Techno-Economic Analysis of Wind Energy Potential in North-Eastern of Thailand

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ชื่อวิทยานิพนธ์ การวิเคราะห์เชิงเทคนิคและเศรษฐศาสตร์ของพลังงานลมภาคตะวันออกเฉียงเหนือของประเทศไทย
ผู้เขียน นาย ณัฏฐพัชร์ ปวินท์ธนาธร
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บทคัดย่อ

แผนพัฒนาพลังงานทางเลือกของประเทศไทยพยายามลดการพึ่งพาการผลิตไฟฟ้าจากเชื้อเพลิงฟอสซิล โดยตั้งเป้าหมายการผลิตไฟฟ้าจากพลังงานลม 3,002 เมกะวัตต์ ภายในปี 2579 นอกจากนี้ปัญหาการขาดแคลนไฟฟ้าในภาคตะวันออกเฉียงเหนือของประเทศไทยยังต้องให้ความสำคัญเพื่อสร้างเสถียรภาพด้านพลังงานของประเทศไทย ดังนั้นจึงต้องศึกษาการประเมินศักยภาพทรัพยากรพลังงานลมในภาคตะวันออกเฉียงเหนือของประเทศไทย บทความนี้นำเสนอการวิเคราะห์ทางเทคนิคและเศรษฐกิจของศักยภาพพลังงานลมของ 5 สถานีในภาคตะวันออกเฉียงเหนือของประเทศไทย ได้แก่ บุรีรัมย์ ร้อยเอ็ด ศรีสะเกษ สุรินทร์ และอุบลราชธานี ภายใน 4 ปี (พ.ศ. 2560-2563) ทุกๆ 10 นาที ซึ่งเก็บข้อมูลจากกรมอุตุนิยมวิทยาไทย (สพฐ.) ที่ระดับความสูง 10 เมตรจากระดับพื้นดิน บทความนี้เน้นที่สภาพอากาศของลมที่ความสูง 60 เมตรและ 80 เมตรเหนือระดับพื้นดินโดยใช้ WAsP เพื่อจำลองความเร็วลมเฉลี่ยและความหนาแน่นของพลังงานของแต่ละสถานี นอกจากนี้ การศึกษานี้ใช้เครื่องกำเนิดไฟฟ้ากังหันลม Vestas V52-850 kW และ Vestas V90-2,000 kW เพื่อคำนวณการผลิตพลังงานสุทธิประจำปีของแต่ละสถานี นอกจากนั้นการศึกษานี้ยังใช้เครื่องมือทางเศรษฐกิจเพื่อประเมินความเป็นไปได้ของการลงทุนอีกด้วย

ผลการศึกษาพบว่า จังหวัดร้อยเอ็ดเป็นทำเลที่เหมาะสมที่สุดในการสร้างกังหันลม มีความเร็วลมเฉลี่ยและความหนาแน่นของพลังงานเท่ากับ 5.95 เมตรต่อวินาที และ 265 วัตต์ต่อตารางเมตร ที่ความสูง 60 เมตร อีกทั้งที่ความสูง 80 เมตร มีความเร็วลมเฉลี่ยและความหนาแน่นของพลังงานเท่ากับ 6.15 เมตรต่อวินาที และ 311 วัตต์ต่อตารางเมตร ดังนั้น การผลิตพลังงานทั้งปีสามารถสร้างได้ที่ 18.932 กิกะวัตต์ชั่วโมง และ 56.322 กิกะวัตต์ชั่วโมง ที่ความสูง 60 เมตร และ 80 เมตร ตามลำดับ โดยมีราคาการผลิตไฟฟ้าต่อหน่วยที่ 0.09 ดอลลาร์/กิโลวัตต์ชั่วโมง และ 0.07 ดอลลาร์/กิโลวัตต์ชั่วโมง โดยจังหวัดอื่นๆ มีการผลิตพลังงานทั้งปีที่ 10.674 กิกะวัตต์ชั่วโมง สำหรับจังหวัดบุรีรัมย์ 12.152 กิกะวัตต์ชั่วโมง สำหรับจังหวัดศรีสะเกษ 12.969 กิกะวัตต์ชั่วโมง สำหรับจังหวัดสุรินทร์ และ 8.508 กิกะวัตต์ชั่วโมง สำหรับจังหวัดอุบลราชธานีที่ระดับความสูง 60m โดยมีราคาต่อหน่วย 0.15 ดอลลาร์/กิโลวัตต์ชั่วโมง, 0.14 ดอลลาร์/กิโลวัตต์ชั่วโมง, 0.13 ดอลลาร์/กิโลวัตต์ชั่วโมง และ 0.2 ดอลลาร์/กิโลวัตต์ชั่วโมง ตามลำดับ อีกทั้งที่ความสูง 80 เมตร

การผลิตพลังงานทั้งปีสามารถสร้างได้ที่ 33.437 กิกะวัตต์ชั่วโมง โดยมีต้นทุนต่อหน่วยที่ 0.11 ดอลลาร์/กิโลวัตต์ชั่วโมงสำหรับจังหวัดบุรีรัมย์, 45.737 กิกะวัตต์ชั่วโมง โดยมีต้นทุนต่อหน่วยที่ 0.09 ดอลลาร์/กิโลวัตต์ชั่วโมงสำหรับจังหวัดศรีสะเกษ, 41.189 กิกะวัตต์ชั่วโมง โดยมีต้นทุนต่อหน่วยที่ 0.09 ดอลลาร์/กิโลวัตต์ชั่วโมงสำหรับจังหวัดสุรินทร์ และ 27.524 กิกะวัตต์ชั่วโมง ด้วยต้นทุนต่อหน่วย 0.14 ดอลลาร์/กิโลวัตต์ชั่วโมงสำหรับจังหวัดอุบลราชธานี

จากการศึกษาการวิเคราะห์โดยใช้เครื่องมือทางเศรษฐศาสตร์พบว่ามีเพียงแค่จังหวัดอุบลราชธานีที่ความสูง 60 เมตรจากระดับพื้นดิน มีศักยภาพการผลิตไฟฟ้าไม่คุ้มค่าสำหรับการลงทุนไม่พิจารณาจากการใช้เครื่องมือทางเศรษฐศาสตร์ โดยพบว่ามูลค่าสุทธิปัจจุบัน (NPV) และ ค่าอัตราผลตอบแทนภายใน (IRR) มีค่าติดลบ ซึ่งชี้ให้เห็นถึงความไม่เหมาะสมในการลงทุน อีกทั้งค่าอัตราส่วนผลตอบแทนต่อต้นทุน (B/C ratio) มีค่า 0.978 ซึ่งมีค่าน้อยกว่า 1 สะท้อนให้เห็นถึงความไม่เหมาะสมในการลงทุนของโครงการ

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Abstract

Thailand's alternative power development plan attempts to reduce the dependence of electrical power generation on fossil fuels by setting a goal of generating electricity from wind energy resources of 3,002MW within year 2,036. Moreover, the shortage of electricity in the North-eastern region of Thailand needs to be cared for to create stability of energy in Thailand. Therefore, the assessment of wind power resource potential in the north-eastern part of Thailand needs to be studied. This paper presents a technical and economic analysis of the wind power potential for five stations in the north-eastern part of Thailand: Buriram, Roi Et, Sri Sa Ket, Surin, and Ubon Ratchathani within 4 years (2017-2020) at a 10-minute interval. The data was collected from Thai Meteorological Department (TMD) at a 10m height above ground level. This paper focuses on the wind climate at 60m and 80m above ground level by using WAsP to simulate the mean wind speed and power density of each station. Moreover, this study uses Vestas V52-850kW and Vestas V90-2,000kW wind turbine generators to calculate the net annual energy production of each station. In addition to evaluating the economic analysis of investment, this study uses economic tools to evaluate the feasibility of investment. The result showed that Roi Et is the most suitable location for a wind farm. The mean wind speeds and power densities are 5.95 m/s and 265 W/m2 at 60m and 6.15 m/s and 311 W/m2 at 80m. The AEP can be generated at 18.932 GWh and 56.322 GWh at 60m and 80m heights respectively for Roi Et with a cost per unit of 0.09 $/kWh and 0.07 $/kWh. The other provinces have an AEP of 10.674 GWh for Buriram, 12.152 GWh for Sri Sa Ket, 12.969 GWh for Surin, and 8.508 GWh for Ubon Ratchathani at 60m height level, with a cost per unit of 0.15 $/kWh, 0.14 $/kWh, 0.13 $/kWh, and 0.2 $/kWh respectively. At 80m height, the AEP is 33.437 GWh with 0.11 $/kWh for Buriram, 45.737 GWh with 0.09 $/kWh for Sri Sa Kat, 41.189 GWh with 0.09 $/kWh for Surin, and 27.524 GWh with 0.14 $/kWh for Ubon Ratchathani.

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I would like to express my sincere thanks to my thesis advisor, Asst.Prof.Dr. Juntakan Taweekun, and Dr. Somchai Saeung, my co-advisor, for invaluable help and constant encouragement throughout the course of this research. I am really grateful for their teaching and advice, not only for the research methodologies but also for 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 them.

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Chapter 1
Introduction

1.1 Background of the research significantly

Energy is a key component of socio-economic development. At present, the largest proportion of generating electricity is fossil fuels, especially coal/lignite and natural gases. Fossil fuels are mainly caused by environmental issues due to the emission of greenhouse gases that lead to climate change. Thailand has a very high percentage of fossil fuel consumption. According to the Energy Policy and Planning Office 2020, Thailand uses natural gas and coal to generate electricity, 58 and 17 percent respectively. Besides, excessive dependence on any one resource affects the high risk of energy security for Thailand. Therefore, renewable energy has become an important resource that needs to be used to generate electricity to replace the excessive dependence on fossil fuel resources.

Renewable energy is a source of energy that is being used to replace the limited fossil fuels that are expected to be depleted in the near future. There are many forms of renewable energy, such as wind energy, hydro energy, solar energy, and biomass, etc. Besides, wind energy is one of the renewable energy sources that Thailand has continually been interested in. Because wind energy is clean and safe. Moreover, wind energy is considered an unlimited resource. In addition, the construction of wind power plants is easily achieved, but wind power electricity generation depends on sufficient wind speed [28]. According to the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy 2019, Thailand has an installed alternative energy capacity of 11,852 MW. It could separate wind energy resources generation of 1,506.8 MW, or 12.7 percent of the total installed alternative energy in Thailand [1]. Furthermore, an alternative energy development plan [2] was created by the Energy Policy and Planning Office that sets the goal of installing electrical power capacity from wind energy resources of 3,002 MW by 2036.

Due to the study, the wind potential to generate electricity in Thailand does not cover the overall country. For example, studies in the central, southern and northern regions of Thailand, for example, studied; a study on the potential of wind energy for electricity generation in the central region of Thailand [3], a study on the potential of power generation from wind energy in the upper northern region [4], and an assessment of micrositing wind energy potential along the coasts of southern Thailand [5]. Therefore, to respond to the alternative energy development plan 2015 to increase the installed energy capacity of wind energy resources by 3,002 MW by 2036, the assessment of wind energy resource potential is crucial information for making an investment decision.

The north-eastern region of Thailand is the largest area in Thailand. The evaluation site is around 168,854 square kilometers. In 2017, northeastern had the capacity to generate 1,600 MW of electrical power but the demand for 3,600 MW. Therefore, the capacity of electricity is a shortage to the demand. Therefore, they needed to import electricity from a hydroelectric power plant in Lao PDR [6]. Wind energy is an important source of energy for producing electrical energy. The study of assessing the wind energy potential in Northeastern Thailand has the objective of assessing the wind energy potential in Khonkean, Mookdaharn, Kalasin, and Nogkhai at the level of hub-height of 60m and 90m above ground level to be the choice of decision for investment in the future by measuring the wind speed, power density, and Weibull parameters. The result of the study found Khonkean was the most suitable province for installing wind farms [8]. The study of wind speed and power characteristics of Kalasin province, Thailand has continued to assess the wind energy potential by using WAsP software to estimate energy yield output in the studied areas with VESTAS 2.0MW as the wind turbine generator. The result found in this area could generate 2,747 MWh/year [7]. However, the economic viability of wind power depends on the area. As a result, the benefits and costs associated with a wind power plant project are affected. Accurate wind resource assessment is thus critical in selecting a profitable location [8,9].

This study will assess wind energy resource potential in the northeastern of Thailand with 5 provinces by collecting 4 years of wind data from 1 January 2017 until 31 December 2020 at a 10minute interval. The data was collected by the Thai Meteorological Department (TMD) at an anemometer height of 10 meters above the ground level to predict mean wind speed, wind direction frequency, Weibull parameters, and power density at the heights of 60m and 80m above the ground level by using the Wind Atlas Analysis and Application Program (WAsP). In addition, the economic evaluation of wind energy production with Vestas 52-850kW and Vestas 90-2000 kW is a concern.

1.2 Objective

1.2.1 To analyze the wind energy in the selected-site province in north-eastern of Thailand

1.2.2 To assess the wind potential for wind power generation in the site-selected of the north-eastern of Thailand

1.2.3 To evaluate the economic feasibility of installing a wind farm for power generation

1.3 The scope of the study

1.3.1 The wind data was obtained from 5 meteorological mast stations in the northeastern of Thailand: Buri Ram, Roi Et, Sri Sa Ket, Surin, and Ubon Ratchathani.

1.3.2 The period of collection was from 2017 to 2020 by 10 minutes.

1.3.3 The wind assessment potential was analyzed by WAsP

1.3.4 The economic analysis used 3 indicators, which consisted of the benefit-cost ratio, net present value, and internal rate of return.

1.4 The anticipated results

1.4.1 Acquiring the data on the wind potential at the selected study site in the north-eastern part of Thailand.

1.4.2 Being able to locate the specific area with the high wind power potential for the deciding to install the wind power electricity generation.

1.5 Organization of Thesis

This thesis is divided into 5 chapters, including this chapter, Introduction, and the other chapters are described below.

Chapter 2 Related theory and literature review, this chapter presents the general circulation of wind models, wind characteristics in Thailand, the potential of wind energy, the definition of wind rose, statistical analysis of wind data, the analysis by the WAsP program, and evaluation of economic feasibility. Moreover, this chapter presents the literature reviews that are involved in this research.

Chapter 3 Methodology presents the implementation of this research. Beginning with, the overview of the study area to explain the general information about the wind climate in each province. Secondly, the topography simulation. This sector will simulate the elevation and roughness of the area. Thirdly, simulation of wind potential energy. This sector will present the statistics of the wind climate. Fourthly, a simulation of annual wind energy production. At the end of this chapter, I will present the evaluation and economic analysis of wind energy production.

Chapter 4 Results and Discussion provides the wind climate statistics of the meteorological site at 10m above ground level. Moreover, the WAsP program is used to explore the wind resource potential around the meteorological station, including elevation, roughness, mean wind speed, and power density, to be the criteria for site selection for a wind farm. The wind farm sites will provide information about the wind climate statistics at the different height levels based on the hub-height of the wind turbines. The wind climate statistic is used to estimate the annual wind energy production and the capacity factor of the wind farm. At the end of this chapter, the economic analysis of the wind farm will provide the value of the return on investment and the cost per unit for wind energy generation.

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

Chapter 2
Related Theory and Literature Review

2.1 The General Circulation of Wind Model

The wind is caused by the difference in solar radiation absorption between the different areas. The area that absorbed a high amount of solar radiation has a higher air temperature in that area, so air at a high temperature expands and becomes buoyant in the atmosphere, resulting in low air pressure in that area. Following that, the area with the lower air temperature will experience a displacement of the high air pressure to the area with the lower air pressure. The motion of the different atmospheric pressures caused the wind [12].

Due to the different absorption of solar radiation in the equatorial region, which is higher than in the rest of the world, that causes the hot air to float and, as a result, low pressure in those areas. The floating hot air will return to the Earth’s surface in the Northern and Southern Hemispheres and will be 30 degrees north and south of the equatorial region. This causes the cooling mass air movement to replace itself at the low pressure area at the equator. The formation of the circulation pattern was known as "Hedly Cell", as shown in the figure 1.

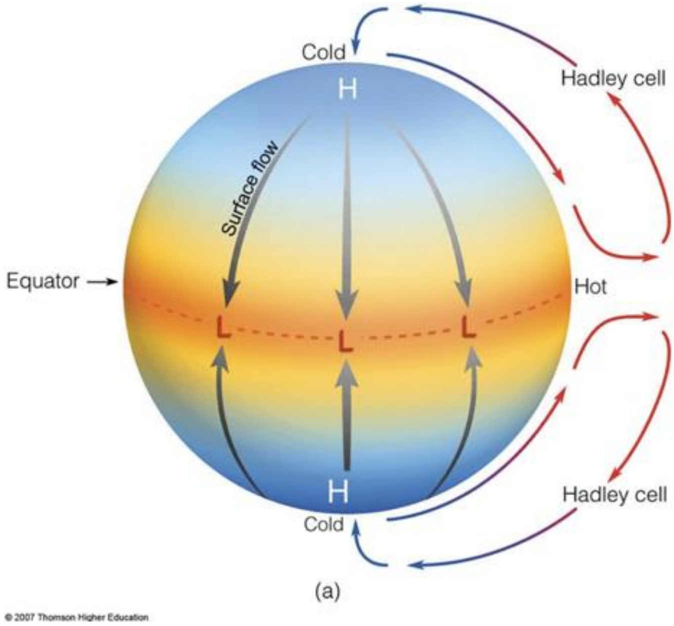


Figure 1: The general circular motion of wind flow [51]

The global wind is caused by the air pressure and temperature differences in the upper atmosphere. The air or wind is accelerated from high pressure to low pressure areas. Figure 2 has shown the Coriolis Effect causes the deviation of mass air that affects the wind moving to the other part of the world.

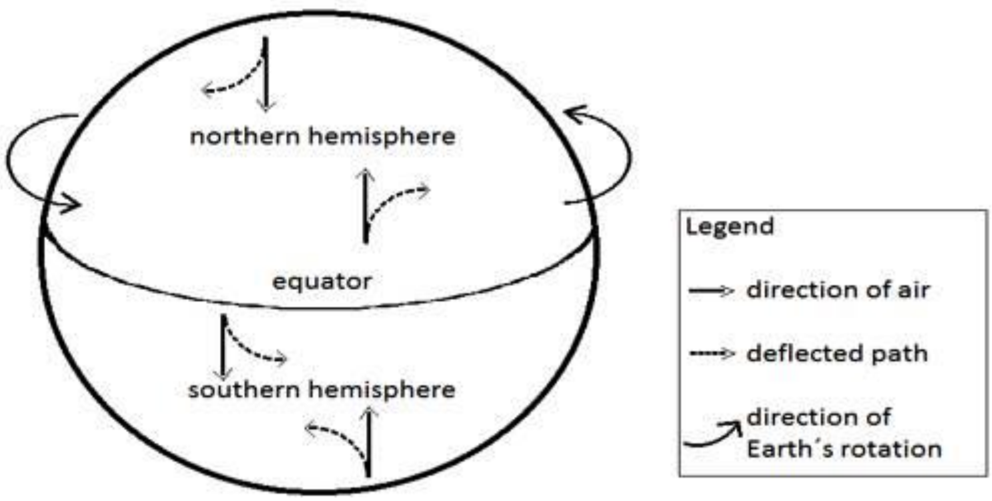


Figure 2: The deviation in wind is caused by the Coriolis Effect [52].

2.2 Wind characteristic in Thailand

2.2.1 Seasoning wind flow

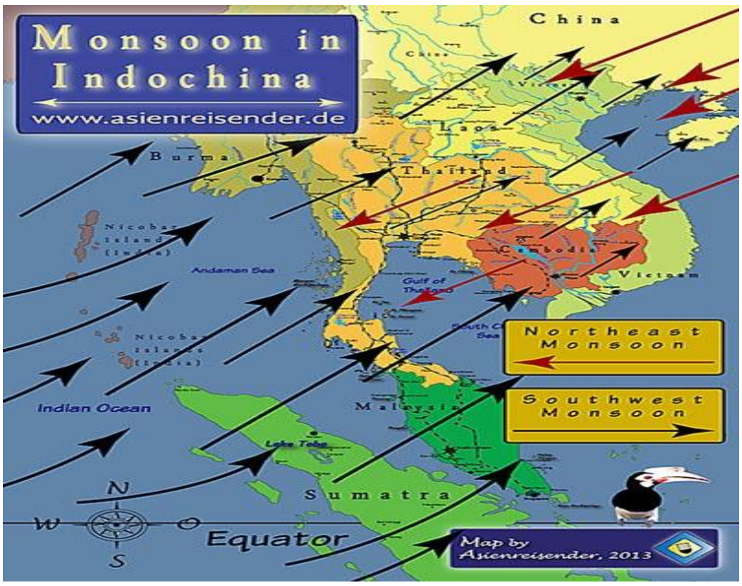


Figure 3: The wind flow of the monsoon in Thailand [53].

The monsoon circulation pattern wind flow is mainly the surface winds that hit over Thailand [12]. The transformation of wind direction is caused by the movement of the Intertropical Convergence Zone (ITCZ). The moving Intertropical Convergence Zone (ITCZ) lies in the equatorial trough, a low-pressure surface in the trade wind that effects increased convection, cloudiness, and precipitation [13]. The effect of Intertropical Convergence Zone movement has the critical affect to the monsoon circulation pattern in Thailand. Thailand has mainly two characteristics of the monsoon.

2.2.1.1 Northeast Monsoon

The monsoon originates from high pressure areas in the northern hemisphere of Mongolia and China. Around mid-October, the northeast monsoon prevails over Thailand until mid-February, bringing cold and dry air masses from its source to cover Thailand, making the sky clear, cold and generally dry. Especially in the North and Northeast. The southern region will have a lot of rain, especially on the south and east coast. Because this monsoon brought moisture from the Gulf of Thailand, it brought cover.

2.2.1.2 Southwest Monsoon

The southwest monsoon prevails over Thailand. Between mid-May and mid-October with a source from high pressure areas in the southern hemisphere of the Indian Ocean which blows from the center as a southeast wind and turns into a southwesterly wind as it blows over the equator. This monsoon will bring humid air masses from the Indian Ocean to Thailand, causing clouds and general rain, especially along the coast. And the mountains in the wind will have more rain than other areas.

2.2.2 Local wind in Thailand

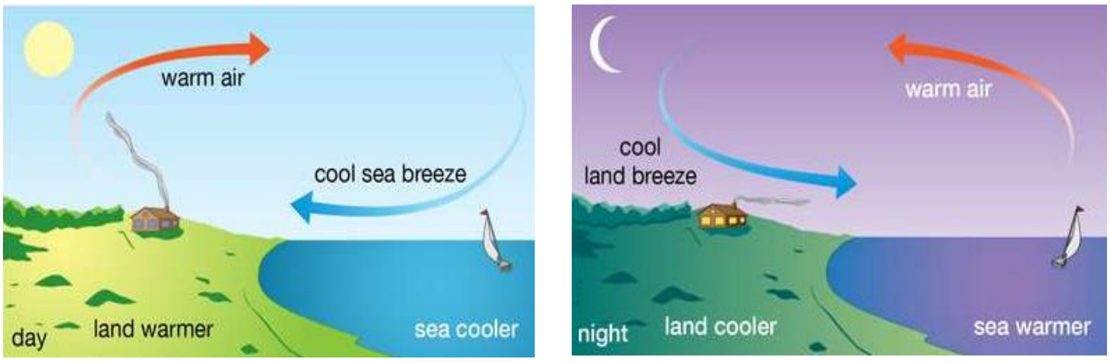


Figure 4: Land breeze and Sea breeze Diagram [54].

2.2.2.1 Land Breeze and Sea Breeze

Land breezes and sea breezes are two types of wind in Thailand. They are caused by the difference in heating capacity between water and dry land. In daylight, the land absorbs solar radiation better than the water. Therefore, the land has a higher air temperature than the water, which causes the temperature to expand and the atmosphere to buoyant, leading to the lower air pressure of the land. In contrast, after sunset, the dry land also cools quicker than the water, so the air pressure of the land will be higher than the water.

2.2.2.2 Mountain Breeze and Valley Breeze

During the day, the mountain absorbs solar radiation more rapidly than the valley. Therefore, the air from the mountain heats up and floats into the atmosphere, affecting the lower air temperature of the valley instead of the mountain. It affects the valley wind or valley breeze that occurs. In contrast, at night the cooling of the mountain is better than the valley, leading to the air pressure of the mountain being higher than the valley. The mountain air pressure leads to the valley air pressure being lower, which is called the mountain breeze. Due to the geographical location of the mountain and valley, the phenomena of wind are interrupted by wind shear, turbulence, and the acceleration of wind over the ridge.

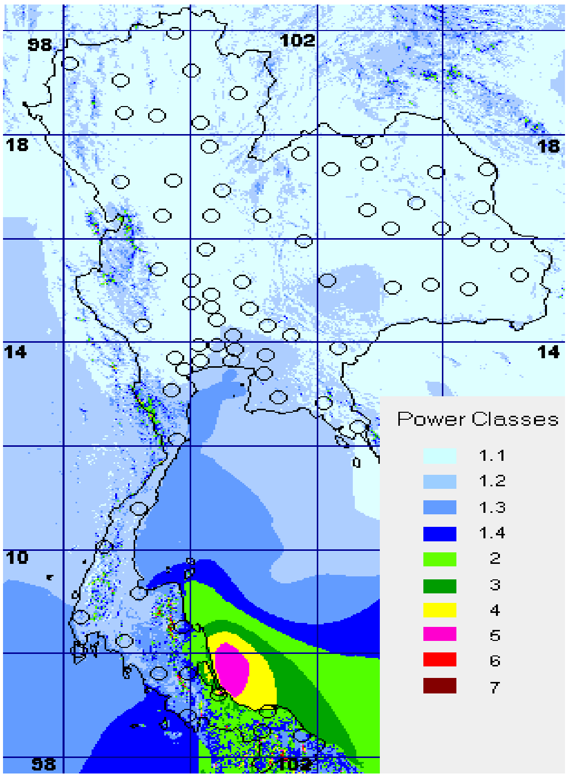
2.3 The potential of wind energy

Wind energy is one of the most intermittent energy resources that Thailand has continuously been interested in. According to the "Thailand Alternative Energy Situation 2019" report [1], Thailand had a total capacity to generate electricity from alternative energy resources of 11,852 MW, followed by solar energy, large hydro power, wind energy, biogas, MSW, small hydro power, and geothermal power. The growth rate of wind energy from 2015 to 2019 increased by 36.6%. Not the end of that, the alternative energy development plan encourages the policy to attract private sector investment on alternative energy industry to achieve the goal in 2036. The target for alternative resource electricity generation in 2036 was 19,684.4 MW, while the target for wind energy resources to generate electricity was 3,002MW [2].

Table 1. The alternative energy plan to generate electrical power

Alternative Energy	Installed Capacity (MW)					Growth rate (%)	Target (MW)
	2015	2016	2017	2018	2019	2018-2019	2036
Solar	1,419.6	2,446.1	2,697.2	2,962.5	2,982.6	0.7	6,000
Wind	233.9	507.0	627.8	1,102.8	1,506.8	36.6	3,002
Small Hydro power	172.1	182.1	182.3	187.7	187.8	0.1	376
Biomass	2,726.6	2,814.7	3,157.3	3,372.9	3,410.1	1.1	5,570
Biogas	372.5	434.9	475.4	505.2	530.0	4.9	1,280
MSW	131.7	145.3	191.5	317.8	314.7	(1.0)	550
Large Hydro power	2,906.4	2,906.4	2,906.4	2,919.7	2,919.7	-	2,906.4
Geothermal power	-	-	-	0.3	0.3	-	-

The consequence is that Thailand is near the equator region, which affects the low-moderate average wind speeds in this region. Thailand has average wind speed about 2.8-4 m/s or power class 1-1.4 that was measured at 10 meters above the ground level, as shown in figure, the study of wind energy potential was conducted in 1975 by the Thai Meteorological Department. By the way, the general hub-height of a wind turbine is 50-65 meters above ground level. In 2001, Thailand's wind speed potential map was improved to higher elevation at 50 meters above the ground level. The results showed the suitable areas have an average wind speed of not less than power class 3: 6.4-7 m/s or 300-400 kW/m^2 at 50 meters above ground level. The coastal area of the Thai Gulf is indicated to have the best wind potential. Moreover, the upper-southern region around the western coast of the Thai Gulf had an average wind speed of 4.4 m/s at 50 meters' height. This is caused by the northeast monsoon and southwest monsoon that affect and produce strong winds in Thailand annually [15].



THAILAND WIND POWER CLASSES

Elevation		1.1		1.2		1.3		1.4		2		3		4		5		6		7	
10 m	m/s	0		2.8		3.6		4.0		4.4		5.1		5.6		6.0		6.4		7.0	9.4
	W/m^2	0		25		50		75		100		150		200		250		300		400	1,000
30 m	m/s	0		3.3		4.1		4.7		5.2		5.9		6.5		7.0		7.4		8.2	11.0
	W/m^2	0		40		80		120		160		240		320		400		480		640	1,600
50 m	m/s	0		3.6		4.4		5.1		5.6		6.4		7.0		7.5		8.0		8.8	11.9
	W/m^2	0		50		100		150		200		300		400		500		600		800	2.000

Figure 5: The average wind speed and wind power class map in Thailand at 10m [1].

2.4 Wind Rose

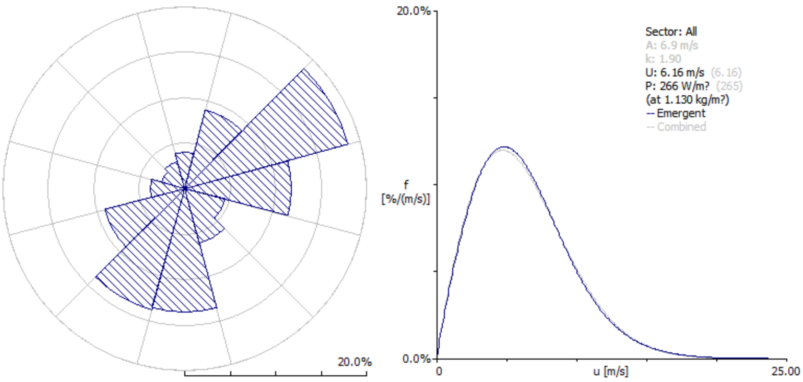


Figure 6: The distribution of wind speed and wind direction.

For the optimum exploitation of wind energy, the frequency and direction of wind prevailing are the important parameters that need to be analyzed. To generate the most possible electricity, the turbines should be adjusted to the direction that has the highest frequency of wind prevailing [15].

A wind rose is a map diagram that summarizes wind data for a specific area over a specified time period. A wind rose is used to demonstrate the percentage of wind prevailing from each direction [16].

2.5 Statistical Analysis of Wind Data [17]

Wind speed is the significant parameter for analyzing the clustering of wind farms for electricity generation. Thus, to evaluate the accuracy of the mean wind speed, the statistical distribution method is needed as the tool. The Weibull distribution is one of the statistical distributions that has been found to be an accurate and adequate statistic tool in analyzing and interpreting wind speed. Moreover, the Weibull distribution is also used for predicting wind characteristics to determine wind energy potential [18-20]. The WAsP climate analysis program references a Weibull distribution function that is fitted to the measured histograms to provide scale parameter (A-scale parameter) and shape parameter (k-shape) for each sector [21-22].

2.5.1 Shape parameter (k-shape)

This is a parameter that characterizes the wind distribution. In the area with low "k", it indicates that the frequency of low wind speed in that area is more frequent than high wind speed. In contrast, if that area has a high "k", that means the frequency of high wind speed is more often than low wind speed [20].

$$k = \begin{cases} 1.05\, v^{0.5}\ if\ v < 3 \\ 0.95\, v^{0.5}\ if\ 3 < v < 4 \\ 0.83\, v^{0.5}\ if\ v > 4 \end{cases} \quad (1)$$

Where; v = The observing wind speed (m/s)

2.5.2 Parameter Scale (c-scale parameter)

This parameter is related to the average wind speed. If the average wind speed has a high value, "c" will be high, but in contrast, if the average wind speed has a low value, "c" will also be low [20].

$$c = \frac{\bar{v}}{\Gamma\left(1+\frac{1}{k}\right)} \tag{2}$$

Where; $\bar{v}$ = The average wind speed (m/s)

2.5.3 Probability Density Function

The most probable wind speed and the maximum wind energy can be found by following the equation [23].

$$V_{mp} = c\left(\frac{k-1}{k}\right)^{1/k} \tag{3}$$

$$V_{maxE} = c\left(\frac{k+2}{k}\right)^{1/k} \tag{4}$$

Where; V_{mp} = The probable mean wind speed (m/s)

V_{maxE} = The maximum wind energy (m/s)

c = scale parameter (m/s)

k = Shape parameter

Another important parameter for analyzing wind resource potential is the wind power density. The calculation formula can be expressed with the equation [18].

$$\frac{P}{A} = \frac{1}{2}pc^3\left(1+\frac{3}{k}\right) \tag{5}$$

Where; $\frac{P}{A}$ = Wind power density (W/m^2)

p = Average density of air (1.23 kg/m^3)

The Weibull probability density function is used to explain the behavior of the wind speed and frequency distribution. The calculation formula can be expressed with the equation [20].

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp^{-\left(\frac{V}{c}\right)^{k}} \quad (6)$$

2.5.4 Vertical Extrapolation of Wind Speed

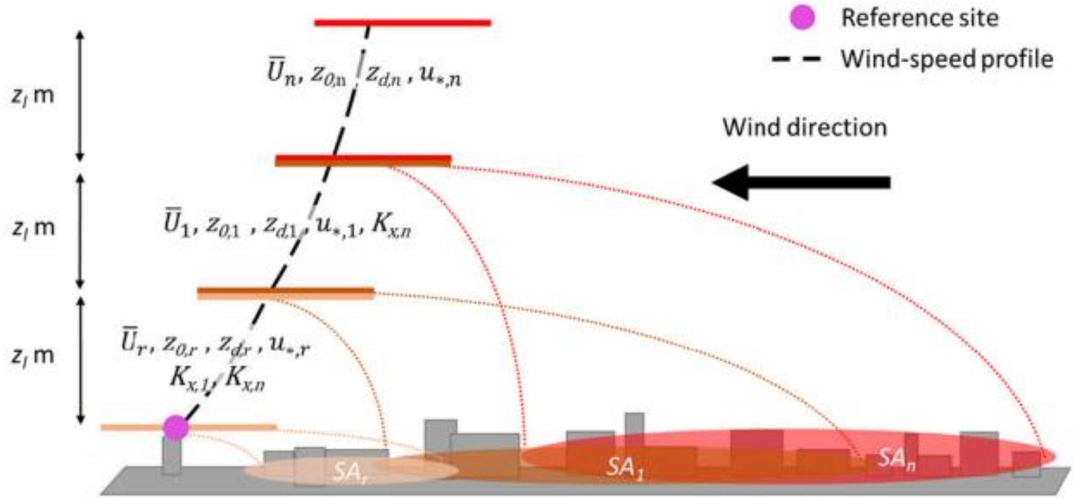


Figure 7: Vertical wind speed at different heights [55].

In general, the anemometer has been placed at a 10meter height above the ground level. However, a modern wind turbine is usually operated at 50 meters above ground level, which means the extrapolation of wind speed at the wind turbine hub-height needs to be analyzed to estimate the actual wind speed at the different heights above the anemometer standard height. The effect of roughness terrain and elevation has influenced the wind speed and power density. The logarithmic wind law can be used to calculate the wind speed at different height level that can write the formula as follows: [24].

$$V(h_2) = V(h_1)\frac{\ln(h_2/h_0)}{\ln(h_1/h_0)} \quad (7)$$

Where; $V(h_2)$ = The wind speed at different height

$V(h_1)$ = The wind speed at reference height

h_1 = The reference height level

h_2 = The height level that need to calculate

h_0 = The roughness length

2.5.5 Analysis of the wind energy output

The analysis of wind energy output is the process of applying the site-selection of a wind farm to predict the net annual energy production. The speculation of wind turbines is one of the parameters that affect wind energy production. In this study, using VESTAS V52 and VESTAS V90, are the wind turbines that are used in this study. The annual energy production can be calculated by the equation [26].

$$AEP = T\left[\int_{v_i}^{v_r} P_r\left(\frac{v_0^2 - v_i^2}{v_r^2 - v_i^2}\right) f(v)\, dV + \int_{v_r}^{v_0} P_r f(v)\, dV\right] \quad (8)$$

Where; AEP = Annual energy production

T = The annual operating time

$f(v)$ = The Weibull probability function

P_r = The rated power of wind turbine

v_r = The rated speed of wind turbine

v_i = The cut-in wind speed of wind turbine

v_0 = The cut-out wind speed of wind turbine

The capacity factor is one of the significant performance parameter of wind energy production that indicates the potential output of wind energy. The capacity factor is used to indicate the generation rate of the wind power turbine system [26]. The capacity factor of wind turbine is the ratio of the actual wind energy output over the time period or AEP and the rated power capacity of wind turbine (E_{rate}). The equation can be written following;

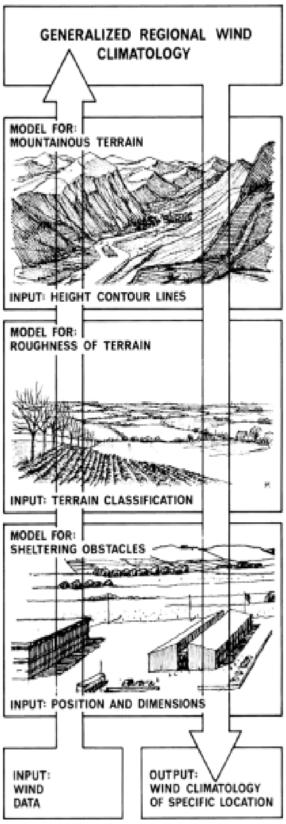
$$C_f = \frac{AEP}{E_{rate}} \quad (9)$$

2.6 The Analysis by the WAsP Program

Figure 8: The Wind Atlas Analysis and Application Program [56].

The Wind Atlas Analysis and Application Program (WAsP) is a program that has been developed by the Denmark Riso National Meteorology Laboratory, WAsP is the industry standard for assessing the wind resource to calculate the energy yield and potential wind resource of the location site of a wind turbine or wind farm. WAsP contains complete dataset models for calculating wind climate that were affected by the turbulence of complex terrain flow models, such as the effect of sheltering obstacles, surface roughness changes, and height contour line variation. [27].

WAsP uses the time-series of raw-meteorological data of wind speed and wind direction to calculate the generalized observing wind distribution. The five main calculation activities within WAsP are listed below [22, 29, 30].



WAsP analysis: from wind data to generalised wind climate

1. Time-series of wind speed and direction → observed wind climate (OWC)
2. OWC + met. mast site description → generalised wind climate (wind atlas)

WAsP application: from generalised to predicted wind climate

3. Generalised wind climate + site description → predicted wind climate (PWC)
4. PWC + power curve → annual energy yield of wind turbine

Wind farm production: from predicted wind climate to gross yield

5. PWC + wind turbine (WTG) characteristics → 'WAsP gross' wind farm yield
6. PWC + WTG characteristics + wind farm layout → wind farm wake losses
7. 'WAsP gross' yield – wake losses → 'WAsP net' wind farm yield

Post-processing: from 'WAsP net' yield to net yield (P_{50} and P_x)

8. 'WAsP net' yield – technical losses → net annual energy yield (P_{50})
9. Net yield – uncertainty estimate → Net yield P_x

Figure 9: WAsP wind atlas analysis methodology [28].

2.6.1 Analysis of raw wind data

The analysis of time-series of wind data provides a statistical summary of the observed wind climate at the specific site of a meteorological station or wind turbine. The Observed Wind Climate (OWC) Wizard and the WAsP Climate Analyst are the software that are used to implement the time-series analysis. The implementation is followed as follows:

Time-series of wind speed and direction —> observed wind climate (OWC)

The observed wind climate (OWC) provides the calculated data for wind statistics analysis, which includes;

- The frequency of wind prevailing in each direction
- The Weibull scale parameter (A-parameter)
- The Weibull shape parameter (k-parameter)
- The mean wind speed
- The mean power density

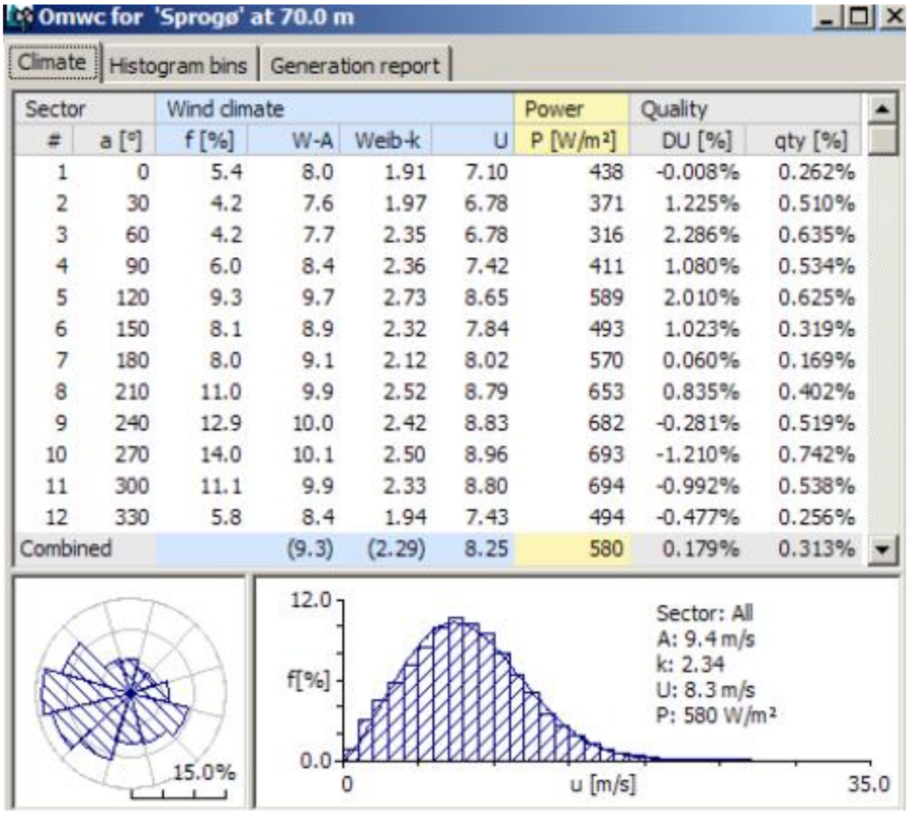


Figure 10: The wind analysis's observing wind climate (OWC) [22].

2.6.2 Generation of wind atlas data

A regional wind climate or wind atlas data set is obtained from converting the analysis of wind data with clean respect to the site-specific conditions. The obtained wind atlas data sets provide the wind distribution of wind statistics with a site-independent around study areas that have been reduced to certain standard conditions. The implementation is followed as follows:

Observed wind climate + met. station site description —> regional wind climates

2.6.3 Prediction of wind climate

The estimation of wind climate is used to predict the actual or expected wind climate around the selected sites by inverse calculation, introducing descriptions of the terrain around the site, e.g., roughness and elevation. The implementation is followed as follows:

Regional wind climate + site description —> predicted wind climate

The result of estimating wind climate will provide the wind statistics analysis of the area around a selected site at any height level that was studied. The wind statistics include:

- The frequency of wind prevailing in each direction
- The Weibull scale parameter (A-parameter)
- The Weibull shape parameter (k-parameter)
- The mean wind speed
- The mean power density

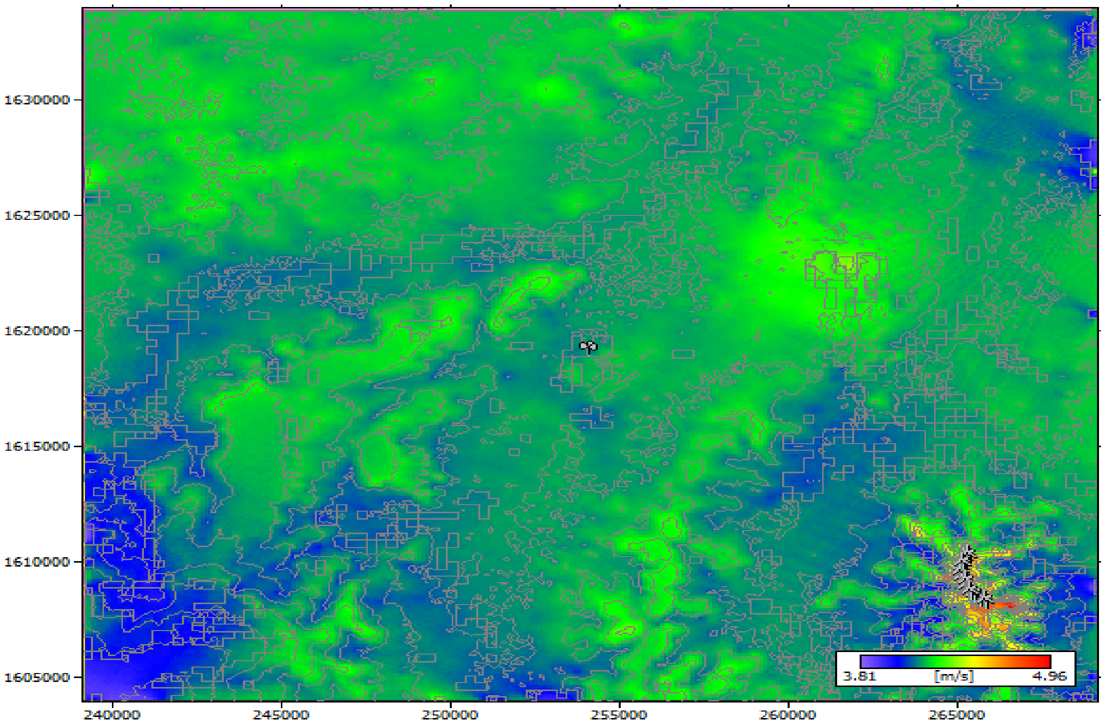


Figure 11: The estimation of wind climate around the selected site

Sector [?]	Variable	Mean	Min	at	Max	at
All	Air density	1.125 kg/m?	1.114 kg/m?	(266626, 1608116)	1.128 kg/m?	(269126, 1633816)
All	Weibull-A	4.7 m/s	4.3 m/s	(239226, 1611016)	5.5 m/s	(266626, 1608016)
All	Weibull-k	1.66	1.59	(266526, 1606516)	1.70	(263126, 1604116)
All	Mean speed	4.19 m/s	3.81 m/s	(239226, 1611016)	4.96 m/s	(266626, 1608016)
All	Power density	97 W/m?	76 W/m?	(269126, 1608816)	162 W/m?	(266626, 1608016)
All	Elevation	197.6 m	170.0 m	(269126, 1633816)	320.0 m	(266626, 1608116)
All	RIX	0.0%	0.0%	(269126, 1633816)	0.4%	(266426, 1607716)
All	Turbulence intensity					
All	Flow inclination					
All	Delta-RIX	0.0%	0.0%	(269126, 1633816)	0.4%	(266426, 1607716)
All	AEP	925.172 MWh	729.651 MWh	(269126, 1608816)	1.407 GWh	(266626, 1608016)
All	Capacity factor	12.3%	9.7%	(269126, 1608816)	18.7%	(266626, 1608016)
000	Sector frequency	7.4%	6.3%	(265226, 1608816)	8.6%	(266326, 1608016)
000	Weibull-A	4.7 m/s	4.1 m/s	(239226, 1610516)	5.9 m/s	(266426, 1608016)
000	Weibull-k	1.86	1.83	(264626, 1609316)	1.87	(266026, 1610216)
000	Mean speed	4.18 m/s	3.68 m/s	(239226, 1610516)	5.28 m/s	(266426, 1608016)
000	Power density	85 W/m?	58 W/m?	(239226, 1610516)	171 W/m?	(266426, 1608016)
000	Meso roughness	0.104 m	0.039 m	(262126, 1621216)	0.429 m	(239226, 1610716)
000	Obstacles speed					
000	Orographic turn	0.0?	-4.5?	(267226, 1608716)	6.1?	(266526, 1606516)
000	Orographic speed	0.0%	-10.9%	(264926, 1608816)	23.9%	(266426, 1608116)
000	RIX	0.0%	0.0%	(269126, 1633816)	1.2%	(266426, 1607716)
000	Roughness changes	0.3258863	0	(269126, 1633816)	8	(263626, 1613316)
000	Roughness speed	-0.1%	-7.8%	(243026, 1605516)	5.0%	(261826, 1620016)
000	Turbulence intensity					
000	Flow inclination					
000	Delta-RIX	0.0%	0.0%	(269126, 1633816)	1.2%	(266426, 1607716)
000	AEP	837.194 MWh	563.058 MWh	(239226, 1610516)	1.555 GWh	(266426, 1608016)
030	Sector frequency	11.1%	9.8%	(265526, 1606616)	12.2%	(267126, 1607716)
030	Weibull-A	6.5 m/s	5.7 m/s	(269126, 1608816)	7.9 m/s	(266526, 1608016)
030	Weibull-k	2.11	2.02	(266526, 1606516)	2.12	(269126, 1633816)
030	Mean speed	5.76 m/s	5.04 m/s	(269126, 1608816)	7.01 m/s	(266526, 1608016)
030	Power density	195 W/m?	131 W/m?	(269126, 1608816)	352 W/m?	(266526, 1608016)
030	Meso roughness	0.105 m	0.030 m	(269126, 1626816)	0.300 m	(269126, 1633216)
030	Obstacles speed					
030	Orographic turn	0.0?	-4.3?	(266326, 1608016)	6.7?	(265226, 1608916)
030	Orographic speed	0.0%	-7.2%	(264326, 1606816)	23.9%	(266526, 1608016)
030	RIX	0.0%	0.0%	(269126, 1633816)	2.1%	(266326, 1607616)
030	Roughness changes	0.2529097	0	(269126, 1633816)	8	(261926, 1621516)
030	Roughness speed	-0.1%	-6.9%	(242326, 1605516)	4.8%	(261026, 1620216)
030	Turbulence intensity					

Figure 12: The wind statistic of the estimation wind climate around the selected site

2.6.4 Estimation of wind power potential

The mean wind speed, power density, and Weibull distribution are calculated by WAsP to provide the total energy content of the wind resource in the area. Furthermore, the power curve of the wind turbine can be obtained for the calculation to analyze the energy production of wind turbines. The implementation is followed as follows:

Predicted wind climate + the power curve of wind turbine —> Annual energy production (AEP) of wind turbine

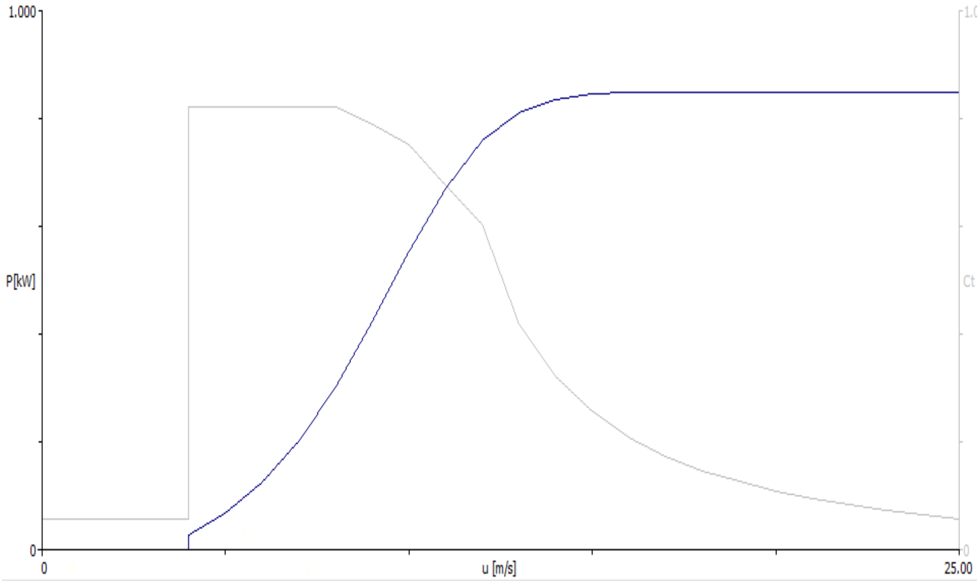


Figure 13: The power production curve of wind turbine (VESTAS V52)

2.6.5 Calculation of wind farm production

Concerning wind farm production, WAsP can estimate the wake losses for the layout sorting of wind turbines and the thrust coefficient curve of the wind turbine. Therefore, the analysis of energy content can estimate the net annual energy production of an individual wind turbine and the entire wind farm. The implementation is followed as follows:

Predicted wind climates + WTG characteristics —> gross annual energy production of wind farm

Predicted wind climates + WTG characteristics + wind farm layout —> wind farm wake losses gross

Annual energy productions + wake losses —> net annual energy production of wind farm

Site description	X-location [m]	Y-location [m]	Elev. [m]	RIX [%]	DR [%]	Ht [m]	U [m/s]	U(w) [m/s]	p [kg/m³]	Gross [GWh]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 01	265314.8	1609850.0	291.8	0.0	0.0	60.0	4.63	4.50	1.116	0.919	0.838	8.77	12.2
Turbine site 002	265429.4	1610008.0	290.9	0.0	0.0	60.0	4.66	4.59	1.117	0.932	0.890	4.55	12.4
Turbine site 003	265271.8	1609048.0	302.7	0.0	0.0	60.0	4.69	4.62	1.115	0.964	0.930	3.62	12.8
Turbine site 004	265200.2	1609485.0	303.2	0.0	0.0	60.0	4.71	4.59	1.115	0.965	0.883	8.45	12.8
Turbine site 005	265185.9	1609241.0	310.0	0.0	0.0	60.0	4.80	4.71	1.115	1.011	0.957	5.37	13.4
Turbine site 006	265372.1	1608640.0	303.6	0.0	0.0	60.0	4.64	4.55	1.115	0.930	0.881	5.24	12.3
Turbine site 008	265744.5	1608124.0	320.0	0.0	0.0	60.0	4.74	4.63	1.114	0.979	0.904	7.64	13.0
Turbine site 009	265272.0	1609675.0	293.5	0.0	0.0	60.0	4.61	4.46	1.116	0.908	0.822	9.46	12.0
Turbine site 010	265372.1	1608840.0	301.8	0.0	0.0	60.0	4.65	4.59	1.116	0.941	0.909	3.36	12.5
Turbine site 011	265608.4	1608275.0	317.1	0.0	0.0	60.0	4.75	4.65	1.114	0.990	0.933	5.74	13.1
Turbine site 012	265465.2	1608425.0	304.0	0.0	0.0	60.0	4.61	4.51	1.115	0.917	0.863	5.87	12.2
Turbine site 013	265907.8	1608028.0	320.0	0.0	0.0	60.0	4.73	4.71	1.114	0.970	0.955	1.58	12.9

Figure 14: The estimated energy production of a wind farm

2.7 Evaluation of Economic Feasibility

2.7.1 Cost Estimation model

Cost estimation refers to the process of forecasting the budget of the project for planning the investment operation, which includes the cost and other resources that are needed to complete the project. Cost estimation is significant to the project's investment. It's necessary to consider it as an important factor in the business plan to use in predicting the accurate economic feasibility of the project, which can reduce the risk of investment. The total cost of the wind farm project can be broken down into four categories, as shown below [31-32]:

Table 2: The total costs of the wind farm project

The turbine cost	- The turbine production - Transportation and installation of the turbine
Civil works	- Transportation and installation of wind turbine and tower - Construction wind turbine foundation (tower) - Other related infrastructure required for installation of wind turbines.
Grid connection cost	- Cabling - substations and buildings
Other capital cost	- Development and engineering costs - Licensing procedures - Consultancy and permits - SCADA (Supervisory, Control and Data Acquisition) and monitoring systems

2.7.2 Economic Analysis

Economic analysis is the evaluation of the costs and benefits of a project. It reflects the feasibility of the project that impacts the company's decision and achievement of the goal. This study will concentrate focus on a financial perspective to evaluate the benefit and impact of the investment. Therefore, the economic analysis of this study will be based on three main elements:

1. Determine and estimate the expenses associated with an investment.
2. Determine and estimate the benefits to be obtained from an investment.
3. Comparing the cost and benefit to select the most suitable project for investment by uses Benefit-Cost ration (BCR), Net Present Value (NPV), Internal Rate of Return (IRR) to be the indicator to analyze the project

2.7.2.1 Net Present Value (NPV)

Net Present Value is the present value of net cash flow. That means the difference between the cash inflow value and cash outflow values over the time period of investment. In capital budgeting and investment planning, net present value (NPV) is used to determine the profitability of a proposed investment or project. [33].

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+i)^t} \tag{10}$$

Where;

B_t = Cash inflows of investment over the time period

C_t = Cash outflows of investment over the time period

i = Loan rate of investment

t = Time period of investment

2.7.2.2 Benefit-Cost Ratio (B/C ratio)

A benefit-cost ratio (BCR) is a monetary or qualitative economic measure that depicts the relationship between the relative costs and benefits of a proposed project. [33].

$$B/C = \frac{\sum_{t=1}^{n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{C_t}{(1+i)^t}} \tag{11}$$

2.7.2.3 Internal rate of Return (IRR)

In a discounted cash flow analysis, the internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero.

2.8 Literature Review

Table 3. The literature review involves to this study

No	Related research	Detail	Research gap	Reference
1	Evaluation of wind energy potential and electricity generation in Northern of Thailand	This research was done to assess the potential for electricity production from wind turbines at 7 stations in the northern region of Thailand at 40m and 80m above the ground level. The data was collected for 1 year from January to December 2008. The statistical method was used in this study to analyze the wind climate.The result of the study showed the annual average wind speed was between 3.36-5.03 m/s.	The suggestion of the study was about the economic feasibility analysis of wind turbine power generation.	[34]
2	A study of wind energy potential for electricity in Nakhon Phanom Province, Thailand	This research was studied to assess the wind energy potential in Nakhon Pranom province at 60m and 90m above the ground level. The observing wind climate in this study was done using the installation of an anemometer at the site selection to collect the real wind climate data. The data was collected for 1 year at every 10-minute interval. The methodology for analyzing the wind climate in this study used statistical analysis in addition to the WAsP program to estimate the annual energy production and capacity factor by using the turbine generator sizes of 0.85MW, 2.0MW, 3.3MW, and 4.5MW as the generators to analyze.	This study was using the turbine generator to estimate power generation that directly impacted the cost of the investment. Therefore, the economic feasibility of wind energy production should be added to the study.	[35]

3	Feasibility study of wind farms under the Thai very small scale renewable energy power producer (VSPP) program	This research was conducted in Nakhon Phanom province, which is located in the northeastern part of Thailand. The objective of this study was to evaluate the suitable area for the installation of a wind turbine by using GIS. Additionally, this study took the data on wind speed and wind direction from the Thai Meteorological Department to analyze the wind energy production and evaluate the unit cost of electricity generation. The analysis of wind energy production used ArcView software to analyze the wind climate data that was observed for 4 years from 2005 to 2009.	The main objective of this research was to evaluate the most suitable area for the installation of wind technology. Therefore, the wind climate observing from TMD was provided at a height of 10m above the ground level. Then to be developed, the research should be analyzed at another height of at least 50m-60m, which is the general hub height of the large scale wind turbines.	[36]
4	Wind speed and power characteristics of Kalasin province, Thailand	This research was a study on the wind energy assessment of Kalasin province, which is located in the upper northeastern part of Thailand. The study used statistical analysis to analyze the wind climate and Weibull parameters at the hub height of 60m, 90m, and 120m above the ground level. The result of this demonstrated the seasoning wind climate. Moreover, this study used four commercial wind turbine generators to estimate the annual energy production and capacity factor of wind turbines by using the WAsP program to analyze.	The further of this study should be investigated the economic feasibility to estimate the cost of wind energy production and the return for investment.	[37]

5	Assessing the wind energy potential in Northeastern Thailand	This study was focused on the assessment of wind energy potential in the northeastern part of Thailand, which consists of Mookdahan, Kalasin, Khon Kean, and Nong Khai provinces. The methodology used statistical analysis to analyze monthly data on the wind climate at the hub height levels of 60m and 90m above the ground level. The data for the wind climate was collected by installing the anemometer at the selected site and collecting for one year (seasoning cycle) from October 2011 to September 2012.	The further of this study should add the turbine generator to estimate the annual energy production and capacity factor of the wind turbine to achieve the objective of this study, which is to inform the decision on whether to invest in the wind turbine in the future.	[38]
6	Micro-siting wind resource assessment and near Shore wind farm analysis in Pakpanang district, Nakhon Si Thammarat province, Thailand	The micro-siting wind resource assessment and near-shore wind farm analysis were presented in this study.The authors studied in Pakpanang district, Nakhon Si Thamarat province in the southern part of Thailand. The wind speed and wind direction data was collected at 120m from the meteorological tower that was installed near the shoreline. This study uses the WAsP program to analyze the wind climate data and estimate the annual energy production of a wind farm.	This research was analyzed for wind climate analysis and estimation of wind energy production. However, the comparison between annual energy production and the project investment cost should be taken into account.	[39]
7	Assessment of wind energy potential for selected areas in Jordan	This study presented a technical assessment of wind energy potential in Jordan based on statistical analysis to determine the wind characteristics. Furthermore, the Rayleigh distribution was used	This research almost provided completely information for wind energy resource investment	[25]

		to analyze the monthly average data and estimate the energy output for wind power generation. Additionally, the economic analysis in this research provided the unit cost of energy production.	but the lack of information for this research is the return on investment that is the important factor for investment decision.	
8	Assessment of wind energy potential and economic evaluation of four wind turbine models for the east of Iran	This research investigated the potential of wind energy in 22 regions in eastern Iran. The methodology of wind climate analysis was based on the WAsP program to analyze the potential of wind energy in the selected area. Moreover, the economic analysis has been concerned with this research by focusing on the unit cost analysis.	The economic analysis of this research just mentioned the unit cost analysis. Therefore, to develop the research, financial economic analysis should be added to demonstrate the return of investment that impacts the decision.	[40]

Table 4 shows the summary of the literature review. Most of the studies used the WAsP to assess the wind resource potential in the study area. This program can analyze and predict the wind characteristics in an annual report. Moreover, the statistical analysis that was used in those studies was used to assess the monthly wind potential. Additionally, the GIS was used to evaluate the suitable area for the installation of a wind turbine. But the pain point of these studies is the economic analysis. There are just a few studies that evaluate the cost of electricity production. Economic feasibility is an important issue that needs to be studied to demonstrate the feasibility of the project's investment. Therefore, this study is trying to evaluate the wind potential and the economic feasibility of the project investment.

Table 4. The summary of the literature review

Reference	Area				Method					Result					
	Northern in Thailand	Northeastern in	Southern in Thailand	Overseas	Statistical Analysis	WAsP	GIS	ArcView	Economic Analysis	Mean Wind Speed	Annual energy	Weibull Distribution	Site-Selection	Economic Feasibility	Cost of the production
1	✓				✓					✓		✓			
2		✓			✓	✓				✓	✓	✓			
3		✓			✓		✓	✓		✓	✓	✓	✓		✓
4		✓			✓	✓				✓	✓	✓			
5		✓			✓					✓		✓			
6			✓			✓				✓	✓	✓			
7				✓	✓				✓	✓	✓	✓			✓
8				✓		✓			✓	✓	✓	✓			✓
This Study		✓				✓			✓	✓	✓	✓		✓	✓

Chapter 3
Methodology

This study is dedicated to assessing the wind energy potential in the north-eastern region of Thailand, including Buri Ram, Roi Et, Sri Sa Ket, Surin, and Ubon Ratchathani. The wind climate data was collected from Thai Meteorological Department within 4 years from 1 January 2017 to 31 December 2020, the data was collected every 10minutes interval. This research will employ the WAsP program to simulate the wind energy potential and take the economic indicators to analyze the feasibility of the investment. Therefore, the implementation of the research will be illustrated in the figure 15.

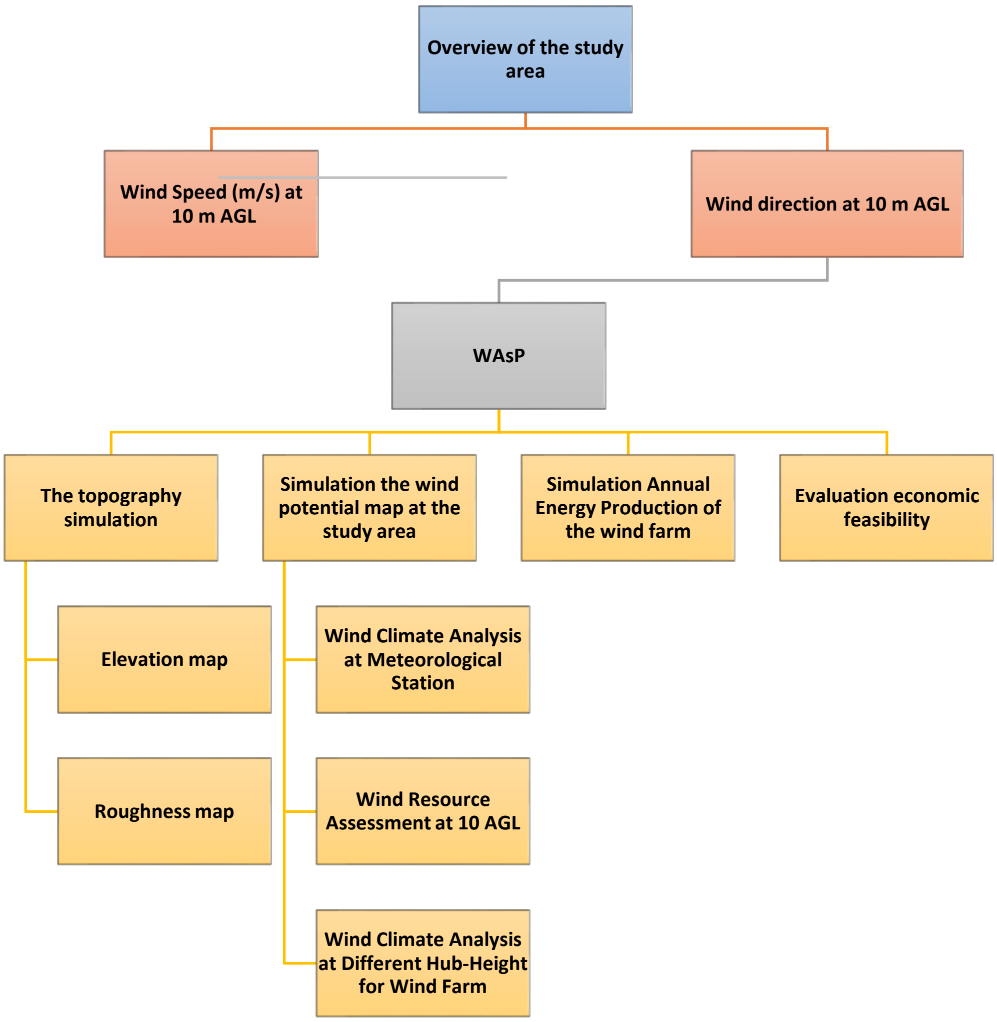


Figure 15: The research implementation of the wind energy resource potential

3.1 Overview of the study area

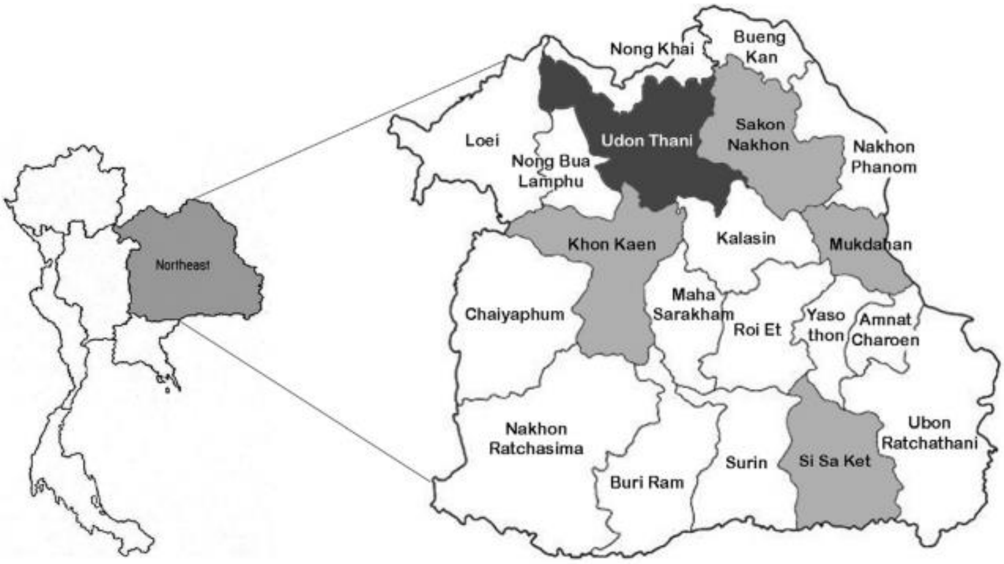


Figure 16: The northeastern region of Thailand map [41].

The Northeast region is the largest area of Thailand, approximately 168,854 square kilometers or having an area of 33.17% of the total areas in Thailand. The topography of the northeastern region is flatland. Some areas have mountains, especially in the central part of the region. The highest point of the northeastern region is at Phu Luang Peak in Loei province, 1,835 meters above sea level. The Northeast region consists of 20 provinces as follows: Loei, Nong Khai, Nakhon Phanom, Bueng Kan, Udon Thani, Nong Bua Lamphu, Sakon Nakhon, Khon Kaen, Kalasin, Mukdahan, Chaiyaphum, Maha Sarakham, Roi Et, Yasothon, Amnat Charoen, Nakhon Ratchasima, Buriram, Surin, Sisaket, Ubon Ratchathani.

Territory

- The north connects with Laos. The northernmost territory is Bueng Kan District in Nong Khai Province. The Mekong River is a natural border in this area.
- The east connects with Laos. The easternmost land is Khong Chiam District in Ubon Ratchathani Province. The Mekong River is a natural border in this area.

- The west contacts the central region. The westernmost land is Na Haeo District in Loei Province, with the Phetchabun Mountains and Dong Phaya Yen Mountains as the border.
- The south connects with Cambodia and the eastern region of Thailand. The southernmost territory is Khon Buri District in Nakhon Ratchasima Province. Phanom Dong Rak Mountain and the ridge are the boundary line in this area.

Wind Climate

The northeastern region is characterized by two types of monsoon, as follows:

1. Northeast Monsoon

This type of monsoon is the most frequently occurring type of wind prevailing in this area. The northeast monsoon will blow from October to February. It will cause cold and dry weather in this area.

2. Southwest Monsoon

The southwest monsoon will bring moist air masses from the sea and ocean to cover this area from May to September, causing the rainy season.

Tropical Cyclone

The tropical cyclone that moved into the northeastern region of Thailand originated from the South China Sea and the western North Pacific Ocean. Most of the tropical cyclones will weaken their storm forces to become depression storms that cause heavy rain and flooding in some areas. The typical tropical cyclone that moves through the northeastern region of Thailand starts in June and ends at the end of November.

3.1.1 Overview of Buri Ram Province

Figure 17: The overview area around the meteorological station in Buri Ram province.

Location: Latitude : 14°37'57.0"N

Longitude : 102°43'04.1"E

Universal Transverse Mercator (UTM) Zone : 48 P

Nong Bot Sub-district, Nang Rong district, Buri Ram province has a total area of 769.8 square kilometers with a total population of 113,864 people. Most of this area is flat and lowland.

Territory:

- Northland connects to Chamni and Mueang Buriram Districts.
- Eastland connects to Prakhon Chai Chaloem Phrakiat District.
- Southland connects to Lahan Sai and Pakham Districts.
- Westland connects to Non Suwan and Nong Kee Districts.

3.1.2 Overview of Roi Et Province

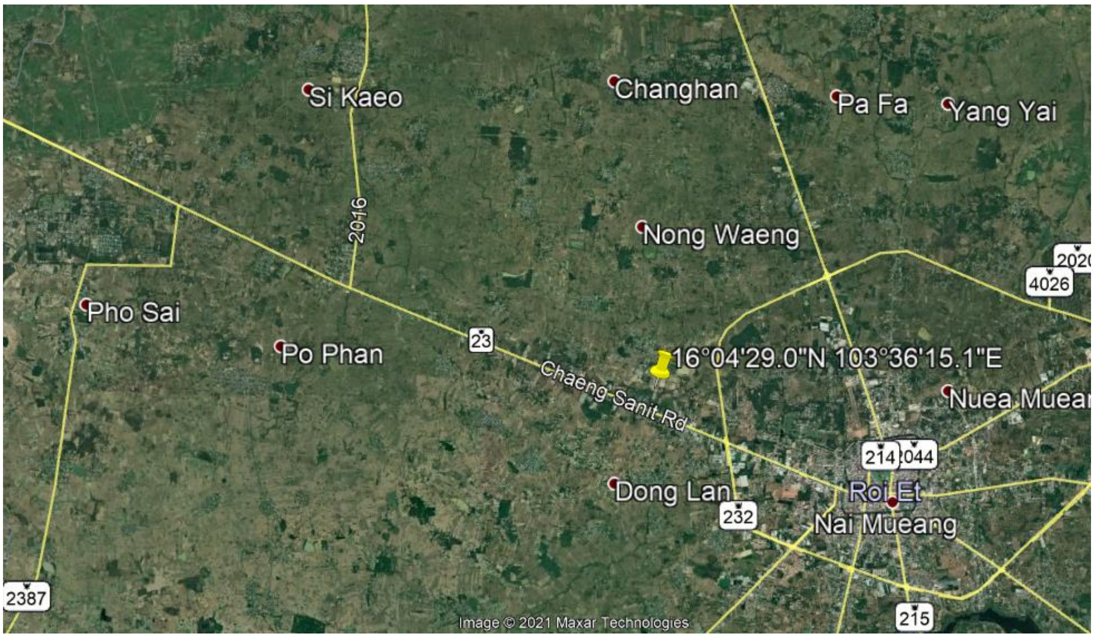


Figure 18: The overview area around the meteorological station in Roi Et province.

Location: Latitude : 16°04'29.0"N

Longitude : 103°36'15.1"E

Universal Transverse Mercator (UTM) Zone : 48 P

Nong Waeng Sub-district, Mueang Roi Et District, Roi Et province has a total area of 493.6 square kilometers with a total population of 153,567 peoele. The topography of this area is characterized by an undulating plain area.

Territory:

- Northland connects to Mueang Maha Sarakham (Maha Sarakham Province) and Changhan Districts.
- Eastland connects to Thawat Buri District.
- Southland connects to Att Samart and Chaturaphak Phiman Districts.
- Westland connects to Sri Somdet District.

3.1.3 Overview of Sri Sa Ket Province

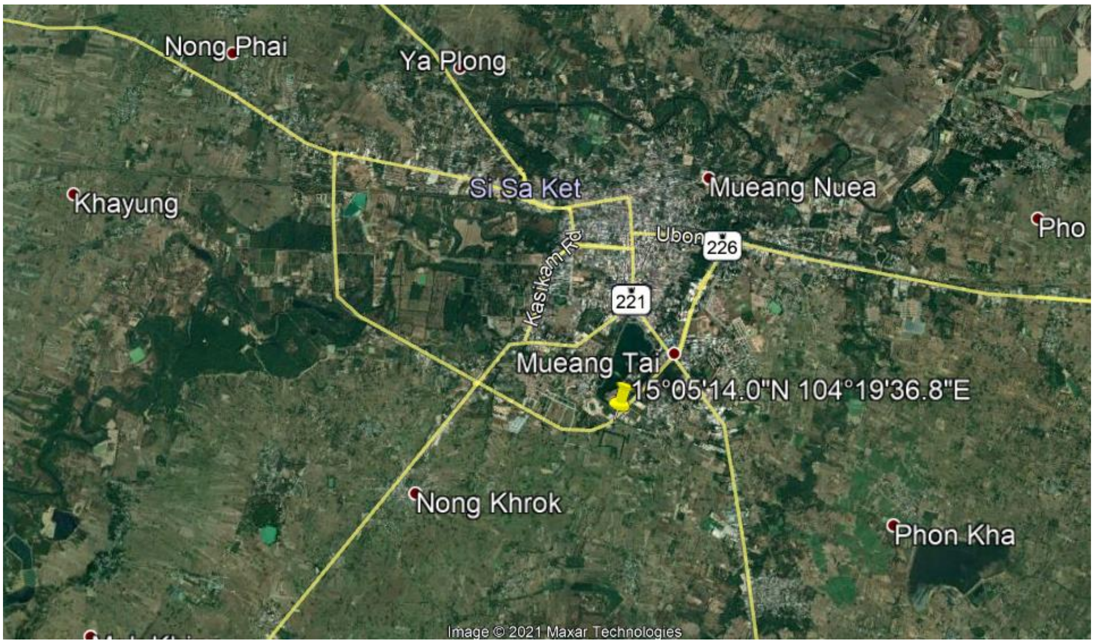


Figure 19: The overview area around the meteorological station in Sri Sa Ket province.

Location: Latitude : 15°05'14.0"N

Longitude : 104°19'36.8"E

Universal Transverse Mercator (UTM) Zone : 48 P

Mueang Tai Sub-district, Mueang Sri Sa Ket District, Sri Sa Ket province has a total area of 576.366 square kilometers with a total population of 138,707 persons. The topography of this area is characterized by a plateau area which is a large field.

Territory:

- Northland connects to Rasi Salai and Yang Chum Noi Districts.
- Eastland connected to Kanthararom District.
- Southland connects to Nam Kliang, Phay, and Wang Hin Districts.
- Westland connects to Uthumphon Phisai District.

3.1.4 Overview of Surin Province

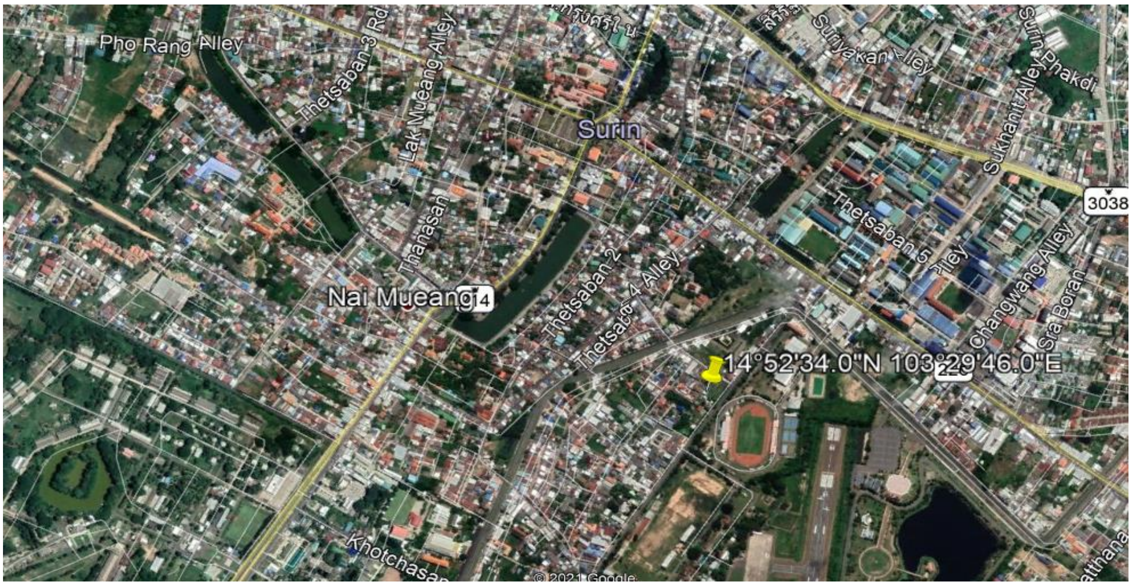


Figure 20: The overview area around the meteorological station in Surin province.

Location: Latitude : 14°52'34.0"N

Longitude : 103°29'46.0"E

Universal Transverse Mercator (UTM) Zone : 48 P

Mueang Surin District, Surin province has a total area of 1,066.26 square kilometers with a total population of 258,139 persons. Most of the topography in this area is lowland, but some areas are uplands alternating with slope areas. This area is the most important district in Surin province due to its location at the center of administration, the economy, and transportation.

Territory:

- Northland connects to Satuk District (Buriram Province) and Chom Phra District.
- Eastland connected to Khwao Sinrin, Sikhoraphum, and Lamduan District.
- Southland connects to Prasat District.
- Westland connects to Krasang District (Buriram Province).

3.1.5 Overview of Ubon Ratchathani Province

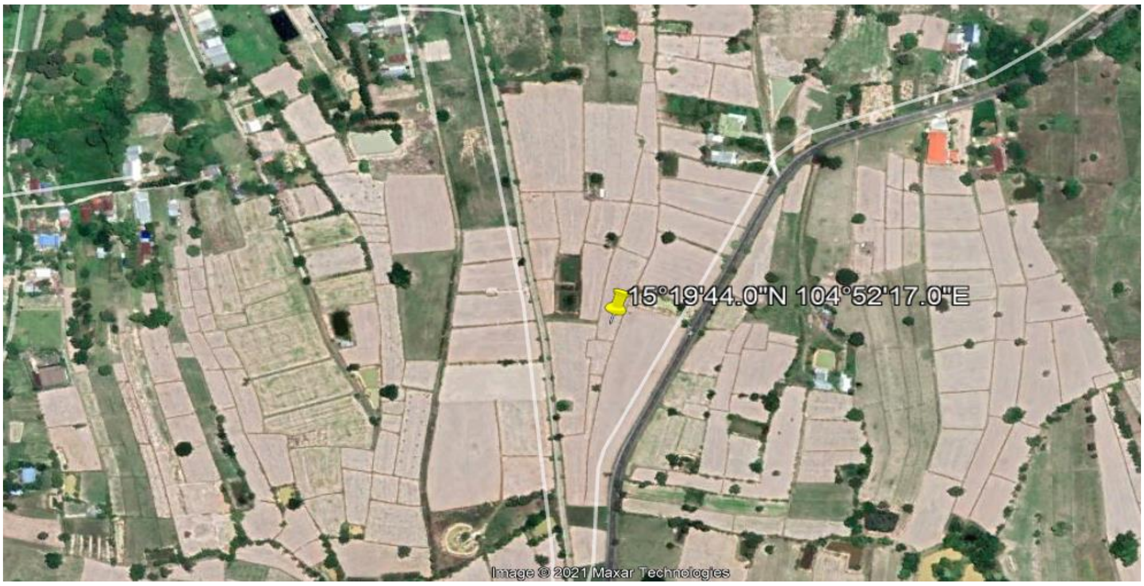


Figure 21: The overview area around the meteorological station in Ubon Ratchanthani province.

Location: Latitude : 15°19'44.0''N

Longitude : 104°52'17.0''E

Universal Transverse Mercator (UTM) Zone : 48 P

Mueang Ubon Ratchathani District, Ubon Ratchathani Province, has a total area of 406.4 square kilometers with a total population of 223,819 people. Most of the topography in this area is the plain area alternating with slope complex area that more than 35 percent of the slope level. Agriculture is the most common occupation that occurs in this area.

Territory:

- Northland connects to Muang Sam Sip and Lao Suea Kok Districts.
- Eastland connected to Don Mot Daeng and Sawang Wirawong Districts.
- Southland connects to Sawang Wirawong, Warin Chamrap, and Kanthararom Districts (Sisaket Province).
- Westland connects to Khueang Nai District.

3.2 The topography simulation

The topography inputs to WAsP software are given by a "Vector map" that contains the height contour line (Elevation map) and the roughness change lines (Roughness map). The Map projection defines a coordinate system on the surface of the earth like the Universal Transverse Mercator (UTM) and the World Geodetic System (WGS) 1984 as a reference datum by using the specific location of "Latitude-Longitude" to express a region on the actual surface of the Earth. The Vector map is the combination of the elevation map and roughness map to be a base calculation reference around the selected site. In this study, the extension for the elevation and roughness maps were used 30 x 30 kilometers to assess the potential around meteorological stations [42].

Table 5. The site location and UTM zone of the meteorological station

Station	Location		Universal Transverse Mercator (UTM) Zone
	Latitude (m E)	Longitude (m N)	
1. Buri Ram	254175.94	1618916.76	48 P
2. Roi Et	350703.61	1777704.37	48 P
3. Sri Sa Ket	427663.50	1668083.80	48 P
4. Surin	338211.76	1645168.61	48 P
5. Ubon Ratchathani	486194.70	1694707.19	48 P

3.2.1 Elevation map

The effect of wind flow from height variations around the site is a necessary concern. The height of the terrain at each grid point is the necessary input to be calculated. The contour line represents the elevation line. The evidence of hills or more complex terrains influences the prevailing wind flow, the change in the elevation change line can influence the mean wind speed e.g. a 5 percents height increase will impact on the mean wind speed 5 percents as well.

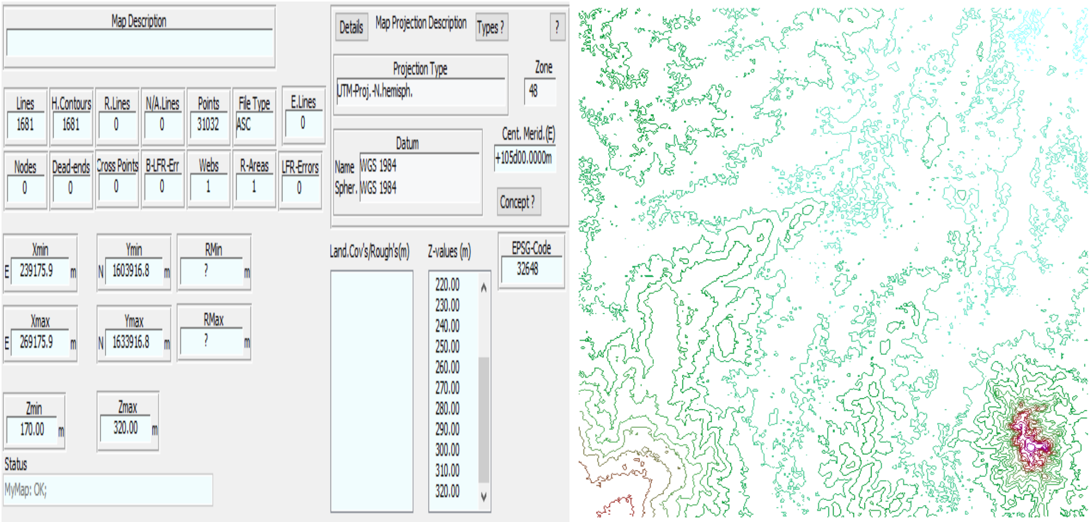


Figure 22: The methodology to create the elevation map.

The practice of elevation map

- Size of map**;** The elevation map should extend 2-3 times the horizontal scale of the reference site e.g. meteorological mast or wind turbine site. In this study was extended 30km x 30km of the horizontal of the meteorological mast as the reference site
- Set the map projection and map datum in WAsP map editor to set up the location in the map
- To be the accuracy and detail of the elevation map, the coordinates and elevation must be in meter scale.
- Apply the database of GWA-Warehouse terrain and convert the data to create the elevation map
- Check range of elevation in final map.

3.2.2 Roughness map

Table 6: The land cover specification in the GlobCover database to roughness lengths [43].

No.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0.0
2.	Permanent snow and ice	0.0004
3.	Bare areas	0.005
4.	Grassland, savannas or lichens/mosses	0.03
5.	Sparse vegetation	0.05
6.	Cropland or Shrubland	0.1
7.	Wetlands	0.2
8.	Mosaic natural vegetation / cropland	0.3
9.	Flooded forest or mosaic grassland / forest	0.5
10.	Flooded forest or shrubland	0.6
11.	Urban areas	1.0
12.	Forests	1.5

The GWA-Roughness-GlobCover is one of the roughness length products provided by the Global Wind Atlas warehouse map. It is used to classify the land cover classes with 12 different roughness lengths by using a conversion table as shown in table 6.

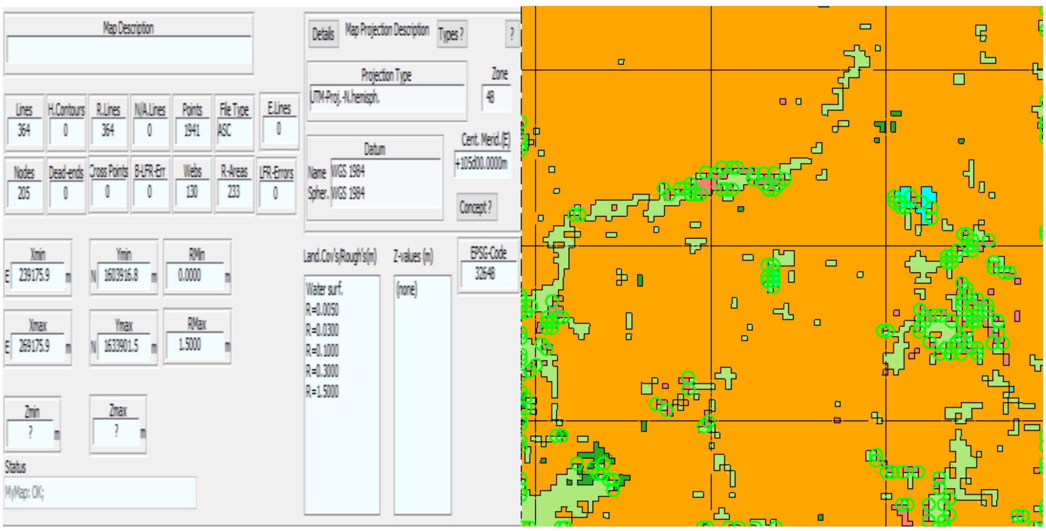


Figure 23: The methodology to create a roughness map.

The practice of roughness map

- **Size of map;** The map should extend 2-3 times the horizontal scale of the reference site e.g. meteorological mast or wind turbine site. In this study was extended 30km x 30km of the horizontal of the meteorological mast as the reference site
- Set the map projection and map datum in WAsP map editor to set up the location in the map
- To be the accuracy and detail of the roughness map, the coordinates and roughness lengths must be in meter scale.
- Apply the database of GWA-Warehouse terrain and convert the data to create the roughness map
- Check the dead ends and cross points, the existence of their points is prohibited.
- The LFR-errors should not be transpired. Therefore, it needs to check the consistency of roughness values.

3.3 Simulation the wind potential map in the study area

By modeling wind flow throughout the terrain, the WAsP model applies many models to generalize a set of wind observational data into a regionally representative wind climatology. The WAsP has been used for wind resource estimation, wind data analysis by using a set of long-term wind speed and wind direction data at a reference site, and also the relevant terrain effects such as height contour and roughness have been taken into account to simulate the turbulence effect [44-45].

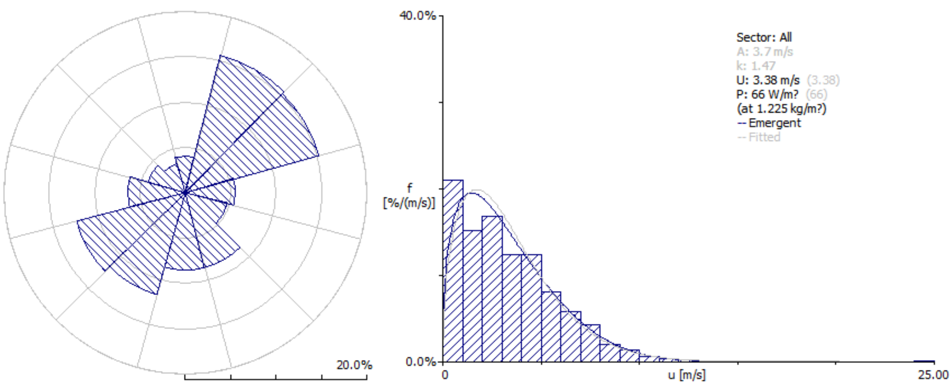


Figure 24: The wind rose and the Weibull parameters that were shown by WAsP.

Using raw wind climate data as the original data source, the observed wind climate indicates the likely long-term wind climate at anemometer height at the place of the meteorological mast. [29]. The wind climatological input contains the wind direction distribution and the sector-wise distribution of the mean wind speed. WAsP Climate Analysis uses the Weibull distribution to represent the sector-wise wind speed distribution [46].

3.4 Simulation Annual Energy Production of the wind farm

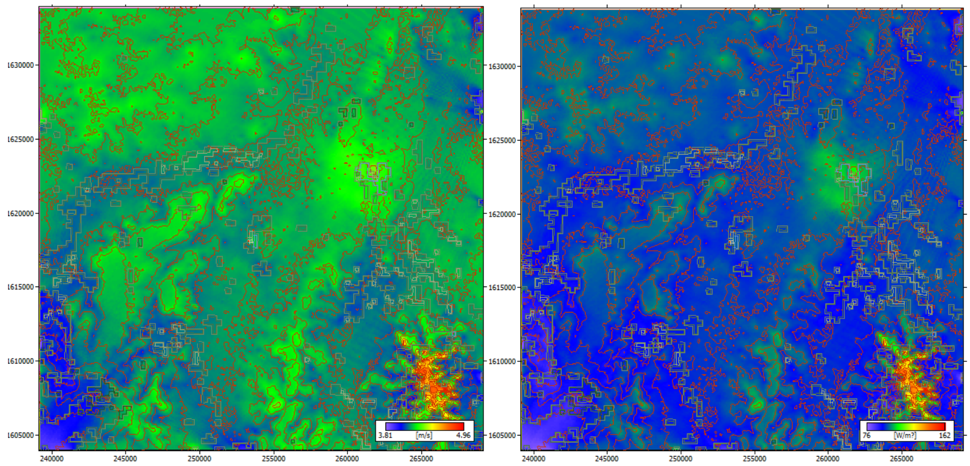


Figure 25: The mean wind speeds and power densities map

The WAsP software is used to perform wind climate prediction at the hub-height level above the ground level, where the data consists of wind speed, wind direction, and Weibull parameters at the selected wind farm sites. The results of simulating wind climate prediction are used to calculate the expected energy yield. The wind farm selected sites were carefully chosen by using elevation, roughness, mean wind speed, and power density maps for decision making.

Table 7. Wind turbine generator specifications

Model	Rotor diameter	Hub height	Cut-in wind speed	Cut-out wind speed	Rated wind speed	Rated power	Power density
Vestas V52	52 m	60 m	4.0 m/s	25.0 m/s	14.0 m/s	850 kW	400.2 W/m^2
Vestas V90	90 m	80 m	4.0 m/s	25.0 m/s	13.0 m/s	2,000 kW	314.4 W/m^2

The Vestas V52-850kW and Vestas V90-2MW wind turbine generators were used for power analysis at 60m height and 80m height above ground level respectively. The specifications of the wind turbine generators are shown in table 7. Additional, the power curve of wind turbine generators is shown in Figure 26-27.

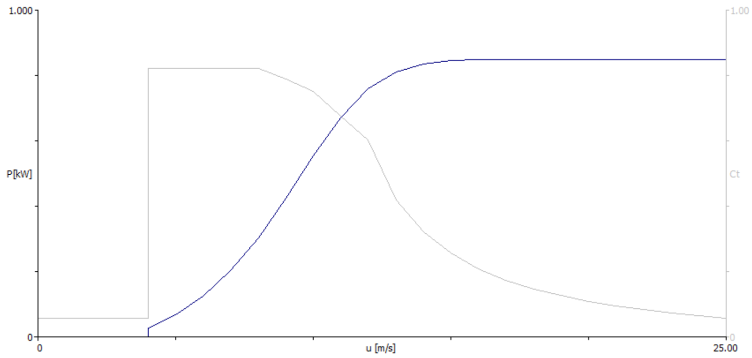


Figure 26. Power curve of Vestas V52 turbine generator

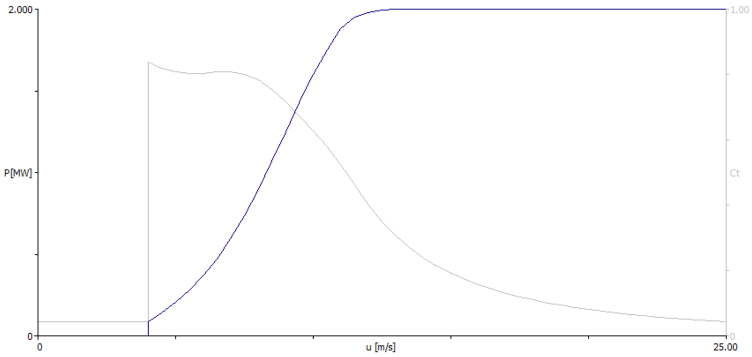


Figure 27. Power curve of Vestas V90 turbine generator

3.5 Evaluation economic feasibility

An economic valuation is used to support investment decisions, to demonstrate the return on investment and the cost per unit of electricity generation in the studied area. In which the cost estimation will be evaluated as follows:

1.) Value of land use
2.) Cost of wind turbines
3.) Construction costs
4.) Grid connection costs
5.) Other capital costs, such as development and engineering costs, licensing procedures, and monitoring systems.
6.) Loan payment

The cost of the land use is estimated by the Treasury Department of Thailand in terms of the exchange rate of 30 Baht/USD. The land value is calculated from the estimation of the installation area of one wind turbine by using the height of the wind turbine (h) and the width of the specified rotor diameter. This study used 3 times the rotor diameter, so the value of land used would be $3h \times 3h$ in terms of a square meter [47-48] and other costs would be estimated in terms of average price based on reference [32]. The evaluation of economic feasibility consists of three financial indicators [49].

1.) Benefit-Cost Ratio (B/C ratio),
2.) Net Present Value (NPV), and
3.) Internal Rate of Return (IRR)

In addition, the purchase of electricity per unit is in accordance with the Feed-in-Tariff (FiT) supported policy of the Thai government [50].

Chapter 4
Result and Discussion

The data of this study were collected from the Thai Meteorological Department (TMD) for 4 years, from 1 January 2017 to 31 December 2020 at every 10minutes interval, with the height level 10m above ground level at each station in 5 provinces. The WAsP program is used to calculate the wind potential statistics, including the mean wind speed, power density, Weibull parameters, and frequency distribution. Moreover, this study will estimate the annual wind energy production of the wind farm by using Vestas V52 and Vestas V90 to be the turbine generator. At the end of this study, the economic feasibility analysis is used to demonstrate the return on investment for the project.

4.1 The topography simulation of elevation and roughness

The map projection is the Universal Transverse Mercator (UTM) coordinate system Zone 48 and the datum is WGS-1984 [15]. The elevation and roughness maps were created using the WAsP Map Editor tool in the WAsP Program (Figure 1-5) with a map extension of 30 km × 30 km. The elevation map of each station demonstrates the height contour lines of the area around the station; a) NANG RONG Hydrometeorological Station, b) ROI ET Weather Observing Station, c) SRI SA KET Agrometeorological Station, d) SURIN Weather Observing Station, and e) UBON Weather Observing Station. The GWA-Roughness-GlobCover is one of the roughness length products provided by the Global Wind Atlas warehouse map. It is used to classify the land cover classes with 12 different roughness lengths by using a conversion table as shown in table 6.

4.1.1 The topography simulation of elevation and roughness in Buri Ram province

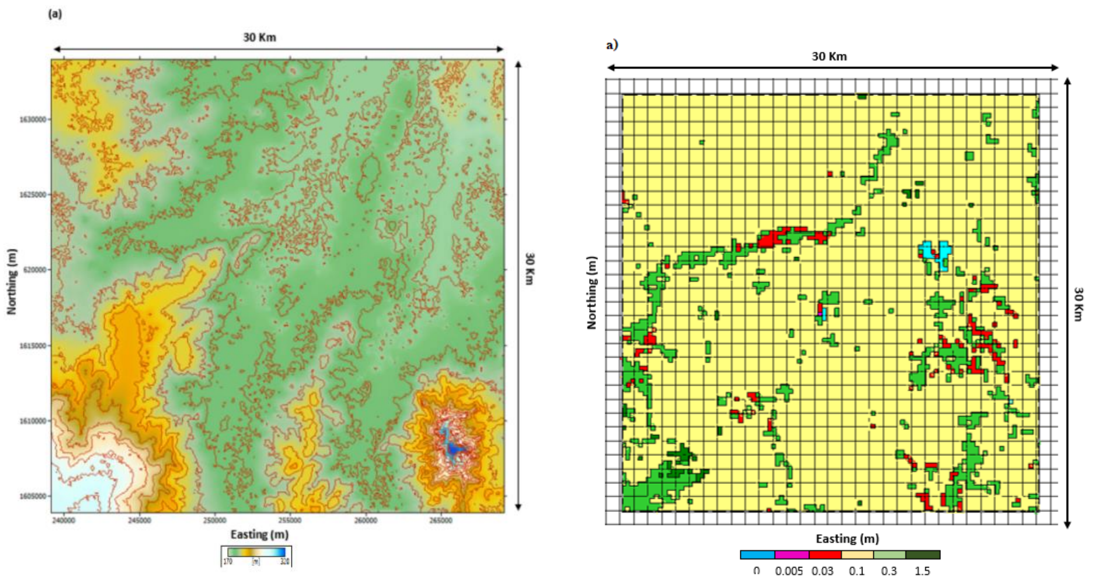


Figure 28: Elevation and roughness map of NANG RONG Hydrometeorological Station

The elevation map of NANG RONG Hydrometeorological Station in Buri Ram province has a total of 1,681 height contours and 364 roughness change lines, with the highest elevation of about 320 meters above sea level. Whereas, most of the areas are the plain areas alternating with the plateau in the southeast, most areas are cropland or shrubland, according to the roughness map.

Table 8: The land cover and roughness length of NANG RONG Hydrometeorological Station

NO.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0
2.	Bare areas	0.005
3.	Grassland, savannas or lichens/mosses	0.03
4.	Cropland or Shrubland	0.1
5.	Mosaic natural vegetation / cropland	0.3
6.	Forests	1.5

4.1.2 The topography simulation of elevation and roughness in Roi Et province

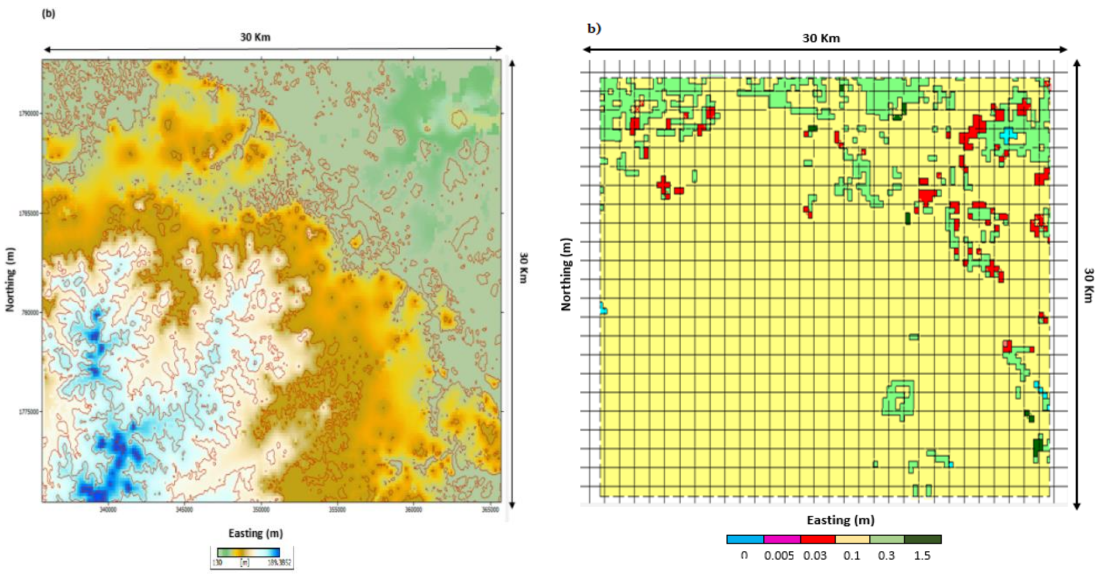


Figure 29: Elevation and roughness map of ROI ET Weather Observing Station

The elevation map of ROI ET Weather Observing Station in Roi Et province has a total of 1,943 height contours and 255 roughness change lines. The southwest of the map area is the highest elevation, at about 190 meters above sea level. Whereas, most of the areas are plain areas with the specification of land cover is either cropland or shrubland, according to the roughness map.

Table 9: The land cover and roughness length of ROI ET Weather Observing Station

NO.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0
2.	Bare areas	0.005
3.	Grassland, savannas or lichens/mosses	0.03
4.	Cropland or Shrubland	0.1
5.	Mosaic natural vegetation / cropland	0.3
6.	Forests	1.5

4.1.3 The topography simulation of elevation and roughness in Sri Sa Ket province

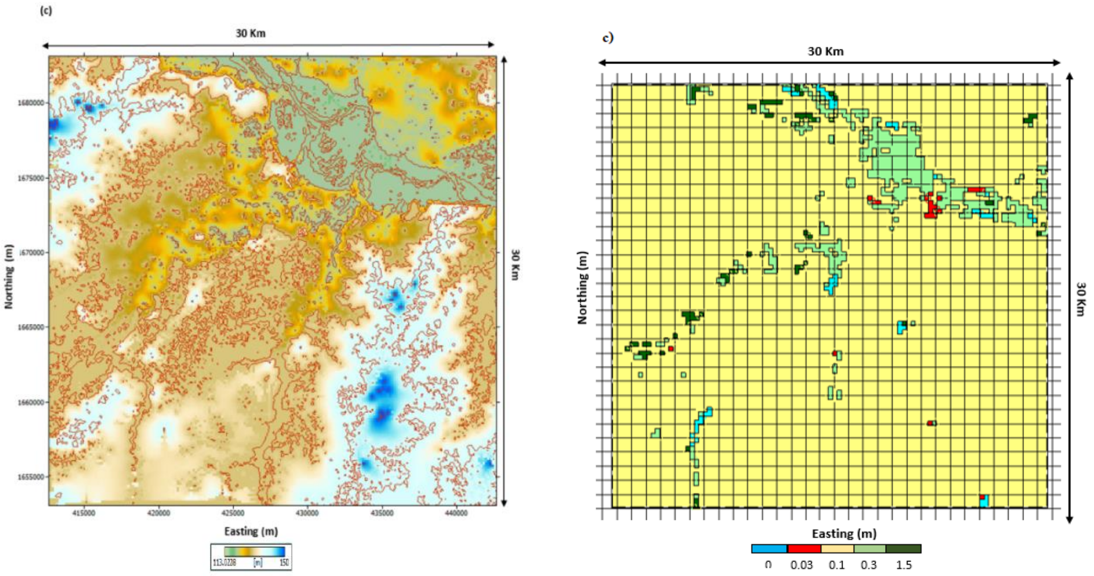


Figure 30: Elevation and roughness map of SRI SA KET Agrometeorological Station

The elevation map of SRI SA KET Agrometeorological Station in Sri Sa Ket province has a total of 2,422 height contours and 179 roughness change lines. The highest elevation is about 150 meters above sea level. Most of the areas are plain areas with the specification of land cover is cropland or shrubland, according to the roughness map.

Table 10: The land cover and roughness length in SRI SA KET Agrometeorological Station

NO.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0
2.	Grassland, savannas or lichens/mosses	0.03
3.	Cropland or Shrubland	0.1
4.	Mosaic natural vegetation / cropland	0.3
5.	Forests	1.5

4.1.4 The topography simulation of elevation and roughness in Surin province

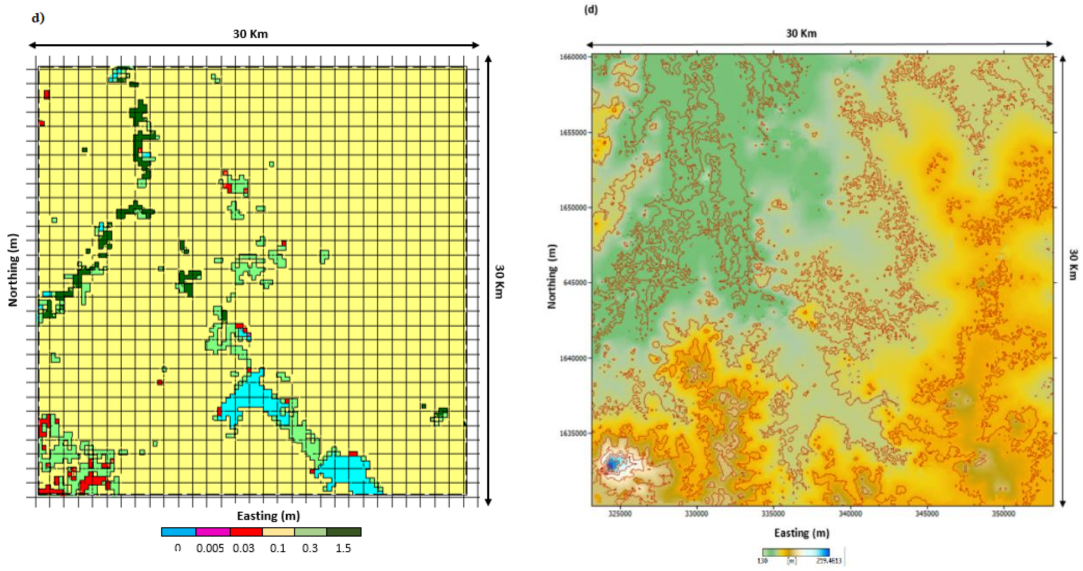


Figure 31: Elevation and roughness map of SURIN Weather Observing Station

The elevation map of the SURIN Weather Observing Station in Surin province has a total of 1,921 height contours and 267 roughness change lines. The highest elevation is about 220 meters above sea level, whereas most of the areas are cropland or shrubland, according to the roughness map.

Table 11: The land cover and roughness of SURIN Weather Observing Station

NO.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0
2.	Bare areas	0.005
3.	Grassland, savannas or lichens/mosses	0.03
4.	Cropland or Shrubland	0.1
5.	Mosaic natural vegetation / cropland	0.3
6.	Forests	1.5

4.1.5 The topography simulation of elevation and roughness in Ubon Ratchathani

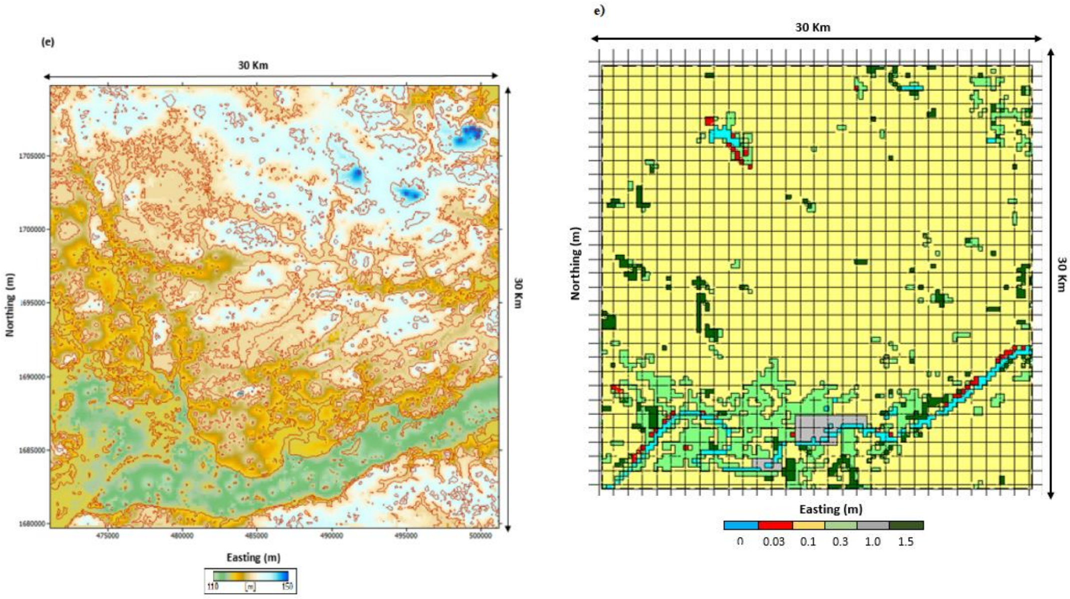


Figure 32: Elevation and roughness map of UBON Weather Observing Station

The elevation map of the UBON Weather Observing Station at Ubon Ratchathani has a total of 2,341 height contours and 531 roughness change lines, with the highest elevation of about 150 meters above sea level. Whereas, most of the areas are either cropland or shrubland, according to the roughness map.

Table 12: The land cover and roughness of UBON Weather Observing Station

NO.	Land Cover Class Name	Roughness Length (m)
1.	Water bodies	0
2.	Bare areas	0.005
3.	Grassland, savannas or lichens/mosses	0.03
4.	Cropland or Shrubland	0.1
5.	Mosaic natural vegetation / cropland	0.3
6.	Forests	1.5

4.2 Simulation the wind potential energy

4.2.1 Wind Climate Analysis at meteorological station

Table 13. Wind statistics of 5 provinces where meteorological station is located at 10m height.

Station	Location		Universal Transverse Mercator (UTM) Zone	Elevation (m)	Mean Wind Speed (m/s) at 10 m	Power Density (W/m²) at 10 m
	Latitude (m E)	Longitude (m N)				
1. Buri Ram	254175.94	1618916.76	48 P	181	2.67	35
2. Roi Et	350703.61	1777704.37	48 P	160	3.96	92
3. Sri Sa Ket	427663.50	1668083.80	48 P	130	3.38	66
4. Surin	338211.76	1645168.61	48 P	150	3.05	43
5. Ubon Ratchathani	486194.70	1694707.19	48 P	131	2.93	34

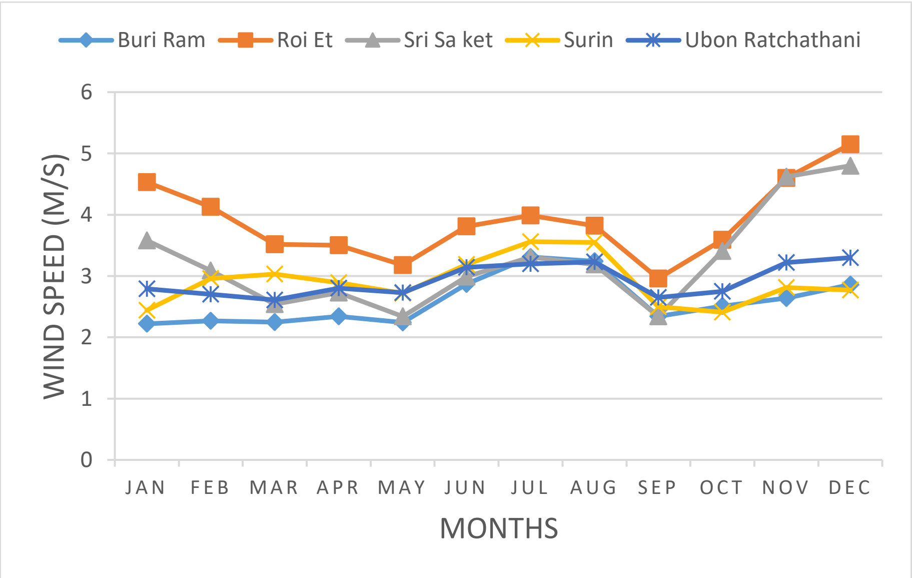


Figure 33. Annual wind speed of 5 meteorological stations in North-eastern of Thailand at 10 m.

The wind statistics of each station as shown in Table 13 demonstrate the mean wind speed and power density of wind resources in the study area at 10meters above ground level. The mean wind speed and power density were 2.67 m/s and 35 W/m^2 for Buri Ram, 3.96 m/s and 92 W/m^2 for Roi Et, 3.38 m/s and 66 W/m^2 for Sri Sa Ket, 3.05 m/s and 43 W/m^2 for Surin, and 2.93 m/s and 34 W/m^2 for Ubon Ratchathani. The typical cut-in wind speed is 3.5 m/s, but the mean wind speed of some stations was insufficient. Therefore, this study is dedicated to assessing the suitable hub height level of wind turbines. The sector-wise wind statistic including the frequency of wind prevailing, mean wind speed, power density, and Weibull parameters can be separated to demonstrate for each station following as:

4.2.1.1 The sector-wise wind climate Buri Ram meteorological station (Nang Rong)

The sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at Buri Ram meteorological station. The most frequent wind prevailing was from a 120^o angle. The mean wind speed was 2.77 m/s, the power density was 34 W/m^2, while the strongest mean wind speed was from a 30^o angle, where the mean wind speed and power density were 3.55 m/s and 60 W/m^2 respectively. The wind statistic distribution can be shown in the following table 14 and figure 34.

Table 14: Sector-wise wind statistics of Buri Ram at 10m

Angle[^{o}]	0^o	30^o	60^o	90^o	120^o	150^o	180^o	210^o	240^o	270^o	300^o	330^o
f [%]	7.6	12.3	8.9	6.3	15.9	10.6	9.6	10.2	8.3	4	3.1	3.2
A [m/s]	3	4	3.2	2.5	3.1	2.2	2.2	3.2	3.5	2.8	2.2	1.9
K	1.54	1.75	1.61	1.4	1.53	1.38	1.34	1.45	1.42	1.17	1.16	1.31
U [m/s]	2.69	3.55	2.82	2.29	2.77	2.01	1.98	2.93	3.14	2.7	2.08	1.71
P [W/m^2]	31	60	34	22	34	15	15	44	56	51	24	10
$^a\Delta$U [%]	2.58	2.51	2.90	3.39	0.62	-0.74	-0.02	0.46	0.96	0.11	1.39	2.20

Where; f = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density
$^a\Delta$U = Speed discrepancy

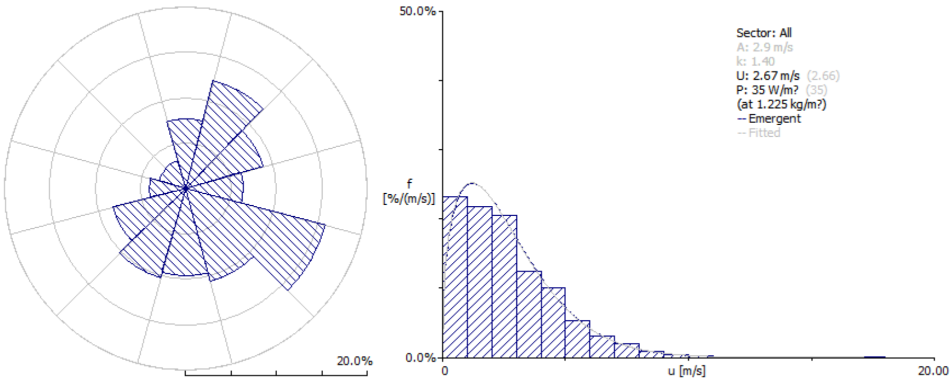


Figure 34. Wind rose and Weibull distribution of Buri Ram at 10m

4.2.1.2 The sector-wise wind climate Roi Et meteorological station

The sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at Roi Et meteorological station. The most frequent wind prevailing was from a 60^{o} angle. This direction had the strongest mean wind speed and power density. The values were 5.6 m/s for the mean wind speed and 202 W/m^2 for the power density.

Table 15: Sector-wise wind statistics of Roi Et at 10m

Angle[^{o}]	0^o	30^o	60^o	90 ^{o}	120^o	150^o	180^o	210^o	240 ^{o}	270^o	300^o	330^o
f [%]	3.8	8.3	19.2	12.1	4.7	6.2	13.5	13.7	8.6	3.9	2.7	3.1
A [m/s]	2.8	4.5	6.3	4.9	2.6	3.1	3.8	4.2	4.7	4.2	3.1	2.9
K	1.44	1.66	2.04	1.71	1.48	1.54	1.78	2.05	2.27	1.78	1.3	1.31
U [m/s]	2.57	4.05	5.6	4.4	2.34	2.75	3.4	3.69	4.17	3.71	2.9	2.7
P [W/m^2]	30	96	202	119	22	33	52	57	76	68	51	41
$^a\Delta$U [%]	2.81	0.05	0.62	0.99	1.10	0.29	-0.21	1.37	3.67	4.78	0.93	1.18

Where; f = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density
$^a\Delta$U = Speed discrepancy

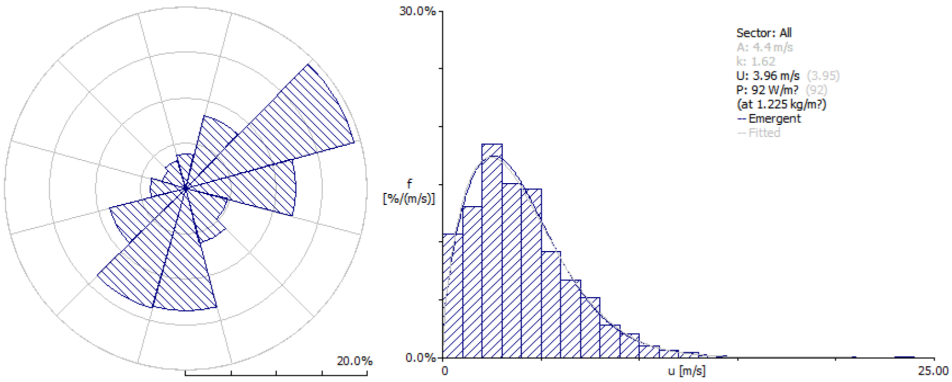


Figure 35. Wind rose and Weibull distribution of Roi Et at 10m

4.2.1.3 The sector-wise wind climate Sri Sa Ket meteorological station

The sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at Sri Sa Ket meteorological station. The most frequent winds prevailing was from 30^{o} and 60^{o} angles. Both of these directions had the strongest mean wind speeds of 5.15 m/s and 4.76 m/s, which had a power density of 143 W/m^2 and 127 W/m^2 respectively.

Table 16. Sector-wise wind statistics of Sri Sa Ket at 10m

Angle[^{o}]	0^{o}	30^{o}	60^{o}	90 ^{o}	120^{o}	150^{o}	180^{o}	210^{o}	240 ^{o}	270^{o}	300^{o}	330^{o}
f [%]	4.1	15.6	15.2	5.5	4.7	8.5	8.5	11.7	12.3	6.3	4.3	3.3
A [m/s]	2.6	5.8	5.4	2.8	2	2.2	2.1	3.2	4.1	3.9	3.2	2.4
K	1.51	2.26	1.98	1.32	1.27	1.3	1.44	1.61	1.83	1.65	1.31	1.19
U [m/s]	2.37	5.15	4.76	2.58	1.82	2	1.89	2.84	3.6	3.45	2.97	2.26
P [W/m^2]	22	143	127	35	13	17	12	60	60	60	55	29
$^{a}\Delta$U [%]	5.77	2.02	1.84	2.15	1.78	0.63	2.52	1.84	3.04	4.80	3.18	5.52

Where; *f* = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density
$^{a}\Delta$U = Speed discrepancy

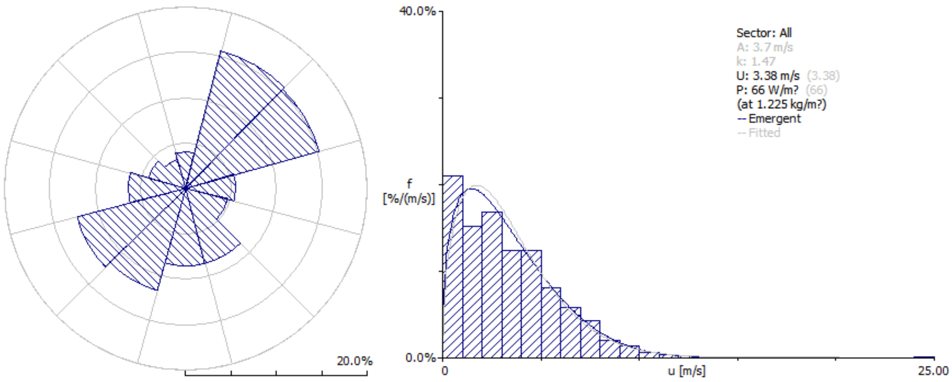


Figure 36. Wind rose and Weibull distribution of Sri Sa Ket at 10m

4.2.1.4 The sector-wise wind climate Surin meteorological station

The sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at Surin meteorological station. Most of the wind prevailing was from a 30^o angle or northeast direction, which had a mean wind speed of 3.77 m/s and a power density of 71 W/m^2.

Table 17: Sector-wise wind statistics of Surin at 10m

Angle[^{o}]	0^o	30^o	60^o	90 ^{o}	120^o	150^o	180^o	210^o	240 ^{o}	270^o	300^o	330^o
f [%]	6.5	13.8	8.7	5.9	8.1	19	10.1	10.8	5.8	4.3	3.3	3.7
A [m/s]	3.1	4.2	4.1	3	3	3.6	2.9	3.6	3.3	3	2.5	2.1
K	1.62	1.79	1.75	1.54	1.54	1.74	1.79	1.73	1.63	1.43	1.26	1.32
U [m/s]	2.77	3.77	3.68	2.71	2.73	3.18	2.59	3.22	2.98	2.73	2.29	1.92
P [W/m^2]	32	71	67	32	32	44	23	46	39	37	27	15
$^a\Delta$U [%]	3.93	2.05	4.24	4.33	2.81	0.35	3.23	5.08	5.08	5.23	4.59	4.31

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

$^a\Delta$U = Speed discrepancy

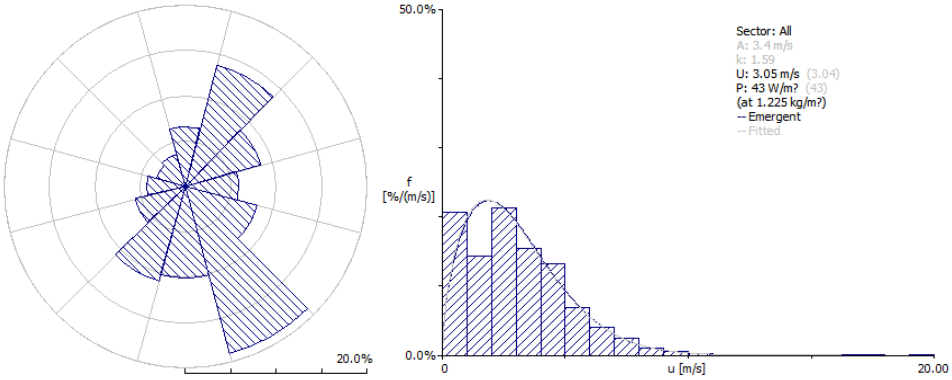


Figure 37: Wind rose and Weibull distribution of Surin at 10m

4.2.1.5 The sector-wise wind climate Ubon Ratchathani meteorological station

The sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at the Ubon Ratchathani meteorological station. The most frequent wind prevailing was from a 30^o angle, which had a mean wind speed of 3.1 m/s and a power density of 38 W/m^2, while the strongest mean wind speed was from a 300^o angle, where the mean wind speed and power density were 3.48 m/s and 54 W/m^2 respectively.

Table 18: Sector-wise wind statistics of Ubon Ratchathani at 10m

Angle[^{o}]	0^o	30^o	60^o	90 ^{o}	120^o	150^o	180^o	210^o	240 ^{o}	270^o	300^o	330^o
f [%]	11.5	16.6	7.6	5.6	7.3	12.7	9.6	8.5	8.2	5	4.3	3.2
A [m/s]	3.4	3.5	3.1	2.9	3	3.1	2.9	3.6	3.7	3.5	3.9	2.6
K	1.66	1.84	1.48	1.72	1.87	1.83	1.89	2.11	2.07	1.83	1.83	1.4
U [m/s]	2.99	3.1	2.84	2.57	2.62	2.79	2.61	3.18	3.3	3.11	3.48	2.35
P [W/m^2]	39	38	39	24	23	28	22	36	41	39	54	24
$^a\Delta$U [%]	-1.65	-0.78	-1.63	1.58	1.54	-0.63	-0.10	0.63	0.80	1.74	3.13	2.37

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

$^a\Delta$U = Speed discrepancy

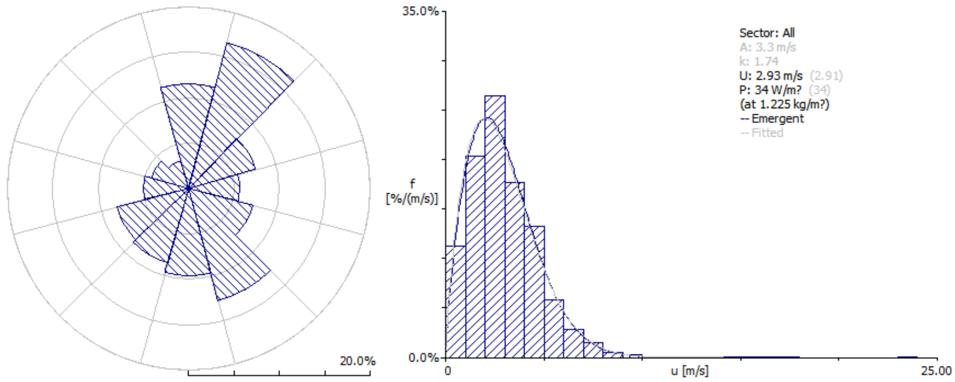


Figure 38: Wind rose and Weilbull distribution of Ubon Ratchathani at 10m

4.2.2 Wind Resource Assessment by WAsP at 10m AGL

The objective of this study is to assess the wind potential around the station that was studied by evaluating the wind climate to create the mean wind speed map and the mean power density map of the areas. The result of this study will be used to determine the wind farm site selection. The wind farm selected sites were carefully chosen by using elevation, roughness, mean wind speed, and power density for decision making. In particular, the mean wind speed and power density are the main key factors for wind farm site selection. The elevation and roughness maps are shown in figures 28-32. The mean wind speed and power density maps with high resolution are shown in figures 39-43.

4.2.2.1 Wind resource map in Buri Ram province

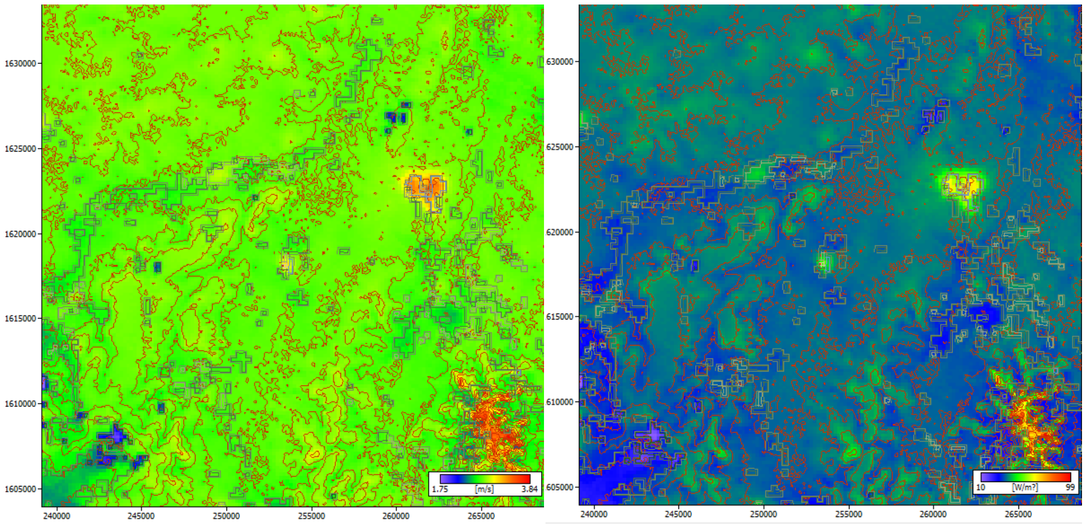


Figure 39: Buri Ram province's high-resolution mean wind speed and power density maps

The evaluation of the mean wind speed and the wind power density in the area around the meteorological station can estimate the result of the mean wind speed and the wind power density in Buri Ram province following this;

- The highest mean wind speed is 3.64 m/s
- The lowest mean wind speed is 1.75 m/s
- The highest wind power density is 99 W/m^2
- The lowest wind power density is 10 W/m^2

4.2.2.2 Wind resource map in Roi Et province

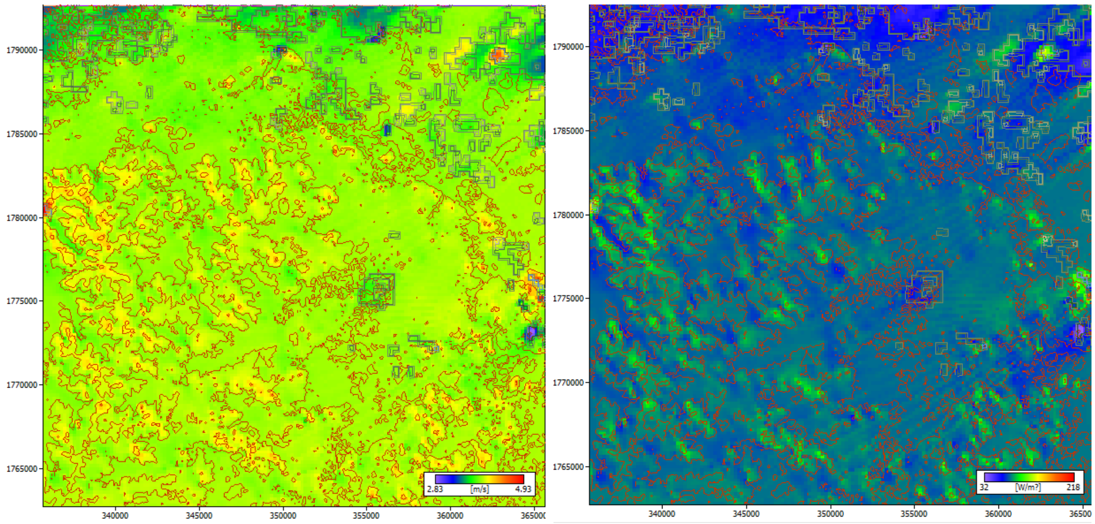


Figure 40: Roi Et province's high-resolution mean wind speed and power density maps

The evaluation of the mean wind speed and the wind power density in the area around the meteorological station can estimate the result of the mean wind speed and the wind power density in Roi Et province following this;

- The highest mean wind speed is 4.93 m/s
- The lowest mean wind speed is 2.83 m/s
- The highest wind power density is 218 W/m^2
- The lowest wind power density is 32 W/m^2

4.2.2.3 Wind resource map in Sri Sa Ket province

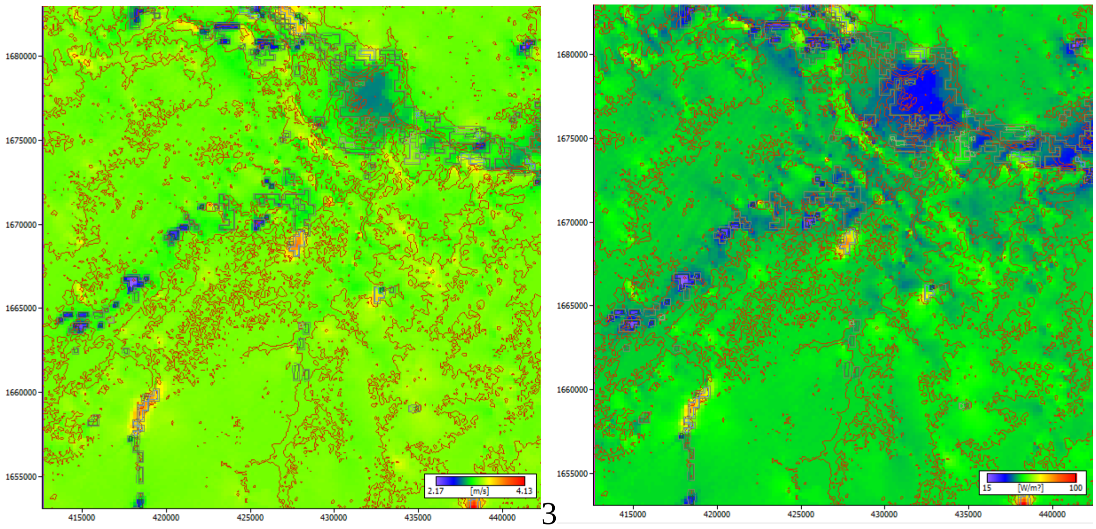


Figure 41: Sri Sa Ket province's high-resolution mean wind speed and power density maps

The evaluation of the mean wind speed and the wind power density in the area around the meteorological station can estimate the result of the mean wind speed and the wind power density in Sri Sa Ket province following this;

- The highest mean wind speed is 4.13 m/s
- The lowest mean wind speed is 2.17 m/s
- The highest wind power density is 100 W/m^2
- The lowest wind power density is 15 W/m^2

4.2.2.4 Wind resource map in Surin province

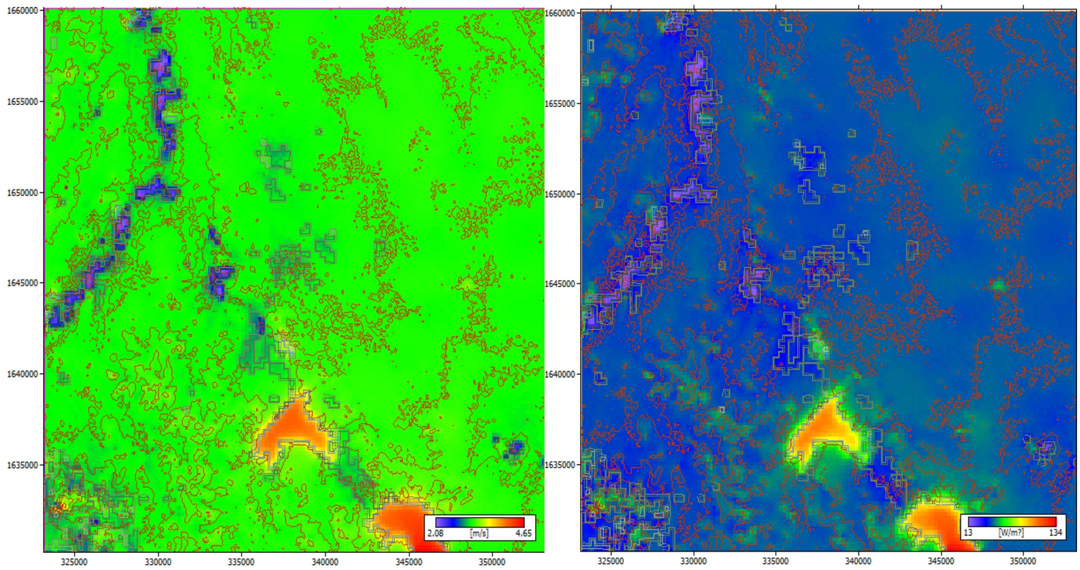


Figure 42: Surin province's high-resolution mean wind speed and power density maps

The evaluation of the mean wind speed and the wind power density in the area around the meteorological station can estimate the result of the mean wind speed and the wind power density in Surin province following this;

- The highest mean wind speed is 4.65 m/s
- The lowest mean wind speed is 2.08 m/s
- The highest wind power density is 134 W/m^2
- The lowest wind power density is 13 W/m^2

4.2.2.5 Wind resource map in Ubon Ratchathani province

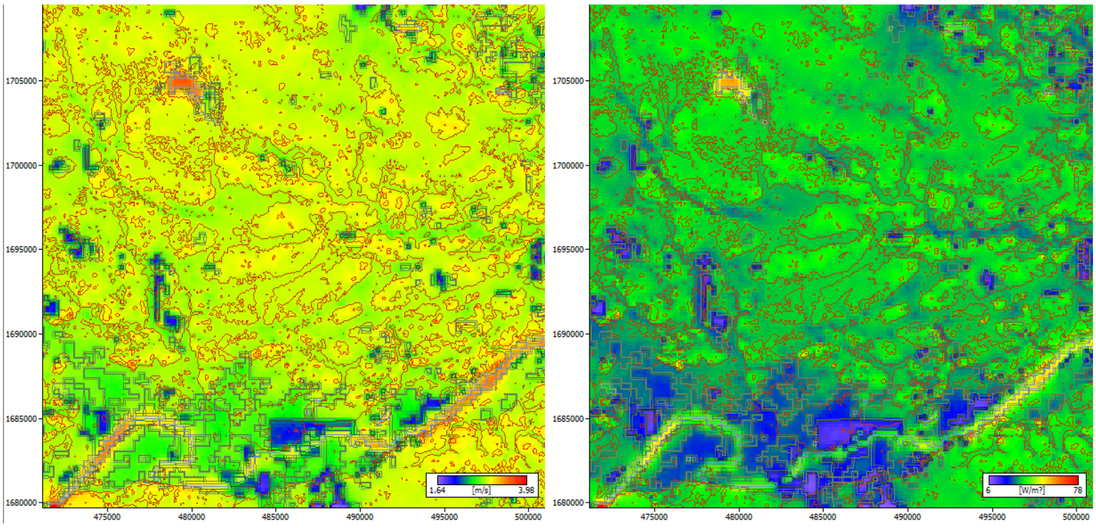


Figure 43: Ubon Ratchathani's high-resolution mean wind speed and power density maps

The evaluation of the mean wind speed and the wind power density in the area around the meteorological station can estimate the result of the mean wind speed and the wind power density in Ubon Ratchathani province following this;

- The highest mean wind speed is 1.64 m/s
- The lowest mean wind speed is 3.98 m/s
- The highest wind power density is 78 W/m^2
- The lowest wind power density is 6 W/m^2

4.2.3 Wind Climate Analysis at different hub-height for wind farm

4.2.3.1 Wind climate analysis at wind farm site in Buri Ram province

Table 19: Sector-wise wind statistics of wind farm site at Buri Ram at 60m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	6.4	10.7	10.4	9.5	15.2	9.3	8.1	9.4	9.4	5	3.4	3.3
A [m/s]	4.8	7.2	6.6	5.2	5.3	3.5	3.5	4.8	6.2	5.7	4.1	3.7
K	1.85	2.04	1.94	1.75	1.78	1.66	1.61	1.7	1.69	1.43	1.39	1.58
U [m/s]	4.26	6.35	5.89	4.62	4.74	3.16	3.15	4.28	5.5	5.2	3.73	3.33
P [W/m^2]	89	268	224	122	128	42	43	100	214	230	88	52

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

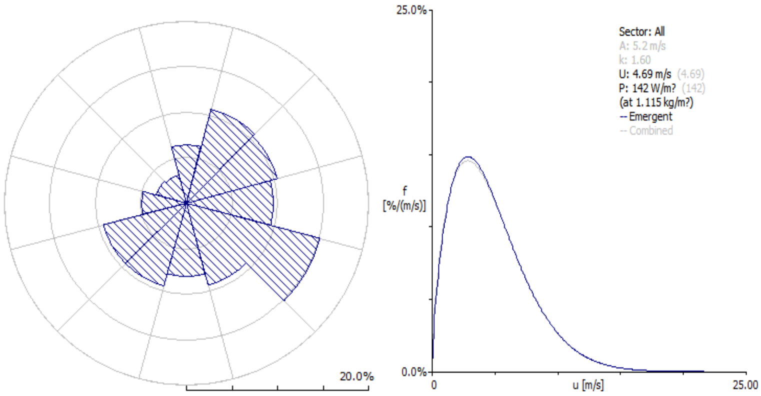


Figure 44: Wind rose and Weilbull distribution of wind farm site at Buri Ram at 60m

Table 20: Sector-wise wind statistics of wind farm site at Buri Ram at 80m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	6.6	10.8	10.1	9.1	15.4	9.6	8.2	9.4	9.1	4.9	3.4	3.3
A [m/s]	5.2	7.6	7	5.5	5.7	3.8	3.8	5.1	6.5	6.1	4.4	4
K	1.91	2.12	2	1.8	1.85	1.71	1.66	1.76	1.75	1.47	1.44	1.63
U [m/s]	4.59	6.77	6.16	4.85	5.07	3.42	3.4	4.58	5.79	5.49	3.99	3.62
P [W/m^2]	108	312	249	136	151	51	52	117	239	256	102	64

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

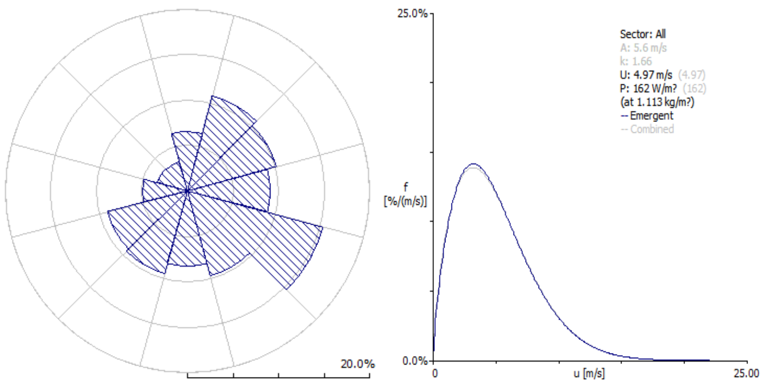


Figure 45: Wind rose and Weilbull distribution of wind farm site at Buri Ram at 80m

Table19-20 demonstrates the sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at 60 meters from Buri Ram. The most frequent wind prevailing was from 120° or the southeast (SE) side. The mean wind speed was 4.72 m/s and the power density was 128 W/m^2. Moreover, with the hub-height level at 80 meters, the most frequent wind prevailing was from the 120° or southeast (SE) side. The mean wind speed was 5.07 m/s and the power density was 151 W/m^2.

4.2.3.2 Wind climate analysis at wind farm site in Roi Et Province

Table 21: Sector-wise wind statistics of wind farm site at Roi Et at 60m

Angle[°]	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
f [%]	4	8.9	18.6	11.7	4.6	6.2	13.5	13.8	9.1	3.8	2.7	3.1
A [m/s]	4.6	7.4	9.3	7.4	4.1	4.8	6.1	6.7	8	6.3	5	4.7
K	1.72	1.98	2.26	2.01	1.75	1.87	2.15	2.48	2.65	2.17	1.57	1.58
U [m/s]	4.12	6.56	8.25	6.58	3.67	4.29	5.4	5.97	7.15	5.55	4.47	4.24
P [W/m^2]	89	308	541	307	62	92	158	191	313	171	128	108

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

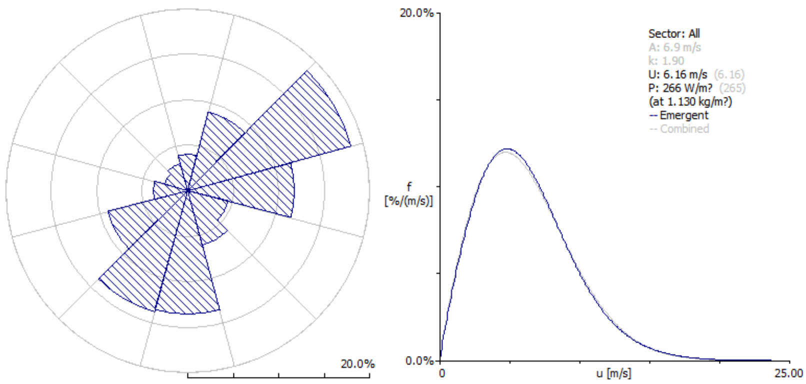


Figure 46: Wind rose and Weibull distribution of wind farm site at Roi Et at 60m

Table 22: Sector-wise wind statistics of wind farm site at Roi Et at 80m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	4	8.8	18.7	11.7	4.6	6.2	13.5	13.8	9.1	3.8	2.7	3.1
A [m/s]	4.9	7.9	9.9	7.9	4.4	5.2	6.5	7.3	8.5	6.8	5.4	5.1
K	1.78	2.05	2.35	2.08	1.82	1.93	2.22	2.55	2.72	2.24	1.62	1.63
U [m/s]	4.4	6.97	8.74	7.04	3.93	4.6	5.77	6.52	7.59	5.98	4.8	4.54
P [W/m^2]	104	357	624	362	73	109	188	243	367	207	152	127

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

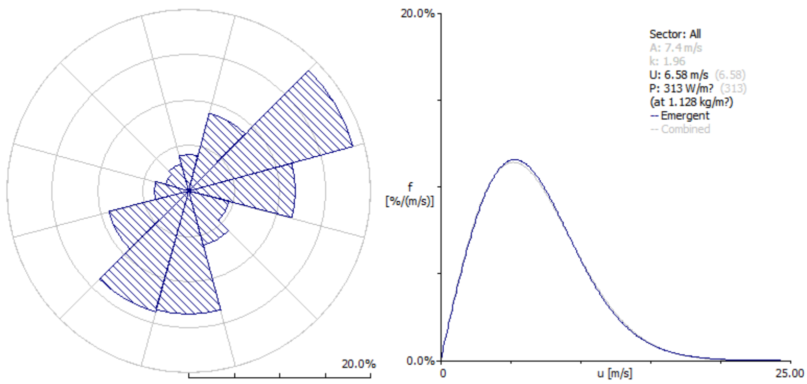


Figure 47. Wind rose and Weibull distribution of wind farm site at Roi Et at 80m

Table 21-22 demonstrates the sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at 60 meters of Roi Et. The most frequent wind prevailing was from 60° or northeast (NE) side. The mean wind speed was 8.25 m/s and the power density was 541 W/m^2. Moreover, the hub-height level at 80 meters, the most frequent wind prevailing was from 60° or northeast (NE) side. The mean wind speed was 8.74 m/s and the power density was 624 W/m^2.

4.2.3.3 Wind climate analysis at wind farm site in Sri Sa Ket province

Table 23. Sector-wise wind statistics of wind farm site at Sri Sa Ket at 60m

Angle[º]	0º	30º	60º	90 º	120º	150º	180º	210º	240 º	270º	300º	330º
f [%]	5.2	15.5	14.6	5.2	4.7	8.4	9	12.1	11.9	6	4.1	3.4
A [m/s]	4	7.8	7.5	4.1	3	3.4	3.4	5.1	6.3	5.8	5	3.6
K	1.65	2.69	2.38	1.59	1.52	1.57	1.71	1.96	2.22	2.01	1.58	1.44
U [m/s]	3.56	6.95	6.63	3.65	2.7	3.08	3.06	4.55	5.58	5.16	4.47	3.27
P [W/m^2]	61	286	271	69	30	42	37	104	170	148	128	57

Where; *f* = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density

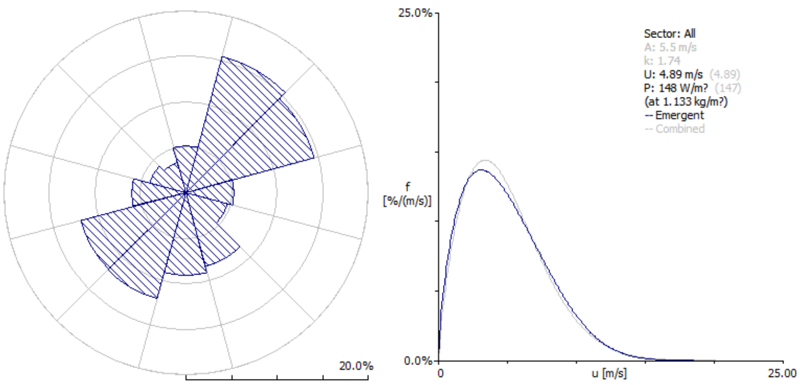


Figure 48. Wind rose and Weilbull distribution of wind farm site at Sri Sa Ket at 60m

Table 24. Sector-wise wind statistics of wind farm site at Sri Sa Ket at 80m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	5.1	15.3	14.7	5.3	4.7	8.4	8.9	12	12	6	4.1	3.4
A [m/s]	4.2	8.4	8	4.5	3.2	3.7	3.7	5.5	6.8	6.3	5.4	3.8
K	1.7	2.77	2.46	1.64	1.57	1.62	1.77	2.02	2.3	2.07	1.63	1.48
U [m/s]	3.73	7.48	7.13	4.01	2.91	3.3	3.26	4.85	5.99	5.57	4.82	3.45
P [W/m^2]	67	349	328	88	35	50	43	122	205	180	153	65

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

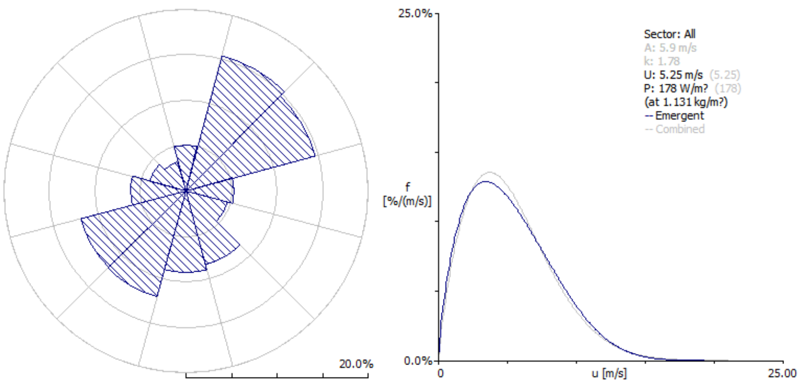


Figure 49. Wind rose and Weilbull distribution of wind farm site at Sri Sa Ket at 80m

Table 23-24 demonstrates the sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at 60 meters from Sri Sa Ket. The most frequent wind prevailing was from 30o or north north-east (NNE) side. The mean wind speed was 6.63 m/s and the power density was 271 W/m^2. Moreover, with the hub-height level at 80 meters, the most frequent wind prevailing was from 30° or north north-east (NNE) side. The mean wind speed was 7.48 m/s and the power density was 349 W/m^2.

4.2.3.4 Wind climate analysis at wind farm site in Surin province

Table 25. Sector-wise wind statistics of wind farm site at Surin at 60m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	6.5	13.8	8.7	5.9	8.1	16.7	11.9	10.8	6.1	4.3	3.4	3.7
A [m/s]	5.2	7.2	6.4	4.6	4.8	6.5	5.6	6.2	5.8	4.8	4.1	3.5
K	1.96	2.15	2.12	1.86	1.87	2.08	2.06	2.05	1.98	1.72	1.53	1.58
U [m/s]	4.64	6.41	5.67	4.13	4.26	5.75	4.93	5.51	5.1	4.24	3.65	3.16
P [W/m^2]	110	266	187	82	90	198	126	176	144	98	73	45

Where; *f* = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density

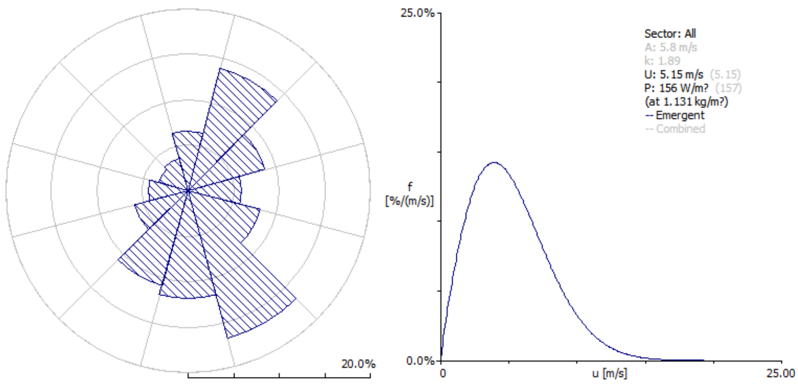


Figure 50. Wind rose and Weilbull distribution of wind farm site at Surin at 60m

Table 26. Sector-wise wind statistics of wind farm site at Surin at 80m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	6.5	13.8	8.7	5.9	8.1	16.7	11.9	10.8	6.1	4.3	3.4	3.7
A [m/s]	5.6	7.8	6.9	5	5.1	6.9	5.9	6.5	6	5.1	4.4	3.8
K	2.02	2.22	2.19	1.92	1.93	2.11	2.1	2.11	2.04	1.77	1.58	1.63
U [m/s]	4.99	6.89	6.11	4.44	4.55	6.08	5.18	5.79	5.34	4.55	3.95	3.4
P [W/m^2]	133	321	225	99	106	230	143	198	161	116	88	54

Where; *f* = frequency
A = Weibull-A
k = Weibull-k
U = mean speed
P = power density

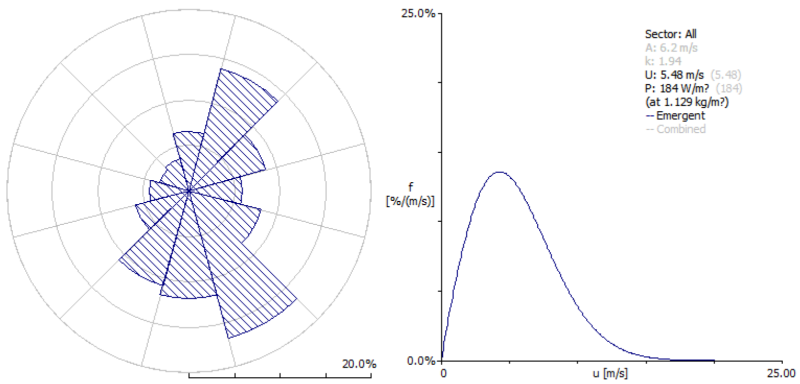


Figure 51. Wind rose and Weibull distribution of wind farm site at Surin at 80m

Table 25-26 demonstrates the sector-wise Weibull parameters, mean wind speed, power density, and frequency of prevailing wind at 60 meters of Surin. The most frequent wind prevailing was from 150° or south-south-east (SSE) side, which had the mean wind speed was 5.75 m/s and the power density was 198 W/m^2. Moreover, the hub-height level at 80 meters, the most frequent wind prevailing was from 150° or south-south-east (SSE) side. The mean wind speed was 6.08 m/s and the power density was 230 W/m^2.

4.2.3.5 Wind climate analysis at wind farm site in Ubon Ratchathani province

Table 27. Sector-wise wind statistics of wind farm site at Ubon Ratchathani at 60m

Angle[º]	0º	30º	60º	90 º	120º	150º	180º	210º	240 º	270º	300º	330º
f [%]	11.3	15.9	7.6	5.7	7.6	12.7	9.4	8.2	8.1	5.2	4.5	3.7
A [m/s]	5.2	5.7	4.9	4.7	4.7	5	4.6	5.5	6.6	5.7	6.3	4.2
K	2.01	2.22	1.81	2.05	2.26	2.21	2.26	2.54	2.49	2.23	2.21	1.74
U [m/s]	4.58	5.04	4.33	4.13	4.16	4.39	4.09	4.86	5.87	5.07	5.55	3.71
P [W/m^2]	103	126	98	75	70	84	67	102	182	128	169	65

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

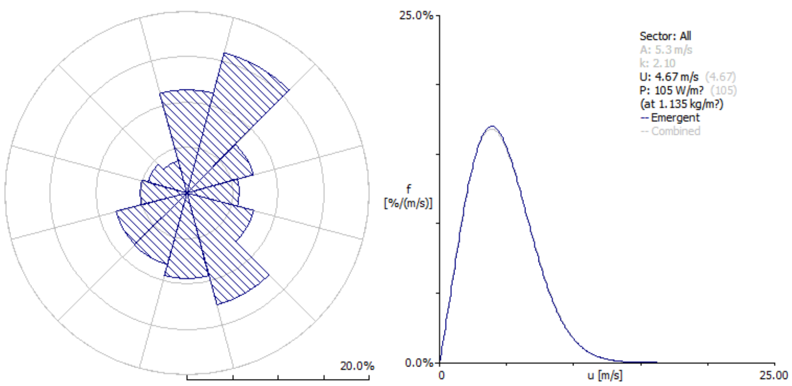


Figure 52: Wind rose and Weibull distribution of wind farm site at Ubon Ratchathani at 60m

Table 28. Sector-wise wind statistics of wind farm site at Ubon Ratchathani at 80m

Angle[°]	0°	30°	60°	90 °	120°	150°	180°	210°	240 °	270°	300°	330°
f [%]	11.3	16	7.6	5.7	7.5	12.7	9.4	8.2	8.1	5.2	4.4	3.7
A [m/s]	5.6	6.1	5.2	5	5	5.3	5	5.9	7	6.1	6.7	4.5
K	2.08	2.28	1.87	2.12	2.33	2.28	2.33	2.62	2.55	2.3	2.28	1.79
U [m/s]	4.98	5.38	4.64	4.42	4.45	4.7	4.39	5.23	6.22	5.42	5.94	3.98
P [W/m^2]	129	149	116	89	83	100	80	124	212	152	201	77

Where; *f* = frequency

A = Weibull-A

k = Weibull-k

U = mean speed

P = power density

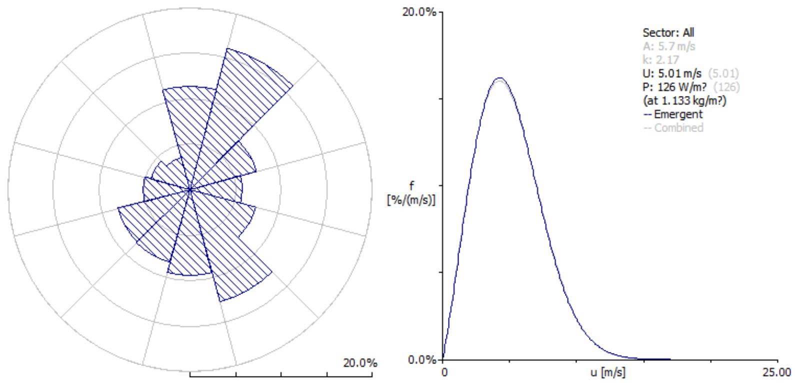


Figure 53. Wind rose and Weilbull distribution of wind farm site at Ubon Ratchathani at 80m

Table 27-28 demonstrates the sector-wise Weibull parameters, mean wind speed, power density, and frequency of wind prevailing at 60 meters from Ubon Ratchathani. The most frequent wind prevailing was from 30° or north-north-east (NNE) side. The mean wind speed was 5.04 m/s and the power density was 126 W/m^2. Moreover, with the hub-height level at 80 meters, the most frequent wind prevailing was from 30° or north-north-east (NNE) side. The mean wind speed was 5.38 m/s and the power density was 149 W/m^2.

4.3 The estimation annual wind energy production of the wind farm

In order to study the annual energy production and the capacity factor of the wind farm, the VESTAS 850kW and VESTAS 2MW have been chosen to be wind turbine generators to generate electricity from wind energy resources at the hub-height levels of 60m and 80m above the ground level, respectively. The wind turbine specification was shown in table 7 and the power curve of a wind turbine was shown in figure 26-27. This study used 12 wind turbines to estimate the annual wind energy production at any height level. Therefore, the result of this sector will demonstrate the statistical analysis as follows:

- Total gross annual energy production
- Total net annual energy production
- The proportional wake loss
- The capacity factor of wind farm
- The mean wind speed
- The net mean wind speed by reduced the wake loss
- Air density
- Power density

Moreover, this sector will demonstrate the result of the wind climate and wind energy production of the individual wind turbines that are members of the wind farm site to be useful information for further study.

4.3.1 Estimation the annual energy production at wind farm in Buri Ram province

Table 29. Statistical analysis at 60m of wind farm site at Buri Ram.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	11.425	0.952	0.908	1.011
Total net AEP [GWh]	10.764	0.897	0.822	0.957
Proportional wake loss [%]	5.78	-	1.58	9.46
Capacity factor [%]	12.6	-	12	13.4
Mean speed [m/s]	-	4.69	4.61	4.8
Mean speed (wake-reduced) [m/s]	-	4.59	4.46	4.71
Air density [kg/m^3]	-	1.115	1.114	1.117
Power density [W/m^2]	-	138	130	148

Table 30. Statistical analysis at 80m of wind farm site at Buri Ram.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	37.185	3.099	2.99	3.245
Total net AEP [GWh]	33.473	2.789	2.52	3.077
Proportional wake loss [%]	9.98	-	2.84	15.74
Capacity factor [%]	17.7	-	17.1	18.5
Mean speed [m/s]	-	4.98	4.91	5.08
Mean speed (wake-reduced) [m/s]	-	4.79	4.62	4.98
Air density [kg/m^3]	-	1.113	1.112	1.115
Power density [W/m^2]	-	159	151	169

The net annual production (AEP) of a wind farm at Buri Ram, which consists of 12 wind turbine sites, is shown in table 29-30. For the hub height level of the wind turbine at 60m, the mean wind speed (wake-reduced) and power density were 4.59 m/s and 138 W/m^2, respectively. The total capacity factor of the wind farm was 12.6%, which meant the total net AEP was 10.764 GWh. In addition, at the hub height level of the wind turbine at 80m, the mean wind speed (wake-reduced) and power density were 4.79 m/s and 159 W/m^2, respectively. The total capacity factor of the wind farm was 17.7%, which meant the total net AEP on average was 33.473 GWh.

Table 31: The individual wind statistic of the wind turbine in Buri Ram at 60m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [MWh]	Loss [%]	CF [%]
Turbine site 001	472594.1	1679894	131	60	4.49	685.023	12.4	10.4
Turbine site 002	472665.3	1680067	130.9	60	4.47	669.745	15.46	10.5
Turbine site 003	472754.4	1680237	131.1	60	4.48	678.872	15.65	10.7
Turbine site 004	472852.4	1680379	131.2	60	4.57	737.046	9.28	10.8
Turbine site 005	473021.7	1680446	131	60	4.52	700.842	12.53	10.6
Turbine site 006	473195.4	1680477	130.8	60	4.51	692.909	11.94	10.4
Turbine site 007	473355.8	1680566	135.2	60	4.55	715.702	11.67	10.7
Turbine site 008	473533.9	1680602	135.1	60	4.57	728.159	9.3	10.6
Turbine site 009	473743.3	1680606	131.8	60	4.57	732.784	7.27	10.5
Turbine site 010	473925.9	1680562	130.7	60	4.56	727.4	7.17	10.4
Turbine site 011	474095.2	1680477	128.1	60	4.53	709.046	6.8	10.1
Turbine site 012	474273.3	1680437	130.6	60	4.57	730.899	4.33	10.1

Table 32: The individual wind statistic of the wind turbine in Buri Ram at 80m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	265314.8	1609850	291.8	80	4.68	2.583	14.31	17.2
Turbine site 002	265429.4	1610008	290.9	80	4.8	2.802	7.7	17.3
Turbine site 003	265271.8	1609048	302.7	80	4.82	2.887	7.03	17.7
Turbine site 004	265200.2	1609485	303.2	80	4.76	2.697	13.92	17.9
Turbine site 005	265185.9	1609241	310	80	4.89	2.923	9.91	18.5
Turbine site 006	265372.1	1608640	303.6	80	4.74	2.75	9.59	17.3
Turbine site 007	265744.5	1608124	320	80	4.83	2.819	11.63	18.2
Turbine site 008	265272	1609675	293.5	80	4.62	2.52	15.74	17.1
Turbine site 009	265372.1	1608840	301.8	80	4.79	2.849	6.86	17.4
Turbine site 010	265608.4	1608275	317.1	80	4.83	2.858	10.37	18.2
Turbine site 011	265465.2	1608425	304	80	4.73	2.708	10.17	17.2
Turbine site 012	265907.8	1608028	320	80	4.98	3.077	2.84	18.1

4.3.2 Estimation the annual energy production at wind farm in Roi Et province

Table 33: Statistical analysis at 60m of wind farm site at Roi Et.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	20.662	1.722	1.634	1.84
Total net AEP [GWh]	18.932	1.578	1.414	1.702
Proportional wake loss [%]	8.37	-	0.99	17.41
Capacity factor [%]	22.8	-	21.7	24.4
Mean speed [m/s]	-	6.16	6.02	6.32
Mean speed (wake-reduced) [m/s]	-	5.95	5.72	6.13
Air density [kg/m^3]	-	1.131	1.13	1.131
Power density [W/m^2]	-	265	250	285

Table 34: Statistical analysis at 80m of wind farm site at Roi Et.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	65.5	5.458	5.255	5.716
Total net AEP [GWh]	56.322	4.693	3.953	5.152
Proportional wake loss [%]	14.01	-	2	27.37
Capacity factor [%]	31.1	-	30	32.6
Mean speed [m/s]	-	6.56	6.45	6.7
Mean speed (wake-reduced) [m/s]	-	6.15	5.75	6.41
Air density [kg/m^3]	-	1.129	1.128	1.129
Power density [W/m^2]	-	311	296	329

The net annual production (AEP) of a wind farm at Roi Et, which consists of 12 wind turbine sites, is shown in table 33-34. For the hub height level of the wind turbine at 60m, the mean wind speed (wake-reduced) and power density were 5.95 m/s and 265 W/m^2, respectively. The total capacity factor of the wind farm was 22.8%, which meant the total net AEP was 18.932 GWh. In addition, at the hub height level of the wind turbine at 80m, the mean wind speed (wake-reduced) and power density were 6.15 m/s and 311 W/m^2, respectively. The total capacity factor of the wind farm was 31.1%. The consequence of the total net AEP was 56.322 GWh.

Table 35: The individual wind statistic of the wind turbine in Roi Et at 60m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	336069.3	1780897	160	60	5.97	1.591	11.34	23.8
Turbine site 002	335915.3	1780743	155.7	60	6.13	1.702	7.49	24.4
Turbine site 003	336197.6	1781051	160	60	5.82	1.486	14.31	23
Turbine site 004	336345.1	1781198	161.2	60	5.81	1.477	13.86	22.7
Turbine site 005	336460.6	1781358	162.3	60	5.72	1.414	17.41	22.7
Turbine site 006	336601.8	1781493	163.3	60	5.79	1.47	13.61	22.6
Turbine site 007	336794.2	1781525	164.9	60	5.93	1.566	8.69	22.7
Turbine site 008	336980.3	1781500	168	60	6.05	1.649	3.93	22.8
Turbine site 009	337147.1	1781403	170	60	6.09	1.67	3.59	23
Turbine site 010	337339.5	1781333	170	60	6.09	1.669	2.62	22.7
Turbine site 011	337557.7	1781249	164.1	60	6.01	1.623	2.02	22
Turbine site 012	337750.1	1781166	163.7	60	6	1.618	0.99	21.7

Table 36: The individual wind statistic of the wind turbine in Roi Et at 80m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	336069.3	1780897	160	80	6.07	4.567	18.85	32.1
Turbine site 002	335915.3	1780743	155.8	80	6.33	5.022	12.16	32.6
Turbine site 003	336197.6	1781051	160	80	5.91	4.241	22.89	31.4
Turbine site 004	336345.1	1781198	161.2	80	5.88	4.181	23.25	31.1
Turbine site 005	336460.6	1781358	162.3	80	5.75	3.954	27.35	31
Turbine site 006	336601.8	1781493	163.3	80	5.91	4.239	21.78	30.9
Turbine site 007	336794.2	1781525	164.9	80	6.13	4.659	14.49	31.1
Turbine site 008	336980.3	1781500	168	80	6.35	5.047	7.89	31.3
Turbine site 009	337147.1	1781403	170	80	6.37	5.077	7.18	31.2
Turbine site 010	337339.5	1781333	170	80	6.41	5.153	5.25	31
Turbine site 011	337557.7	1781249	164.1	80	6.35	5.081	4.29	30.3
Turbine site 012	337750.1	1781166	163.7	80	6.39	5.148	2.02	30

4.3.3 Estimation the annual energy production at wind farm in Sri Sa Ket province

Table 37: Statistical analysis at 60m of wind farm site at Sri Sa Ket.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	12.784	1.065	1.02	1.108
Total net AEP [GWh]	12.152	1.013	0.931	1.058
Proportional wake loss [%]	4.94	-	0.55	11.46
Capacity factor [%]	14.1	-	13.5	14.7
Mean speed [m/s]	-	4.89	4.83	4.95
Mean speed (wake-reduced) [m/s]	-	4.81	4.69	4.86
Air density [kg/m^3]	-	1.133	1.133	1.134
Power density [W/m^2]	-	147	140	155

Table 38. Statistical analysis at 80m of wind farm site at Sri Sa Ket.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	42.821	3.568	3.452	3.657
Total net AEP [GWh]	39.126	3.26	2.874	3.487
Proportional wake loss [%]	8.63	-	1.28	19.23
Capacity factor [%]	20.4	-	19.7	20.9
Mean speed [m/s]	-	5.24	5.19	5.29
Mean speed (wake-reduced) [m/s]	-	5.07	4.86	5.17
Air density [kg/m^3]	-	1.131	1.131	1.132
Power density [W/m^2]	-	176	169	182

The net annual production (AEP) of a wind farm at Sri Sa Ket, which consists of 12 wind turbine sites, is shown in table 37-38. For the hub height level of the wind turbine at 60m, the mean wind speed (wake-reduced) and power density were 4.81 m/s and 147 W/m^2, respectively. The total capacity factor of the wind farm was 14.1%, which meant the total net AEP was 12.152 GWh. In addition, at the hub height level of the wind turbine at 80m, the mean wind speed (wake-reduced) and power density were 5.07 m/s and 176 W/m^2, respectively. The total capacity factor of the wind farm was 20.9%, which meant the total net AEP was 39.126 GWh.

Table 39: The individual wind statistic of the wind turbine in Sri Sa Ket at 60m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	424434.9	1681516	139.9	60	4.82	1.015	0.55	13.5
Turbine site 002	424612.6	1681421	140	60	4.82	1.014	1.87	13.7
Turbine site 003	424779.5	1681304	140	60	4.83	1.021	2.14	13.8
Turbine site 004	424929.8	1681171	136.3	60	4.85	1.044	1.96	14.1
Turbine site 005	425092.7	1681049	133.6	60	4.85	1.055	2.23	14.3
Turbine site 006	425226.2	1680912	135.1	60	4.86	1.058	2.28	14.4
Turbine site 007	425384.9	1680766	135.3	60	4.82	1.028	2.42	14
Turbine site 008	425585.3	1680741	138.7	60	4.78	0.992	7.22	14.2
Turbine site 009	425777.3	1680770	138.8	60	4.69	0.931	11.46	13.9
Turbine site 010	425961	1680824	140	60	4.76	0.981	10.29	14.5
Turbine site 011	426153.1	1680862	140	60	4.78	0.994	10.27	14.7
Turbine site 012	426312.7	1680897	137.5	60	4.81	1.019	6.03	14.4

Table 40: The individual wind statistic of the wind turbine in Sri Sa Ket at 80m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	424434.9	1681516	139.9	80	5.16	3.407	1.28	19.7
Turbine site 002	424612.6	1681421	140	80	5.13	3.367	3.63	19.9
Turbine site 003	424779.5	1681304	140	80	5.13	3.365	3.86	20
Turbine site 004	424929.8	1681171	136.3	80	5.16	3.434	3.46	20.3
Turbine site 005	425092.7	1681049	133.6	80	5.16	3.472	4.15	20.7
Turbine site 006	425226.2	1680912	135.1	80	5.17	3.487	4.1	20.7
Turbine site 007	425384.9	1680766	135.3	80	5.13	3.393	4.44	20.3
Turbine site 008	425585.3	1680741	138.6	80	5	3.139	12.82	20.5
Turbine site 009	425777.3	1680770	138.7	80	4.86	2.874	19.23	20.3
Turbine site 010	425961	1680824	140	80	4.92	2.978	17.83	20.7
Turbine site 011	426153.1	1680862	140	80	4.94	3.019	17.44	20.9
Turbine site 012	426312.7	1680897	137.5	80	5.02	3.191	10.63	20.4

4.3.4 Estimation the annual energy production at wind farm in Surin province

Table 41. Statistical analysis at 60m of wind farm site at Surin.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	13.535	1.128	1.11	1.142
Total net AEP [GWh]	12.969	1.081	1.058	1.105
Proportional wake loss [%]	4.18	-	0.75	5.6
Capacity factor [%]	15	-	14.7	15.1
Mean speed [m/s]	-	5.15	5.11	5.18
Mean speed (wake-reduced) [m/s]	-	5.07	5.03	5.12
Air density [kg/m^3]	-	1.131	1.131	1.131
Power density [W/m^2]	-	156	154	158

Table 42: Statistical analysis at 80m of wind farm site at Surin.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	44.764	3.73	3.656	3.79
Total net AEP [GWh]	41.189	3.432	3.325	3.658
Proportional wake loss [%]	7.99	-	1.35	10.47
Capacity factor [%]	21.3	-	20.9	21.6
Mean speed [m/s]	-	5.49	5.44	5.52
Mean speed (wake-reduced) [m/s]	-	5.32	5.25	5.45
Air density [kg/m^3]	-	1.129	1.129	1.129
Power density [W/m^2]	-	184	180	187

The net annual production (AEP) of a wind farm at Surin, which consists of 12 wind turbine sites, is shown in table 41-42. For the hub height level of the wind turbine at 60m, the mean wind speed (wake-reduced) and power density were 5.07 m/s and 156 W/m^2, respectively. The total capacity factor of the wind farm was 15%, which had a total net AEP of 12.969 GWh. In addition, at the hub height level of the wind turbine at 80m, the mean wind speed (wake-reduced) and power density were 5.32 m/s and 184 W/m^2, respectively. The total capacity factor of the wind farm was 21.3%, which had a total net AEP of 41.189 GWh.

Table 43: The individual wind statistic of the wind turbine in Surin at 60m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	344823.5	1633554	160	60	5.05	1.073	3.39	14.7
Turbine site 002	344978.8	1633460	160	60	5.03	1.058	5.09	14.8
Turbine site 003	345124.4	1633347	160	60	5.04	1.065	4.88	14.9
Turbine site 004	345264.7	1633244	160	60	5.08	1.088	3.69	15
Turbine site 005	345431.8	1633136	160	60	5.04	1.062	5.6	14.9
Turbine site 006	345572.1	1633018	160	60	5.08	1.085	4.35	15
Turbine site 007	345739.3	1632878	159.4	60	5.09	1.09	4.56	15.1
Turbine site 008	345901.1	1632737	159.1	60	5.09	1.092	3.93	15.1
Turbine site 009	346057.5	1632624	158.6	60	5.07	1.078	4.82	15
Turbine site 010	346219.3	1632484	158.5	60	5.09	1.084	4.49	15.1
Turbine site 011	346375.7	1632344	158.8	60	5.09	1.089	4.57	15.1
Turbine site 012	346521.3	1632209	158.9	60	5.12	1.105	0.75	14.8

Table 44: The individual wind statistic of the wind turbine in Surin at 80m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	344823.5	1633554	160	80	5.3	3.41	6.73	20.9
Turbine site 002	344978.8	1633460	160	80	5.25	3.325	9.47	21
Turbine site 003	345124.4	1633347	160	80	5.26	3.349	9.38	21.1
Turbine site 004	345264.7	1633244	160	80	5.32	3.442	7.67	21.3
Turbine site 005	345431.8	1633136	160	80	5.26	3.332	10.43	21.2
Turbine site 006	345572.1	1633018	160	80	5.31	3.423	8.69	21.4
Turbine site 007	345739.3	1632878	159.4	80	5.33	3.455	8.38	21.5
Turbine site 008	345901.1	1632737	159.1	80	5.33	3.449	8.23	21.4
Turbine site 009	346057.5	1632624	158.6	80	5.31	3.426	8.71	21.4
Turbine site 010	346219.3	1632484	158.5	80	5.33	3.442	8.56	21.5
Turbine site 011	346375.7	1632344	158.8	80	5.35	3.479	8.21	21.6
Turbine site 012	346521.3	1632209	158.9	80	5.45	3.659	1.34	21.2

4.3.5 Estimation the annual energy production at wind farm in Ubon Rachathani province

Table 45. Statistical analysis at 60m of wind farm site at Ubon Ratchathani.

Variable	Total	Mean	Min	Max
Total gross AEP [MWh]	9491.367	790.947	760.741	812.481
Total net AEP [MWh]	8508.426	709.036	669.745	737.046
Proportional wake loss [%]	10.36	-	4.33	15.65
Capacity factor [%]	10.5	-	10.1	10.8
Mean speed [m/s]	-	4.67	4.62	4.71
Mean speed (wake-reduced) [m/s]	-	4.53	4.47	4.57
Air density [kg/m^3]	-	1.135	1.134	1.135
Power density [W/m^2]	-	105	101	108

Table 46. Statistical analysis at 80m of wind farm site at Ubon Ratchathani.

Variable	Total	Mean	Min	Max
Total gross AEP [GWh]	33.027	2.752	2.665	2.815
Total net AEP [GWh]	27.524	2.294	2.074	2.477
Proportional wake loss [%]	16.66	-	7.04	25.18
Capacity factor [%]	15.7	-	15.2	16.1
Mean speed [m/s]	-	5	4.95	5.03
Mean speed (wake-reduced) [m/s]	-	4.72	4.58	4.84
Air density [kg/m^3]	-	1.133	1.132	1.133
Power density [W/m^2]	-	125	120	128

The net annual production (AEP) of a wind farm at Ubon Ratchathani consists of 12 wind turbine sites, as shown in table 45-46. For the hub height level of the wind turbine at 60m, the mean wind speed (wake-reduced) and power density were 4.53 m/s and 105 W/m^2, respectively. The total capacity factor of the wind farm was 10.5%, which had a total net AEP of 8.508 GWh. In addition, at the hub height level of the wind turbine at 80m, the mean wind speed (wake-reduced) and power density were 4.72 m/s and 125 W/m^2, respectively. The total capacity factor of the wind farm was 15.7%. The consequence of the total net AEP was 27.524 GWh.

Table 47: The individual wind statistic of the wind turbine in Ubon Ratchathani at 60m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [MWh]	Loss [%]	CF [%]
Turbine site 001	472594.1	1679894	131	60	4.49	685.023	12.4	10.4
Turbine site 002	472665.3	1680067	130.9	60	4.47	669.745	15.46	10.5
Turbine site 003	472754.4	1680237	131.1	60	4.48	678.872	15.65	10.7
Turbine site 004	472852.4	1680379	131.2	60	4.57	737.046	9.28	10.8
Turbine site 005	473021.7	1680446	131	60	4.52	700.842	12.53	10.6
Turbine site 006	473195.4	1680477	130.8	60	4.51	692.909	11.94	10.4
Turbine site 007	473355.8	1680566	135.2	60	4.55	715.702	11.67	10.7
Turbine site 008	473533.9	1680602	135.1	60	4.57	728.159	9.3	10.6
Turbine site 009	473743.3	1680606	131.8	60	4.57	732.784	7.27	10.5
Turbine site 010	473925.9	1680562	130.7	60	4.56	727.4	7.17	10.4
Turbine site 011	474095.2	1680477	128.1	60	4.53	709.046	6.8	10.1
Turbine site 012	474273.3	1680437	130.6	60	4.57	730.899	4.33	10.1

Table 48: The individual wind statistic of the wind turbine in Ubon Ratchathani at 80m

Site description	X-location [m]	Y-location [m]	Elev. [m]	Ht [m]	U(w) [m/s]	Net. [GWh]	Loss [%]	CF [%]
Turbine site 001	472594.1	1679894	131	80	4.67	2.216	19.39	15.7
Turbine site 002	472665.3	1680067	130.9	80	4.58	2.073	25.2	15.8
Turbine site 003	472754.4	1680237	131.1	80	4.58	2.098	25.02	16
Turbine site 004	472852.4	1680379	131.2	80	4.77	2.377	15.56	16.1
Turbine site 005	473021.7	1680446	130.9	80	4.7	2.263	18.82	15.9
Turbine site 006	473195.4	1680477	130.8	80	4.66	2.182	20.44	15.6
Turbine site 007	473355.8	1680566	135.2	80	4.74	2.308	17.39	15.9
Turbine site 008	473533.9	1680602	135.1	80	4.76	2.356	14.78	15.8
Turbine site 009	473743.3	1680606	131.8	80	4.79	2.411	11.92	15.6
Turbine site 010	473925.9	1680562	130.7	80	4.77	2.382	12.43	15.5
Turbine site 011	474095.2	1680477	128.1	80	4.77	2.377	11.33	15.3
Turbine site 012	474273.3	1680437	130.6	80	4.84	2.477	7.04	15.2

Table 49. The comparison of the annual energy production of each province.

Province	Annual Energy Production at 60m (GWh)	Capacity factor at 60m (%)	Annual Energy Production at 80m (GWh)	Capacity factor at 80m (%)
Buri Ram	10.764	12.6	33.473	17.7
Roi Et	18.932	22.8	56.322	31.1
Sri Sa Ket	12.152	14.1	39.126	20.4
Surin	12.969	15	41.189	21.3
Ubon Ratchathani	8.508	10.5	27.524	15.7

In table 49, it is shown that Roi Et has the most potential for annual energy production and the capacity factor to generate electricity compared with the other provinces. This province could generate 18.932 GWh with the capacity factor of 22.8 percent at the hub height of wind turbines of 60 meters above the ground level and 56.322 GWh with 31.1 percent of a capacity factor at the hub height of 80 meters above the ground. After the Roi Et Surin, this province could generate 12.969 GWh with a capacity factor of 15 percent at the hub height of 60 meters above the ground level. Moreover, at the hub height of 80 meters above the ground level, this province could generate an annual energy production of 41.189 GWh with a capacity factor of 21.3 percent. The last province that has the lowest potential to generate electricity is Ubon Ratchathani that has the annual energy production of 8.508 GWh and 27.524 GWh at the hub height of 60 meters and 80 meters above the ground level with the capacity factor of 10.5 percent and 15.7 percent, respectively.

4.4 Economic Analysis

An economic analysis will be performed to demonstrate the cost per unit of electricity generated to comply with consumer affordability and can demonstrate the benefits of investment to reduce the risk of investment. The value of land used, wind turbine costs, grid-connected costs, construction costs, and other capital costs were used in the study.

Table 50. The economic analysis of wind farm around the study station.

Study Area	Wind Turbine	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Wind farm at Buri Ram	Vestas V52	20	850	12	60	243,000	1,408,981.25	217,493.75	264,775	32,241,580
	Vestas V90	20	2,000	12	80	432,000	3,315,250	511,750	623,000	75,488,000
Wind farm at Roi Et	Vestas V52	20	850	12	60	388,800	1,408,981.25	217,493.75	264,775	32,649,820
	Vestas V90	20	2,000	12	80	691,200	3,315,250	511,750	623,000	76,213,760
Wind farm at Sri Sa Ket	Vestas V52	20	850	12	60	648,000	1,408,981.25	217,493.75	264,775	33,375,580
	Vestas V90	20	2,000	12	80	1,152,000	3,315,250	511,750	623,000	77,504,000
Wind farm at Surin	Vestas V52	20	850	12	60	324,000	1,408,981.25	217,493.75	264,775	32,468,380
	Vestas V90	20	2,000	12	80	576,000	3,315,250	511,750	623,000	75,891,200
Wind farm at Ubon Ratchathani	Vestas V52	20	850	12	60	648,000	1,408,981.25	217,493.75	264,775	33,375,580
	Vestas V90	20	2,000	12	80	1,152,000	3,315,250	511,750	623,000	77,504,000

(10)	(11)
10.674	0.15
33.437	0.11
18.932	0.09
56.322	0.07
12.152	0.14
39.126	0.10
12.969	0.13
41.189	0.09
8.508	0.2
27.524	0.14

Note;
(1) Wind farm life time (year)
(2) Wind turbine rated power (kW)
(3) Number of wind turbine (unit)
(4) Hub-height (meter)
(5) Land used value (USD)
(6) Wind turbine initial cost (USD)
(7) Grid connection cost (USD)
(8) O & M cost (USD)
(9) Total investment cost (USD)
(10) Annual electricity generated (GWh)
(11) Per unit electricity

Economic analysis has indicated that the return of investment in each wind farm station under the condition of an interest rate of 4%, additional with feed-in-tariff at the price of 0.202 $/kWh. The economic possibility of investing in wind farms was possible, with a positive B/C ratio, NPV, and IRR at all stations except Ubon Ratchathani, at a height of 60 meters above ground level.

- Roi Et province had the highest mean wind speed, with a mean wind speed of 5.95 m/s at a height of 60 meters above the ground level and 6.15 m/s at a height of 80 meters above the ground level, resulting in electricity generation at a cost per unit of $0.09/kWh and $0.07/kWh respectively.
- Buri Ram province, costs per unit for electricity generation were $0.15/kWh and $0.11/kWh at heights of 60 and 80 meters respectively.
- Si Sa ket province's costs per unit for electricity generation were $0.14/kWh and $0.10/kWh at heights of 60 and 80 meters respectively.
- Surin province's costs per unit for electricity generation were $0.13/kWh and $0.09/kWh at 60 and 80 meters respectively, and this province had a high economic value considered with the economic indicator. Therefore, Surin is one of the other provinces that had high economic feasibility after Roi Et.
- Ubon Ratchathani had been considered to be the province with the lowest economic feasibility. This province was unsuitable for wind farm investment due to low mean wind speed and high production costs, with costs of $0.2/kWh and $0.14/kWh at highs of 60 and 80 meters respectively.

Table 51. The economic indicator of wind farm at the study area.

Study Area	Wind Turbine	Interest Rate	NPV	B/C Ratio	IRR
Wind Farm site at Buri Ram	VESTAS V52	4 %	6,794,939.03	1.27062	29%
	VESTAS V90	4 %	39,132,520.12	1.70002	68%
Wind Farm site at Roi Et	VESTAS V52	4 %	29,141,047.59	2.22546	106%
	VESTAS V90	4 %	101,381,237.91	2.83628	162%
Wind Farm site at Sri Sa Ket	VESTAS V52	4 %	9,952,045.11	1.39741	34%
	VESTAS V90	4 %	53,149,571.02	1.93752	79%
Wind Farm site at Surin	VESTAS V52	4 %	12,915,204.94	1.53303	50%
	VESTAS V90	4 %	60,093,535.88	2.08302	100%
Wind Farm site at Ubon Ratchathani	VESTAS V52	4 %	(51,631.03)	0.97837	-1%
	VESTAS V90	4 %	21,299,227.84	1.36299	33%

Chapter 5
Conclusion and Recommendation

5.1 Conclusion

The result of the study in 5 stations during 4 years of wind speed data collection at 10m above ground level has demonstrated that the mean speed value and power density of Buri Ram were 2.67 m/s and 35 W/m^2, Roi Et were 3.96 m/s and 92 W/m^2, Sri Sa Ket were 3.38 m/s and 66 W/m^2, Surin were 3.05 m/s and 43 W/m^2, and last, Ubon Ratchathani were 2.93 m/s and 34 W/m^2, respectively.

The consequence was that the mean wind speed of each station was lower than the average cut-in wind speed for the wind turbine. Therefore, this study has continued to study at 60m and 80m hub-height above ground level, using WAsP software to extrapolate wind speeds for different hub heights. Figures 39-43 illustrate the mean wind speed and power density of the area around the study stations as criteria for wind farm selection site. Vestas V52-850 kW and Vestas V90-2,000 kW are turbine generators that will be installed to calculate the annual energy production at the wind farm sites.

The result showed the wind farm site of each station at a hub height of 60m had a wind speed and power density of 4.59 m/s and 138 W/m^2 for Buri Ram, 5.95 m/s and 265 W/m^2 for Roi Et, 4.81 m/s and 147 W/m^2 for Sri Sa Ket, 5.07 m/s and 156 W/m^2 for Surin, 4.53 m/s and 105 W/m^2 for Ubon Ratchathani. Therefore, the AEP generated 10.674 GWh, 18.932 GWh, 12.152 GWh, 12.969 GWh, and 8.508 GWh respectively at each station.

The result of the mean wind speed and power density of each station at 80m were 4.79 m/s and 159 W/m^2 for Buri Ram, 6.15 m/s and 311 W/m^2 for Roi Et, 5.07 m/s and 176 W/m^2 for Sri Sa Ket, 5.32 m/s and 184 W/m^2 for Surin, and 4.72 m/s and 125 W/m^2 for Ubon Ratchathani. At this hub-height, each wind farm site has generated an AEP of 33.437 GWh, 56.322 GWh, 39.126 GWh, 41.189 GWh, and 27.524 GWh respectively.

For the economic feasibility of investment, table 30 demonstrated the cost of production and per-unit cost of energy generation that showed all of the wind farm sites in each province were economically feasible for investment except the wind farm site in Ubon Ratchathani province at 60m due to the negative economic indicators that resulted from low mean wind speed and high cost of production. Finally, the wind farm site in Roi Et province, from the results of annual energy production and economic feasibility, was indicated to be the most suitable wind farm site for investment.

5.2 Recommendation

5.2.1 This study was collecting data on the wind climate from the Thailand Meteorological Department (TMD). The wind data was observed the wind climate at the site where the anemometer was installed, but it might not be the particular site that you want to study. Therefore, to increase the accuracy of collecting the wind climate data, the researcher should install an anemometer to collect the actual observed wind data at the interested site.

5.2.2 In the part of economic feasibility analysis, this study was using the average price of the turbine generator, O&M price, grid-connected value, and land value. As a result, the cost of investment is more accurate, which is important for investment planning and decision-making. The cost of estimation should be collected as the actual price to reduce the risk of investment. The accuracy of cost estimation is reflected in the return of investment that affects the feasibility of investment.

5.2.3 In this study, it was mentioned that the decision of wind farm site selection used the mean wind speed, power density, elevation, and roughness. Therefore, further study on optimal site selection should use multi-criteria decision analysis (MCDA) as the criteria model for selecting the particular site. Due to this, MCDA has reflected the weight of factors that affect the investment decision, e.g. economic impact, environmental impact, and technical impact.

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