughness length for an offshore windfarm was provided. The data input was also informed to each station by locations and, zones, The map projection is the Universal Transverse Mercator (UTM) which was used to coordinate the system, and the datum of WGS-1984 was used.

CHAPTER 4

RESULT AND DISCUSSION

The data of the study were collected from Thai Meteorological Department (TMD) for 4 years from 2017-2020 at every 10 minutes' interval at altitude of 10 m above ground level at each station along the Gulf of Thailand. By the WAsP program, the data were calculated for the wind potential statistics including the mean wind speed, power distribution, and frequency distribution at each station at 10 m a.g.l. After that, the optimal wind farm that provided insufficiency of the mean wind speed was found and filtered out to the station. Multi Criteria Decision Analysis (MCDA) tool was also applied to find the best wind farm station. In each criterion, the environment, installation, and the wild life were concerned. The Annual Energy Production (AEP) for stations selected from WAsP were finally analyzed.

4.1 Wind Potential Analysis of the Gulf of Thailand (GoT)

In this section, the analysed results of the raw wind data to provide wind potential in each station were discussed. The wind potential as Weibull parameters, main wind directions, the mean wind speed, and power density were shown in **Table 4.1**. The results showed that there were 4 stations that the mean wind speed was more than 3 m/s at 10 m. They were Rayong, Prachuap Khiri Khan, Songkhla and Narathiwat with 3.45 m/s, 3.24 m/s, 3.10 m/s and 3.60 m/s of wind speed, and 67 W/m^2, 54 W/m^2, 44 W/m^2 and 82 W/m^2 of power density, respectively.

Table 4.1 Hourly wind potential of Gulf of Thailand (GoT) at 10 m for 4 years 2017-2020

Station	Weibull distribution		Main Wind Direction (°)	Mean Wind speed (m/s)	Power density (W/m^2)
	Scale parameter (c) m/s	Shape parameter (k)			
1.Khlongyai	3.0	1.97	90	2.65	22
2.Phliu	2	1.5	60	2.06	18
3.Rayong	3.9	1.54	240	3.45	67
4.Prachuap Khiri Khan	3.5	1.46	240	3.24	54
5.Chumphon	2.7	1.32	300	2.51	30
6.Koh Samui	2.9	1.46	270	2.60	30
7.Nakhon Si Thammarat	2.3	1.17	300	2.31	28
8.Songkhla	3.4	1.6	120	3.10	44
9.Pattani	2.4	1.24	120 and 240	2.21	25
10.Narathiwat	3.7	1.31	240	3.63	82

The observed wind climate (OWC) data that were analysed from WAsP Climate analysis provided the Weibull distribution and wind rose data. The results of wind data could distribute in each sector of frequency distribution with the following wind distribution tables and figures in each station.

1. Khlongyai Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Khlong Yai indicated that the highest mean wind speed was 2.95 m/s at 210°, accounted for 7% of all frequency direction as shown in **Table 4.2** and **Figure 4.1.**

Table 4.2 Khlongyai wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	2.5	2.8	1.56	2.48	24
2	30	2.8	2.6	1.34	2.39	27
3	60	13.6	3	1.81	2.68	25
4	90	25.3	3	2.54	2.63	17
5	120	5.7	2.6	1.52	2.37	22
6	150	7.5	3.1	2.32	2.73	21
7	180	3.8	2.9	1.85	2.58	22
8	210	7	3.3	2.15	2.95	28
9	240	9.1	3.1	1.86	2.79	28
10	270	12.2	3.2	1.99	2.88	28
11	300	5.9	2.5	1.87	2.25	14
12	330	4.6	2.6	1.54	2.35	21

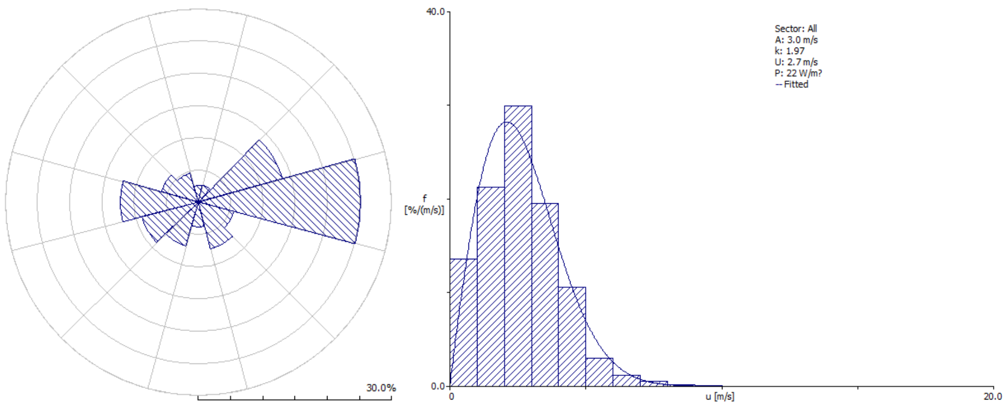


Figure 4.1 Wind Rose (Left) and Wind frequency distribution (Right) Khlongyai Station at 10 m

2. Phliu Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Phliu indicated that the highest mean wind speed was 2.89 m/s at 240°, accounted for 6.2% of all frequency direction as shown in **Table 4.3** and **Figure 4.2**.

Table 4.3 Phliu wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	4.8	1.4	0.96	1.38	11
2	30	21	2	1.5	1.82	10
3	60	13.8	1.5	1.05	1.42	9
4	90	5.3	1.2	0.99	1.22	7
5	120	6.5	1.8	1.37	1.69	9
6	150	7.7	2.5	1.64	2.24	17
7	180	9.2	3	1.83	2.64	24
8	210	11.5	3.8	2.1	3.4	44
9	240	6.2	3.2	1.61	2.89	37
10	270	4.2	2.3	1.34	2.14	20
11	300	4.7	2	1.28	1.89	15
12	330	4.9	1.7	1.13	1.59	11

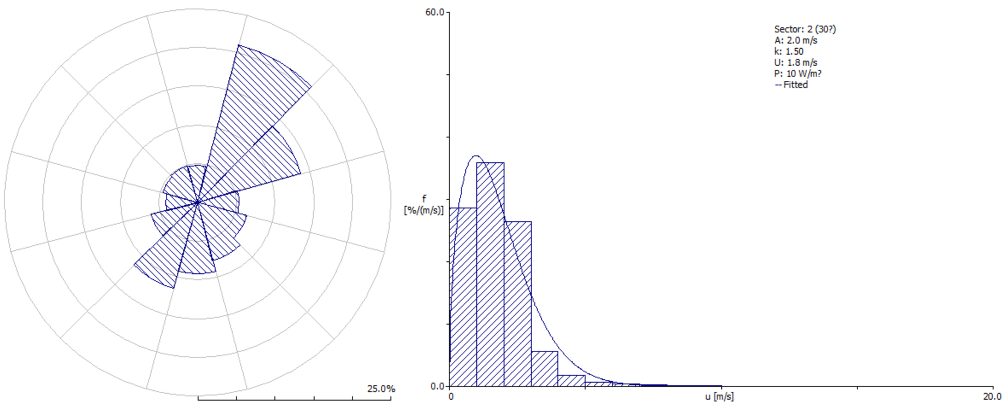


Figure 4.2 Wind Rose (Left) and Wind frequency distribution (Right) Phliu Station at 10 m

3. Rayong Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Rayong indicated that the highest mean wind speed was 5.3 m/s at 240°, considered as 21% of all frequency direction as shown in **Table 4.4** and **Figure 4.3**.

Table 4.4 Rayong wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	3.7	1.8	1.26	1.69	11
2	30	6.8	2.2	1.44	2	14
3	60	5.2	2.2	1.16	2.12	25
4	90	5.7	2	1.18	1.89	17
5	120	8.3	3.1	1.36	2.84	44
6	150	8.8	2.8	1.57	2.53	25
7	180	10.1	3.2	1.76	2.88	32
8	210	15.3	4.2	2.11	3.76	59
9	240	21	6	2.42	5.3	148
10	270	9.9	5.7	2.27	5.05	134
11	300	3.1	2.5	1.16	2.4	37
12	330	2.2	0.8	0.73	0.95	8

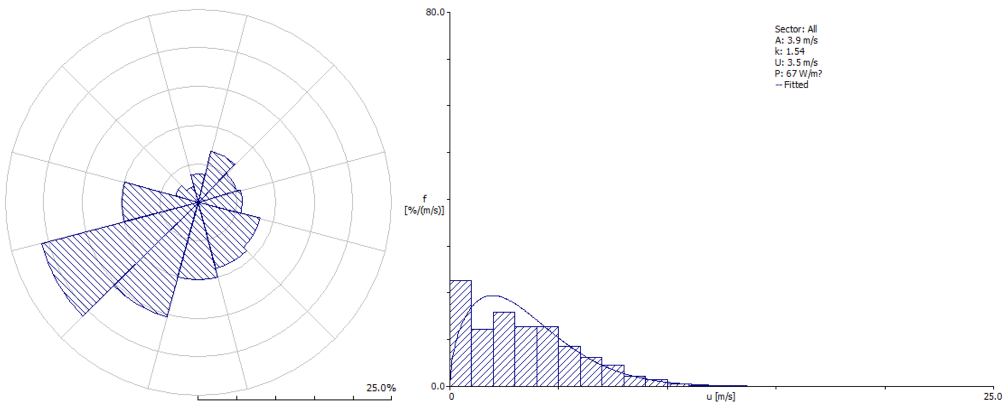


Figure 4.3 Wind Rose (Left) and Wind frequency distribution (Right) Rayong Station at 10 m

4. Prachuap Khiri Khan Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Prachuap Khiri Khan showed that the highest mean wind speed was 5.13 m/s at 150°, considered as 11.2% of all frequency direction in **Table 4.5** and **Figure 4.4**.

Table 4.5 Prachuap wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	7	4.9	2.09	4.38	94
2	30	5.2	5.3	2.33	4.72	107
3	60	2.8	4.3	2.04	3.8	63
4	90	3.1	3.7	1.62	3.3	54
5	120	6.6	4.3	1.79	3.78	72
6	150	11.2	5.8	2.36	5.13	136
7	180	6.4	3.4	1.48	3.12	51
8	210	11.4	3.1	1.94	2.76	25
9	240	14.7	3.4	1.73	3.06	39
10	270	11.4	2.9	1.46	2.67	33
11	300	11.7	2	1.69	1.8	8
12	330	8.6	2.2	1.31	2.05	18

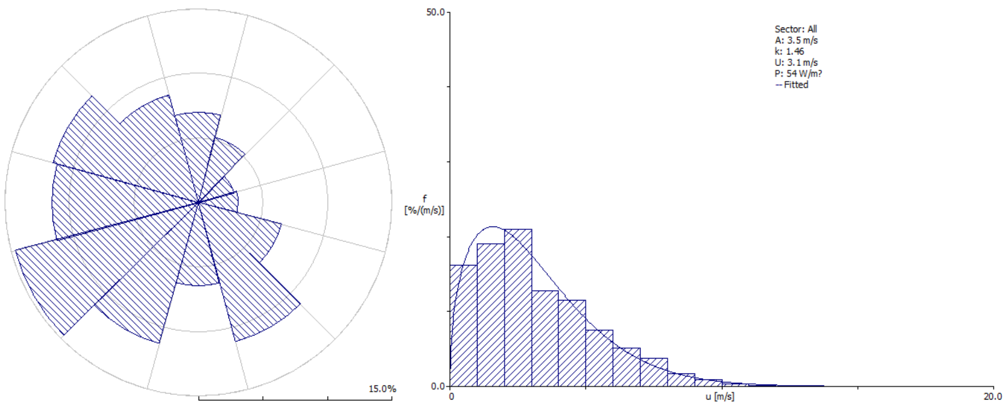


Figure 4.4 Wind Rose (Left) and Wind frequency distribution (Right) Prachuap Station at 10 m

5. Chumphon Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Chumphon showed that the highest mean wind speed was 3.98 m/s at 60°, counted as 7.7% of all frequency direction, displayed in **Table 4.6** and **Figure 4.5**.

Table 4.6 Chumphon wind climate distribution at 10 m

Sector		Wind climate				Power
Number	**Angle [°]**	**Frequency [%]**	**Weibull-A [m/s]**	**Weibull-k**	**Mean speed [m/s]**	**Power density [W/m^2]**
1	0	3.2	1.4	1.25	1.29	5
2	30	5.1	2.8	1.35	2.53	32
3	60	7.7	4.5	2.11	3.98	70
4	90	7.4	4.1	2.31	3.66	50
5	120	7.2	3.5	1.93	3.08	35
6	150	3.7	1.9	1.25	1.78	13
7	180	4.3	2.1	1.34	1.91	14
8	210	4.8	2.6	1.53	2.37	21
9	240	5.1	2.7	1.45	2.47	26
10	270	16	3.7	1.62	3.3	54
11	300	22.5	2.1	1.27	1.91	15
12	330	12.7	1.6	1.81	1.44	4

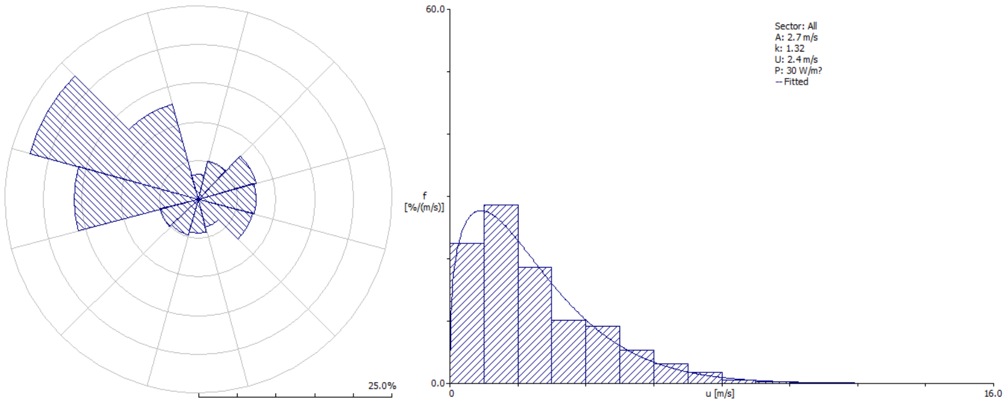


Figure 4.5 Wind Rose (Left) and Wind frequency distribution (Right) Chumphon Station at 10 m

6. Koh Samui Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Koh Samui showed that the highest mean wind speed was 3.75 m/s at 60°, counted as 6.2% of all frequency direction, displayed in **Table 4.7** and **Figure 4.6**.

Table 4.7 Koh Samui wind climate distribution at 10 m

Sector		Wind climate				Power
Number	**Angle [°]**	**Frequency [%]**	**Weibull-A [m/s]**	**Weibull-k**	**Mean speed [m/s]**	**Power density [W/m^2]**
1	0	3.9	2.1	1.28	1.91	15
2	30	7.1	3.1	1.62	2.74	31
3	60	6.2	4.2	1.95	3.75	63
4	90	9	4.4	1.94	3.9	72
5	120	15.6	4.2	2.04	3.69	58
6	150	8	3.2	1.67	2.86	34
7	180	4.4	2.9	1.51	2.65	31
8	210	3.2	2	1.68	1.8	8
9	240	3.5	1.5	1.44	1.39	5
10	270	17.5	2.1	1.77	1.83	8
11	300	15.6	2.1	1.64	1.89	10
12	330	6.1	2	2.33	1.73	5

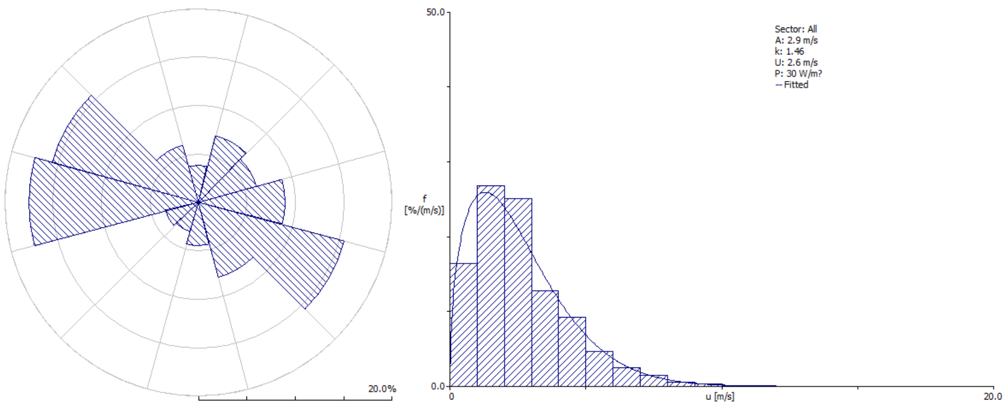


Figure 4.6 Wind Rose (Left) and Wind frequency distribution (Right) Koh Samui Station at 10 m

7. Nakhon Si Thammarat Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Nakhon Si Thammarat revealed that the highest mean wind speed was 4.06 m/s at 90°, considered as 10.9% of all frequency direction in **Table 4.8** and **Figure 4.7**.

Table 4.8 Nakhon Si Thammarat wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	4.7	1.9	1.11	1.82	17
2	30	6.4	2.7	1.44	2.44	26
3	60	9.2	3.8	1.81	3.35	49
4	90	10.9	4.6	2	4.06	78
5	120	8.5	3.4	1.4	3.07	54
6	150	5.7	2.1	1.28	1.95	16
7	180	5.1	2.3	1.33	2.07	18
8	210	7.6	2.2	1.22	2.07	21
9	240	7.7	2	1.28	1.82	13
10	270	11.9	1.8	1.27	1.65	10
11	300	13.4	1.7	1.28	1.6	9
12	330	8.9	1.7	1.27	1.54	8

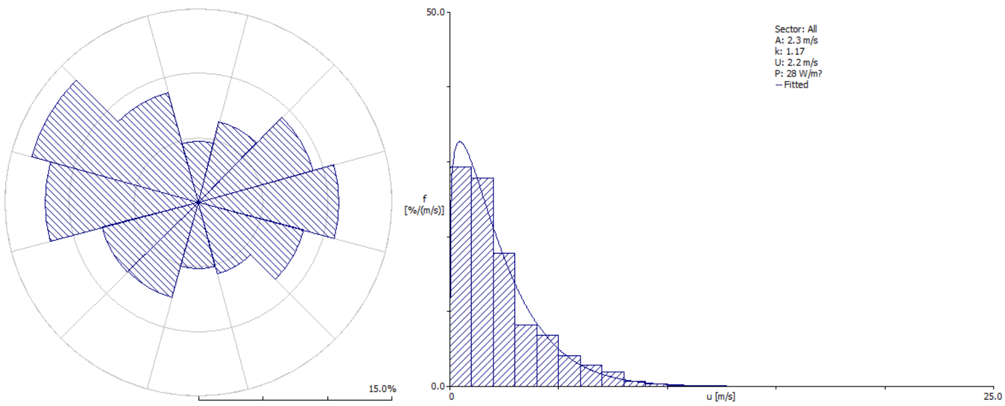


Figure 4.7 Wind Rose (Left) and Wind frequency distribution (Right) Nakhon Si Thammarat Station at 10 m

8. Songkhla Station

According to the wind climate analysist, the results of the observed wind climate (OWC) data in Songkhla showed that the highest mean wind speed was 4.17 m/s at 60°, counted as 13.4% of all frequency direction, exhibited in **Table 4.9** and **Figure 4.8**.

Table 4.9 Songkhla wind climate distribution at 10 m

Sector		Wind climate				Power
Number	**Angle [°]**	**Frequency [%]**	**Weibull-A [m/s]**	**Weibull-k**	**Mean speed [m/s]**	**Power density [W/m2]**
1	0	1.4	2.5	1.5	2.27	19
2	30	4.1	3.8	1.98	3.37	45
3	60	13.4	4.7	2.61	4.17	68
4	90	14.2	4.1	2.15	3.62	52
5	120	24.7	3.7	1.7	3.32	51
6	150	11	2.2	1.39	1.99	15
7	180	6.3	2.1	1.37	1.92	14
8	210	6.2	2.2	1.38	1.98	15
9	240	13.3	3.6	1.52	3.24	56
10	270	3.2	3.6	1.56	3.26	54
11	300	1.1	1.9	1.06	1.88	21
12	330	1.1	1.7	1.15	1.63	12

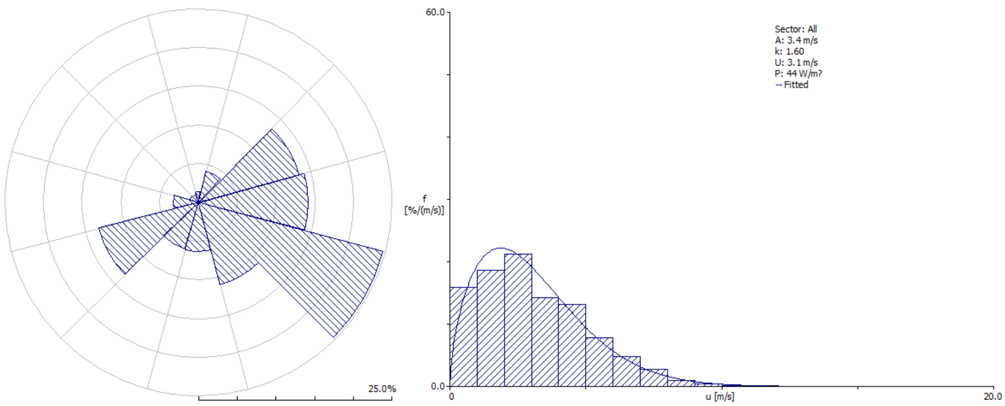


Figure 4.8 Wind Rose (Left) and Wind frequency distribution (Right) Songkhla Station at 10 m

9. Pattani Station

Regarding the wind climate analysist, the results of the observed wind climate (OWC) data in Pattani showed that the highest mean wind speed was 2.62 m/s at 60°, accounted for 7% of all frequency direction, shown in **Table 4.10** and **Figure 4.9**.

Table 4.10 Pattani wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	4.8	1.8	0.97	1.83	25
2	30	6.2	2.7	1.27	2.55	36
3	60	7	2.8	1.31	2.62	37
4	90	8.9	2.7	1.41	2.5	29
5	120	11.4	2.9	1.4	2.62	33
6	150	10.3	2.5	1.32	2.28	24
7	180	7.3	1.6	1.16	1.49	9
8	210	8.6	1.9	1.25	1.74	12
9	240	11.4	2.3	1.36	2.08	17
10	270	11	2.5	1.31	2.32	26
11	300	8.3	2.5	1.21	2.35	31
12	330	4.9	1.6	0.89	1.68	24

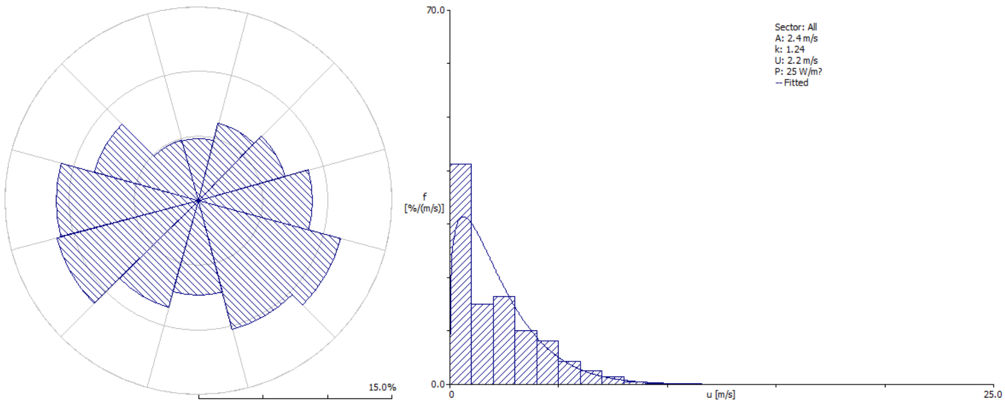


Figure 4.9 Wind Rose (Left) and Wind frequency distribution (Right) Pattani Station at 10 m

10. Narathiwat Station

Regarding the wind climate analysist, the results of the observed wind climate (OWC) data in Narathiwat showed that the highest mean wind speed was 6.74 m/s at 90°, considered as 12.6% of all frequency direction in **Table 4.11** and **Figure 4.10**.

Table 4.11 Nartahiwat wind climate distribution at 10 m

Sector		Wind climate				Power
Number	Angle [°]	Frequency [%]	Weibull-A [m/s]	Weibull-k	Mean speed [m/s]	Power density [W/m^2]
1	0	0.9	3.4	1.67	3.02	40
2	30	3.8	4.6	2.78	4.13	64
3	60	9.8	6.5	2.85	5.81	174
4	90	12.6	7.5	2.99	6.74	264
5	120	10.5	6	2.05	5.31	170
6	150	4.7	2.9	1.64	2.6	26
7	180	9.3	2.3	1.7	2.03	12
8	210	8.1	1.9	1.91	1.71	6
9	240	28.8	3	1.91	2.63	22
10	270	8	2.5	1.63	2.21	16
11	300	2.3	2.4	1.42	2.17	19
12	330	1.3	3.2	1.57	2.87	37

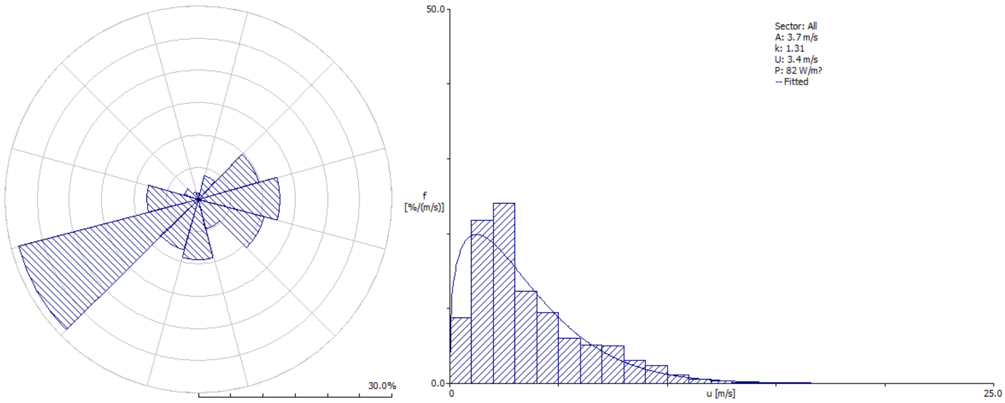


Figure 4.10 Wind Rose (Left) and Wind frequency distribution (Right) Narathiwat Station at 10 m

The monthly mean wind speed at the average of 4 years was shown in **Table 4.12** and **Figure 4.11 - 4.12** The results showed that almost all of the wind data were insufficient to provide power in some months, but the average wind data were interesting at Rayong, Prachuap, Songkhla and Narathiwat stations. Therefore, these stations should be in site selection process.

Based on meteorological data, the seasons and monsoon in the Gulf of Thailand were classified as follows:

The winter or Northeast monsoon season starts from the middle of October to the middle of February. There was a lot of rain in the Gulf of Thailand, especially from October to November.

Sumer or pre-monsoon starts from the middle of February to the middle of May. The weather in the Gulf of Thailand is warming up in partial upper parts.

The rainy or Southwest monsoon season starts from the middle of May to the middle of October. This season saw a lot of rain. In the Gulf of Thailand, there will be ample rain from now until the end of the year.

From the seasonal and monsoon in the table, it is clear the Gulf of Thailand is affected by the direction of the monsoon. In winter, there will be heavy rain and storms at the end of the year in the lowest part of the study area. As a result, the wind value may fluctuate according to the nature of the incoming monsoons.

Table 4.12 Monthly wind speed potential and season in the Gulf of Thailand

Station / Month	1.Khlongyai	2.Phliu	3.Rayong	4.Prachvap	5.Chumphon	6.Koh Samui	7.Nakhon Si Thammarat	8.Songkhla	9.Pattani	10.Narathiwat	Season / Monsoon
January	2.64	1.93	2.17	2.82	2.38	3.23	2.43	3.46	2.04	4.15	Winter / Northeast monsoon
February	2.88	2.09	2.45	2.87	2.55	3.91	2.78	4.03	2.26	4.8	Winter / Northeast monsoon Summer / Pre-monsoon
March	2.83	1.93	3.56	3.46	2.5	3.08	2.62	3.28	1.97	4.32	Summer / Pre-monsoon
April	2.97	1.86	3.02	3.37	2.38	2.86	2.47	2.95	1.96	4.25	Summer / Pre-monsoon

Table 4.12 (Cont'd) Monthly wind speed potential and season in the Gulf of Thailand

Station / Month	1.Khlongyai	2.Phliu	3.Rayong	4.Prachvap	5.Chumphon	6.Koh Samui	7.Nakhon Si Thammarat	8.Songkhla	9.Pattani	10.Narathiwat	Season / Monsoon
May	2.76	1.63	2.72	3.16	2.47	1.9	1.81	2.8	2.05	3.52	Summer / Pre-monsoon Rainy / Southwest monsoon
June	2.45	2.03	5.08	3.25	2.47	1.78	1.97	2.76	1.87	3.06	Rainy / Southwest monsoon
July	2.7	2.34	5.1	3.4	2.57	1.93	2.02	3.06	2.14	3.08	Rainy / Southwest monsoon
August	2.53	2.31	5.41	3.18	2.68	1.92	2.19	3.31	2.18	3.09	Rainy / Southwest monsoon
September	2.35	1.82	3.16	2.91	2.6	1.91	1.98	2.83	2.12	3.08	Rainy / Southwest monsoon
October	2.24	1.65	1.91	2.33	2.15	2.03	1.84	2.65	2.05	3	Rainy / Southwest monsoon Winter / Northeast monsoon
November	2.38	1.81	2.33	3.55	2.39	3.08	2.23	2.62	1.52	2.98	Winter / Northeast monsoon
December	2.56	1.93	2.43	3.34	2.46	3.52	2.41	3.08	1.61	3.84	Winter / Northeast monsoon

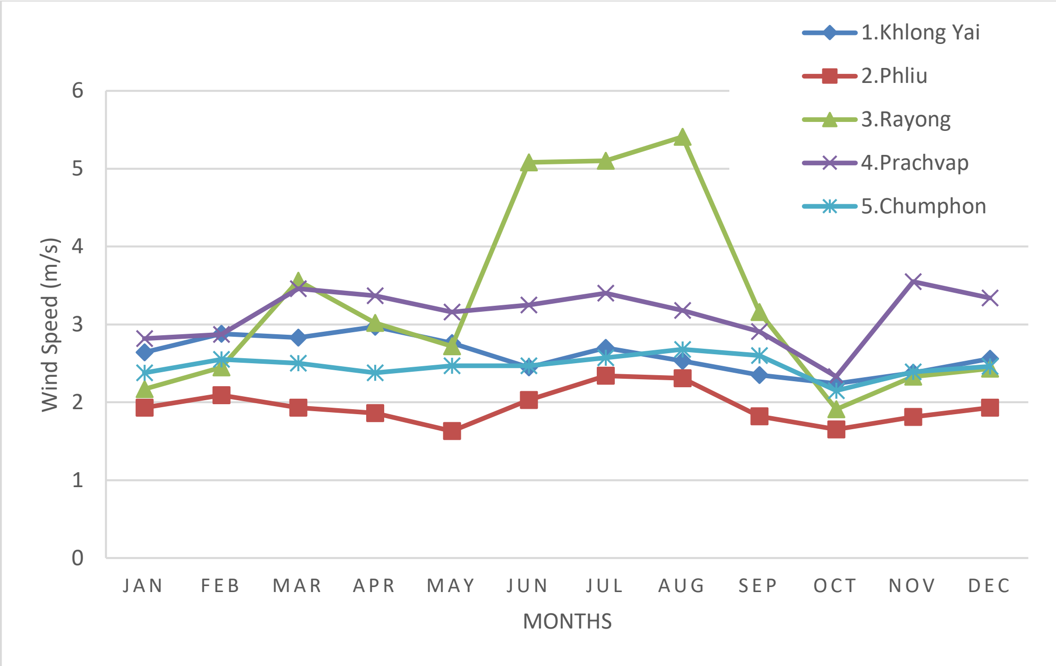


Figure 4.11. Annual wind speed patterns for the 5 AWS site along the coast line of the GoT at 10 m

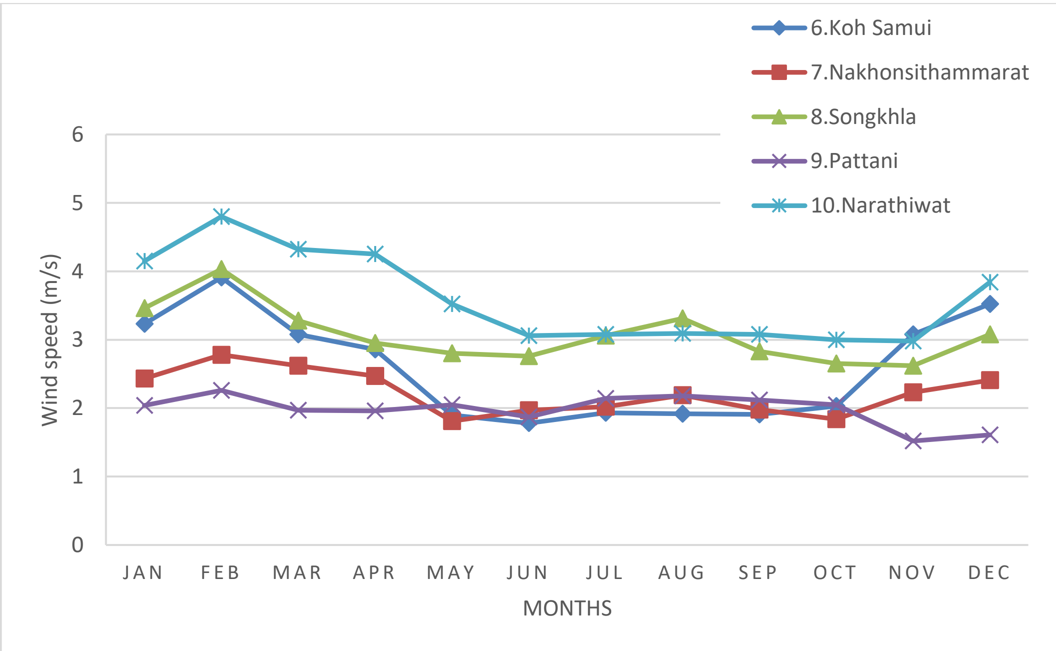


Figure 4.12. Annual wind speed patterns for the 5 AWS site along the coast line of the GoT at 10 m

4.2 Site Selection for offshore wind farm

The wind stations were selected by above 3 m/s of the mean wind speed at 10 m. In this section, criteria decision was followed up, and the Analytic hierarchy process (AHP) method was used to score and find the suitable site for the wind farm. The results of the criteria were discussed as follows:

1. Territorial Water

The Gulf of Thailand is separated into 5 areas from the shore: Internal Waters, Territorial Waters, Contiguous Zone, and Exclusive Economic Zones, respectively, in total of 202,676.20 km^2, [16] as shown in **Figure 4.13**. The green and yellow area are Internal and Territorial water, respectively. In this study, areas which were not far than 12 nautical miles were tested.

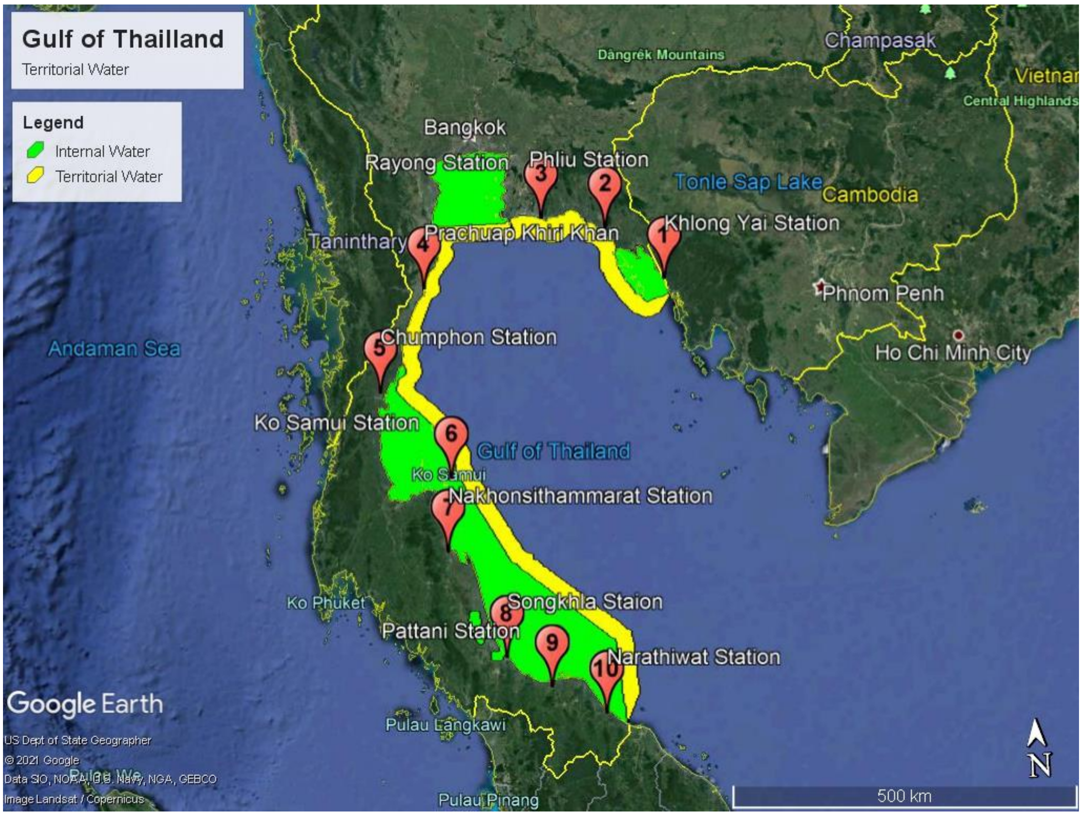


Figure 4.13. Overview of Territorial Water in Gulf of Thailand

2. Military Areas

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

3. Aircraft Routes

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

4. Social Impacts

People who lived at a coast line area could be impacted from noise and other visual effects. Other sites except Rayong 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 in the site, so a wind farm could impact on scenery and a number of tourists coming to this site. In consequence, it could not be a good turbine site.

5. Environment Impacts

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 Prachuap Khiri Khan Shore. [15] This topic needed to be further studied in order to concern about impacts for marine life around this shore. However, this could be a minor effect for site selection.

6. Sea Depth

Although the deepest area of GoT is 80 m, the average depth is around 50 m. The sites that were selected in this study should be around 10-20 m deep, so they were not considered an effective site to be selected.

4.3 AHP Results

From the values of the criteria that obtained from advisors in yellow areas (**Table 4.13**), the pairwise comparison matrix (PCM) could be used to calculate the values in each criterion in order to compute the Consistency Ratio (C.R.). The results from C.R. calculation were 0.08 > 0.1, which were accepted.

Table 4.13 Pairwise comparison for site selection criteria

Criteria	Territorial Water	Sea Depth	Military Areas	Aircraft Routes	Pipelines and cables	Social Impacts	Environment Impacts
Territorial Water	1	7	5	5	2	7	7
Sea Depth	1/7	1	1/5	1/5	1/7	1/2	1/2
Military Areas	1/5	5	1	2	1/7	5	5
Aircraft Routes	1/5	5	1/2	1	1/5	5	5
Pipelines and Cables	1/2	7	7	5	1	8	8
Social Impacts	1/7	2	1/5	1/5	1/8	1	2
Environment Impacts	1/7	2	1/5	1/5	1/8	1/2	1

According to the hierarchy analysis in the above-mentioned criteria for each site, the values of pairwise comparison matrix are provided in **Table 4.14** – **4.20**.

Table 4.14 Pairwise comparison matrix of wind farm site selection (Territorial water)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	**1**	**1**	**1/2**	**1/4**
Prachuap Khiri Khan	**1**	**1**	**1/4**	**1/2**
Songkhla	**2**	**4**	**1**	**2**
Narathiwat	**4**	**2**	**1/2**	**1**

The results of the pairwise comparison matrix for the territorial water indicated Consistency Ratio (C.R.) = 0.05 which was accepted.

Table 4.15 Pairwise comparison matrix of wind farm site selection (Sea depth)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	1	1	2
Prachuap Khiri Khan	1	1	1	2
Songkhla	1	1	1	2
Narathiwat	1/2	1/2	1/2	1

The results of the pairwise comparison matrix for the sea depth indicated Consistency Ratio (C.R.) = 0 which was accepted.

Table 4.16 Pairwise comparison matrix of wind farm site selection (Military areas)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	2	2	1/2
Prachuap Khiri Khan	1/2	1	2	1/2
Songkhla	1/2	1/2	1	1/2
Narathiwat	2	2	2	1

The results of the pairwise comparison matrix for the military areas showed Consistency Ratio (C.R.) = 0.03 which was accepted.

Table 4.17 Pairwise comparison matrix of wind farm site selection (Aircraft routes)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	1	4	1/2
Prachuap Khiri Khan	1	1	4	1/2
Songkhla	1/4	1/4	1	1/4
Narathiwat	2	2	4	1

The results of the pairwise comparison matrix for the aircraft routes revealed Consistency Ratio (C.R.) = 0.02 which was accepted.

Table 4.18 Pairwise comparison matrix of wind farm site selection (Pipelines and cables)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	1/8	1	1/7
Prachuap Khiri Khan	8	1	8	2
Songkhla	1	1/8	1	1/7
Narathiwat	7	1/2	7	1

The findings of the pairwise comparison matrix for the pipelines and cables showed Consistency Ratio (C.R.) = 0.01 which was accepted.

Table 4.19 Pairwise comparison matrix of wind farm site (Social impacts)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	1/4	1/2	1/6
Prachuap Khiri Khan	4	1	3	1/2
Songkhla	2	1/3	1	1/4
Narathiwat	6	2	4	1

The results of the pairwise comparison matrix for the Social impacts indicated Consistency Ratio (C.R.) = 0.01 which was accepted.

Table 4.20 Pairwise comparison matrix of wind farm site (Environment impacts)

Site	Rayong	Prachuap Khiri Khan	Songkhla	Narathiwat
Rayong	1	2	1/2	1/4
Prachuap Khiri Khan	1/2	1	2	1/2
Songkhla	2	1/2	1	1/2
Narathiwat	4	2	2	1

The results of the pairwise comparison matrix for the Environment impact showed Consistency Ratio (C.R.) = 0.13 which was accepted.

The results of the eigenvector criteria and selection are provided as the hierarchy decision in **Table 4.21**. The selection weight was calculated from the summary of the criteria weight multiply by the eigenvector at each wind farm site.

Table 4.21 Result of hierarchy site selection decision

Criteria / Selection	Territorial Water	Sea Depth	Military Area	Aircraft Routes	Pipeline and cable	Social Impact	Environment Impact	Selection weight
Criteria weight	0.34	0.03	0.13	0.12	0.31	0.04	0.03	
Rayong	0.13	0.29	0.27	0.25	0.06	0.07	0.17	0.15
Prachuap Khiri Khan	0.12	0.29	0.20	0.25	0.53	0.30	0.21	0.29
Songkhla	0.43	0.29	0.14	0.08	0.06	0.12	0.19	0.21
Narathiwat	0.31	0.14	0.39	0.42	0.35	0.50	0.43	0.35

After the criteria of selection were discussed, the results of the mean wind speed at 50 and 84 m in **Table 4.22** were from the wind speed equation called Class 1 for all sites, at 0-5.6 m/s at 50 m. The AHP Process was completed and the defined data value with matrix calculator were found that there were two selected sites: the first site was Narathiwat with the highest selection weight, and the second site was Prachuap Khiri Khan.

Table 4.22 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	Environment Impact	Sea Depth	Selection weight
	50 m	84 m								
Rayong	4.18	4.45	✓	✓	*	×	*	✓	✓	0.15
Prachuap Khiri Khan	3.93	4.18	✓	*	✓	✓	✓	*	✓	0.29
Songkhla	3.78	4	✓	*	×	×	✓	✓	✓	0.21
Narathiwat	4.4	4.69	✓	✓	*	✓	✓	✓	✓	0.35

4.4 Wind assessment analysis for selected sites.

The optimal wind farm from AHC was at Narathiwat site with the highest selection weight. In this study, apart from Narathiwat site, Prachuap Khiri Khan site was considered an optimal wind farm to be alternative as the secondary selection. To calculate an Annual Energy Product (AEP), Wind turbine Vestas V112 - 3.0MW offshore turbines were used to simulate by WAsP in order to provide wind assessment and wind maps from the selected sites.

4.4.1 The First wind farm selected site.

As the first selected site, Narathiwat site is located at the southern border of Thailand. Its territorial water contacts with Malaysia border. At 84 m of height, there was the mean wind speed and wind power density at 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 4.14** and **Table 4.23**.

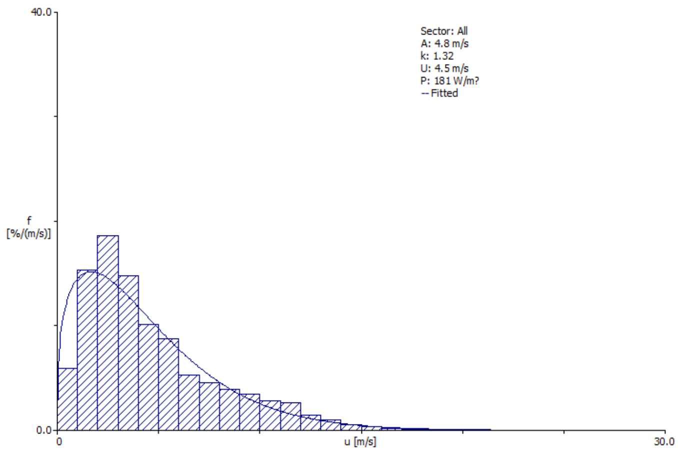


Figure 4.14 Narathiwat site Weibull distribution at 84 m

Table 4.23 Statistic of sector distribution at Narathiwat site

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

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 of Vestas V112 – 3.0 MW at 84 m of height. **Table 4.24** organized 2 rows and 14 columns of the wind turbines at Narathiwat site. The space of the turbines was 560 m per row and 1120 m per column from 112 m of the hub diameter and the hub rotation facing at 240° with stagger rows.

Table 4.24 Narathiwat **w**ind turbine site location

Site description	X-location [m]	Y-location [m]	Elev. [m]	AEP Net. [GWh]	Loss [%]	CF [%]
Turbine 1	829037.2	707032	0	9.64	0.87	37
Turbine 2	828477.2	708001.9	0	9.585	1.79	37.1
Turbine 3	827917.2	708971.9	0	9.598	2.04	37.3
Turbine 4	827357.2	709941.9	0	9.619	2.15	37.4
Turbine 5	826797.2	710911.8	0	9.631	2.25	37.5
Turbine 6	826237.2	711881.8	0	9.652	2.29	37.6
Turbine 7	825677.2	712851.7	0	9.671	2.33	37.7
Turbine 8	825117.2	713821.6	0	9.693	2.35	37.7
Turbine 9	824557.2	714791.6	0	9.72	2.37	37.9
Turbine 10	823997.2	715761.6	0	9.753	2.39	38
Turbine 11	823437.2	716731.5	0	9.786	2.39	38.1
Turbine 12	822877.2	717701.4	0	9.816	2.39	38.2
Turbine 13	822317.2	718671.4	0	9.839	2.37	38.3
Turbine 14	821757.2	719641.3	0	9.869	2.22	38.4
Turbine 15	828272.2	707237	0	9.506	1.78	36.8
Turbine 16	827712.2	708206.9	0	9.479	2.45	36.9
Turbine 17	827152.2	709176.9	0	9.508	2.58	37.1
Turbine 18	826592.2	710146.8	0	9.529	2.66	37.2
Turbine 19	826032.2	711116.8	0	9.557	2.69	37.3
Turbine 20	825472.2	712086.7	0	9.581	2.71	37.4
Turbine 21	824912.2	713056.7	0	9.604	2.71	37.5
Turbine 22	824352.2	714026.6	0	9.624	2.73	37.6
Turbine 23	823792.2	714996.6	0	9.666	2.73	37.8
Turbine 24	823232.2	715966.5	0	9.707	2.73	37.9
Turbine 25	822672.2	716936.4	0	9.742	2.72	38.1
Turbine 26	822112.2	717906.4	0	9.771	2.71	38.2
Turbine 27	821552.2	718876.4	0	9.797	2.67	38.3
Turbine 28	820992.2	719846.3	0	9.849	2.28	38.3

The statistical results of the wind farms at Narathiwat site are shown in **Table 4.25**. Since the wind farm location was aligning 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%.

Table 4.25 The statistical results of Narathiwat wind farm site

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	277.37	9.9	9.68	10.09
Total net AEP [GWh]	270.79	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

The high resolution of the wind maps of this site is shown in **Figure 4.15-4.17**. It consists of a mean wind speed map, a power density map and an Annual Energy Production (AEP) map in 50 × 50 km^2 area of Narathiwat site with 200 resolutions. The wind directions, the wind farm site and area map were sourced from Google Earth Pro as shown in **Figure 4.18**.

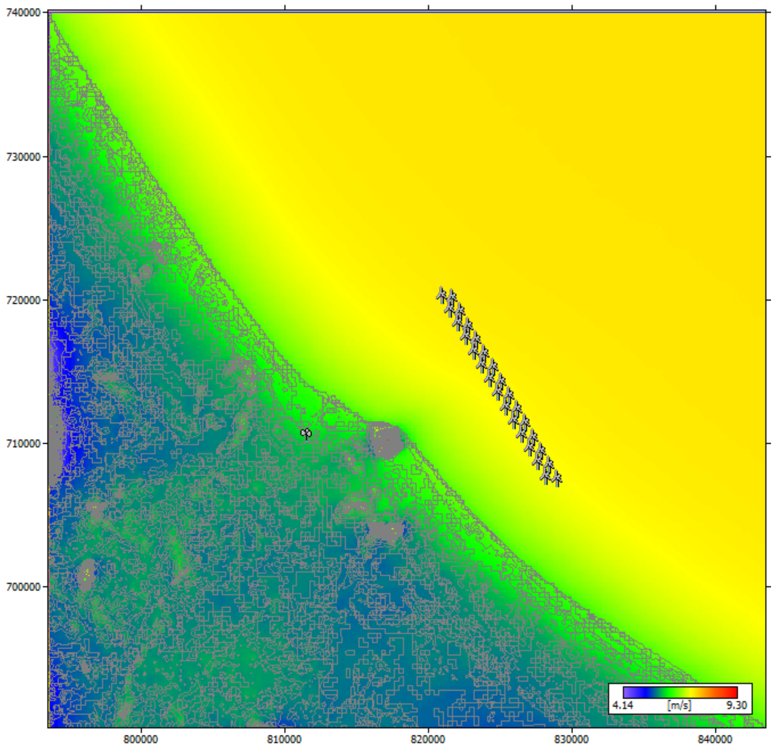


Figure 4.15 Mean wind speed map of Narathiwat at 84 m agl

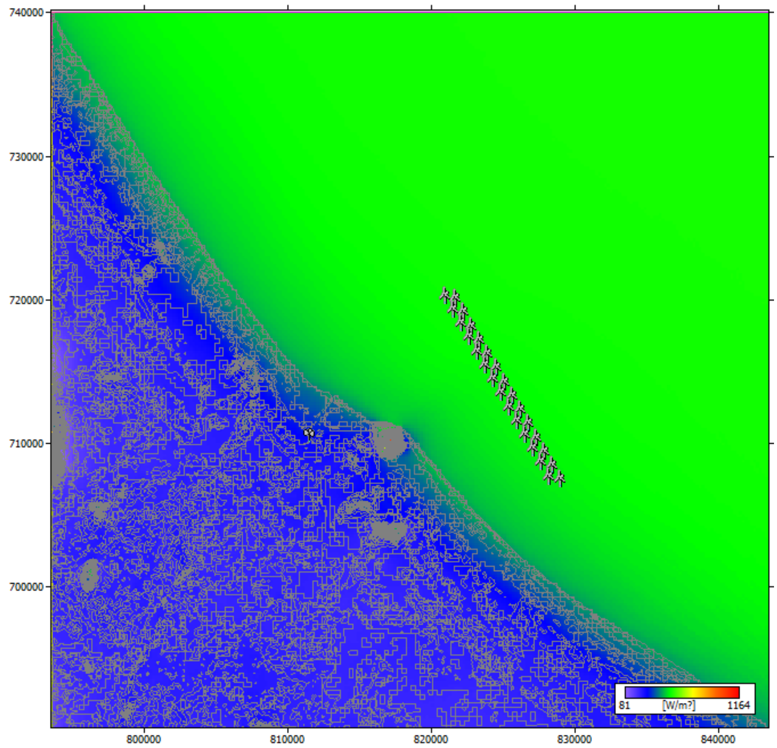


Figure 4.16 Wind power density map of Narathiwat at 84 m agl

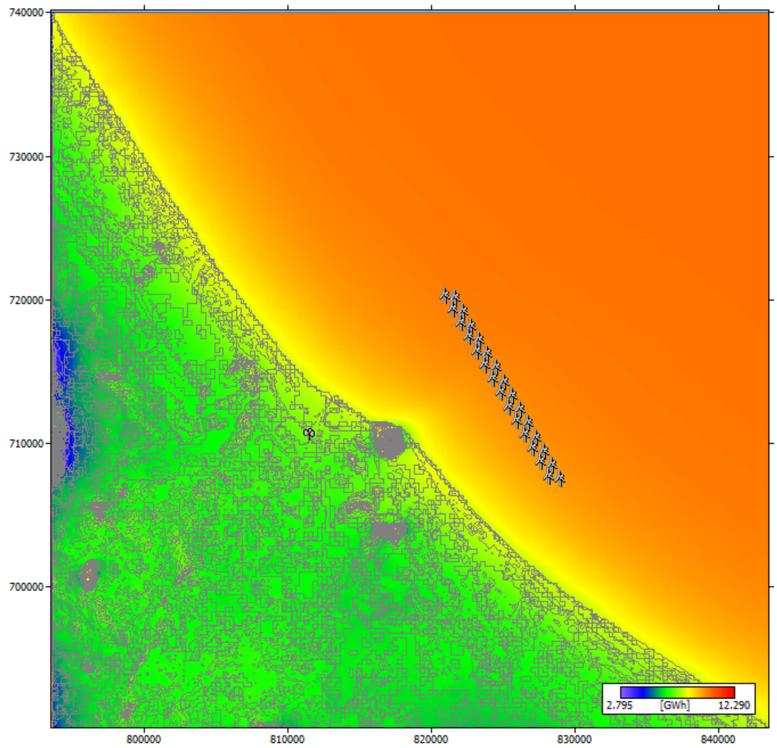


Figure 4.17 AEP map of Narathiwat at 84 m agl

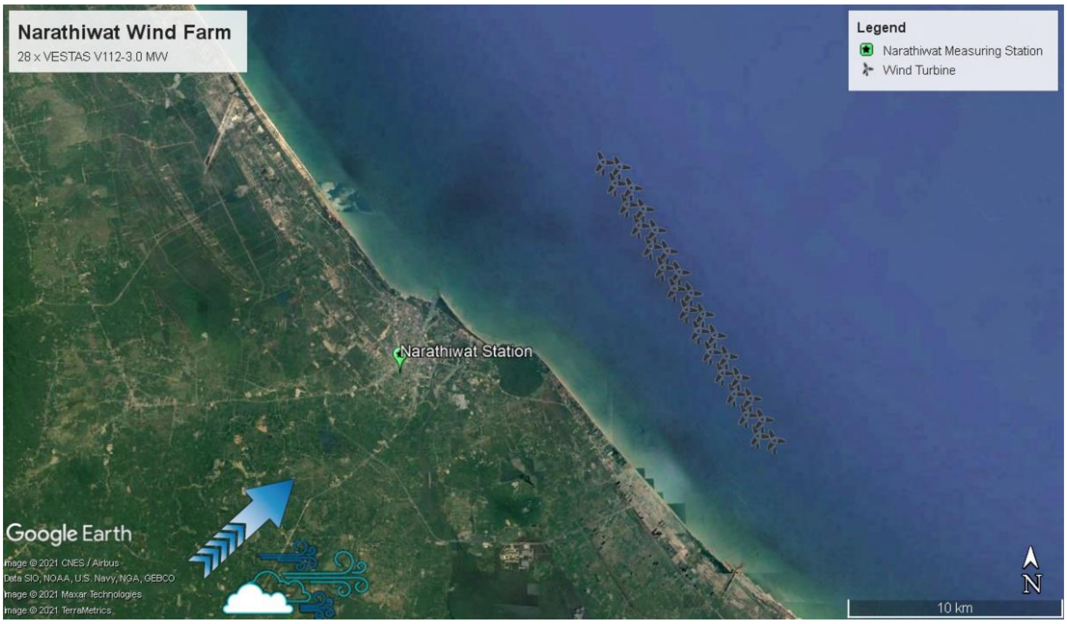


Figure 4.18 The selected wind farm site and Wind direction from South South-West (SSW) at Narathiwat Site

4.4.2 The Alternative wind farm selected site

As the selected secondary wind farm site, Prachuap Khiri Khan is located in the upper part of the south of Thailand and contacts 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 4.19** and **Table 4.26**. The mean wind speed and power density at 84 m of height were 4.1 m/s and 121 W/m^2, respectively with most wind frequency distribution from 240° or the South South-West (SSW) side.

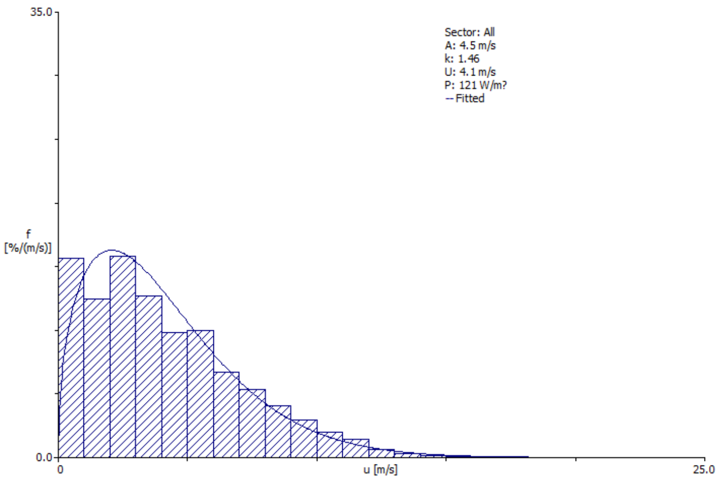


Figure 4.19 Weibull distribution at 84 m at Prachuap Khiri Khan site

Table 4.26 Statistic of sector distribution at Prachuap Khiri Khan site

Angle°	Frequency (%)	Weibull-A (m/s)	Weibull-k	Mean speed (m/s)	Power density (W/m^2)
0°	7.1	6.3	2.04	5.61	202
30°	5.4	6.8	2.16	6.01	236
60°	3	5.4	1.77	4.81	149
90°	3.2	4.5	1.5	4.1	114
120°	6.7	5.5	1.78	4.93	159
150°	11.2	7.4	2.32	6.6	294
180°	6.5	4.5	1.41	4.07	123
210°	11.3	4.1	1.82	3.64	62
240°	14.4	4.5	1.72	4.02	90
270°	11.1	3.8	1.45	3.49	75
300°	11.5	2.7	1.59	2.38	21
330°	8.5	2.8	1.22	2.64	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 in 4 rows and 7 columns at Prachuap Khiri Khan site. The space of the turbines was 560 m per row and 1120 m per column from 112 m of the hub diameter in **Table 4.27**.

Table 4.27 Prachuap Khiri Khan **w**ind turbine site location

Site description	X-location [m]	Y-location [m]	Elev. [m]	AEP Net. [GWh]	Loss [%]	CF [%]
Turbine 1	597486	1309584	0	8.433	4.98	33.7
Turbine 2	596926	1310554	0	8.199	7.32	33.6
Turbine 3	596366	1311524	0	8.134	7.78	33.5
Turbine 4	595806	1312494	0	8.087	7.97	33.4
Turbine 5	595246	1313464	0	8.04	8.07	33.3
Turbine 6	594686	1314434	0	8.013	7.79	33
Turbine 7	594126	1315404	0	8.04	6.75	32.8
Turbine 8	596721	1309789	0	8.224	6.96	33.6
Turbine 9	596161	1310759	0	8.066	8.37	33.5
Turbine 10	595601	1311729	0	7.992	8.89	33.4
Turbine 11	595041	1312699	0	7.938	9.07	33.2
Turbine 12	594481	1313669	0	7.897	9.05	33
Turbine 13	593921	1314639	0	7.881	8.44	32.7
Turbine 14	593361	1315609	0	8.023	5.72	32.4
Turbine 15	596516.1	1309024	0	8.423	4.64	33.6
Turbine 16	595956.1	1309994	0	8.176	7.03	33.4

Table 4.27 (Cont'd) Prachuap Khiri Khan **w**ind turbine site location

Site description	**X-location [m]**	**Y-location [m]**	**Elev. [m]**	**AEP Net. [GWh]**	**Loss [%]**	**CF [%]**
Turbine 17	595396.1	1310964	0	8.09	7.59	33.3
Turbine 18	594836.1	1311934	0	8.023	7.88	33.1
Turbine 19	594276.1	1312904	0	7.958	8.06	32.9
Turbine 20	593716.1	1313874	0	7.931	7.8	32.7
Turbine 21	593156.1	1314844	0	7.929	6.72	32.3
Turbine 22	595751.1	1309229	0	8.424	4.07	33.4
Turbine 23	595191.1	1310199	0	8.274	5.24	33.2
Turbine 24	594631.1	1311169	0	8.198	5.64	33
Turbine 25	594071.1	1312139	0	8.131	5.75	32.8
Turbine 26	593511.1	1313109	0	8.065	5.72	32.5
Turbine 27	592951.1	1314079	0	8.048	5.19	32.3
Turbine 28	592391.1	1315049	0	8.075	3.43	31.8

The statistical results of the wind farms are shown in **Table 4.28**. For Prachuap wind farm site at 84 m of wind turbine height, the Wake Loss was 6.86% which means the total net of AEP were missing from the gross AEP of 16.698 GWh. That is, that mean percent of wind farm efficiency at this site was 93.4 % from proportional wake loss 6.86%.

Table 4.28 The statistical results of Prachuap Khiri Khan wind farm site

Variable	**Total**	**Mean**	**Min**	**Max**
Total gross AEP [GWh]	243.409	8.693	8.362	8.875
Total net AEP [GWh]	226.711	8.097	7.881	8.433
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]	-	1.148	1.148	1.148
Power density [W/m^2]	-	405	373	428

200 high resolutions of the wind maps of Prachuap Khiri Khan at 84 m of height and 50 × 50 km^2 was provided, including the mean wind speed, the power density and the AEP map area as shown in **Figure 4.20-4.22**. The interior details of the wind farm were discussed later. Along the shore, the wind farms with wind directions were provided from Google Earth Pro as shown in **Figure 4.23**.

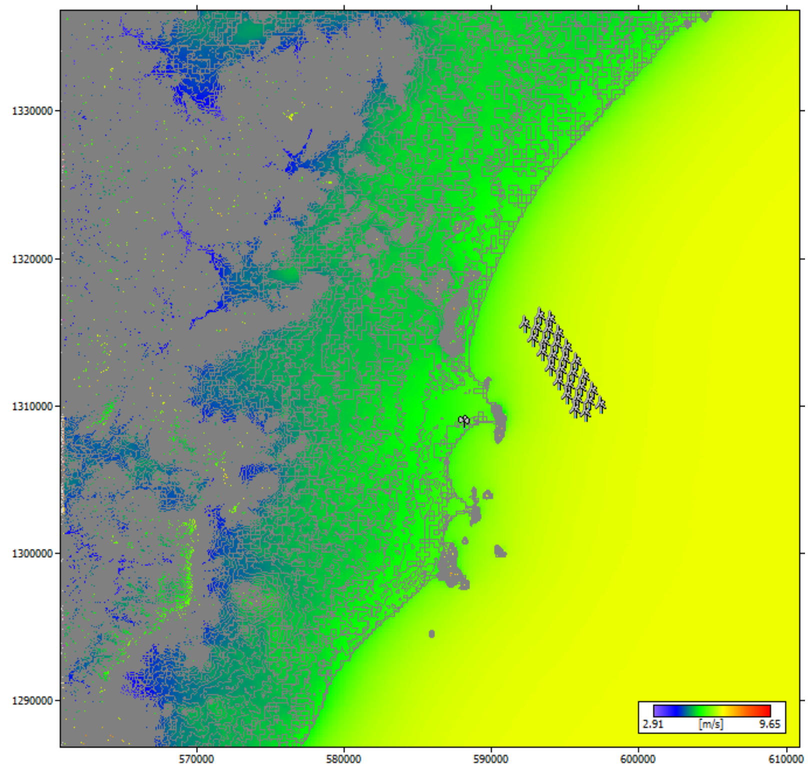


Figure 4.20 Mean wind speed map of Prachuap Khiri Khan at 84 m agl

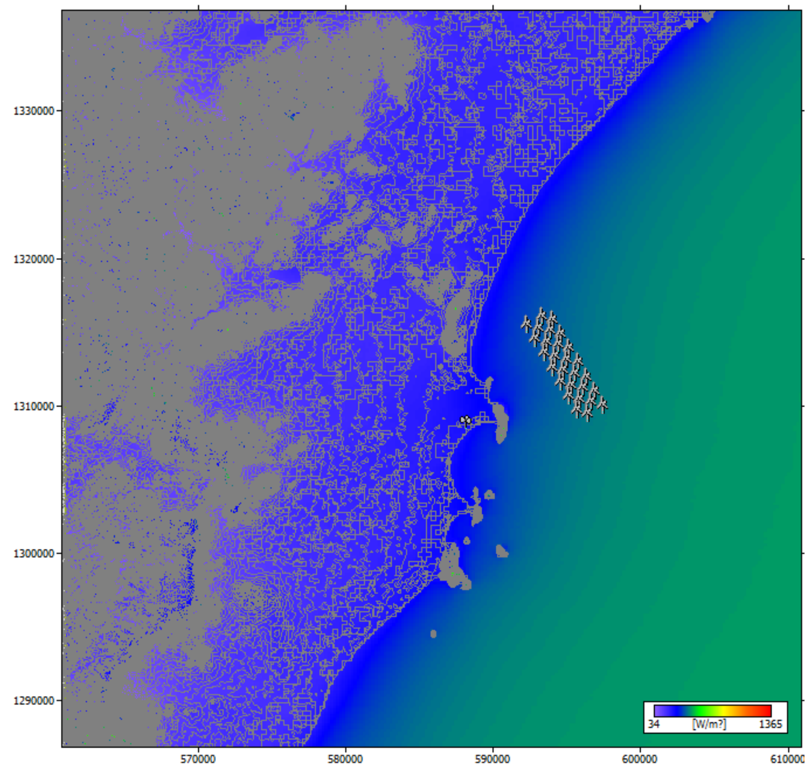


Figure 4.21 Wind power density map of Prachuap Khiri Khan at 84 m agl

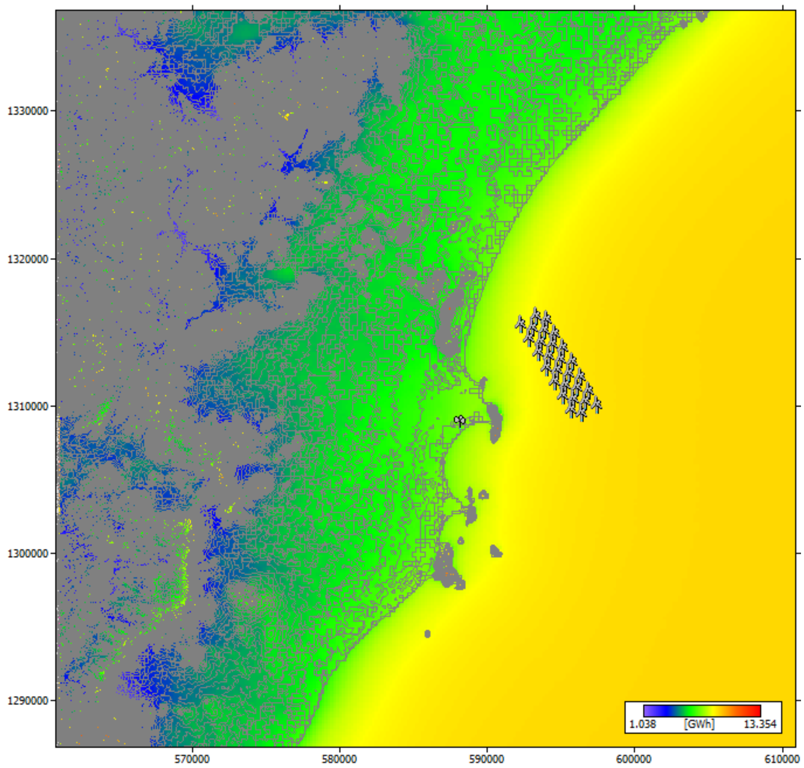


Figure 4.22 AEP map of Prachuap Khiri Khan at 84 m agl

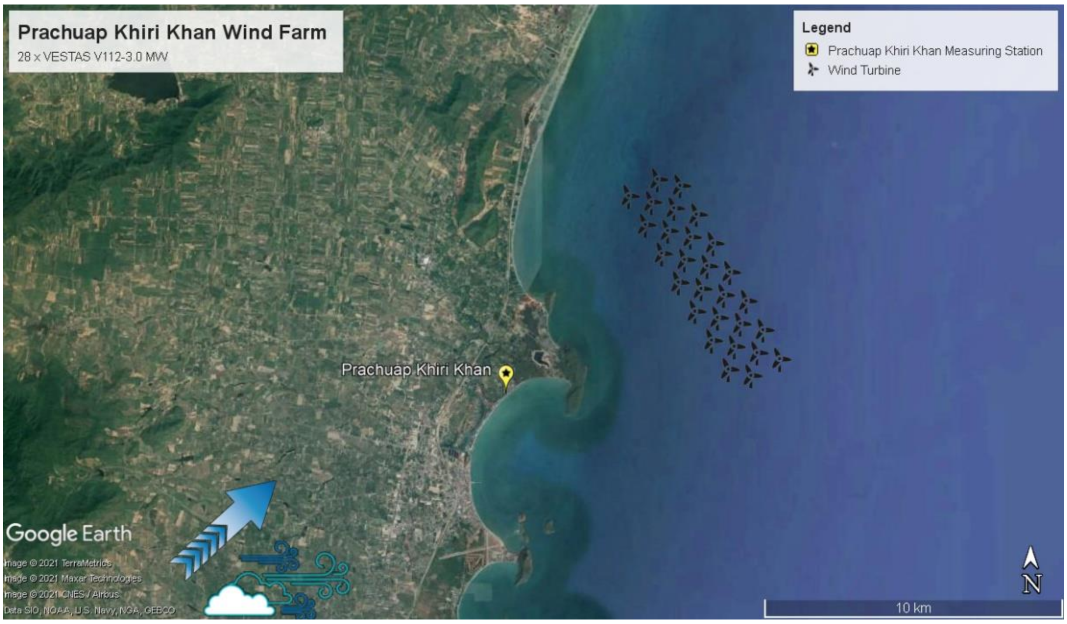


Figure 4.23 The selected wind farm site and Wind direction from South South-West (SSW) at Prachuap Khiri Khan Site

In these results, the station is along the coast line on the east side of Thailand, or the Gulf of Thailand. The results of the wind assessment in 10 m agl demonstrated that Thailand had class 1 wind speeds, but still sufficient to produce electricity from the minimum cut-in wind speeds of offshore wind turbine specifications in 4 sites studied. To provide an optimal offshore wind farm within the limitations of the criteria by using Multi Criteria Decision Analysis (MCDA) methods with Analytic Hierarchy Criteria (AHC) tools. From wind measurements in each station, the stations with the most wind potential were Rayong, Narathiwat, Prachuap Khiri Khan, and Songkhla station, respectively. But when under the criteria, the suitable wind farms in the first rank of selection weight were Narathiwat, Prachuap Khiri Khan, Songkhla, and Rayong stations, respectively. And the stations that could provide offshore wind farms were Narathiwat and Prachuap Khiri Khan, which met some of the criteria.

At these two selection sites, the frequency of wind distribution at the Narathiwat site was quite more constant than at the Prachuap Khiri Khan site, and it affected the wind speed measurement and analysis. However, the expansion of a larger wind farm scale at the Prachuap Khiri Khan site should be concerned about the limitations of the restriction zone, economic impacts, and other impacts on marine imitation. Therefore, the Narathiwat site could be a better choice, but there were some criteria to be concerned about. Due to the deepest sea, this wind farm site could not be installed far away from the coarse line. A further study was needed on other criteria concerned.

CHAPTER 5

CONCLUSION AND FURTHER STUDY

5.1 Conclusions

In this study, the wind resource assessment and offshore wind farm site selection in the Gulf of Thailand were separated into 10 site stations. From the Thai meteorological mast in both the East and South East of Thailand, consisting of: Khlongyai station, Phliu station, Rayong station, Prachuap Khiri Khan station, Chumphon station, Koh Samui station, Nakhon Si Thammarat station, Songkhla station, Pattani station, and Narathiwat station, measuring at 10 m above ground level every 10 minutes within up-to-date wind data for 4 years (2017-2020).

The result from WAsP Program provides wind potential in The Gulf of Thailand demonstrate mean wind speed and power density in Khlonyai 2.65 m/s and 22 W/m^2, Phliu 2.06 m/s and 18 W/m^2, Rayong 3.45 m/s and 67 W/m^2, Prachuap Khiri Khan 3.24 m/s and 54 W/m^2, Chumphon 2.51 m/s and 30 W/m^2, Koh Samui 2.60 m/s and 30 W/m^2, Nakhon Si Thammarat 2.31 m/s and 28 W/m^2, Songkhla 3.10 m/s and 44 W/m^2, Pattani 2.21 m/s and 25 W/m^2 and Narathiwat 3.61 m/s and 82 W/m^2. The seasonal or monsoon wind in the Gulf of Thailand can be classified as: winter or northeast monsoon, which brings a lot of rain, especially from October to November; summer or pre-monsoon, where the weather in upper parts of the Gulf of Thailand will warm up and the rainy or southwest monsoon will bring ample rain from the middle of October to the end of the year.

There were four stations with more than 3 m/s of the mean wind speed: Rayong, Prachuap Khiri Khan, Songkhla and Narathiwat, which were considered a minimum for cut-in wind turbines with Vestas-V112 Offshore wind turbine specification. In addition, MCDA in the Analytic Hierarchy Process (AHP) was used for the optimal offshore wind farms. From the results of the AHP in 7 criteria, there are no areas in this study far more than 12 nm from shore and the deepest area is more than 10-20 m deep in the territorial and sea depth criteria. There were two sites with some conflict; Prachuap Khiri Khan and Songkhla are located near the areas of military zone criteria. In aviation route criteria, Songkhla was deemed unsuitable because it is located close to a civil airport and aircraft routes. For the pipeline and cable criteria, there were two sites unsuitable: Rayong and Songkhla, to prevent the danger from the gas pipelines beneath the ground from Rayong to Songkhla. In social and environmental impact criteria, there were some conflicts in Rayong and Prachuap Khiri Khan. The result of AHP analyzed the selection weight were Narathiwat 35%, Prachuap Khiri Khan 29%, Songkhla 21% and Rayong 15%. And addition of criteria limitation, the most optimal site was the Narathiwat site. However, due to some limitations, the other selected site was Prachuap Khiri Khan with partial conflicts.

To analyze the wind assessment at 84 m agl of the turbine height at Prachuap Khiri Khan and Narathiwat sites, 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 net Annual Energy Productive (AEP) of 28×V112 turbines was 226.7 GWh and 270.8 GWh, the capacity factor was 33.1% and 37.7% with a proportional wake loss were 6.86%

and 2.37% respectively. The wind direction was from 240° South South-West (SSW) direction in both sites but quiet more wind at Narathiwat site. At Narathiwat site, the net AEP values were quite high. The turbine alignments at Narathiwat site were in 2 rows and 14 columns, but at Prachuap Khiri Khan site, they were in 4 rows and 7 columns with more wake loss turbulence, which can help to reduce by separation of the wind turbine space in rows with 5D and 10D in column. The 200 m high resolution wind map with 50×50 km^2 showed that there was more wind power value energy in all assessments mean wind power, power density and AEP that means more distance from the shore was better for wind values.

The most optimal and suitable offshore wind farm in the Gulf of Thailand in this study was the Narathiwat site, with the highest wind potential and annual energy product located south of Thailand. The Prachuap Khiri Khan site was an alternate wind farm selected site with partial criteria conflicts, but the location is located in the middle of Thailand, which means it needs more study, in order to determine its worthiness for investment or for installation of electricity grids in further study.

5.2 Further study

5.2.1 In this study, wind observation was used to measure from onshore for more accuracy and less tolerance, and the wind data at offshore wind should be measured by observation.

5.2.2. To provide more certain decision results in the criteria data, a further study in some part of criteria or some areas is suggested due to the lack of some research data that may cause unsuitable wind farm sites.

5.2.4 In this study, the Annual Energy Product (AEP) was calculated by one of the offshore wind turbine specifications at 84 m agl height. Future studies should select offshore wind turbines in a variety of specifications and height levels to determine the best and most suitable offshore wind farm in the Gulf of Thailand.

5.2.5 The minimum cut-in wind speed in this study was 3 m/s, which filtered 6 of 10 out of the selection for MCDA methods. Further study should provide less cut-in wind speed to optimize with wind characteristics in the Gulf of Thailand that are quite poor in class 1 of wind classification.

5.2.6 Wind farm economic analysis from installation distance and sea depth should be studied and calculated for worth in wind farm establishment. And should be analysis in long-term investing for net present value (NPV) and internal rate of return (IRR) in the case of wind farm electricity products and investing.

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Accepted for publication in the International Journal of Renewable Energy Research (IJRER) on September 9, 2021.