Investigation of Wind Energy in Southern Thailand

Ismail Kamdar

**A Thesis Submitted in Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Energy Technology
Prince of Songkla University
2022**

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Thesis Title Investigation of Wind Energy in Southern Thailand

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Thesis Title Investigation of Wind Energy in Southern Thailand

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Academic Year 2021

ABSTRACT

Wind energy is one of the most promising renewable energy technologies worldwide; however, assessing potential sites for wind energy exploitation is a challenging task. This study presents a site suitability analysis to develop a small–scale wind farm in south–eastern Thailand and the technical evaluation of wind energy potential using three available wind turbine models for prospective onshore wind farm at Krabi and Songkhla sites. To this aim, the most recent available data over a period of 3 to 4 years, recorded near the surface, at ten weather stations of the Thai Meteorological Department (TMD) were acquired. The analysis was conducted using standard wind–industry software WAsP. It was found that the mountain peaks and ridges are highly suitable for small–scale wind farm development. The selected sites in south–eastern Thailand have mean wind speeds ranging from 5.1 m/s to 9.4 m/s. Moreover, annual energy production (AEP) of 102 MWh to 311 MWh could be generated using an Enercon E–18 wind turbine with a rated power of 80-kW at the hub height of 28.5 m. The Levelized Cost of Energy (LCOE) reveals that the development cost of a small–scale wind farm is lowest in the Songkhla and Yala provinces of Thailand, therefore these two locations from the investigated study region are financially most suitable. Moreover, WAsP analyses after technical evaluation indicates that Enercon E-40/5.40 500 kW wind turbine model produces the highest total gross AEP and total net AEP for Krabi and Songkhla sites. Besides, the Vergnet GEV MP-C 275 kW turbine model shows slightly higher capacity factor in case of both sites. The findings could encourage researchers to further investigate low–speed wind energy mechanisms in tropical regions, and the demonstrated approach could be reused for other regions.

Keywords: WAsP, site assessment, wind energy potential, wind turbine model, Thailand.

DEDICATION

This thesis is dedicated to my beloved parents, brother and my sisters.

ACKNOWLEDGEMENT

My deepest gratitude to Allah Almighty who has bestowed the opportunities and guided me to complete this project and the program for which it was undertaken.

My humble gratitude and appreciation to my advisor Asst. Prof. Dr. Juntakan Taweekun for the tremendous help throughout this program. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advices on both research as well as on my career have been invaluable.

I am grateful to my examining committee, Dr. Aliashim Albani of the Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, Dr. Thanansak Theppaya, Dr. Kittinan Maliwan and Dr. Somchai Saeung of the Faculty of Engineering, Prince of Songkla University for the valuable time devoted to my thesis and their kindness, comments and helpful suggestion.

Special thanks to Miss Yosita Laomanatsawee (Nook), Energy Technology Program academic officer and Ms. Khatiyaporn Jaroenwatanan (PR) Faculty of Engineering Public Relations Officer for their excellent suggestions and guidance with the essential academic and immigration processes, respectively.

Thanks to Mr. Shahid Ali of the Griffith University, Gold Coast and all my learning partners especially Mr. Tariq Khan for valuable suggestion and encouragement.

Finally, a big thanks to the Graduate School of PSU for the financial support to this thesis under a grant of an Interdisciplinary Graduate School (IGS).

Ismail Kamdar

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LIST OF ABBREVIATIONS

WAsP	Wind Atlas Analysis and Application Program
AEP	Annual Energy Production
CF	Capacity Factor
LCOE	Levelized Cost of Energy
TMD	Thai Meteorological Department
PDP	Power Development Plan
AEDP	Alternative Energy Development Plant
GHG	Greenhouse gas
AGL	Above Ground Level
ASL	Above Sea Level
FIT	Feed-in tariff
GW	Gigawatt
MW	Megawatt
TWh	Terawatt-hour
MWh	Megawatt-hour
kWh	Kilowatt-hour
W/m^2	Watt per square meter
m/s	meter per second
IEC	International Electrotechnical Commission

LIST OF PUBLICATIONS

1. Ismail Kamdar, Shahid Ali, Juntakan Taweekun*, Hafiz Muhammad Ali (2021). Wind Farm Site Selection Using WAsP Tool for Application in the Tropical Region. Sustainability. (Impact Factor 3.251; ISI Web of Science: SCIE). https://doi.org/10.3390/su132413718
2. Ismail Kamdar, Juntakan Taweekun* (2022). A Comparative Study of Wind Characteristics Between South-western and South-eastern Thailand Using Different Wind Turbine Models. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences. https://doi.org/10.37934/arfmts.92.1.149161
3. Ismail Kamdar, Juntakan Taweekun* (2021). Assessment of Wind Energy Potential of Hat Yai (Songkhla), Thailand. IOP Conference Series: Materials Science and Engineering. DOI:10.1088/1757-899X/1163/1/012001

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CHAPTER 1

INTRODUCTION

1.1. Background

Energy has a leading impact in the advancement of any nation. The prosperity of a nation largely depends on its stability of energy use [1]. Global renewable energy exploitation has increased over times, due to the urgency to meet global climate commitments that discourage the use of fossil fuels as energy sources [2, 3]. Recently, wind power has evolved to a dominant sustainable energy option to mitigate energy effects on anthropogenic pollutants in the atmosphere [4, 5]. Wind energy is also replenishable on human timescale and is a cost-effective energy option in the long run. Because of these advantages, wind energy is frequently discussed and deployed by various nations [6]. A glimpse of the energy statistics reveals that the global installed wind-generation capacity reached 651 GW in 2019 [4], and even during the pandemic significant growth was noted in the wind energy production capacity worldwide: it is expected to reach 817 GW before the year 2021 ends [7].

In recent decades, the demand of energy has increased globally as a result of growing population and socio-economic progress. The overall energy consumption will rise up to 6% globally during 2010-2040 as reported by the International Energy Outlook (IEO). Negative impacts of greenhouse gas (GHG) on environment and security of energy supplies have made the government organizations to increase the exploitation of various sources of renewables. Wind energy is one of the clean and inexhaustible sources of renewables and it can be utilized for the generation of electricity by means of wind turbines [8, 9].

Thailand is situated near the equator. It has relatively low to moderate wind speeds that average about 3 to 5 m/s. However, there are areas with appropriate topography, such as canyons, slopes and mountain ranges, which have higher wind speeds and a utilizable annual mean wind speed of no less than 6.4 m/s [10]. The time patterns of surface wind direction are characterized by the monsoon system. Thailand has two types of monsoons namely the southwest and the northeast monsoon that affect Thailand annually. The southwest monsoon generally runs between May and October bringing warm and moist air from the Indian Ocean, causing strong winds at mountain ridges in the northern lowlands and southern uplands of Thailand. The northeast monsoon runs from November to March bringing cold and dry air from the South China Sea, which causes extreme winds in the Gulf of Thailand and coastal parts of southern peninsular Thailand. On average the temperature in southern Thailand is high. In 2018, the minimum monthly mean temperature recorded for January was 26.4°C and the maximum mean temperature recorded for May was 28.5°C in southern Thailand [11]. Thus, this high temperature generally substantiates the need for inspection of southern Thailand for energy purposes.

The current total installed electricity generation capacity of Thailand is almost 46,682 MW, to which around 5,720 MW is imported [12]. Under the Alternative Energy Development Plan (AEDP), the Ministry of Energy, Thailand, has set a target of wind power generation to be 3002 MW by 2036 [13]. A feed-in-tariff (FIT) financial support scheme is introduced in order to promote wind power in the country to ensure wind power projects viability in areas with moderate wind resources. Moreover, in special area like remote areas and islands, where diesel power plants are operating, as well as in the southern Thailand, a premium FIT financial incentive is used to attract investment in wind power projects. The current FIT and FIT premiums are 6.06 and 0.5 Baht/kWh for wind power, respectively.

Currently the total wind power installed capacity in Thailand is around 754 MW which is mainly distributed in the northern, the northeastern, and the southern parts of Thailand [13]. The range of wind power plants is from 6.9 MW to 103.5 MW whereas the current largest wind turbines in nominal capacity is 2.5 MW in Thailand. Wind is caused by unequal heating of the earth’s surface which occurs due to the pressure gradients that arise from the temperature differences. The general macroscale circulation results in the doldrums, situated in regions close to the Equator. Doldrums are characterized by calm prevailing winds and frequent showers, thunderstorms, as well as heavy rainfalls. The southernmost parts of Thailand are situated between 5.5 ^{o}N and 7.0 ^{o}N in the northern hemisphere which is characterized by wind speed of 8 m/s in the monsoon periods to a comforting breeze of 3 m/s at other periods of the year [14].

Wind resource assessment has a significant importance to the exploitation and consumption of wind energy. A precise evaluation of wind resources is crucial to the successful development of wind farms. Therefore, to improve the wind potential use, it is significant for a given site to ensure the effectiveness of assessment.

To simplify mathematical models according to diverse assumptions, commercial companies have developed various software packages. In particular, Wind atlas analysis and application program (WAsP) designed by the Danish Riso National Laboratory (DRNL) has emerged as a convenient instrument for wind resource assessment [15]. WAsP is a computer-based industrial standard tool used all over the world for wind energy evaluation, site selection and energy yield calculations for wind energy facilities in various terrains. WAsP program has typically shown errors of less than 10% [16, 17] and provides satisfactory results even with wind data from a single meteorological station [16].

1.2. Statement of problem

Being a fast-emerging economy, Thailand's primarily consumes from fossil fuels for its energy. Worldwide, Thailand ranks 20^{th} in energy intensity and 34^{th} in emissions intensity (carbon intensity). Regarding electricity generation, natural gas-fired power plants produced about 57% of electricity, while coal and lignite-based power plants accounted for about 18% of the total supply in 2018 [18]. It is clear that conventional energy sources such as natural gas, hard coal and lignite are still the dominant sources of energy in electricity generation. In 2012, the total installed electricity generating capacity in Thailand was recorded as 32,600 MW [19, 20] and it had increased to 45,298 MW in 2019 [21], with 75% being generated from natural gas, coal and lignite. Thailand's Ministry of Energy has forecast in the power development plan for 2018-2037 (PDP 2018: Revision 1) that the total installed electricity generating capacity will reach 77,211 MW at the end of 2037. The objective of Ministry of Energy Thailand is to replace non-renewable energy sources by renewable energy by up to 37%, by the end of 2037 under PDP 2018-2037 [22]. Hence, this objective clearly describes the renewable energy roadmap in Thailand under PDP 2018-2037, to which all energy-related departments are determined [22-25].

Southern parts of Thailand have an increasing trend in power demand by 5-6% yearly due to developments in service and tourism fields, as reported in the year 2018 by the Electricity Generating Authority of Thailand [26]. Consequently, government organizations and wind power developers are continuously seeking the best locations for wind resource assessment. Though feasibility studies [19, 20, 27-30] have been conducted on wind resources for few provinces in southern Thailand in the past, still a detailed study scrutinizing wind resource assessments with a view to investigate potential areas for siting small-scale wind turbines is lacking. It is significant to evaluate the wind energy potential technically by knowing the characteristics of wind in order to estimate the annual electricity production at potential locations [31]. It provides a pathway for wind energy practitioners with the necessary confidence to study their options to confront the increasing energy demands and mitigating risks [32, 33].

1.3. Research objectives

The objective of our study has been described below;

1) To preprocess the raw wind data using WAsP simulation.
2) To analyze the mean wind speed, power density, annual energy production and capacity factor using the available wind turbine models.
3) To estimate the levelized cost of energy (LCOE).

1.4. Research gap

According to the authors' knowledge, there is a gap in the literature, in exploring wind resource assessments for siting small-scale wind turbines using the WAsP tool in the study region, i.e., in southern Thailand. Furthermore, most prior studies are somewhat obsolete due to growing industrialization and demographic changes that have affected land availability.

1.5. Research scope

The aim of this study is to find the appropriate locations for the development of wind farms in future. Though feasibility studies [19, 20, 27-30] have been conducted on wind resources for few provinces in southern Thailand in the past, still a detailed study scrutinizing wind resource assessments with a view to investigate potential areas for siting small-scale wind turbines is lacking. The differences between our study and previous studies are the simulation model, turbine technology, height of wind resource assessment at which it is analysed, its geographical position and duration of wind data. Therefore, the purpose of the present study is to overcome the limitations of previous studies. The findings of this study on practical grounds can diminish the dependence on fossil fuels by using clean and eco-friendly renewable energy source.

1.6. Research significance

This study will allow the regional energy practitioners to figure out their choices to tackle the rising power demands, increasing by 5-6% annually, through renewable wind power. Moreover, this study will also contribute to AEDP Thailand whose objective is to substitute fossil fuels by up to 37% by year 2037 under PDP (2018-2037) national plan.

CHAPTER 2

LITERATURE REVIEWS

2.1. Renewables global status

Energy plays an important role in daily life services such as warming, cooking, manufacturing and transportation. Besides, energy sources have serious impact on strategic policies of countries. Various energy sources (fuel oil, natural gas, wind energy, and solar energy etc.) are being used at present time to provide these services. However, it is significant to get energy from the sources that are safe, reliable and environmentally friendly.

Over the last two decades, the importance of renewable energy sources has grown up. Growing environmental concerns and sustainability issues has compelled various countries around the world to replace conventional energy sources such as fuel oil, coal and natural gas with renewable energy sources such as wind, solar and geothermal [34]. Carbon dioxide (CO_2) emissions are the main environmental concerns related to conventional energy utilization. Fuel combustion increased CO_2 emissions from 20,518 megatonnes (Mt) in 1990 to 32,316 Mt in 2016; this means that CO_2 emissions from fuel combustion grew 57.5% during 1990–2016 [35].

Furthermore, energy supply and demand substantially increased over the world which has drawn more attention towards sustainability issues. Throughout the world, the total primary energy supply has increased from 367,325 Petajoules (PJ) to 576,104 PJ between 1990 and 2016; this means that 56.9% growth has been noticed in the total primary energy supply over 1990-2016 [36]. Similarly, the total final energy consumption increased from 262,554 PJ in 1990 to 400, 062 PJ in 2016; in other words, total energy consumption increased 52.3% over 1990-2016 [37]. Thus, it is essential to exploit energy sources which are reliable, environmentally friendly and sustainable such as renewable energy sources. Exploiting renewable energy sources provide opportunities to alleviate concerns likewise greenhouse gas emissions (GHG), reduce environmental effects and secondary waste, diversify energy supply and ensure sustainability [38]. As reported by the British Petroleum (BP) in its annual report that the fastest growing and five times greater source of energy by 2040 will be renewables which will hold a share of about 14% of the primary energy throughout the world [39]. Also, it is expected that two-third of the global investments in power plants to 2040 will be captured by the renewables [40], as shown in Fig. 2.1.

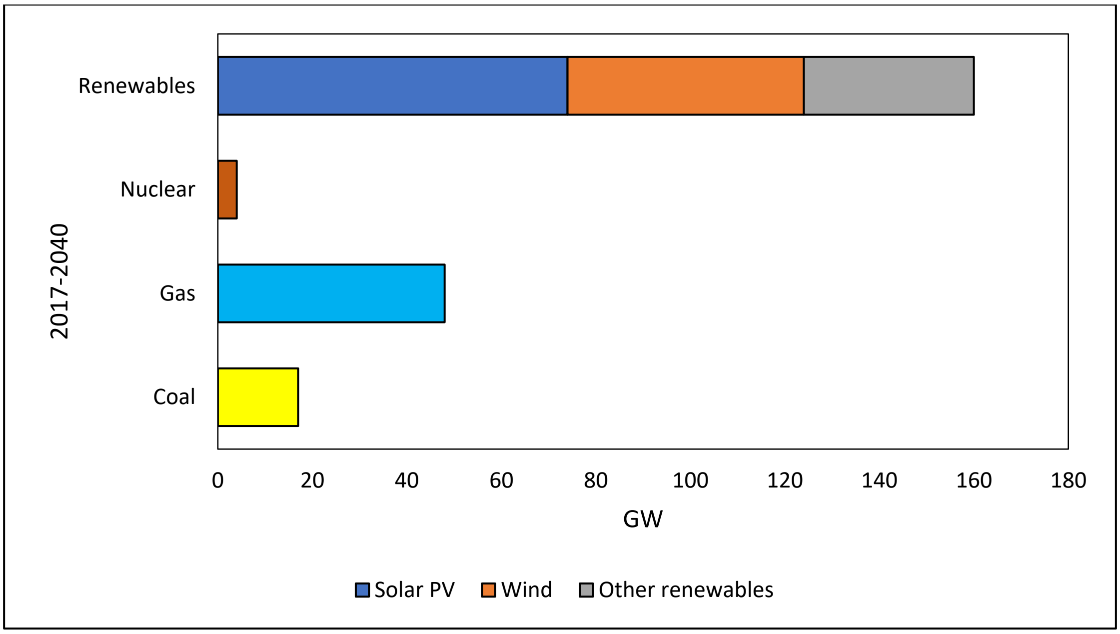


Fig. 2. 1 Global average annual net capacity additions by fuel type from 2017 to 2040 [40].

Due to industrial and economic development, the electricity demand has been significantly increased throughout the world. The world economic growth was estimated at 3.7% in year 2018. In the same period, the global electricity demand grew by 4%, or 900 Terawatt-hour (TWh). Since 2010, it has been noticed the fastest growth when the global economy recovered from the financial crisis of 2007-2008. Similarly, the global total electricity consumption in 2017 reached to 21,372 TWh, 2.6% higher than 2016. The total electricity consumption in Organization for Economic Co-operation and Development (OECD) member countries was 9,518 TWh in 2017, 0.2% higher than in 2016, whereas, the total electricity consumption in non-OECD countries was 11,854 TWh, an increase of 4.6% from 2016. It is expected that the global energy consumption in Non-OECD and OECD countries would be 68%

and 6% higher than today by 2030, respectively. Thus, an environmentally friendly, sustainable and low-cost energy would be required to cope with this growing energy demand challenges in future.

2.2. Wind energy global status

China is leading in case of wind power installed capacity and has increased its wind power from 300 MW in 2000 to 278,324 MW in 2020 and holds 39% of the total wind power capacity globally [41]. Table 2.1 presents the top 10 countries cumulative installed capacity of wind energy. Fig. 2.2 shows the global cumulative wind power capacity from 2017 to 2020.

Table 2. 1 Cumulative installed wind capacity of top 10 countries [41].

S.No.	Country	MW (2017)	MW (2018)	MW (2019)	MW (2020)	% Share
1	PR China	188,232	205,804	229,564	278,324	39
2	USA	89,077	96,488	105,436	122,275	17
3	Germany	50,779	52,932	53,913	55,122	8
4	India	32,938	35,129	37,506	38,625	5
5	Spain	23,170	23,433	25,683	27,494	4
6	France	13,757	15,307	16,643	17,946	3
7	Brazil	12,769	14,707	15,452	17,750	3
8	UK	12,412	13,001	13,617	13,731	2
9	Canada	12,240	12,816	13,413	13,577	2
10	Italy	9780	10310	10760	10810	1

In wind energy installation about 84% share comes from the top ten leading countries while rest of the countries contribute only 16%. In 2020, the Asian-Pacific wind market continued to lead with 336,286 MW, followed by Europe with 194,075 MW, where the leading country is Germany with addition of 55,122 MW while USA leads with 122,275 MW in North America. Brazil continues to the promising market with 17,750 MW in South America. Similarly, South Africa is leading in cumulative installed capacity with 2,465 MW in African region while Egypt with 1,465 MW in Middle-East [41].

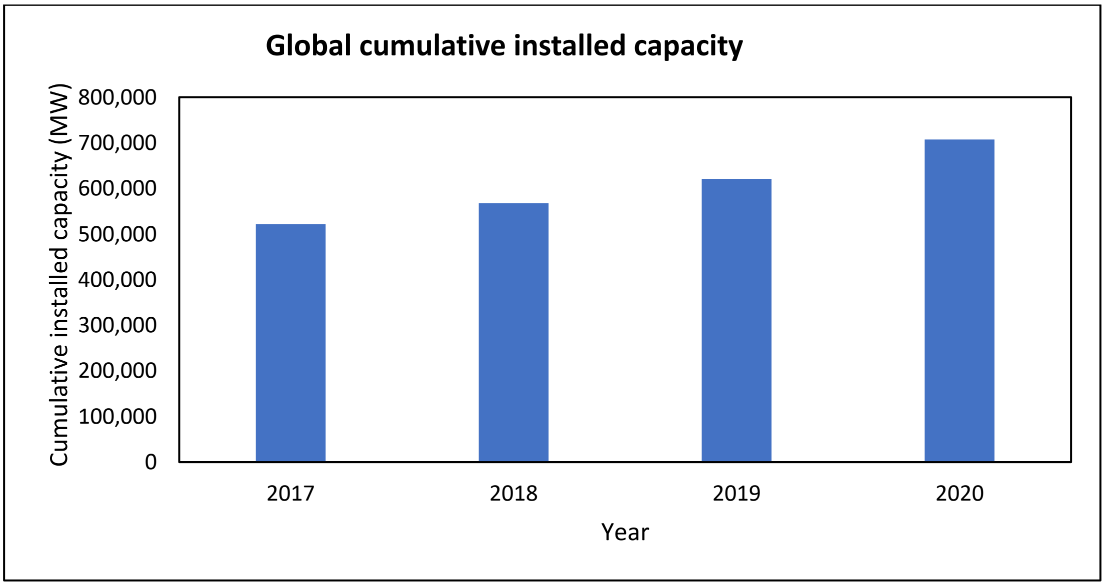


Fig. 2. 2 Global cumulative installed wind capacity from 2017 to 2020 [41].

2.3. Thailand wind energy status

In 1983, Thailand started to exploit its wind energy by installing several small wind turbines ranging from 1 kW to 150 kW at Phuket Island. Due to relatively low wind speed, the growth rate was at modest level especially in the areas close to transmission grids. Thailand has technical wind energy potential of about 17 GW if modern low-speed wind turbines are used but only one-third of this potential can be utilized if conventional wind turbines are adopted instead [42]. Thailand installed about 1500 MW of the total capacity of wind energy in 2020 which has been found a significant increase as compare to 2010 where the total capacity of wind energy was only 6 MW. The total wind energy capacity in Thailand during the past decade is shown in Fig. 2.3.

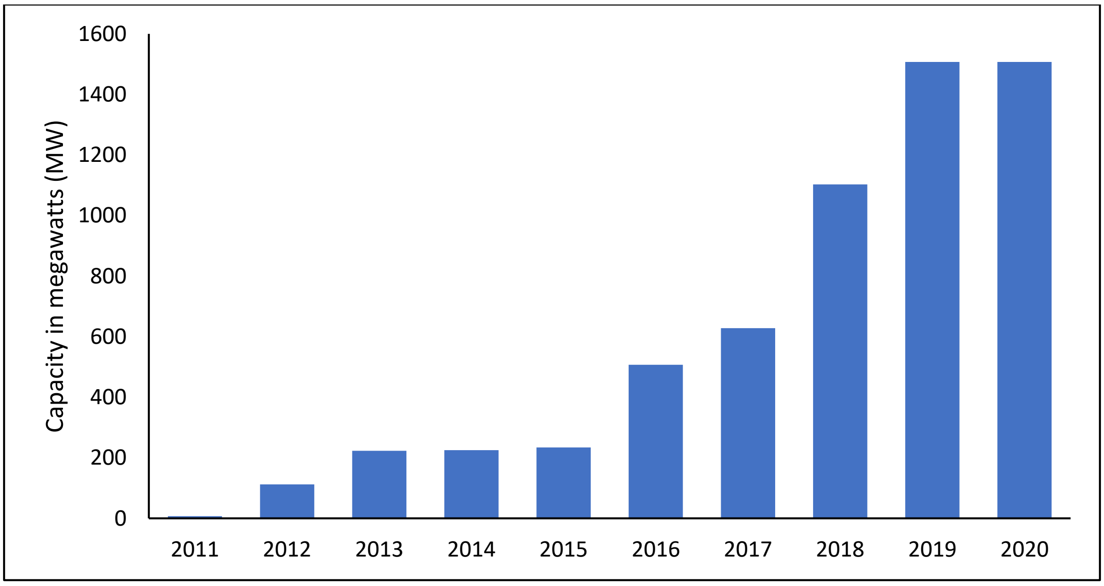


Fig. 2. 3 Total wind energy capacity in Thailand from 2011 to 2020 [43].

2.4. Wind energy: The renewable with the smallest footprint?

It is significant to know that wind energy development has potential impacts on biodiversity. For instance, establishing wind farms can affect the quality of habitat, elevate the risk of fire and attract predators [44]. One of the greatest threats by wind power is the collision of birds and bats with turbine. The highest collision rates are found along forested ridgelines; hence, turbine siting is very important [45, 46]. In year 2012, around 600000 to 888000 bats [47, 48] and 573000 birds that includes 83000 raptors [48] were killed by wind turbines in USA.

It has been observed that about half (46.4%) of all bird collisions in the USA occurs in California, which the most wind turbines found. A review across North America determined that the mortality rates of birds or bats is not affected by the rotor diameter, but in fact the mortality among bats increased because of the greater tower height – especially when it exceeded 65 m [49].

Wind farms can also impact migrating bird populations and resident [50]. This happened to the displacement of some grassland bird species in North and South Dakota due to three wind farms [51]. Wind farms has impacts on both local and distant populations. In eastern Germany wind turbines killed 28% noctule bats that migrated from distant parts of Europe [52].

Wild life can also be affected from wind farm noise. Mammals, reptiles, birds, and amphibians in Portugal has reduced species richness at wind farms [53], possibly also because of cascading effects caused by wind turbines.

Local temperatures can also rise due to wind farms. In Scotland, active wind farms increased 0.18 ºC air temperature and 0.03 g/m3 absolute humidity during the night [54]. It was noticed wind farms located Texas increased the local temperature by 0.72 ºC per decade relative to nearby control sites, based on satellite data [55]. The reason behind this increase in temperature is unknown but might have additional consequences for biodiversity.

2.5. Advantages of wind power

- In case of wind energy there is no dependence on any country as it is easily available around the world for wind energy production.
- With the help of wind energy, the economies of rural populations can be strengthened because wind turbines are normally installed in rural areas and diversify rural economies by providing new types of income.
- In case of wind energy there is no need to use fossil fuel unlike other types of electrical generation when producing energy from wind turbines.
- In case of fossil fuels, the electricity prices vary significantly due to cost of transportation and mining whereas wind energy does not include these costs because it is always available and free.
- Various new short- and long-term jobs are created from wind energy projects for both industry and rural communities in the area of project construction, manufacturing and transportation.
- Wind energy does not utilize fossil fuel as an energy source since it does not pollute the air. Other sources of electricity generation emit poisonous gases that contribute to global climate change while wind energy is free of pollution.

- In case of wind energy land and environment can be preserved because agriculture and animal husbandry can be transferred to nearby areas during installation of the wind turbines.

2.6. Wind resource assessment

Wind resource assessment has a significant importance to the exploitation and consumption of wind energy. A precise evaluation of wind resources is crucial to the successful development of wind farms. Therefore, to improve the wind potential use, it is significant for a given site to ensure the effectiveness of assessment. In the recent past, globally a significant number of scientific studies have been conducted extensively on wind energy.

An overview of some of the important investigations is discussed for a better understanding of the so far accomplished work such as Computational Fluid Dynamics (CFD) simulations has been used in complex mountainous areas of north-eastern Iberian Peninsula, Spain, that showed reasonably high-speed and low-turbulence winds for turbines at the most suitable locations [56]. An evaluation of wind energy potential for small-scale wind turbines has been conducted at hub heights of 10 m and 30 m in the regions of Ontario and Great lakes in Canada [57]. Statistical models such as Weibull and Rayleigh distributions has been used to determine the annual energy density, annual energy production (AEP) and capacity factor in Weno Island, Chuuk State, Micronesia [58]. CFD, WAsP and wind-tunnel testing has been applied in New Zealand's installed infrastructure to improve wind speed forecasting methods for the wind pattern over complex terrain [59]. Potential of wind energy and power law indexes assessment has been investigated for Kudat, Mersing, Kijal, and Langkawi stations in Malaysia. They analyzed that Kudat and Mersing stations show great potential for wind turbines at medium scale while the remaining sites may be suitable for wind turbines at small scale [60].

Similarly, the maximum potential installed wind capacity has been determined in the Caribbean Island of Barbados [61]. Bruck *et al.,* established an innovative cost model to estimate the LCOE obtained by a wind energy source under a Power Purchase Agreement [62]. An artificial intelligence-based optimization technique along with a statistical approach has been used to determine the Weibull parameters and performed technical and economic analyses, such as LCOE, for wind energy at eighteen locations in Pakistan [1]. The Weibull parameters have been analyzed in terms of seasonal and yearly wind speed at 12 m height in the coastal parts of Ghana. They observed that annual wind speed values ranging between 3.88-5.30 m/s and determined that wind turbines which have cut-in speed below 3 m/s and rated wind speed value ranging from 9 to 11 m/s are appropriate for wind farm [63]. Wind resource assessment has been inspected in Cyprus using the Weibull distribution and WAsP. They examined WAsP model more efficient compared to other methods [64]. An inclusive study has been performed regarding wind statistics along with wind power potential at four localities in China [65]. Promsen *et al.,* [66] and Nouri *et al.,* [67] identified optimal sites for wind turbine installation by using short term wind statistics and WAsP model. Boudi and Guerri [68] scrutinized the potential of wind power by utilizing the Wind Atlas Analysis and Application Program (WAsP) at three sites in the north-west coast of Algeria. They evaluated wind speed, AEP and estimated the cost for particular sites using different wind turbine models. Mohammadi *et al.,* [69] used different approaches to measure the Weibull parameters and analyse daily power density in the south part of Alberta, Canada.

Furthermore, wind resource assessment has been studied using WAsP in the southern island of Fiji. They estimated an AEP from 400 MWh to 500 MWh for Suva and 650 MWh for Kadavu [70]. WAsP has been utilized for thirty localities and identified Rakiraki, Nabouwalu and Udu best locations for development of utility scale wind farms in Fiji. They used the turbine model Vergnet with a rated power of 275-kW for AEP calculations as these turbines have been proven secured in extreme weather conditions such as tropical cyclones [71]. Reanalysis data and statistical methods have been used for preliminary wind resource assessment in South Sudan. They analyzed that average wind speed values vary between 5.08 m/s and 2.36 m/s whereas wind power density varies between 128.36 W/m^2 and 14.39 W/m^2 and explored the possibility of development of small wind turbines for electricity generation [72]. Potential of wind energy in eight localities has been studied in the Republic of Djibouti. They investigated the interannual variability of wind by using CFSR and ERA5 models and examined the feasibility of three wind farms of 275 MW through WindPRO program. The results show that 1073 GWh/year of electricity will be generated from the proposed wind farm and the estimated cost of electricity will be in the range of 7.03 US. $ cent/kWh to 9.67 US. $ cent/kWh [73]. Wind energy potential has been investigated using at Tarawa and Abaiang atolls of Kiribati. They analyzed the average wind speed and dominant direction of both sites. The Weibull parameters were estimated using seven different approaches and estimated annual energy production and payback period that showed encouraging results [74]. Mesoscale (WRF) and microscale (WAsP) models have been used for a case study at three sites in the state of Tabasco, Mexico. They calculated the LCOE, the capacity factor, cost of wind turbines and discount rate [75].

CHAPTER 3

MATERIAL AND METHODS

3.1. Study area

Southern Thailand is located on Malay Peninsula, covering an area of about 70,714 km^2 and has a population of more than 9.4 million people. Southern parts of Thailand have shown an increasing trend in power demand by 5–6% yearly due to developments in service and tourism fields, as reported in 2018 by the Electricity Generating Authority of Thailand [26]. It is one of the most electricity–demanding regions in Thailand as a gateway to the Malaysian border in the south, and hence it receives thousands of tourists each year. This emphasis the need of new energy resources that has least environmental effects such as wind energy. Previous studies have shown the highest wind energy potential in southern Thailand. However, most prior studies are somewhat obsolete due to growing industrialization and demographic changes that have affected land availability.

Royal Thai Navy introduced the science of Meteorology to Thailand in 1905. Later, Meteorological and Statistics Section was set up in 1923 under the Ministry of Lands and Agriculture for collection of meteorological data at various observation stations. In August 1936, the Meteorological and Statistics Section was transferred to the Hydrographic Department where it was known as the Meteorological Division. On 23rd June, 1942, the Meteorological was given the status of department which is known as Thai Meteorological Department (TMD). The headquarter of TMD is located in Bangkok which is responsible for weather forecasting and monitoring. It has 4 meteorological centers namely Northern Meteorological Center, Northeastern Meteorological Center, Southern Meteorological Center (west coast) and Southern Meteorological Center (east coast). Fig. 3.1 displays the geographical locations of meteorological stations in the southern region of Thailand.

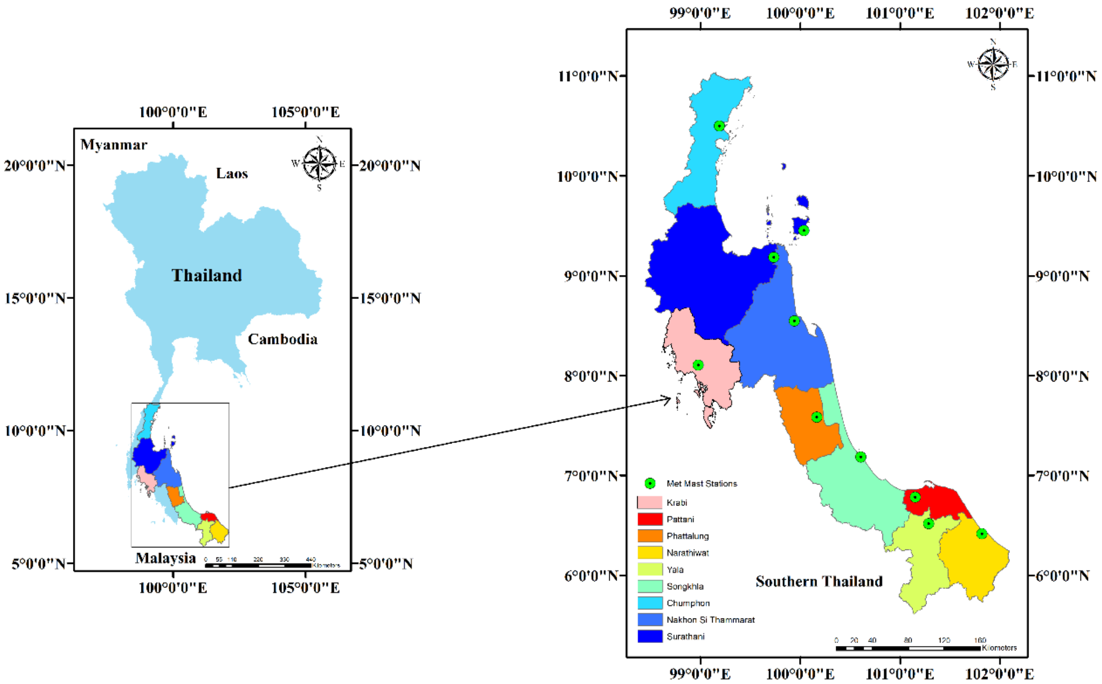


Fig. 3. 1 Study area and distribution of meteorological stations in southern Thailand.

3.2. Overview of methodology

The flow diagram in Fig. 3.2 shows the proposed scheme for siting small-scale wind turbines. The first step as expected is the analysis of raw wind data obtained from Thai Meteorological Department (TMD). In the second step, WAsP Climate Analyst tool is used to generate an estimate of wind climatology for all ten stations. It uses 10-min average wind speed recorded at 10 m above the ground level (AGL). WAsP Climate Analyst estimates wind climatology in the form of a wind rose and a Weibull distribution function. In third step the coordinates and topographic information are entered to the WAsP Map Editor tool to create the surface roughness and contour maps for the ten stations. The fourth step mainly involves the use of WAsP module in terms of mean wind speed, power density and AEP using the different wind turbine models to conduct power analysis for the selected sites. The fifth and final step is the estimation of levelized cost of energy.

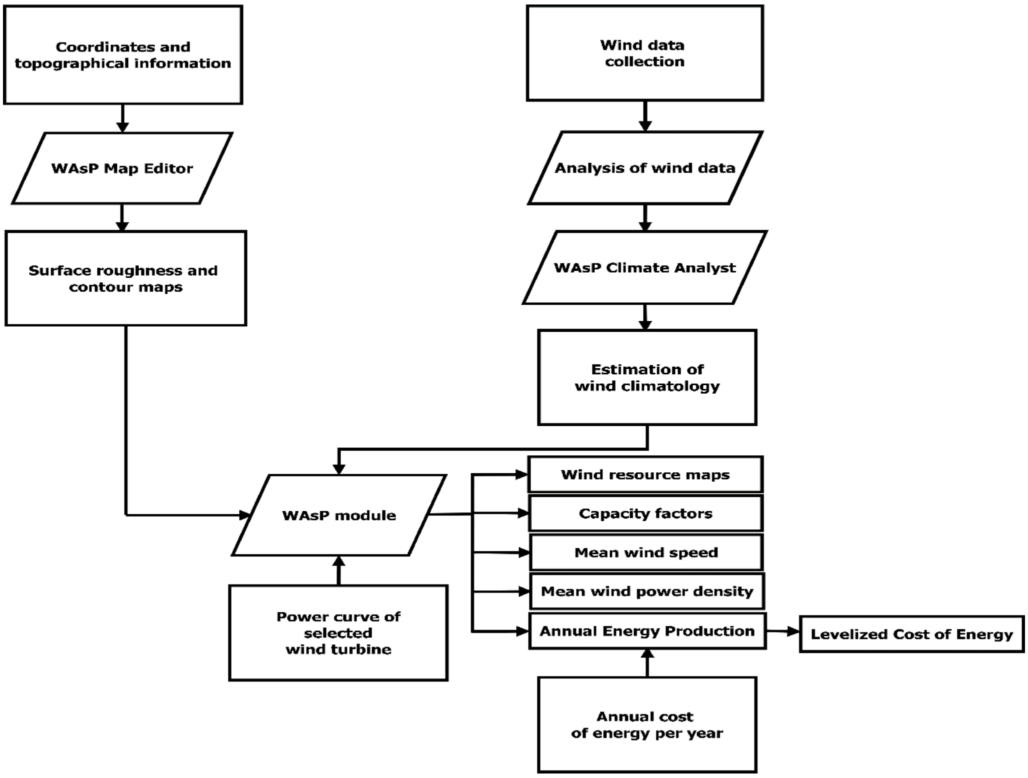


Fig. 3. 2 Flow diagram of the proposed scheme.

3.3. Meteorological mast and wind data preparation

The measurement towers in the Southern Meteorological Center carry meteorological instruments such as anemometers, wind vanes, barometers, thermometers, rain gauges and hygrometers. Along with these, the observation items comprise 10-min average wind speed and wind direction, temperature, rainfall, atmospheric pressure, and relative humidity, which are mainly considered over an international standard period for wind measurement [76]. A description of the various measuring tools is provided in Table 3.1.

Table 3. 1 Tool specifications [77].

Equipment	Sensor type	Instrument range	Accuracy	Height (AGL)
Anemometer	Ultrasonic sensor	0-75 m/s	±2%	10 m
Wind vane	Ultrasonic sensor	0-360°	±2%	
Thermometer	Platinum resistance element	-40 °C to 50 °C	±0.3 °C	
Barometer	Digital	800-1100 hPa	±0.2	
Relative humidity	Thin film	0-100% RH	±2% RH	
Rain gauge	Tumbling cup	0-100 mm/h	2%	

At a minimum, one year of observation data is essential to review the development possibility and to measure the potential wind energy reserve amount [58]. To avoid seasonal bias, this study observed the wind data of ten weather stations located in southern Thailand, at a standard height of 10 m AGL, over a period of 3 to 4 years. The geographical coordinates and measurement periods can be seen in Table 3.2.

Table 3. 2 Description of measurement sites in southern Thailand [78].

Station name	Latitude (°)	Longitude (°)	Altitude (m a.s.l.)	Measurement period	Recovery
Chumphon	10.49	99.18	22	2017-2019	99.24%
Kanchanadit	9.18	99.73	27	2017-2019	98.05%
Koh Samui	9.45	100.03	6	2017-2019	99.06%
Nakhon Si Thammarat	8.54	99.93	5	2017-2019	99.28%
Narathiwat	6.41	101.81	5.13	2017-2019	98.97%
Pattani	6.78	101.15	6	2017-2019	82.55%
Phatthalung	7.58	100.16	4.15	2017-2019	97.05%
Songkhla	7.18	100.60	6	2017-2019	98.94%
Yala	6.51	101.28	36.04	2017-2019	97.13%
Krabi	8.103	98.975	30	2017-2020	93.87%

Note: a.s.l.: above sea level.

This study utilized the raw wind data of ten meteorological stations that we obtained from the online portal (https://www.tmd.go.th/en/) of TMD in separate excel sheets for a period of 3 to 4 years. We used a Python programming language tool. To arrange the multiple data files of each station into a single data file, we imported the files from PC into a single data frame pandas which is a Python library. Then, we selected the wind speed and wind direction data columns and rows while discarded the other data values. Subsequently, we arranged the data of each station into a single text file format.

3.4. The Weibull distribution

Wind speed is the basic factor that must be measured while selecting and designing the wind farm. Its Weibull probability distribution function (PDF) significantly influences the wind turbine performance [79].

The two-parameter Weibull probability distribution is frequently used in calculations to describe the wind speed histogram. It is also utilized in WAsP to study the wind characteristics in every direction as characterized by sectors [80]. Whereas the probability distribution function PDF of a Weibull distribution is defined by Equation (1) [76, 81] :

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

Here, $f(U)$ represents the Weibull probability density function of observing wind speed U (m/s), A defines the Weibull scale parameter in m/s while k indicates the dimensionless Weibull shape parameter. The Weibull shape parameter k takes values between 1 and 3 and describes the behavior of wind in accordance with its speed and shows variations of wind variables as k is small, while large values of k indicate a rather constant wind speed [76, 80].

Then, the corresponding cumulative probability function for the Weibull distribution is expressed in Equation (2) [82]:

$$F(U) = 1 - e^{-\left(\frac{U}{A}\right)^{k}} \tag{2}$$

where $F(U)$ defines the cumulative distribution function of observing wind speed U. The cumulative distribution is the integral of the density or PDF with respect to speed [76].

3.5. Wind Atlas Analysis and Application Program

WAsP is a well-established industrial standard as a computer-based program and has been created by the Department of Wind Energy at the Danish Technical University in 1987 [83]. It is a widely used tool for projects related to wind energy and wind engineering [59] in wind resource evaluation, energy yield calculations, and site selection of wind energy facility.

WAsP uses a linear model composed of a comprehensive collection of individual modules according to the physical characteristics of flows in the planetary boundary layer to predict vertical and horizontal extrapolation of wind [84]. The WAsP flow model requires as inputs: (1) terrain height, (2) surface roughness, and (3) obstacle effects as can be seen in Fig. 3.3, which is also known as the wind atlas methodology. WAsP model can calculate the energy production of a single turbine site or of a wind farm, and considers wake losses, layout, and various other factors. The wind atlas provides a hypothetical wind climate for a featureless and preferably planar topography with an even land cover in case the entire computational domain is under one and the same weather regime [80]. Using wind measurements in actual terrain to study the wind atlas of the region, the WAsP flow model is applied in order to eliminate the regional terrain effects as expressed in Equation (3):

$$W_R = W_A - ORO_A - ROU_A - OBS_A \tag{3}$$

Here, W_R represents the general regional wind climate, W_A defines the recorded wind at the measuring mast, while ORO_A, ROU_A and OBS_A indicate the properties of orography, roughness and obstacles at position A, respectively. The orographic effects on the flow are calculated using spectral BZ (Bessel Expansion on a Zooming Grid) model in WAsP, which is basically based on the Jackson-Hunt theory. Thus, the WAsP model is primarily in the family of the Jackson-Hunt theory [85]. The internal boundary layer height (h) created under influence of variations in surface roughness from z'_{01} to z'_{02} in the windward direction is calculated through the roughness model in WAsP by Equation (4):

$$\frac{h}{z'_0} ln\left(\frac{h}{z'_0} - 1\right) = 0 \cdot 9 \frac{x}{z'_0} \tag{4}$$

where x shows distance to the surface roughness change line and z'_0 is equal to max (z'_{01}, z'_{02}). This study used the newest version of WAsP software, namely WAsP 12 (Version 12.06.0024), WAsP Climate Analyst (Version 3.01.0049), and WAsP Map Editor (Version 12.3.1.54).

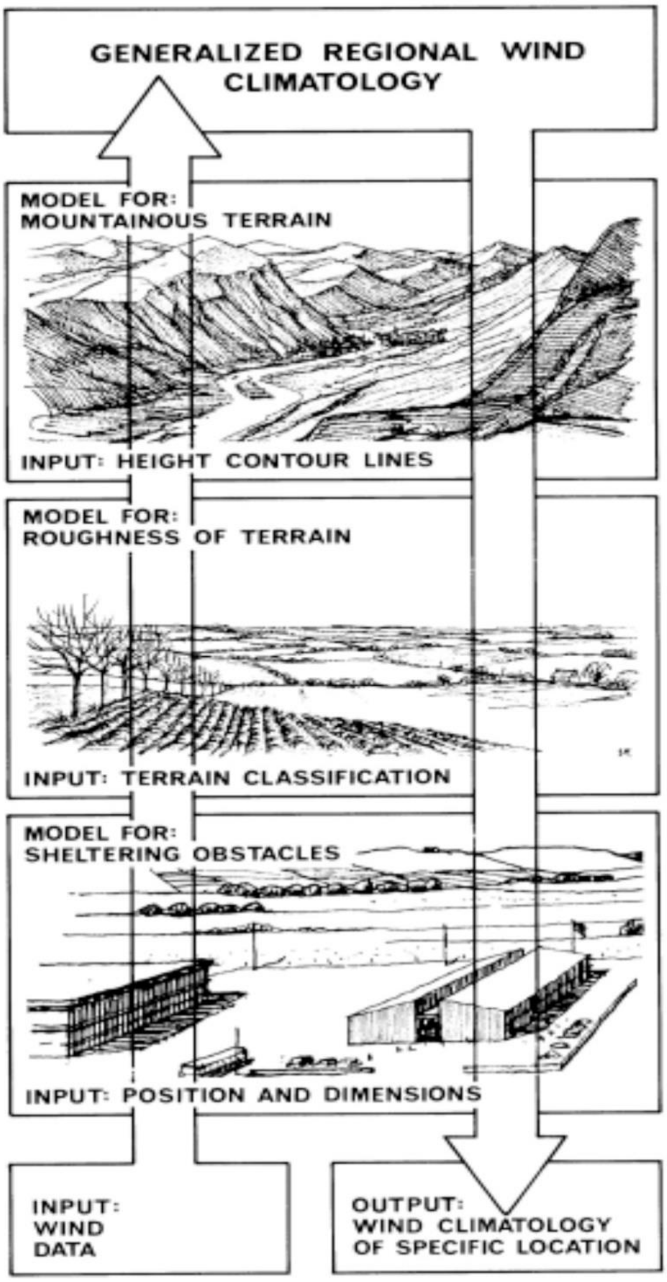
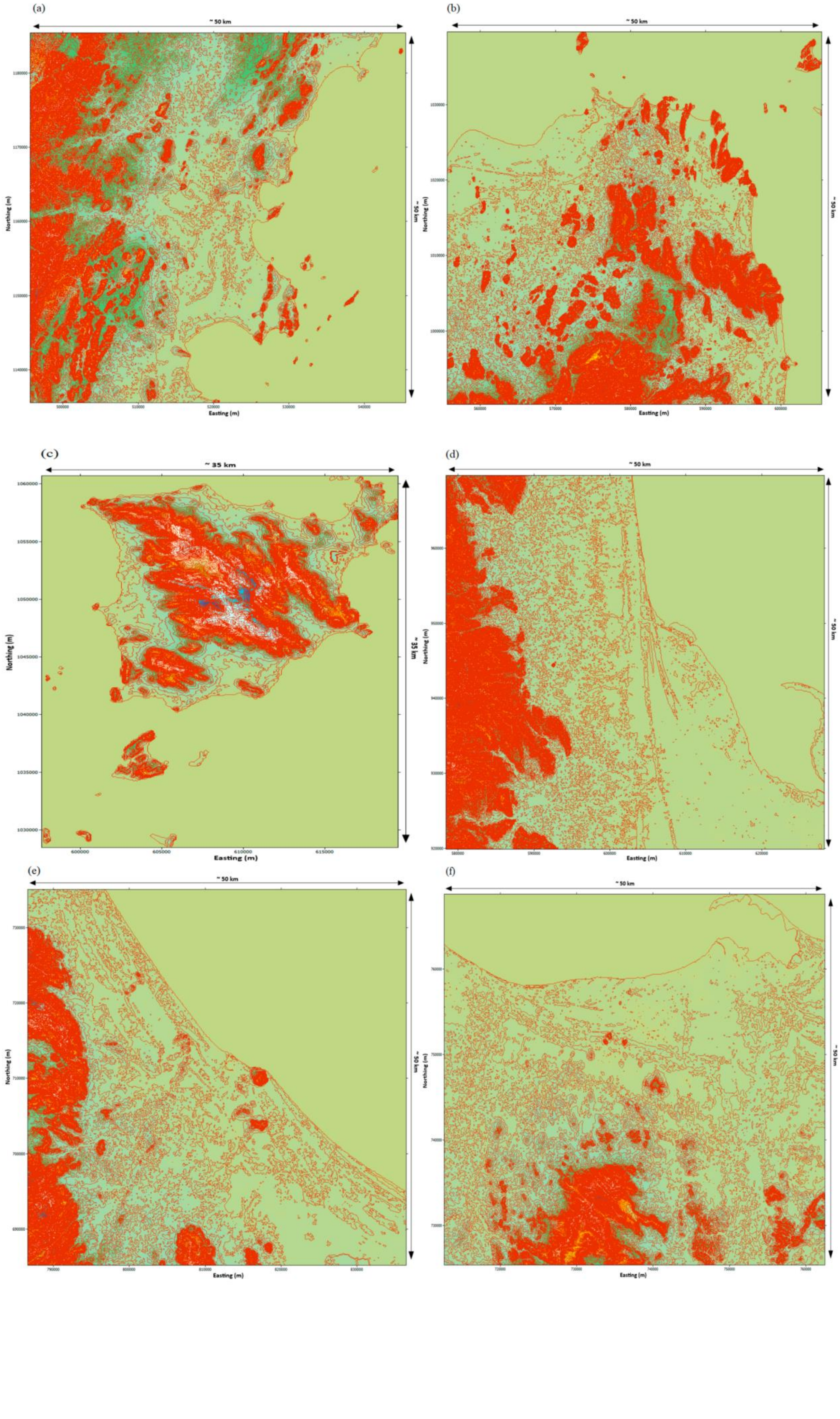


Fig. 3. 3 The wind atlas methodology with inputs and outputs. Regional wind climatology is studied to predict the wind climate and resources at specific location by using the wind data from a meteorological model [86].

3.6. Surface elevation and roughness maps

The elevation and roughness maps of southern Thailand are important inputs to the WAsP tool. Therefore, the WAsP Map Editor tool in WAsP program was used to prepare elevation and roughness maps. The Universal Transverse Mercator coordinate system, Zone 47 along with the datum WGS-1984, was used for the mapping. The maps are Digital Elevation Model (DEM) developed under the Global Wind Atlas (GWA) Warehouse map server which uses the Shuttle Radar Topography Mission (SRTM) data and the Viewfinder for regions outside SRTM coverage. The elevation maps of the study area are presented in Fig. 3.4, which has a horizontal resolution of 3 arc-seconds (approximately 90 m).


(a)
~ 50 km
Northing (m)
Easting (m)
(b)
~ 50 km
Northing (m)
Easting (m)
(c)
~ 35 km
Northing (m)
Easting (m)
(d)
~ 50 km
Northing (m)
Easting (m)
(e)
~ 50 km
Northing (m)
Easting (m)
(f)
~ 50 km
Northing (m)
Easting (m)

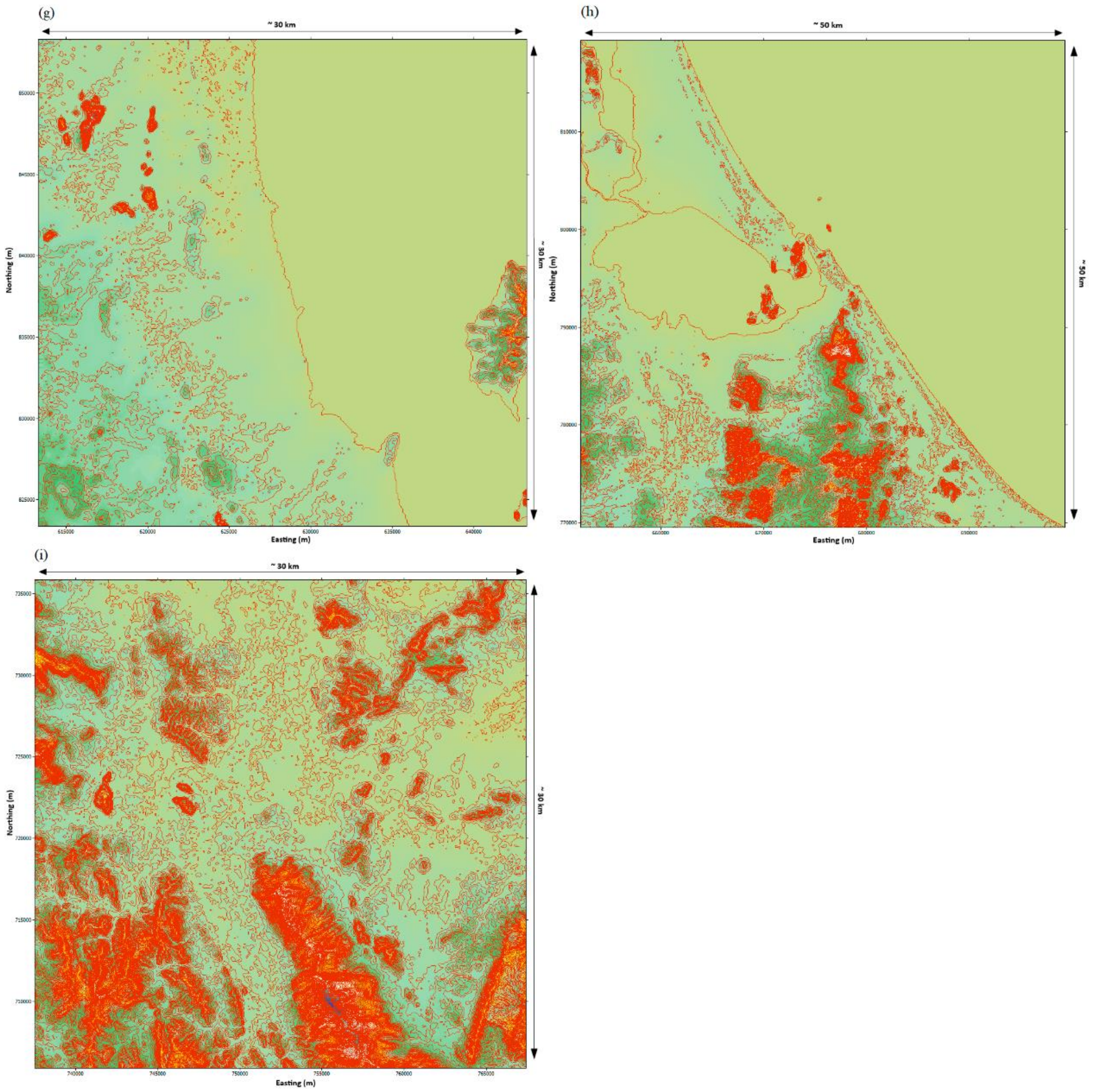
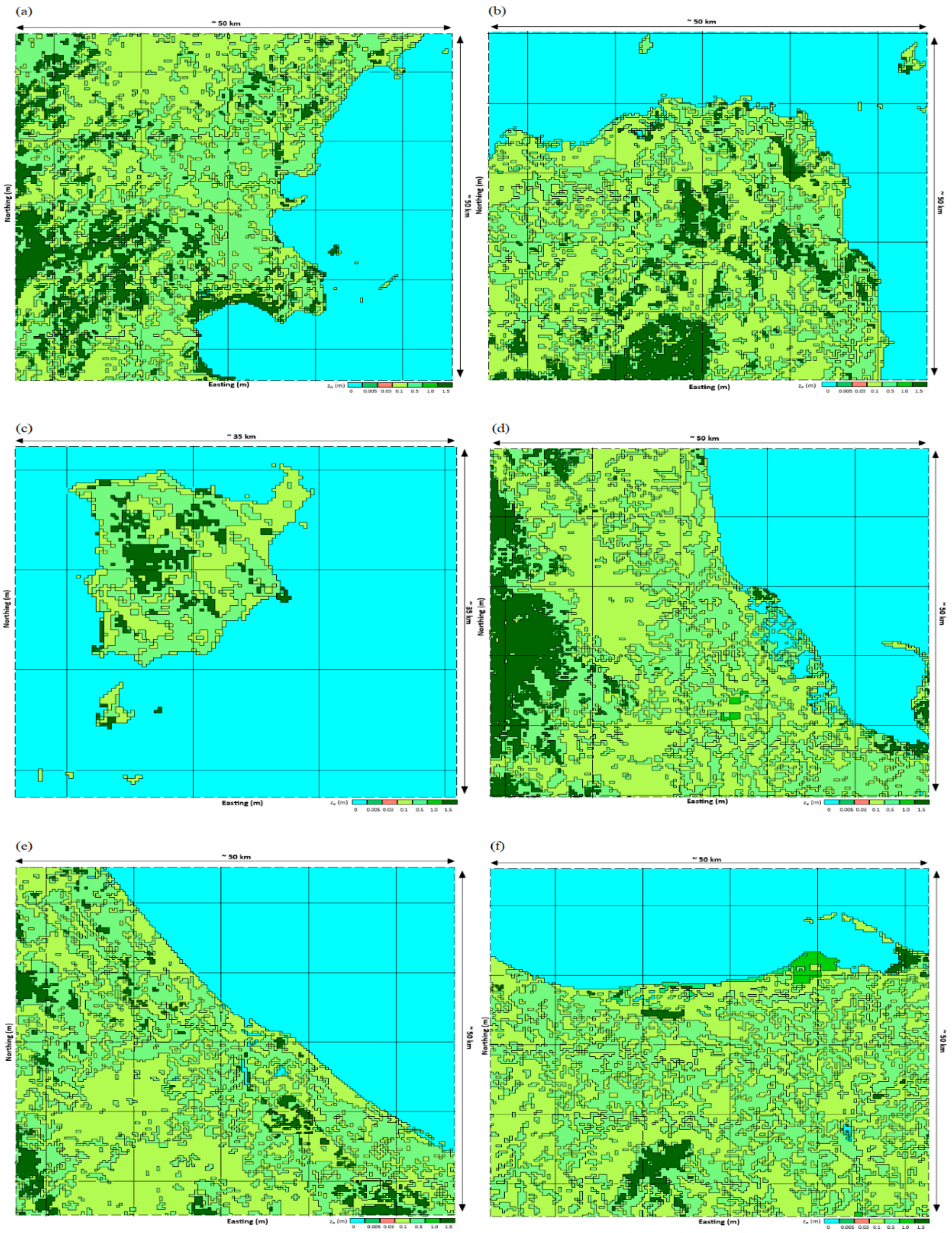


Fig. 3. 4 Elevation maps of the study area: (a) Chumphon (b) Kanchanadit (c) Koh Samui (d) Nakhon Si Thammarat (e) Narathiwat (f) Pattani (g) Phatthalung (h) Songkhla (i) Yala (j) Krabi.

Roughness maps in Fig. 3.5 are formed by using the available data from the GWA Roughness *GlobCover* database provided by the GWA Warehouse map server. The dataset has 22-class land use classification system and has a 10 arc-seconds (approximately 300 m) resolution. Due to insufficient information related to surface roughness with high resolution, the surface roughness in southern Thailand can be characterized into seven types: water bodies, bare areas, grassland, croplands, flooded forest, urban areas and forests; while the surface roughness lengths in WAsP by default are 0, 0.005, 0.03, 0.1, 0.5, 1.0 and 1.5 m, respectively.



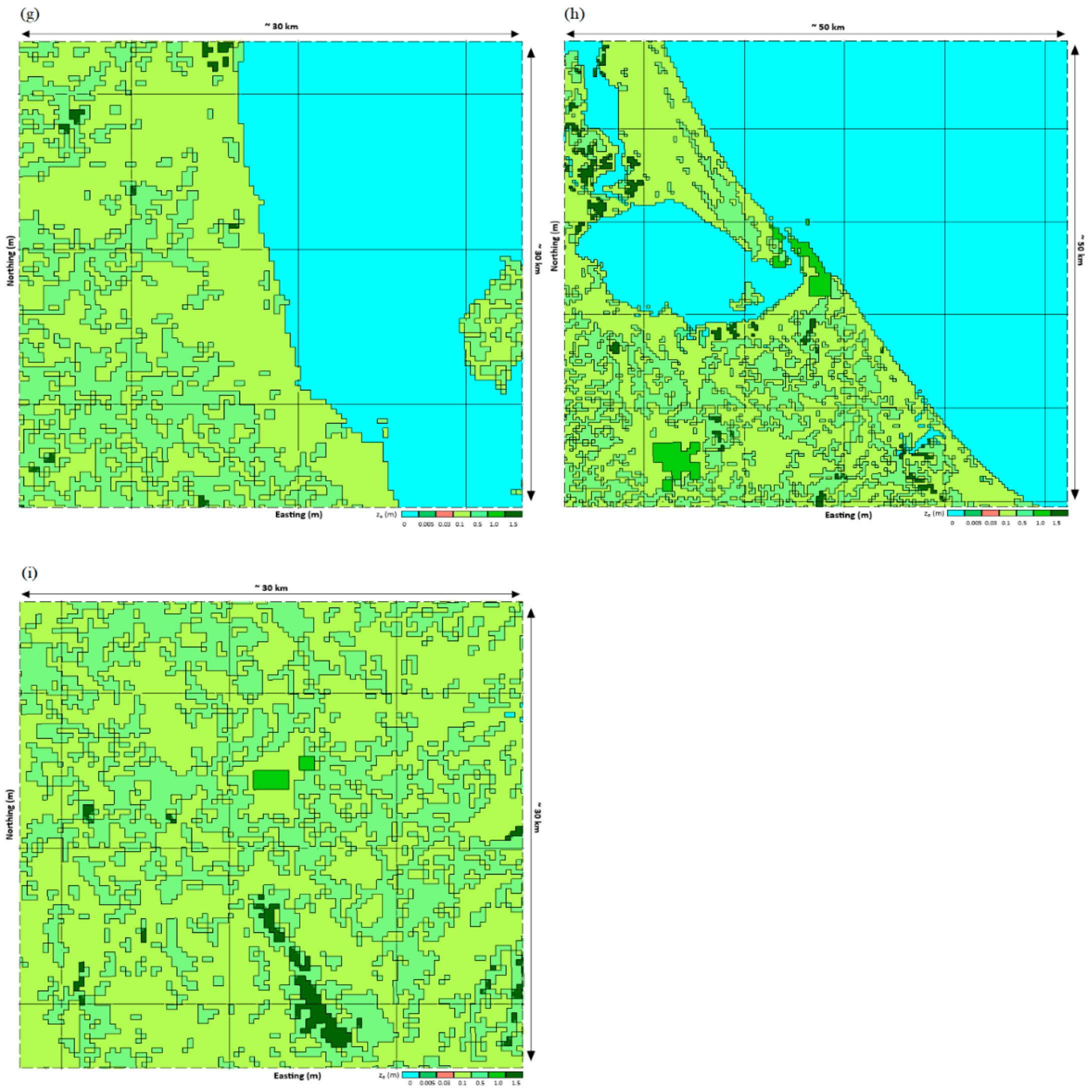


Fig. 3. 5 Surface roughness maps of the study area: (a) Chumphon (b) Kanchanadit (c) Koh Samui (d) Nakhon Si Thammarat (e) Narathiwat (f) Pattani (g) Phatthalung (h) Songkhla (i) Yala (j) Krabi.

3.7. Economic analysis

The LCOE is elaborated as a measure of the average net present value of the generating electricity for a particular system over its lifespan [18, 62]. The LCOE is computed in $/kWh or $/MWh. The details of the input parameters to calculate LCOE are shown in Table 3.3. LCOE is a suitable method for assessing the viability of energy production for commercial service and specifies its effectiveness compared to other technologies [87]. The summarized form of LCOE is given in Eq. (5):

$$\text{LCOE} = \frac{\text{Average total cost to build and operate a power plant over its lifetime}}{\text{Total power generated by the power plant over that lifetime}} \quad (5)$$

or

$$\text{LCOE} = \frac{\text{CAPEX} + \text{OPEX}}{\text{Power production}} \quad (6)$$

Where CAPEX represents the construction or capital cost while OPEX shows the operation and maintenance cost of the facility. The detailed mathematical form of Eqs. (5) and (6) is:

$$LCOE = \frac{C_t + \{\sum_{t=1}^{n} Of_t \,/\, (1+d_r)^t + \sum_{t=1}^{n} Ofv_t \,/\, (1+d_r)^t\} + (FC + HR)}{\sum_{t=1}^{n} P_t \,/\, (1+d_r)^t} \quad (7)$$

Where C_t is the construction or capital expenditure in terms of t^{th} year in USD, Of_t represents the fixed operation while Ofv_t is the variable operation and maintenance expenditures in terms of t^{th} year USD, d_r denotes the discount rate, FC shows fixed cost, HR indicates human resource cost, P_t symbolizes the energy produced in the t^{th} year in MWh, and n is the plant operation period.

Table 3. 3 Variables for the estimation of the LCOE.

Parameters	CAPEX	Fixed OPEX	Variable OPEX	Capacity factor	Lifetime
	Million $/MW	$/kW-yr	$/MWh	%	(t) yr
Wind	2.52	10.28-60.0	4.82-23.0	26.0-52.0	25
Exchange rate	31.24 (THB/$)	-	-	-	-
Discount rate	7.5 (%)	-	-	-	-
FiT_{Fix}	1.81	-	-	-	-
FiT_{Var}	1.85	-	-	-	-

Source: [18]. Note: LCOE: Levelized Cost of Energy, CAPEX: Capital Expenditures, Fixed OPEX: Fixed Operating Expenses, Variable OPEX: Variable Operating Expenses, Year: yr, THB/$: Thai Baht/Dollar, FiT_{Fix}: Fixed Feed-in Tariff, FiT_{Var}: Variable Feed-in Tariff, MW: Megawatt, kW: Kilowatt, MWh: Megawatt-hour.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Analysis of wind speed, wind direction and wind power density

Wind speed is the basic parameter in wind resource assessment for energy production utilizing wind turbines. During proper planning, it is extremely significant to consider different periods of variations such as daily, monthly, annual and seasonal, and the total annual mean wind speed. At extremely high (above 25 m/s) or low (below 3 m/s) wind speeds, possible shutdown periods of the turbine should be identified (when it will be out of service). The capacity factor and predicted power production predominantly depend on the selected wind turbine type, size and manufacturer [79]. Fig. 4.1 illustrates the monthly average wind speed at 10 m (AGL) for the 3-year period. The average wind speed is lower in the months from May to October, while it is higher from November to April due to the northeast monsoon that brings cold and dry air from the South China Sea, causing strong winds in the Gulf of Thailand and coastal regions of south-eastern Thailand.

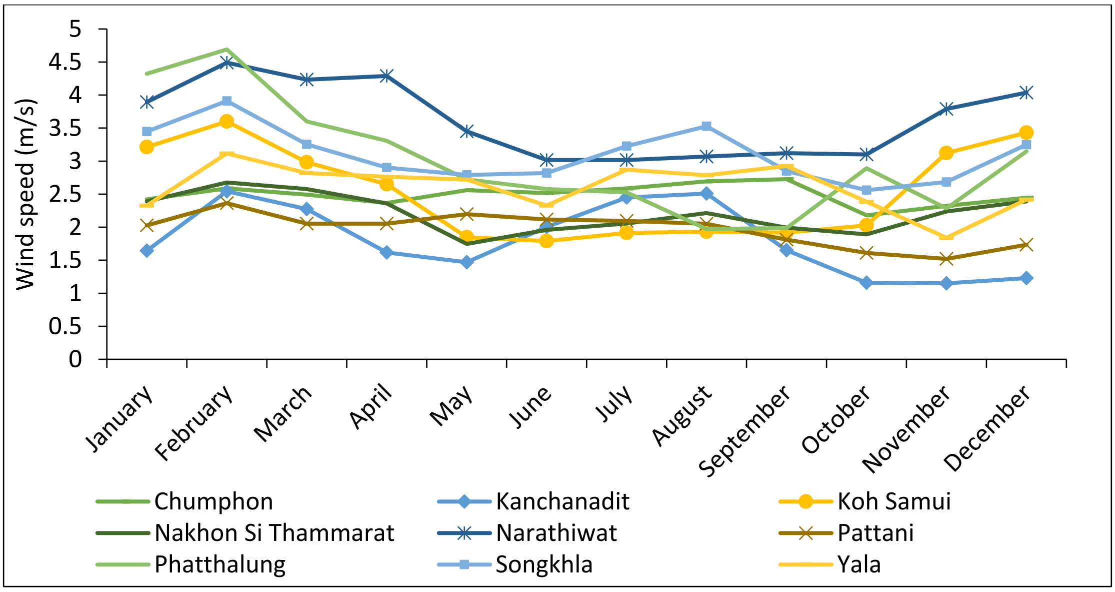
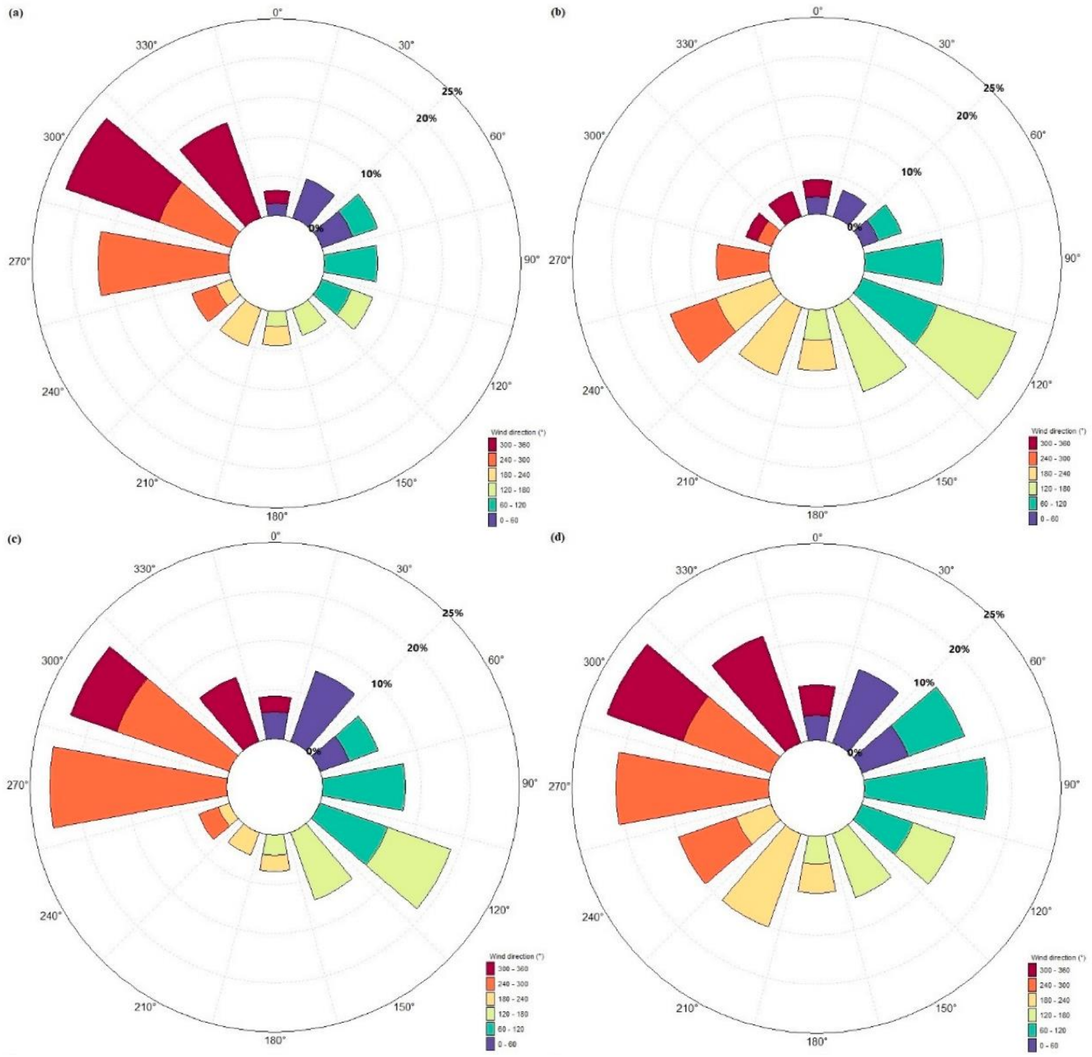


Fig. 4. 1 Monthly average wind speed at 10 m AGL.

The dominant wind direction has a great importance in the evaluation of a wind energy resource [70]. In order to harness the maximal wind energy, the orientation of the wind generator should be perpendicular to the wind direction [79]. Fig. 4.2 clearly depicts the sector-wise distribution as wind roses for south-eastern Thailand in 12 parts, with discrete 30° intervals.



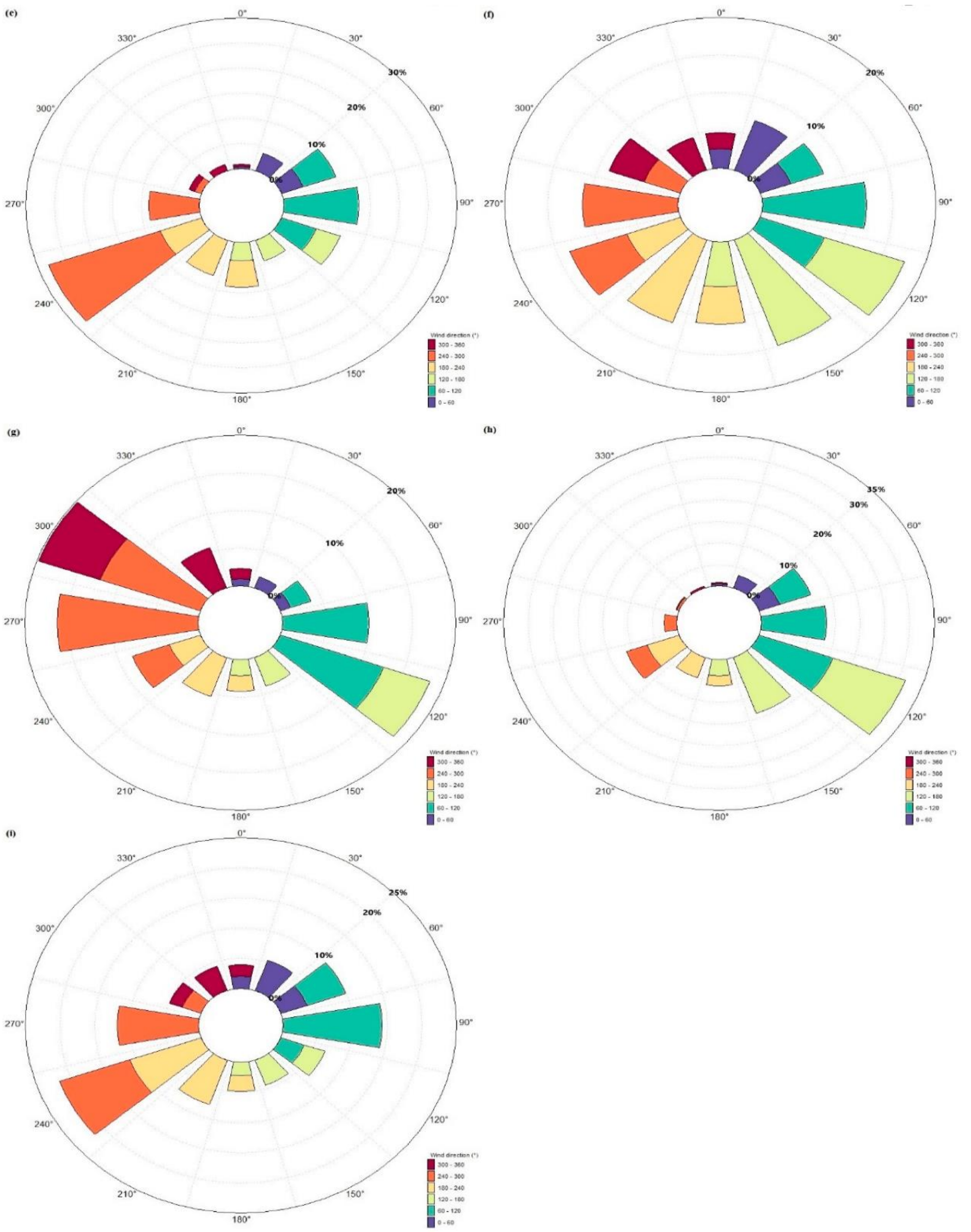


Fig. 4. 2 Wind rose diagrams of south-eastern Thailand: (a) Chumphon, (b) Kanchanadit, (c) Koh Samui, (d) Nakhon Si Thammarat, (e) Narathiwat, (f) Pattani, (g) Phatthalung, (h) Songkhla, and (i) Yala.

The wind rose diagrams in Fig. 4.2 show that the dominant wind direction observed over the three years is northwest in Chumphon and Nakhon Si

Thammarat, whereas it is southwest in Narathiwat and Yala. Similarly, the southeast direction is dominant in Kanchanadit, Pattani and Songkhla. The bi-directional northwest-southeast wind rose is more pronounced in Phatthalung, while west is the dominant direction in Koh Samui. Moreover, the occurrence rate of northwest wind direction for Chumphon and Nakhon Si Thammarat is almost 23%, whereas the occurrence rate of southwest wind for Narathiwat and Yala is about 28% and 22%, respectively. Similarly, the occurrence rate of southeast direction in Kanchanadit, Pattani and Songkhla is prevailing with 21%, 18% and 32%, respectively. The occurrence rate of bi-directional northwest-southeast wind in Phatthalung is almost 24% from northwest and 23% from southeast, while the occurrence rate of west direction in Koh Samui is almost 23%.

Wind power density is the maximum available wind power per unit area and can be expressed as [58, 88]:

$$P = 0.5\rho v^3 \tag{8}$$

Similarly, the mean wind power density can be measured by using the observed wind data, and is given by [89]:

$$\bar{P} = \frac{1}{2N}\bar{\rho}\sum_{i=1}^{Nobs} n_i v_i^3 \tag{9}$$

where $\bar{\rho}$ indicates the mean air density (kg/m^3) of a specific time interval, v_i is the ith wind speed (m/s) and n_i is the number of occurrences of ith speed (frequency).

The wind power density can be divided into seven categories on the basis of wind speed and annual wind power density, as shown in Table 4.1 [58, 90].

Table 4. 1 Wind power density classification scheme [58, 91].

Wind power class	Mean wind speed at 50 m (m/s)	Wind power density at 50 m (W/m^2)	Resource potential
1	3.5-5.6	50-200	Poor
2	5.6-6.4	200-300	Marginal
3	6.4-7.0	300-400	Fair
4	7.0-7.5	400-500	Good

Wind power class	Mean wind speed at 50 m (m/s)	Wind power density at 50 m (W/m^2)	Resource potential
5	7.5-8.0	500-600	Excellent
6	8.0-8.8	600-800	Outstanding
7	Above 8.8	Above 800	Superb

Fig. 4.3 presents the annual mean wind power density in south-eastern Thailand at 28.5 m hub height. The wind energy resource in south-eastern Thailand varies from station to station as shown in Table 3. For south-eastern Thailand, annual mean wind power density with highest value of 802 W/m^2 was found in Phatthalung, which belongs to wind class 7, followed by Yala with 474 W/m^2 and Kanchanadit with 429 W/m^2, and both these stations fall in wind class 4. The minimum annual mean wind power density of 174 W/m^2 was recorded in Chumphon, followed in increasing order by Pattani with 196 W/m^2, and both stations belong to wind class 1; while Nakhon Si Thammarat with 271 W/m^2 falls in wind class 2. Similarly, Narathiwat, Songkhla and Koh Samui were at 390 W/m^2, 378 W/m^2 and 350 W/m^2, respectively, belonging to wind class 3.

Yu and Qu [92] reported that good or excellent potential sites are suitable candidates for establishing a wind energy facility, with wind power density exceeding 400 W/m^2 or even reaching 800 W/m^2, and wind speed on average is above 7.0 m/s. Thus, the various sites in south-eastern Thailand inspected using WAsP possess a very good potential for wind farm.

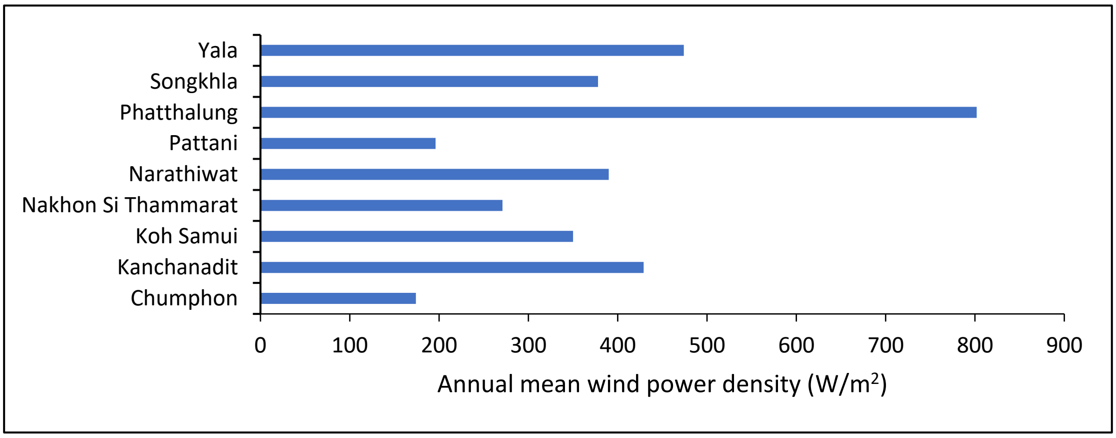


Fig. 4. 3 Annual mean wind power density of south-eastern Thailand at 28.5 m hub height.

4.2. Diurnal wind speed

Fig. 4.4 displays the average wind speed of each hour recorded at 10 m height to show the wind speed diurnal pattern of Krabi and Songkhla sites. It has been observed that both sites examine maximum average wind speed from 2 a.m. to 8 a.m. with minimum average wind speed between 12 p.m. and 10 p.m.

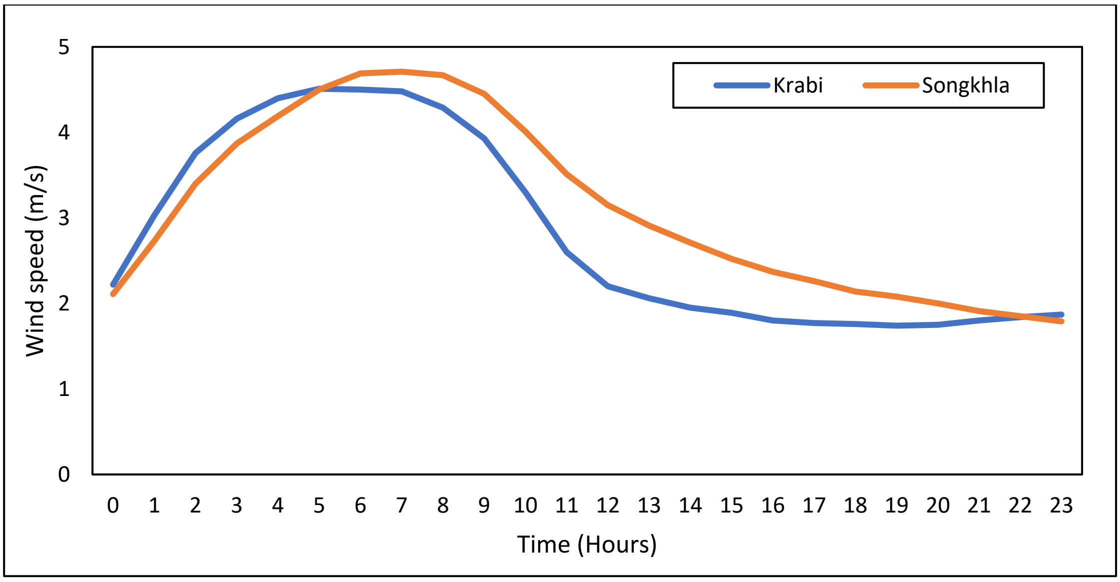


Fig. 4. 4 Diurnal average wind speed for Krabi and Songkhla.

4.3. Frequency distribution of wind speed and wind direction

It is important to consider the frequency distribution of wind speed and wind direction during resource assessment as it gives site specific information.

Fig. 4.5 shows the prevailing wind direction for Krabi which is north-east with a wind speed (3.73 m/s) frequency distribution 22.1%. The values of scale parameter A and shape parameter k are 3.1 m/s and 1.39, respectively.

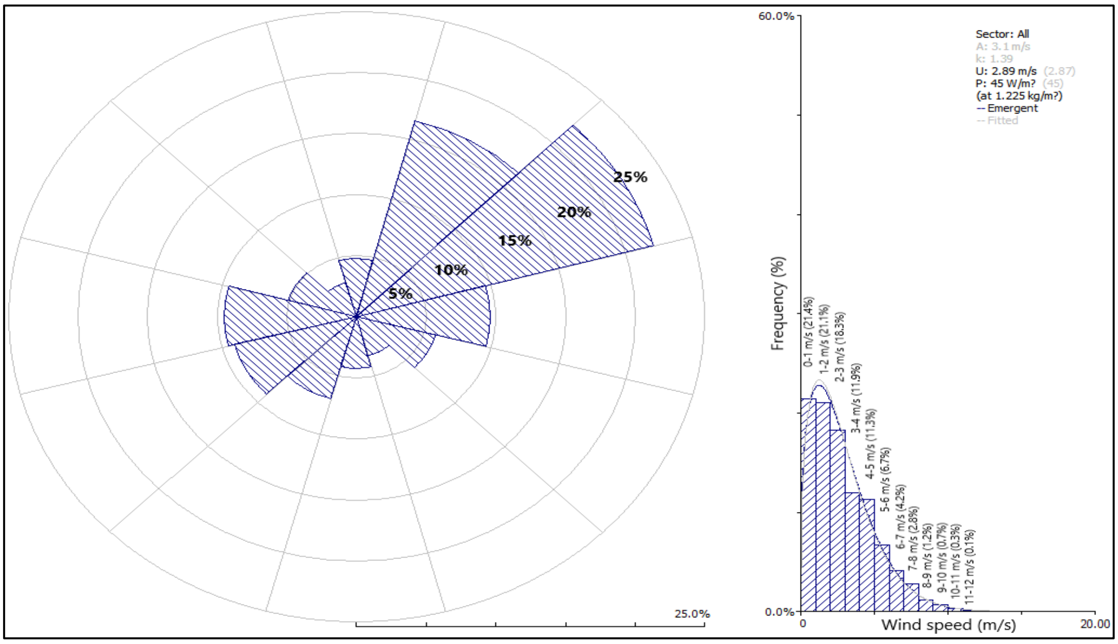


Fig. 4. 5 Wind rose diagram and histogram of frequency distribution of wind speed for Krabi.

Fig. 4.6 presents the prevailing wind direction for Songkhla which is south-east with a wind speed (3.41 m/s) frequency distribution 31.3%. The values of scale parameter A and shape parameter k are 3.5 m/s and 1.60, respectively.

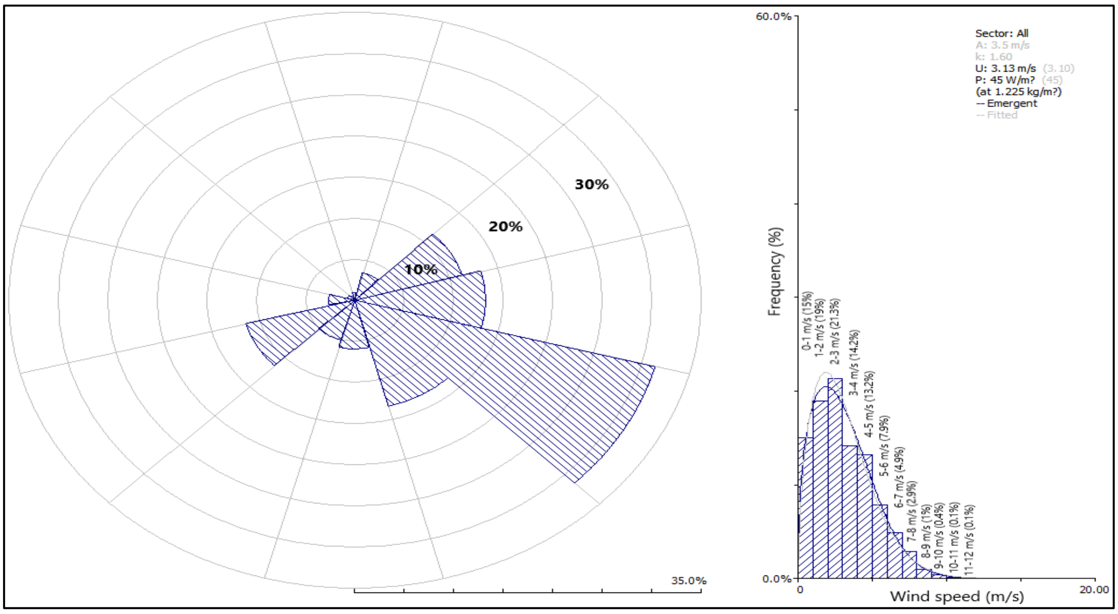


Fig. 4. 6 Wind rose diagram and histogram of frequency distribution of wind speed for Songkhla.

4.4. Wind resource mapping and energy estimation

This section describes the mean wind speed, net AEP and capacity factor using Enercon E-18 wind turbine model for a portion of south-eastern Thailand. Furthermore, wind energy potential using three different available wind turbine models for Krabi and Songkhla sites has been discussed.

The wind resource maps show the mean wind speed extrapolated for a portion of south-eastern Thailand in Fig. 4.7. This study identifies ideal sites in the eight provinces of south-eastern Thailand. WAsP analysis was carried out for the thickly populated, increasing infrastructure and remote areas. Ten stations were inspected by analyzing 3 to 4 years of wind data for prospective wind farm facility. In the next stage, a power analysis was conducted for the selected locations in accordance with the mean wind speed, wind power density, accessibility by using roads, and electrical transmission lines[93].

Wind speed highly varies in direction with respect to different locations; thus, those areas encompassed by the resource grid fall within the WAsP's limits of predictability. Various types of wind turbines can be proposed for the selected sites. However, the wind turbine model for this work is selected on the basis of availability and reliability of information about the specifications of the power curve. Other types of wind turbine models available in the market may be more appropriate than the one used in this assessment. For instance, there is a wind turbine model that is specifically designed for low-speed wind regime, but it lacks specifications in the literature. Eight to ten sites in each station of south-eastern Thailand are selected within the resource map plot for power analysis using the wind generator Enercon E-18 with a rated power of 80 kW. These sites were selected based on the mean wind speed, wind power density, accessibility by using roads and electrical transmission lines.

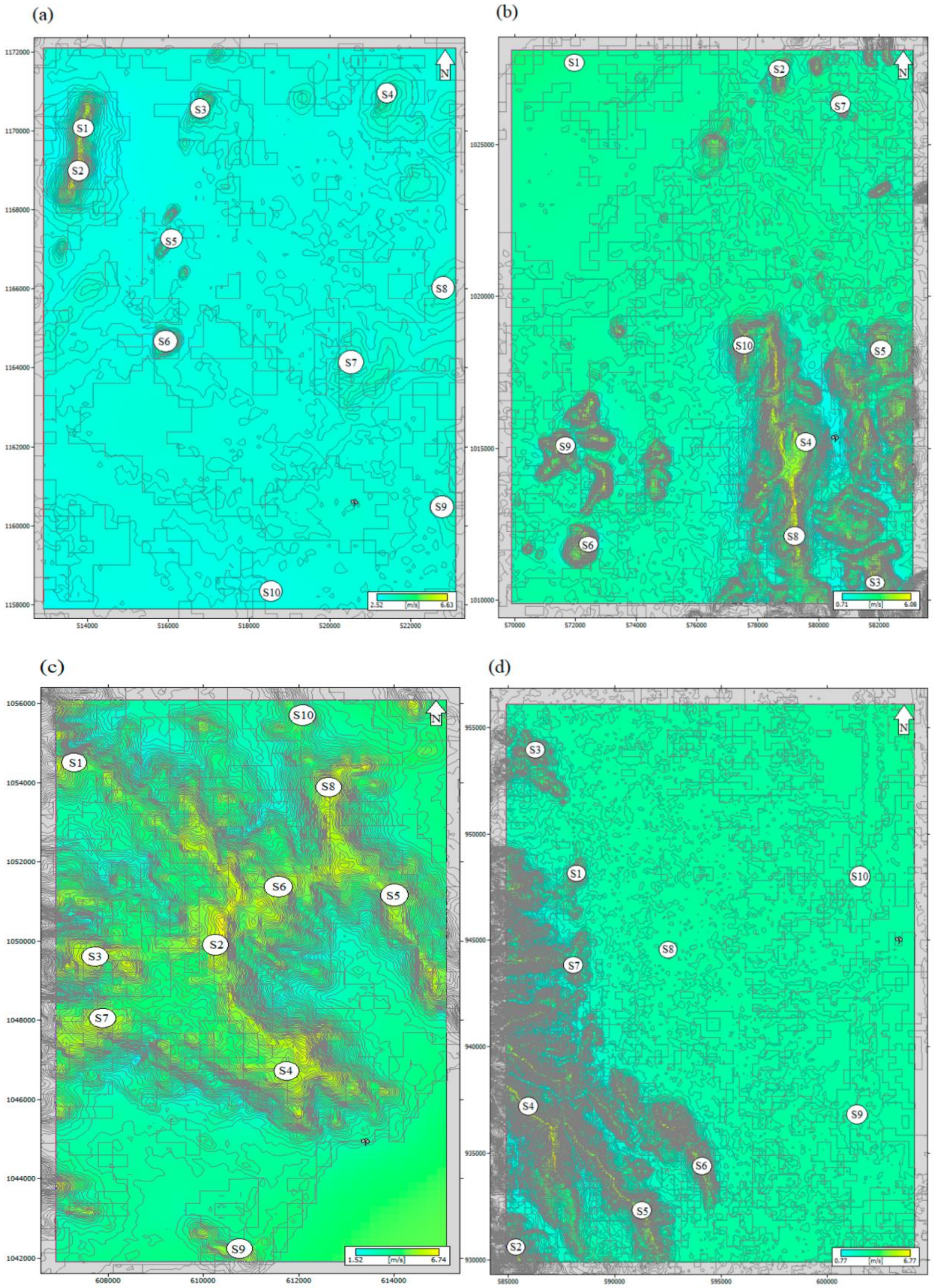
The 10 m measurement towers installed by the TMD are mounted in relatively exposed areas in the south-eastern Thailand. Sites along the ridges, mountain peaks and coastal ridges show good wind speeds within the resource grid at 28.5 m hub height.

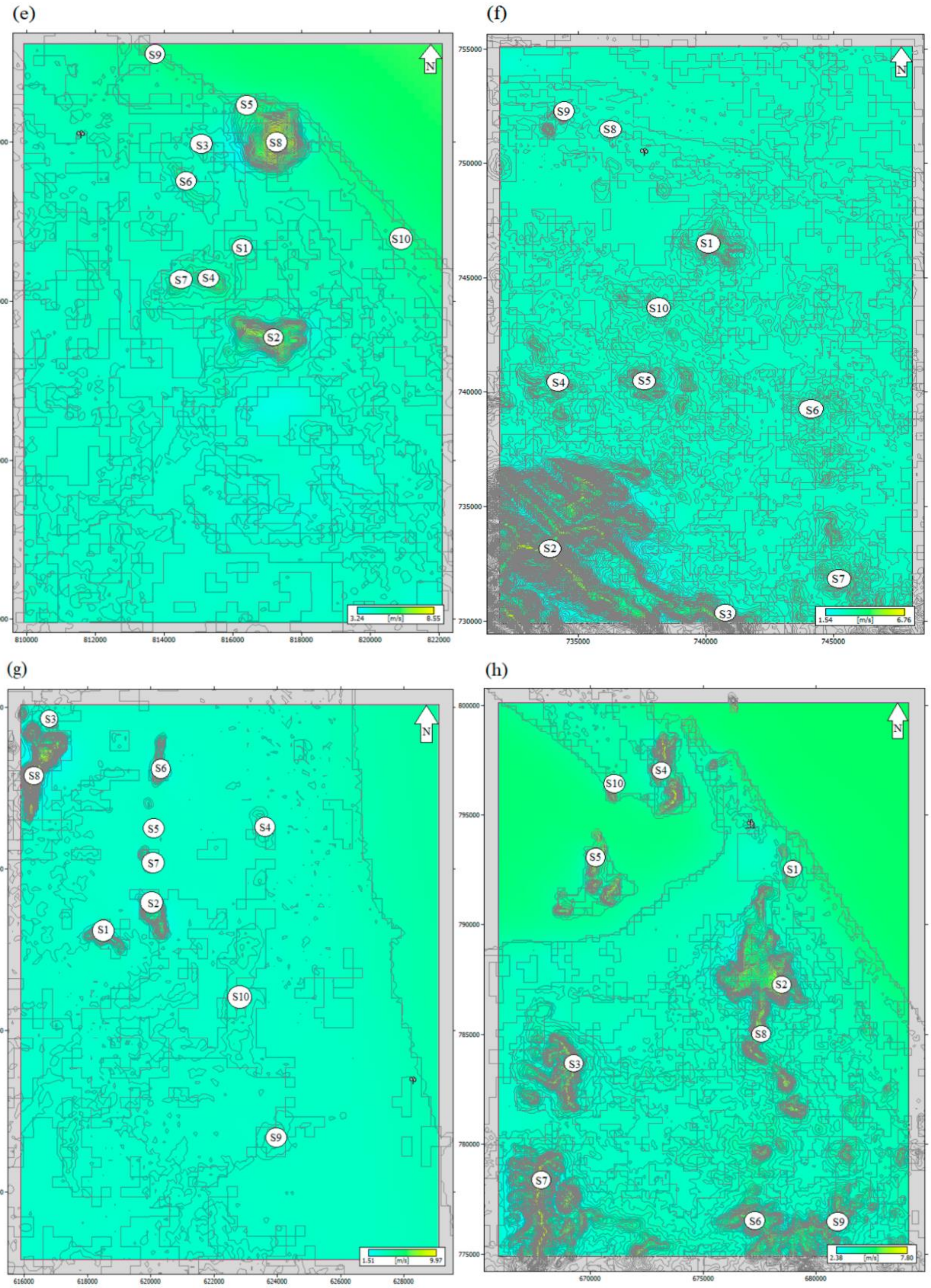
In south-eastern Thailand, the northern stations such as sites along the northwestern ridges (S1 and S2) in Chumphon and mountain peaks (S2, S3, and S8) in Kanchanadit, (S2, S3, S6, S7, S8 and S9) Koh Samui and (S2, S4, S5 and S6) Nakhon Si Thammarat show good potential for wind farm development having mean wind speed of 6.0-6.9 m/s, 5.8-6.7 m/s, 6.0-6.7 m/s and 6.3-6.7, respectively. However, the sites inspected near the coastal side in south (S10) and east (S7, S8 and S9) of Chumphon, northwest (S10) of Kanchanadit and eastern part (S9 and S10) of Nakhon Si Thammarat possess less potential for wind farm facility implementation.

In central stations, all sites along the peaks of mountains (S1 to S10) of Songkhla and northwestern ridges (S1, S6 and S8) of Phatthalung in resource map plot have very good mean wind speed from 5.9 m/s to 7.1 m/s and from 5.9 m/s to 8.8 m/s, respectively. These sites have very good potential for wind farms in the future. However, in Phatthalung, sites on the leeward side (S5) and plain areas (S4, S9 and S10) towards Songkhla lake show less potential for wind park, because of mean wind speed of about 3.4 m/s to 4.3 m/s.

The resource maps show great potential on the mountain peaks and ridges in the southernmost stations, in Narathiwat and Yala provinces in the south-eastern Thailand. All the sites scrutinized in Narathiwat and Yala have mean wind speed around 5.1-8.6 m/s and 5.1-9.4 m/s, except site (S10) close to a meteorological station in Yala that has very little potential (4.2 m/s). Sites inspected along the ridges (S8 and S5) and towards the northern (S9) and eastern (S10) coast in Narathiwat possess good mean wind speeds of about 5.3 m/s to 8.6 m/s, because of proximity to the shore. Further investigation regarding offshore wind speed is required around the coastal regions of Narathiwat that can be expected to have great potential for offshore wind farm facility in the future. On the other hand, the regions (S1, S4, S5, S6, S7, S8, S9 and S10) examined on ridges in Pattani province had less potential for wind farm facility. However, from the resource, it is apparent that the sites on mountain peaks in southwest (S2) and south (S3) show some potential for wind farm development as these sites have mean wind speed of about 5.1 to 6.9 m/s.

The area of south-eastern Thailand is fairly smooth. Regions on the leeward side and plain areas in south-eastern Thailand have much less potential for wind farm facility, as they are surrounded by a lot of artificial obstacles, for instance by high-rise buildings and urban infrastructure, which make airflow highly turbulent and may affect the wind flow. However, mountain peaks and ridges show great potential for prospective wind farm facility which are generally away from the power grid. Hence, small-scale wind turbines can act as a useful power source in such locations [94].


(a)
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
N
2.52 [m/s] 6.63
(b)
S1
S2
S7
S10
S5
S9
S4
S8
S6
S3
N
0.71 [m/s] 6.08
(c)
S10
S1
S8
S6
S5
S2
S3
S7
S4
S9
N
1.52 [m/s] 6.74
(d)
S3
S1
S10
S7
S8
S4
S9
S6
S5
S2
N
0.77 [m/s] 6.77


(e)
S9
S5
S3
S8
S6
S10
S1
S7
S4
S2
N
3.24 [m/s] 8.55
(f)
S9
S8
S1
S10
S4
S5
S6
S2
S7
S3
N
1.54 [m/s] 6.76
(g)
S3
S8
S6
S5
S4
S7
S2
S1
S10
S9
N
1.51 [m/s] 9.97
(h)
S4
S10
S5
S1
S2
S8
S3
S7
S6
S9
N
2.38 m/s 7.80

(i)

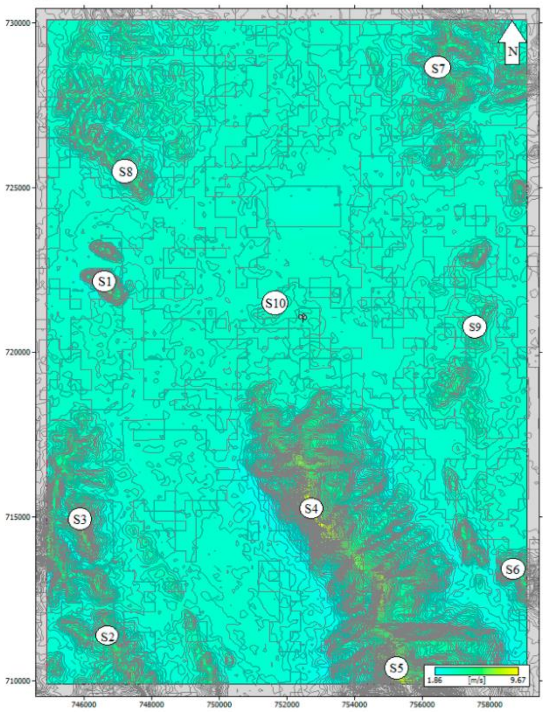


Fig. 4. 7 High resolution wind speed maps of the study area at 28.5 m hub height: (a) Chumphon, (b) Kanchanadit, (c) Koh Samui, (d) Nakhon Si Thammarat, (e) Narathiwat, (f) Pattani, (g) Phatthalung, (h) Songkhla, and (i) Yala.

The average power generated by a wind turbine can be computed by applying the following equation:

$$\bar{P}w = \frac{1}{N}\sum_{i=1}^{N} Pw(U_i) \tag{10}$$

where $Pw(U_i)$ shows the output power which is defined by the turbine power curve.

Also, the energy yield from a wind turbine can be calculated as:

$$E = \sum_{i=1}^{N} Pw(U_i)(\Delta t) \tag{11}$$

where U_i is the wind speed which is averaged over a time interval Δt, N is the number of recorded observations.

Enercon E-18 wind turbine with a rated of 80 kW was used in the power analyses of the identified potential sites. Technical specifications of the turbine are shown in Table 4.2. The cut-in and cut-out speed of the Enercon E-18 wind turbine rotor are 2.5 m/s and 25.0 m/s, respectively.

Table 4. 2 Enercon E-18 wind turbine specifications.

Rotor diameter	Hub height	Cut-in speed	Cut-out speed	Survival wind speed	Rated power	Rated wind speed
18 m	28.5 m	2.5 m/s	25.0 m/s	67.0 m/s	80 kW	12.0 m/s

Wind turbine power curve and a site's wind characteristics can be used to estimate the future energy generation over a specific period [70].

Fig. 4.8 shows the net AEP at the selected sites in each station of south-eastern Thailand. Based on average net AEP generated by WAsP, Songkhla has the highest potential for prospective wind energy development, followed by Yala and Narathiwat in south-eastern Thailand.

In northern stations, the average net AEP for Chumphon, Kanchanadit, Koh Samui and Nakhon Si Thammarat is about 102 MWh, 146 MWh, 173 MWh and 127 MWh, respectively. In Koh Samui, sites (S2, S3, S6, S7 and S8) inspected by WAsP have great potential for wind farm facility with a net AEP of about 180 MWh to 226 MWh. As mentioned previously, Koh Samui is an island and a famous tourist point. Hence, it is linked by an underwater cable to the mainland power plant in Surat Thani. An array of 10 or more 80 kW small-scale wind turbines integrated with other renewables, such as solar, can be used for generating electricity for Koh Samui Island. Also, some sites in Kanchanadit (S2, S3 and S8), Nakhon Si Thammarat (S4 and S5) and Chumphon (S1 and S2) show a net AEP of about 175 to 204 MWh, 197 to 205 MWh and 188 to 232 MWh, respectively. These sites have a great potential for prospective wind farm facility development.

In central stations, Songkhla and Phatthalung show an average net AEP of about 216 MWh and 146 MWh, respectively. All the sites (S1 to S10) inspected by WAsP in Songkhla show great potential for prospective wind farm facility with a net AEP of around 177 to 250 MWh, whereas, some sites (S1, S2, S6 and S8) in Phatthalung along the ridges in northwest display a net AEP around 173 to 211 MWh, and also have very good potential for prospective wind farms.

In the southernmost stations, Yala, Narathiwat and Pattani depict an average net AEP of about 198 MWh, 190 MWh and 109 MWh, respectively. Sites along the ridges and mountainous areas in Yala (S1, S2, S3, S4, S5 and S6) and Narathiwat (S2, S4, S8 and S9) possess a net AEP around 186 to 311 MWh and 197 to 282 MWh, respectively. These sites show the highest potential for prospective wind farm development. Besides, Pattani has only one site (S2) on a mountain peak with net AEP around 218 MWh, and this one is expected to have good potential for wind farm development in the future.

South-eastern Thailand has a population of more than 7.1 million. It is one of the most power consuming regions in Thailand and receives many tourists throughout the year due to popular destinations such as Koh Samui, Koh Pha Ngan and Koh Tao. As reported by the Electricity Generating Authority Thailand, power demand has been increasing by 5 to 6 % in southern Thailand annually, due to development of services and tourism. Hence, the prospective sites scrutinized by WAsP could reduce the burden on the local power distribution stations and would be sufficient to meet the rising power demand in south-eastern Thailand.

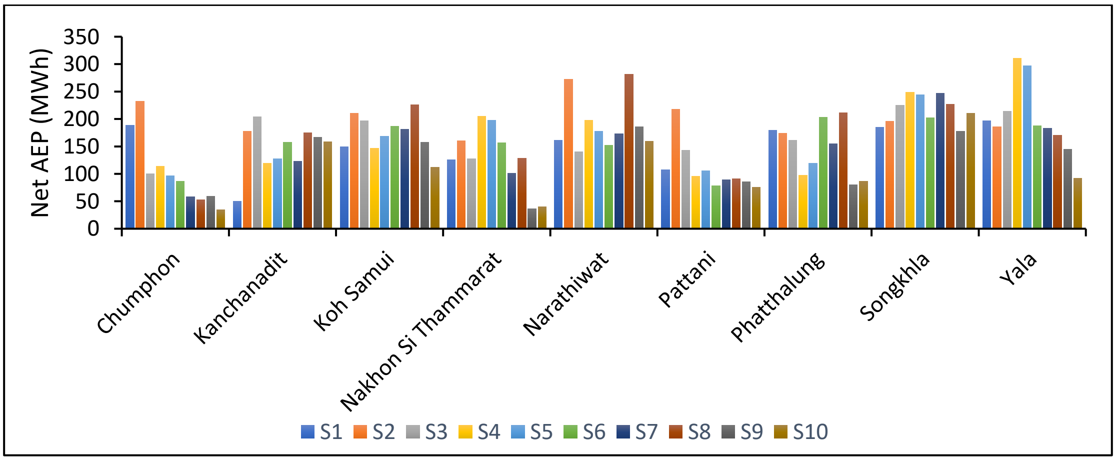


Fig. 4. 8 Net AEP of the selected sites in south-eastern Thailand at a hub height of 28.5 m.

Meanwhile, the capacity factor (C_f) of the wind turbine is defined as the dimensionless ratio of the average power output (P_{out}) and the rated power output (P_r) over a certain period of time (usually over one year) and can be expressed as [95, 96]:

$$C_f = \left(\frac{e^{-\left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_r}{A}\right)^k}}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_f}{A}\right)^k} \right) \tag{12}$$

where V_c, V_f and V_r are the cut-in wind speed, cut-out wind speed and rated wind speed, respectively. Similarly, A signifies the Weibull scale parameter and k is the dimensionless Weibull shape parameter. Then the average power output (P_{out}) can be expressed as:

$$P_{out} = P_r \cdot \left(\frac{e^{-\left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_r}{A}\right)^k}}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_f}{A}\right)^k} \right) \tag{13}$$

Once the value of the average power output (P_{out}) is known, average gross energy production (E_{out}) of a wind turbine can be estimated for a specific duration as:

$$E_{out} = P_{out} \cdot T \tag{14}$$

Also, $T = d \cdot 24$, where T and d represent the time span in hours and in days, respectively.

The capacity factor mainly depends on wind resource and wind turbine technology. An annual capacity factor of 17% or greater is considered desirable for wind power [58]. This study computed the annual capacity factors of the 9 stations in south-eastern Thailand at the 28.5 m hub height using WAsP program. The results show that Songkhla, Yala and Narathiwat have annual capacity factors of 27% or over. Koh Samui, Phatthalung and Kanchanadit have annual capacity factors ranging between 20% and 25%, whereas Nakhon Si Thammarat, Pattani and Chumphon have annual capacity factors of 18%, 16% and 15%, respectively (Fig. 4.9).

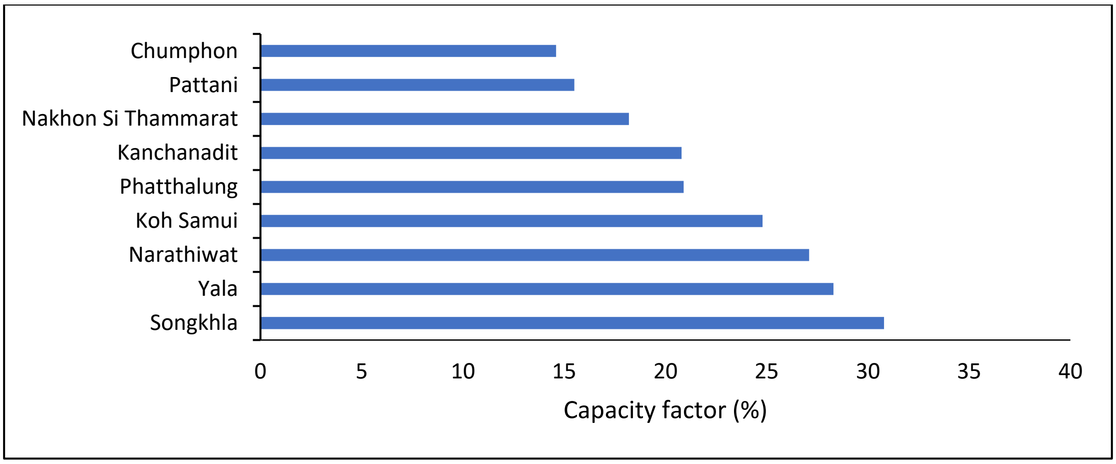


Fig. 4. 9 Capacity factors at south-eastern Thailand specific sites assuming Enercon E-18 wind turbine at a hub height of 28.5 m.

4.5. LCOE analysis

In this section, an economic analysis is done for the installations of the prospective small-scale wind turbines in south-eastern Thailand. LCOE has been calculated for the selected sites using Eq. (6) and Table 3.3, as described in the methodology section, whereas the annual energy yield and capacity factor of the chosen sites were computed using the WAsP module. Using Enercon E-18 wind turbine model, the lowest LCOE is 92.31 $/MWh to 128.89 $/MWh for Songkhla while the highest LCOE is 189.49 $/MWh to 246.52 $/MWh for Chumphon. Further details of LCOE calculation for the selected sites can be seen in Table 4.3**.**

Table 4. 3 Data for the calculation of LCOE.

Sites	AEP (MWh)	CF (%)	LCOE ($/MWh)	
			Fixed and Variable OPEX (min.)	Fixed and Variable OPEX (max.)
Chumphon	102.32	14.61	189.49	246.52
Kanchanadit	146.03	20.83	134.35	179.78
Koh Samui	173.71	24.77	113.74	154.84
Nakhon Si Thammarat	127.91	18.25	152.66	201.94
Narathiwat	190.18	27.14	104.23	143.33
Pattani	109.05	15.54	178.44	233.14
Phatthalung	146.87	20.96	133.54	178.8
Songkhla	216.30	30.84	92.31	128.89
Yala	198.24	28.27	100.26	138.52

Note: CF: capacity factor.

Furthermore, WAsP program is utilized to evaluate the technical potential of wind energy at Krabi and Songkhla sites by using three different wind turbine models available in the literature. The technical description and specification of the wind turbine models are given in Table 4.4.

Table 4. 4 Specification of three different wind turbines.

Wind turbine model	Rated output (kW)	Rotor diameter (m)	Cut in speed (m/s)	Cut out speed (m/s)	Hub height (m)	Swept area (m^2)	Rated speed (m/s)
Vergnet GEV MP-C 275 kW	275	32	3.5	25	55	804	12
Bonus Mk III 300 kW	300	33.4	3	25	30	876	13
Enercon E-40/5.40 500 kW	500	40.3	2.5	25	42	1,275	12

The resource maps of Krabi and Songkhla using WAsP program are displayed in Figs. 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15. The AEP estimated for Krabi using 275 kW wind turbine ranges from 35.162 to 964.939 MWh, with 300 kW wind turbine ranges from 0.006 to 1023 MWh and with 500 kW wind turbine ranges from 0.038 to 1748 MWh. Similarly, the estimated AEP for Songkhla using 275 kW wind turbine ranges from 82.620 to 855.898 MWh, with 300 kW wind turbine ranges from 55.879 to 956.283 MWh and with 500 kW wind turbine ranges from 0.125 to 1540 MWh.

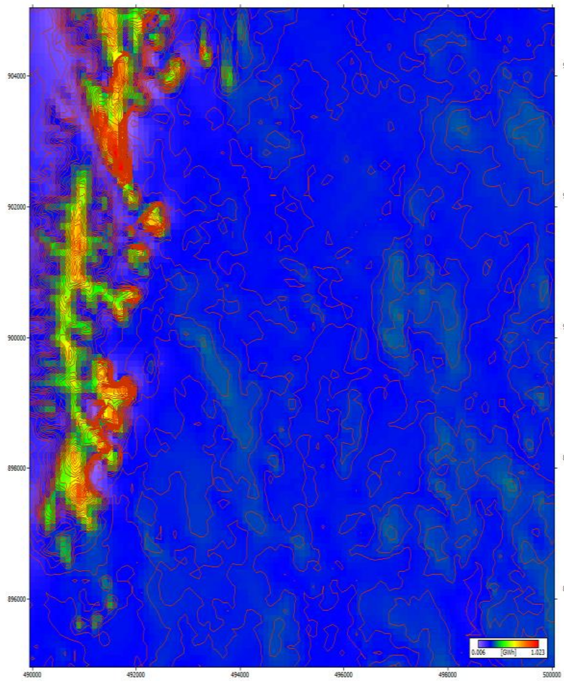


Fig. 4. 10 Mean annual energy production of Krabi at 30 m hub height.

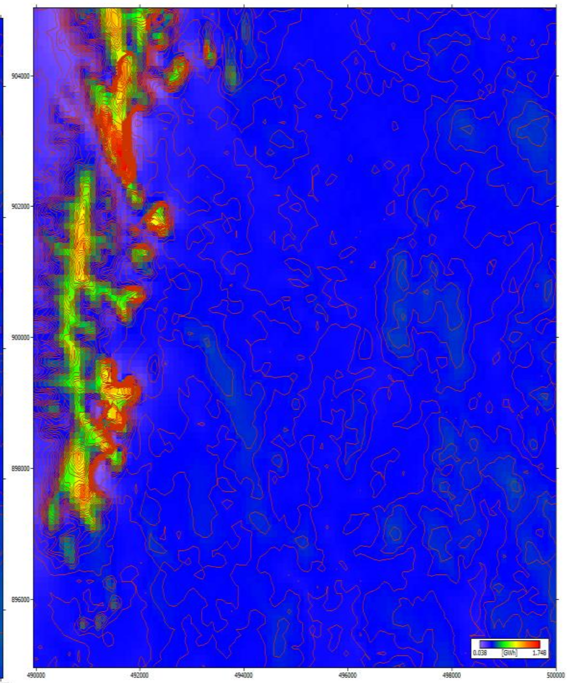


Fig. 4. 11 Mean annual energy production of Krabi at 42 m hub height.

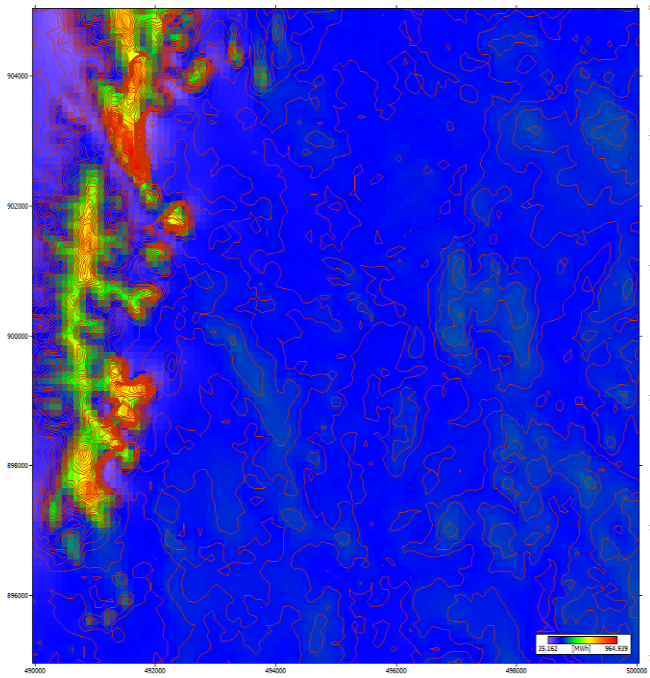


Fig. 4. 12 Mean annual energy production of Krabi at 55 m hub height.

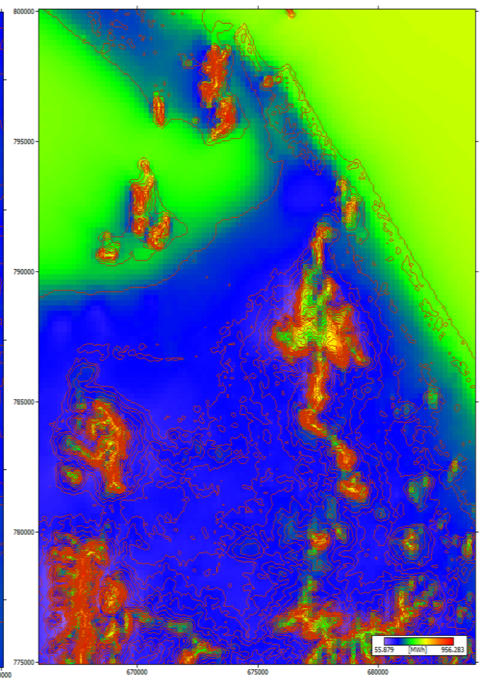


Fig. 4. 13 Mean annual energy production of Songkhla at 30 m hub height.

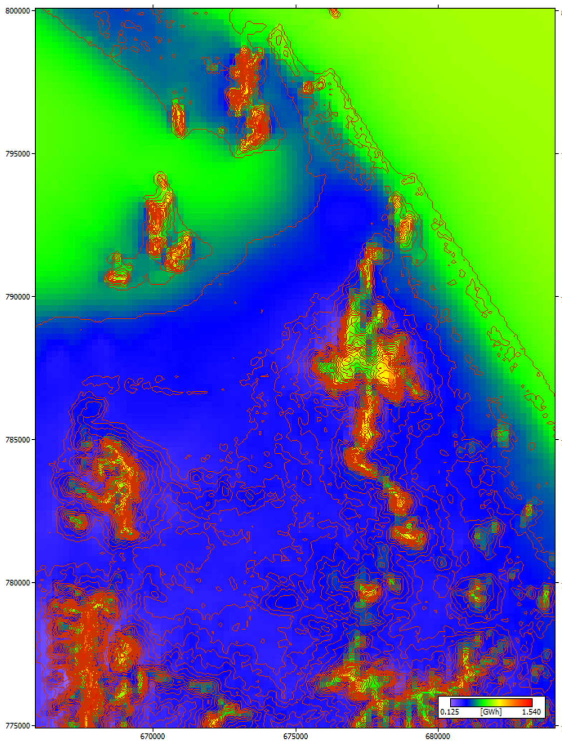


Fig. 4. 14 Mean annual energy production of Songkhla at 42 m hub height.

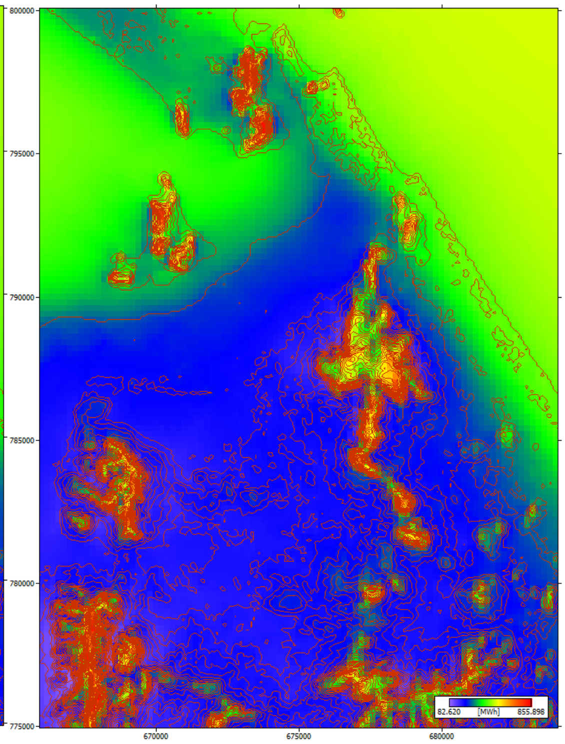


Fig. 4. 15 Mean annual energy production of Songkhla at 55 m hub height.

The statistical analysis of Krabi and Songkhla sites in terms of total gross AEP, total net AEP, proportional wake losses, annual mean wind speed, annual power density and total capacity factor have been evaluated in this study.

The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capacity of 275 kW at 55 m hub height are 7172.545 MWh and 7119.366 MWh, respectively. The mean speed and power density values are 6.85 m/s and 501 W/m2 for Krabi and 6.75 m/s and 374 W/m2 for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.8% and 29.5%, respectively. Further details for both sites are given in Table 4.5.

The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capacity of 300 kW at 30 m hub height are 7768 MWh and 7775.964 MWh, respectively. The mean speed and power density values are 6.87 m/s and 590 W/m^2 for Krabi and 6.55 m/s and 378 W/m^2 for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.1%. Further details for both sites are given in Table 4.6.

Table 4. 5 Summary of annual statistics using Vergnet GEV MP-C 275 kW.

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	7172.545	7119.366	717.254	711.937	496.618	574.905	955.504	843.985
Total net AEP [MWh]	7163.782	7116.63	716.378	711.663	495.374	574.664	955.014	843.662
Proportional wake loss [%]	0.12	0.04	-	-	0.05	0.03	0.25	0.05
Capacity factor [%]	29.8	29.5	-	-	20.5	23.8	39.6	35
Average speed [m/s]	-	-	6.85	6.75	5.59	6.15	8.48	7.38
Wind power density [W/m^2]	-	-	501	374	260	278	972	477

Table 4. 6 Summary of annual statistics using Bonus Mk III 300 kW.

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	7768	7775.964	777	777.596	539	644.544	1014	894.461
Total net AEP [MWh]	7762	7775.245	776	777.524	538	644.525	1013	894.316
Proportional wake loss [%]	0.07	0.01	-	-	0.02	0	0.16	0.02
Capacity factor [%]	29.1	29.1	-	-	20.1	24.1	37.9	33.4
Average speed [m/s]	-	-	6.87	6.55	5.28	5.92	9.19	7.13
Wind power density [W/m^2]	-	-	590	378	260	280	1400	488

The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capcity of 500 kW at 42 m hub height are 12738 MWh and 12391 MWh, respectively. The mean speed and power density values are 6.85 m/s and 533 W/m^2 for Krabi and 6.66 m/s and 372 W/m^2 for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.1% and 28.3%, respectively. Further details for both sites are given in Table 4.7.

Table 4. 7 Summary of annual statistics using Enercon E-40/5.40 500 kW.

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	12738	12391	1274	1239	863	998	1732	1468
Total net AEP [MWh]	12731	12390	1273	12390	861	998	1732	1468
Proportional wake loss [%]	0.06	0.01	-	-	0.01	0	0.13	0.02
Capacity factor [%]	29.1	28.3	-	-	19.7	22.8	39.5	33.5
Average speed [m/s]	-	-	6.85	6.66	5.44	6.03	8.76	7.29
Wind power density [W/m^2]	-	-	533	373	258	276	1131	475

The results reveal that Enercon E-40/5.40 500 kW wind turbine produces the highest total gross AEP and net AEP for Krabi and Songkhla sites. The annual capacity factor slightly varies for the selected wind turbines as it depends on turbine model and site. The Vergnet GEV MP-C 275 kW shows slightly higher capacity factor for both sites.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, the wind resource assessment was done using WAsP software for ten stations in southern Thailand. This study indicates that the regions on the leeward side and plain areas in southern Thailand have poor potential for the establishment of wind farm facility due to various artificial obstacles such as high-rise buildings and other urban infrastructure that make airflow highly turbulent and may affect the wind flow. However, mountain peaks and ridges show a very good potential for the development of small-scale wind power. The maximum average wind speed is found in the months from November to April, with low winds from May to October. The prevailing wind direction observed in Chumphon and Nakhon Si Thammarat is northwest whereas it is southwest in Narathiwat and Yala. Similarly, the southeast direction is predominant in Kanchanadit, Pattani and Songkhla. The northwest-southeast bi-directional wind rose is very pronounced for Yala, while west is the dominant direction in Koh Samui.

This work used WAsP software for the analyses, to create wind resource maps for southern Thailand with earmarked ten sites around each weather station for wind farm facility implementations in future. The wind resource maps at 28.5 m hub height indicate that the highest annual mean wind power density with value of 802 W/m^2 was found in Phatthalung, which belongs to wind class 7, followed by Yala with value of 474 W/m^2 and Kanchanadit with value of 429 W/m^2 that fall in wind class 4. The minimum annual mean wind power density was recorded in Chumphon and Pattani and both stations belong to wind class 1, while Nakhon Si Thammarat with value of 271 W/m^2 falls in wind class 2. Similarly, Narathiwat, Songkhla and Koh Samui were at 390 W/m^2, 378 W/m^2 and 350 W/m^2, respectively, and belong to wind class 3.

Also, the annual capacity factor of the chosen sites using the Enercon E-18 wind turbine with a rated of 80 kW were such that Songkhla, Yala and Narathiwat have annual capacity factors of 27% or over. Koh Samui, Phatthalung and Kanchanadit have annual capacity factors ranging between 20% and 25%, whereas

Nakhon Si Thammarat, Pattani and Chumphon have annual capacity factors of 18%, 16% and 15%, respectively. The LCOE calculation shows Songkhla with the lowest cost from 92.31 to 128.89 $/MWh while Chumphon had the highest cost from 189.49 to 246.52 $/MWh.

Furthermore, Krabi and Songkhla sites were used for the technical potential of wind energy by using three different wind turbine models available in the literature. The main points of wind resource analysis of both sites are:

- Both Krabi and Songkhla sites observe maximum diurnal average wind speed from 2 a.m. to 8 a.m. at height of 10 m AGL.
- Krabi site shows maximum average wind speed of 4.39 m/s in December while Songkhla site indicates the maximum average wind speed of 3.91 m/s in February at height of 10 m AGL.
- The prevailing wind direction in Krabi is north-east. The Weibull scale parameter A and shape parameter k values are 3.1 m/s and 1.39, respectively.
- The prevailing wind direction in Songkhla is south-east with a wind speed. The Weibull scale parameter A and shape parameter k values are 3.5 m/s and 1.60, respectively.
- The total net AEP estimated for Krabi using 275 kW, 300 kW and 500 kW wind turbine models is 7163.782 MWh, 7762 MWh and 12731 MWh, respectively.
- The total net AEP estimated for Songkhla using 275 kW, 300 kW and 500 kW wind turbine models is 7116.63 MWh, 7775.245 MWh and 12390 MWh, respectively.
- The value of capacity factor for Songkhla and Krabi is 29.1% and 28.3%, respectively.
- WAsP analysis shows that Enercon E-40/5.40 500 kW generates the highest total gross AEP and total net AEP for Krabi and Songkhla sites.
- Regarding capacity factor, the Vergnet GEV MP-C 275 kW turbine model shows slightly higher capacity factor in case of both sites.

This methodology can be further adapted for offshore wind farm development and cost analysis of Krabi site must be investigated.

In future analysis, WAsP CFD simulations in complex terrain to maximize production and minimize uncertainty would be beneficial since WAsP CFD would provide more accurate and reliable outcomes at low cost. Moreover, re-powering using WAsP approach to replace old wind turbines of lower capacity with a smaller number of modern turbines of higher capacity would be advantageous.

The findings of this research are likely to promote the idea that the regions near equator, such as Thailand, can exploit the wind energy to decrease its reliance on natural gas, coal and lignite in future. The method used in this work is scientific in its approach and is an effective tool for government organizations and stakeholders in prospective small-scale wind farm implementations in southern Thailand. The approach demonstrated could also be used in wind resource assessments for other parts of the world.

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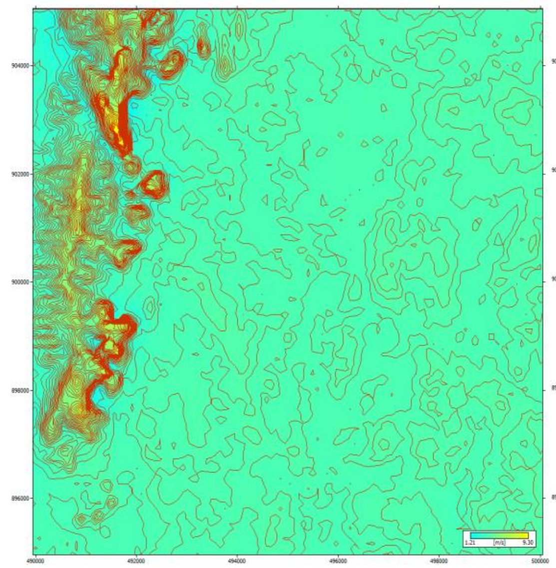
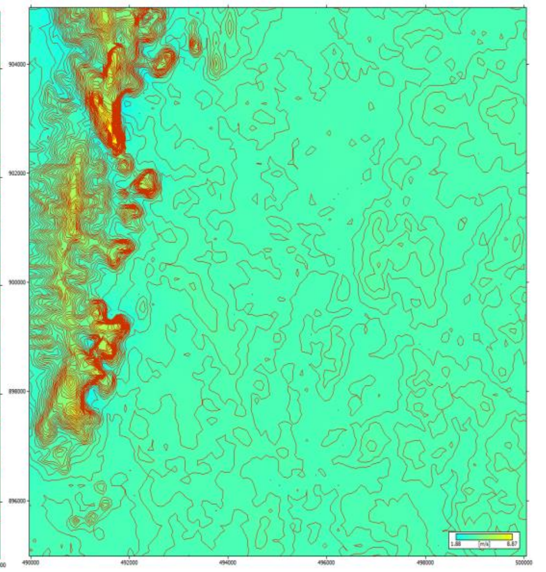
APPENDICES

APPENDIX A

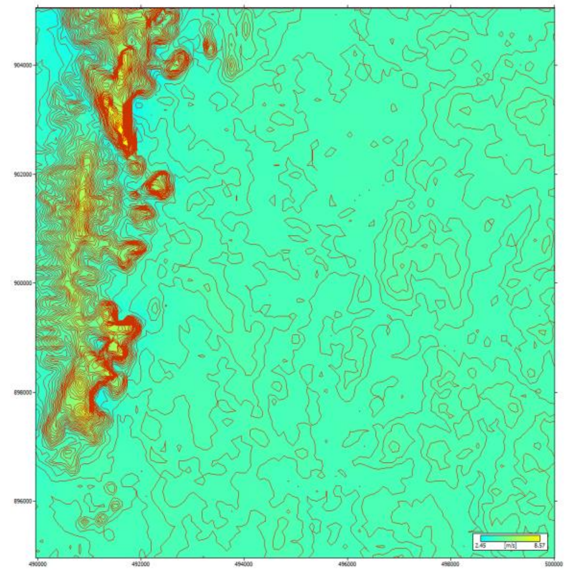
Mean wind speed maps of Krabi sites.



Mean wind speed of Krabi at 30 m hub height.



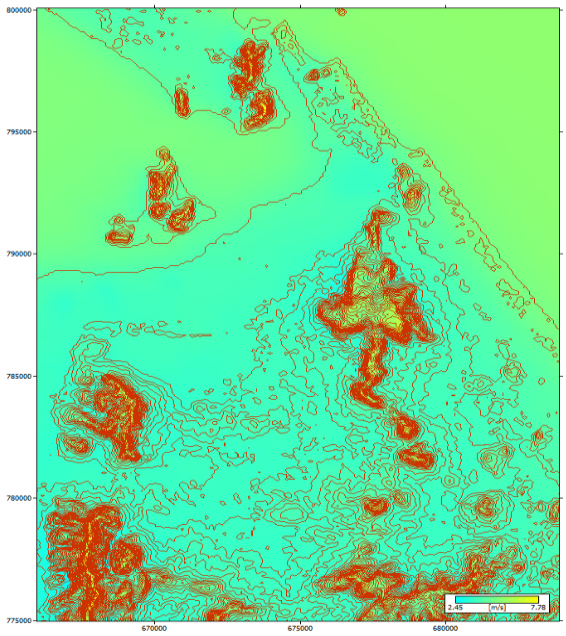
Mean wind speed of Krabi at 42 m hub height.



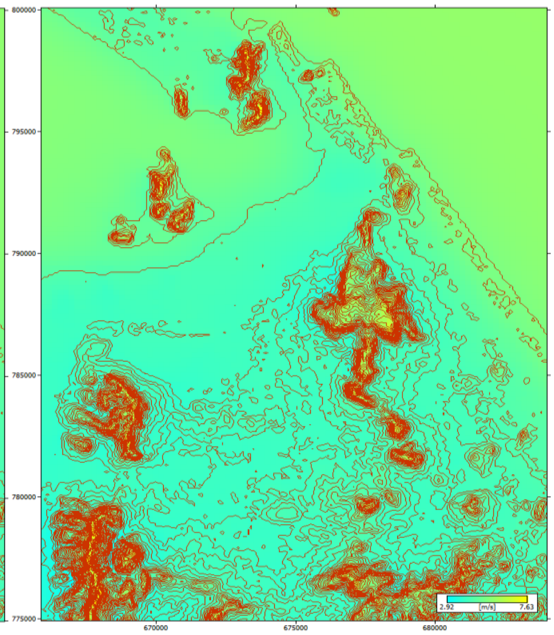
Mean wind speed of Krabi at 55 m hub height.

APPENDIX B

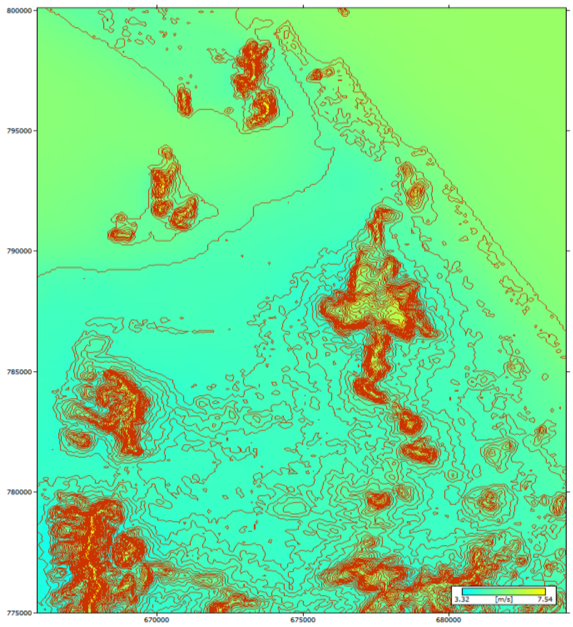
Mean wind speed maps of Songkhla sites.



Mean wind speed of Songkhla at 30 m hub height.



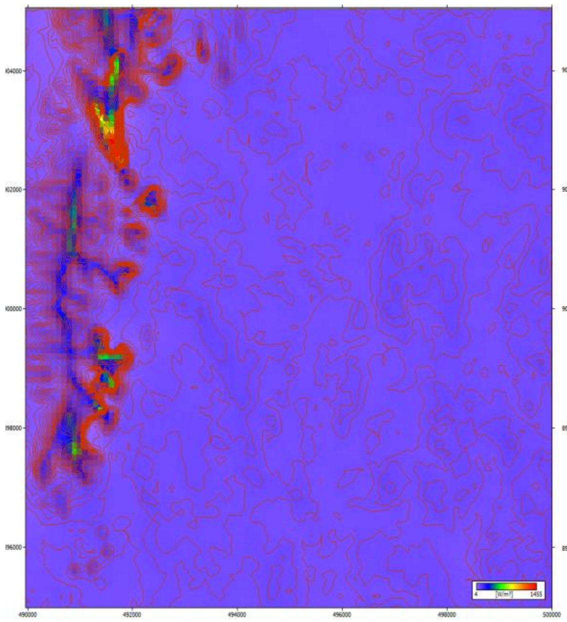
Mean wind speed of Songkhla at 42 m hub height.



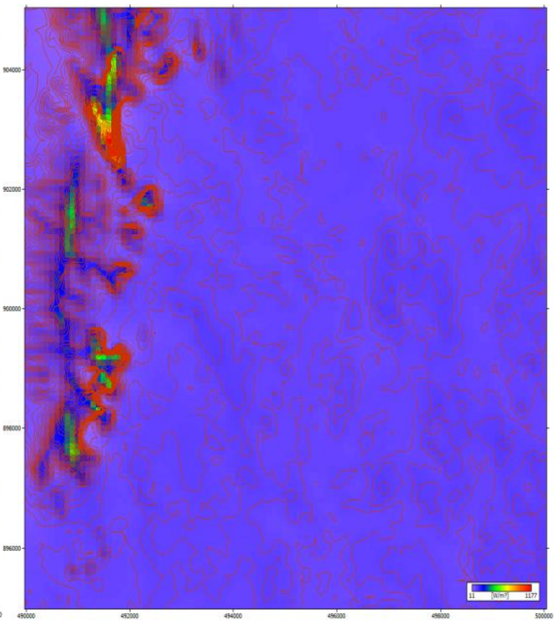
Mean wind speed of Songkhla at 55 m hub height.

APPENDIX C

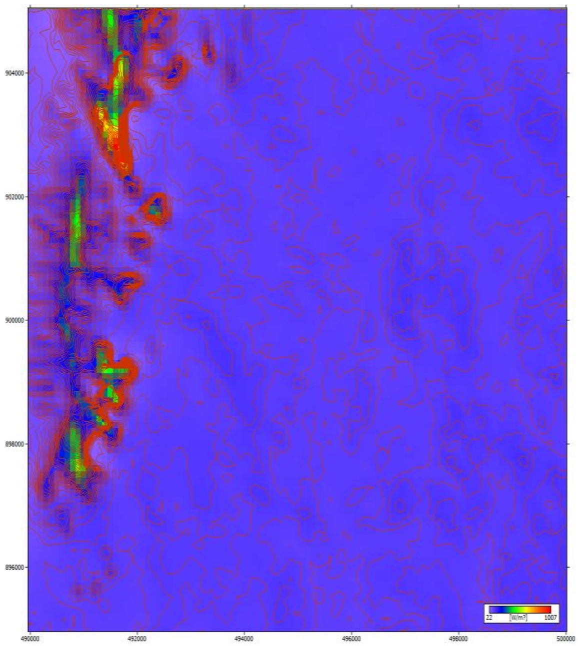
Mean wind power density maps of Krabi sites.



Mean wind power density of Krabi at 30 m hub height.



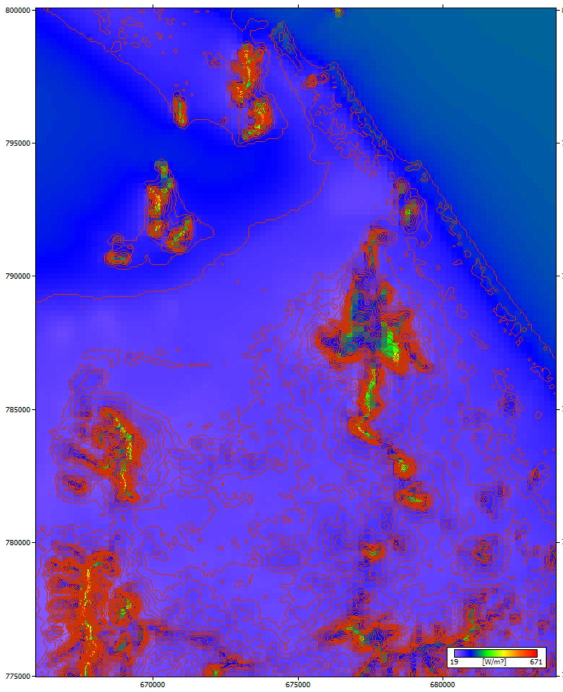
Mean wind power density of Krabi at 42 m hub height.



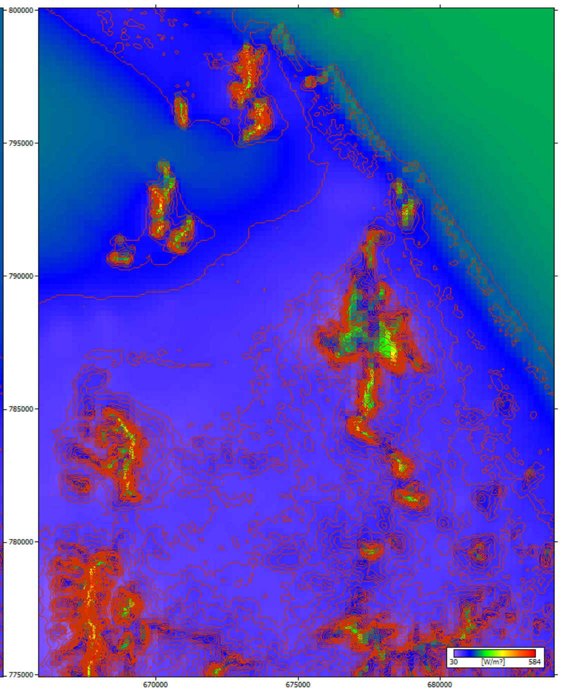
Mean wind power density of Krabi at 55 m hub height.

APPENDIX D

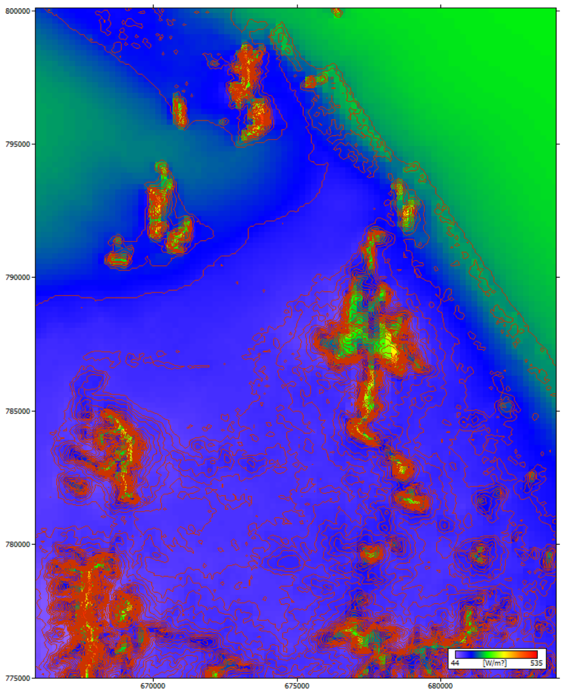
Mean wind power density of Songkhla sites.



Mean wind power density of Songkhla at 30 m hub height.



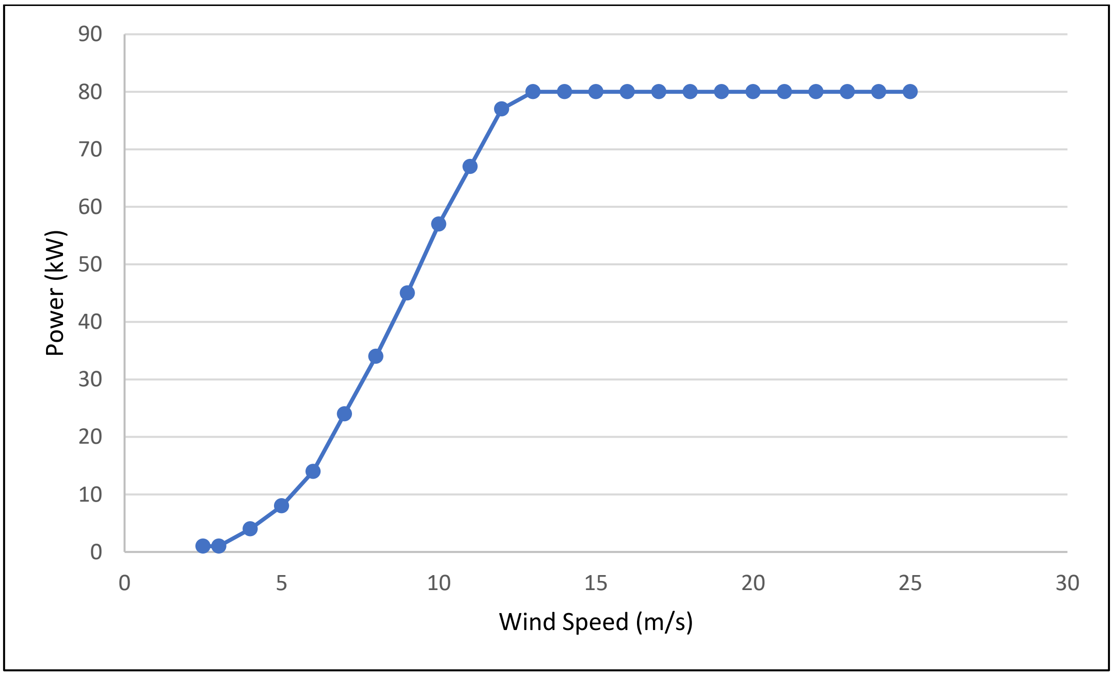
Mean wind power density of Songkhla at 42 m hub height.



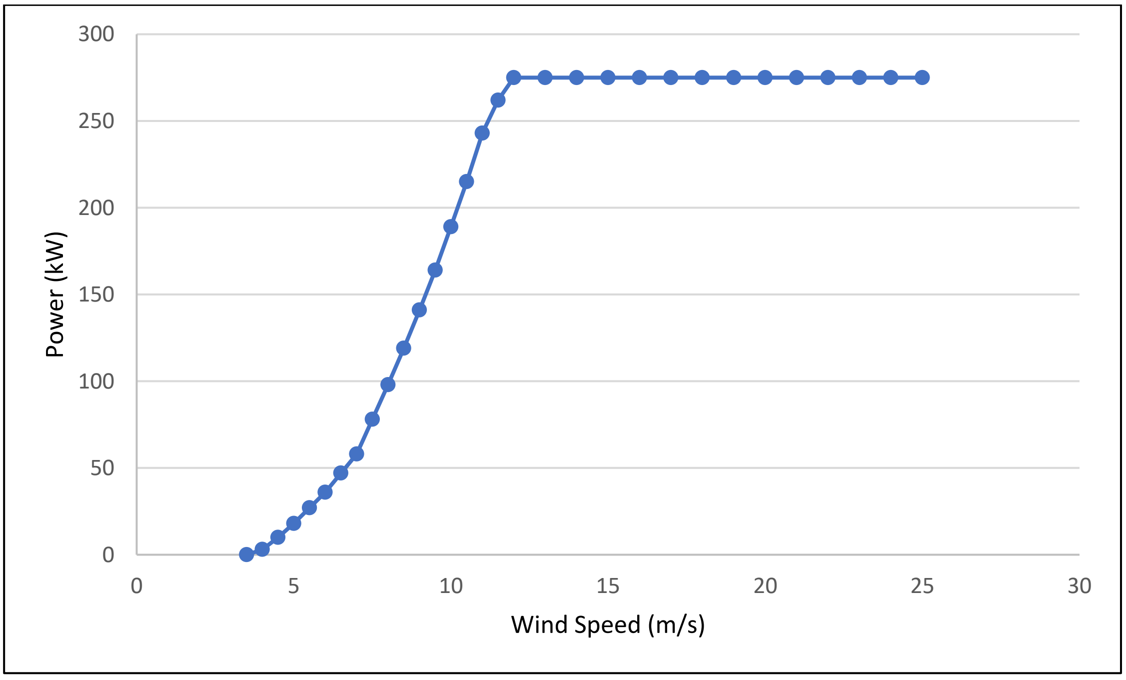
Mean wind power density of Songkhla at 55 m hub height.

APPENDIX E

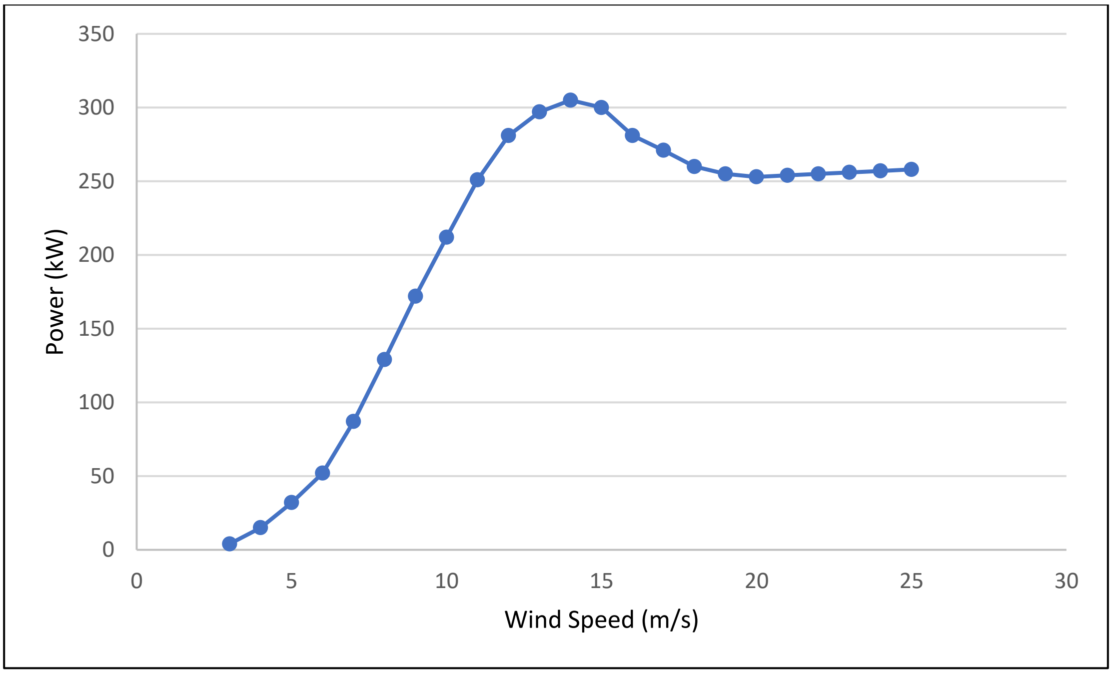
Power curves of wind turbines.



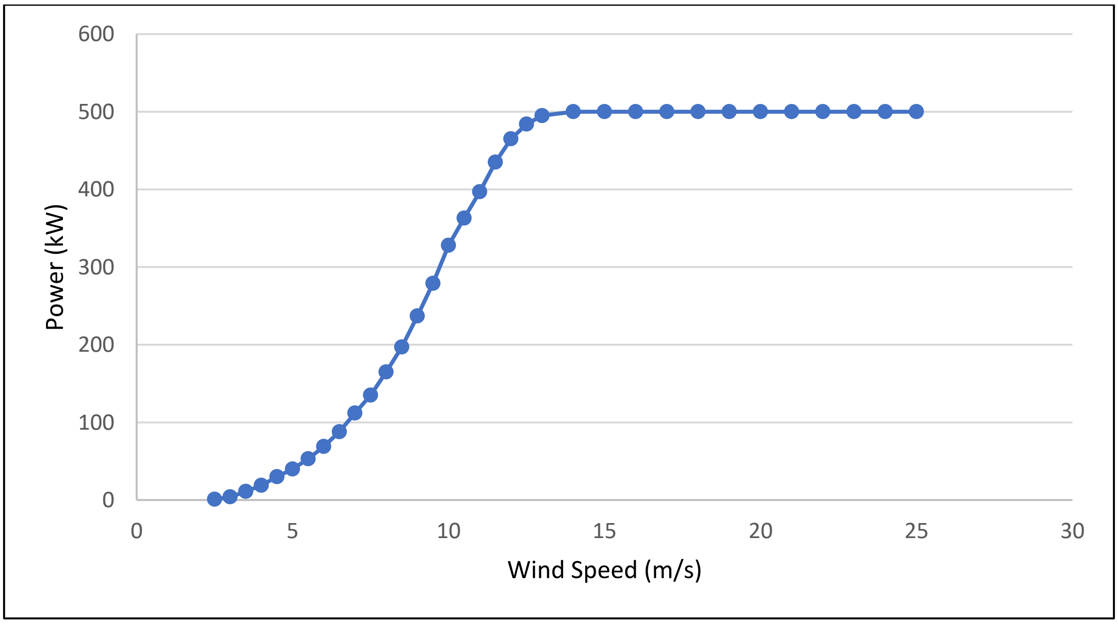
Power curve of the 80 kW Enercon (E-18) wind turbine.



Power curve of the 275 kW Vergnet (GEV MP-C) wind turbine.



Power curve of the 300 kW Bonus (Mk III) wind turbine.



Power curve of the 500 kW Enercon (E-40/5.40) wind turbine.

APPENDIX F

IEC classes for wind turbines [97].

Wind turbine class	I	II	III	IV	S
V_{ref} (m/s)	50	42.5	37.5	30	Values to be specified by the designer
V_{ave} (m/s)	10	8.5	7.5	6	
A I_{15}	0.18	0.18	0.18	0.18	
a	2	2	2	2	
B I_{15}	0.16	0.16	0.16	0.16	
a	3	3	3	3	

Note: The values apply at hub-height wind speed, and V_{ref}: Reference wind speed, V_{ave}: Annual average wind speed, A and B indicate the categories for higher and lower turbulence characteristics, I_{15} denotes the characteristic value of the turbulence intensity at 15 m/s and a is slope parameter to be used in the Normal Turbulence Model equation.

APPENDIX G

Published paper 1 (as a first author)

Sustainability – MDPI (Impact Factor 3.251; Indexing: Web of Science SCIE)

sustainability

MDPI

Article

Wind Farm Site Selection Using WAsP Tool for Application in the Tropical Region

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Abstract: Wind energy is one of the most promising renewable energy technologies worldwide; however, assessing potential sites for wind energy exploitation is a challenging task. This study presents a site suitability analysis to develop a small–scale wind farm in south–eastern Thailand. To this aim, the most recent available data from 2017 to 2019, recorded near the surface, at nine weather stations of the Thai Meteorological Department (TMD) were acquired. The analysis was conducted using standard wind–industry software WAsP. It was found that the mountain peaks and ridges are highly suitable for small–scale wind farm development. Nevertheless, the wind data analysis indicates that regions fall in low–to–moderate wind classes. The selected sites in south–eastern Thailand have mean wind speeds ranging from 5.1 m/s to 9.4 m/s. Moreover, annual energy production (AEP) of 102 MWh to 311 MWh could be generated using an Enercon E–18 wind turbine with a rated power of 80-kW at the hub height of 28.5 m. The Levelized Cost of Energy (LCOE) reveals that the development cost of a small–scale wind farm is lowest in the Songkhla and Yala provinces of Thailand, therefore these two locations from the investigated study region are financially most suitable. The findings could encourage researchers to further investigate low–speed wind energy mechanisms in tropical regions, and the demonstrated approach could be reused for other regions.

Keywords: WAsP; wind energy; site assessment; renewable energy resources; Thailand

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Citation: Kamdar, I.; Ali, S.; Taweekun, J.; Ali, H.M. Wind Farm Site Selection Using WAsP Tool for Application in the Tropical Region. *Sustainability* **2021**, *13*, 13718. https://doi.org/10.3390/su132413718

Academic Editors: Detlef Schulz and M. Sergio Campobasso

Received: 2 October 2021
Accepted: 25 November 2021
Published: 12 December 2021

1. Introduction

Energy is one of the leading impacts on the advancement of any nation. The prosperity of a nation largely depends on its stability of energy use [1]. Global renewable energy exploitation has increased over time, due to the urgency to meet global climate commitments that discourage the use of fossil fuels as energy sources [2,3]. Recently, wind power has evolved as a dominant sustainable energy option to mitigate energy effects on anthropogenic pollutants in the atmosphere [4,5]. Wind energy is also replenishable at the human timescale and is a cost-effective energy option in the long run. Because of these advantages, wind energy is frequently discussed and deployed by various nations [6]. A glimpse at the energy statistics reveals that the globally installed wind–generation capacity reached 651 GW in 2019 [4], and even during the pandemic, significant growth was noted in the wind energy production capacity worldwide, whereby it is expected to reach 817 GW before the year 2021 ends [7].

Being a fast–emerging economy, Thailand primarily consumes fossil fuels for its energy. Worldwide, Thailand ranks 20th in energy intensity and 34th in emissions intensity (carbon intensity). Regarding electricity generation, natural gas–fired power plants produced about 57% of the total electricity supply in 2018, while coal and lignite–based power plants accounted for about 18% [8]. It is clear that conventional energy sources such as natural gas, hard coal, and lignite are still the dominant sources of energy in electricity generation.

In 2012, the total installed electricity generating capacity in Thailand was recorded as 32,600 MW [9,10] and it had increased to 45,298 MW in 2019 [11], with 75% being generated from natural gas, coal, and lignite. Thailand's Ministry of Energy has forecast in the power development plan for 2018–2037 (PDP 2018: Revision 1) that the total installed electricity generating capacity will reach 77,211 MW at the end of 2037. The objective of the Ministry of Energy Thailand is to replace non–renewable energy sources by renewable energy by up to 37% by the end of 2037 under the power development plan (PDP) 2018–2037 [12]. Hence, this objective clearly describes the renewable energy roadmap in Thailand under PDP 2018–2037, to which all energy–related departments are determined [12–15].

Thailand is situated near the equator. It has relatively low to moderate wind speeds that average about 3 to 5 m/s. However, there are areas with appropriate topography, such as canyons, slopes, and mountain ranges, which have higher wind speeds and a utilizable annual mean wind speed of no less than 6.4 m/s [16]. The time patterns of the surface wind direction are characterized by the monsoon system. Thailand has two types of monsoons, namely the southwest and northeast monsoons that affect Thailand annually. The southwest monsoon generally runs between May and October bringing warm and moist air from the Indian Ocean, causing strong winds in mountain ridges in the northern lowlands and southern uplands of Thailand. The northeast monsoon runs from November to March, bringing cold and dry air from the South China Sea, which causes extreme winds in the Gulf of Thailand and coastal parts of the southern peninsular of Thailand. On average, the temperature in south–eastern Thailand is high. In 2018, the minimum monthly mean temperature recorded for January was 26.4 °C and the maximum mean temperature recorded for May was 28.5 °C in south–eastern Thailand [17]. Thus, this high temperature generally substantiates the need for the inspection of south–eastern Thailand for energy purposes.

Southern parts of Thailand have shown an increasing trend in power demand by 5–6% yearly due to developments in service and tourism fields, as reported in 2018 by the Electricity Generating Authority of Thailand [18]. In particular, south–eastern Thailand is one of the most electricity–demanding regions in Thailand as a gateway to the Malaysian border in the south, and hence it receives thousands of tourists each year. South–eastern Thailand covers an area of about 50,599 km^2 and has a population of more than 7.1 million people. Figure 1 displays the geographical locations of meteorological stations in the south–eastern region of Thailand.

Consequently, government organizations and wind power developers are continuously seeking the best locations for wind resource assessment. Though feasibility studies [9,10,19–22] have been conducted on wind resources for a few provinces in southern Thailand in the past, a detailed study scrutinizing wind resource assessments with a view to investigate potential areas for siting small–scale wind turbines is still lacking. Furthermore, most prior studies are somewhat obsolete due to growing industrialization and demographic changes that have affected land availability.

In the recent past, globally a significant number of scientific studies have been conducted extensively on wind energy. A short overview of some of the important investigations is briefly provided below for a better understanding of the accomplished work so far. Yang and Rojas [23] used Computational Fluid Dynamics (CFD) simulations in complex mountainous areas of north–eastern Iberian Peninsula, Spain, and showed reasonably high–speed and low–turbulence winds for turbines at the most suitable locations. Ashtine and Bello [24] conducted an evaluation of wind energy potential for small–scale wind turbines at hub heights of 10 m and 30 m in the regions of Ontario and Great Lakes in

Canada. Ko and Jeong [25] used statistical models such as Weibull and Rayleigh distributions to determine the annual energy density, annual energy production (AEP), and capacity factor in Weno Island, Chuuk State, and Micronesia. Flay and King [26] applied CFD, Wind Atlas Analysis and Application Program (WAsP) models, and wind–tunnel testing in New Zealand's installed infrastructure to improve wind speed forecasting methods for the wind pattern over complex terrain. Rogers and Ashtine [27] determined the maximum potential installed wind capacity in the Caribbean Island of Barbados. Bruck and Sandborn [28] established an innovative cost model to estimate the Levelized Cost of Energy (LCOE) obtained by a wind energy source under a Power Purchase Agreement. Saeed and Ahmed [1] used an artificial intelligence–based optimization technique along with a statistical approach to determine the Weibull parameters and performed technical and economic analyses, such as LCOE, for wind energy at eighteen locations in Pakistan.

Wind resource assessment has significant importance in the exploitation and consumption of wind energy. A precise evaluation of wind resources is crucial to the successful development of wind farms. Therefore, to improve the wind potential use, it is significant for a given site to ensure the effectiveness of the assessment.

To simplify mathematical models according to diverse assumptions, commercial companies have developed various software packages. In particular, WAsP designed by the Danish Riso National Laboratory has emerged as a convenient instrument for wind resource assessment [29]. WAsP is a computer–based industrial standard tool used all over the world for wind energy evaluation, site selection, and energy yield calculations for wind energy facilities in various terrains. The WAsP program has typically shown errors of less than 10% [30,31] and provides satisfactory results even with wind data from a single meteorological station [30]. Various researchers have promoted the WAsP tool for wind resource assessment, including [32] who used WAsP software to study climatology along with wind resource assessment and computed the regional wind atlas for South–Central Kansas, United States. Hernández Galvez and Saldaña Flores [33] applied Weather Research and Forecasting and WAsP for mesoscale and microscale wind resource modeling, respectively. Furthermore, in LCOE, the capacity factor and cost of wind turbines were calculated in the State of Tabasco, Mexico. Ramadan [34] investigated the economic viability of wind farms applying WAsP and WindPRO tools in the Egyptian Sinai Peninsula. Liu and Gao [30] used a long–term tower measurement approach for a meteorological tower with a height of 325 m and 15 levels in Beijing, China, using the Weibull function and WAsP software to calculate the potential of wind energy. Sharma and Ahmed [35] inspected wind resources of the isolated island of Kadavu and the urban Suva peninsula in the Fiji Island at a height of 34 m using WAsP. Verma [36] examined the performance and reliability of an old wind farm located at Madhya Pradesh, India, for repowering, along with an environmental impact and techno–economic analysis. Himri and Merzouk [37] used RETScreen and WAsP tools in the South–West region of Algeria to investigate wind farm financial feasibility and wind resource assessment. Thus, it has been proven that WAsP is a powerful tool for wind resource assessment. However, studies on wind resource assessment using the WAsP model in tropical areas have been limited. The study described here will provide a scientific approach for wind resource assessment in tropical nations like Thailand with a methodology compliant to international standards.

According to the authors' knowledge, there is a gap in the literature in exploring wind resource assessments for siting small–scale wind turbines using the WAsP tool in the study region, i.e., in south–eastern Thailand. Therefore, this study deployed the WAsP tool to site small–scale wind farms through a thorough investigation of the regional wind resources. The WAsP simulation computes the mean wind speed and the mean power density for selected sites of south–eastern Thailand. The power analysis and capacity factor of the sites were calculated for the Enercon E–18 wind turbine with a rated of 80 kW. This will allow the regional energy practitioners to determine their choices to tackle the rising power demands, increasing by 5–6% annually, through renewable wind power. Moreover, this study will also contribute to the Alternative Energy Development Plan for Thailand whose objective is to substitute fossil fuels by up to 37% by 2037 under the power development plan 2018–2037.

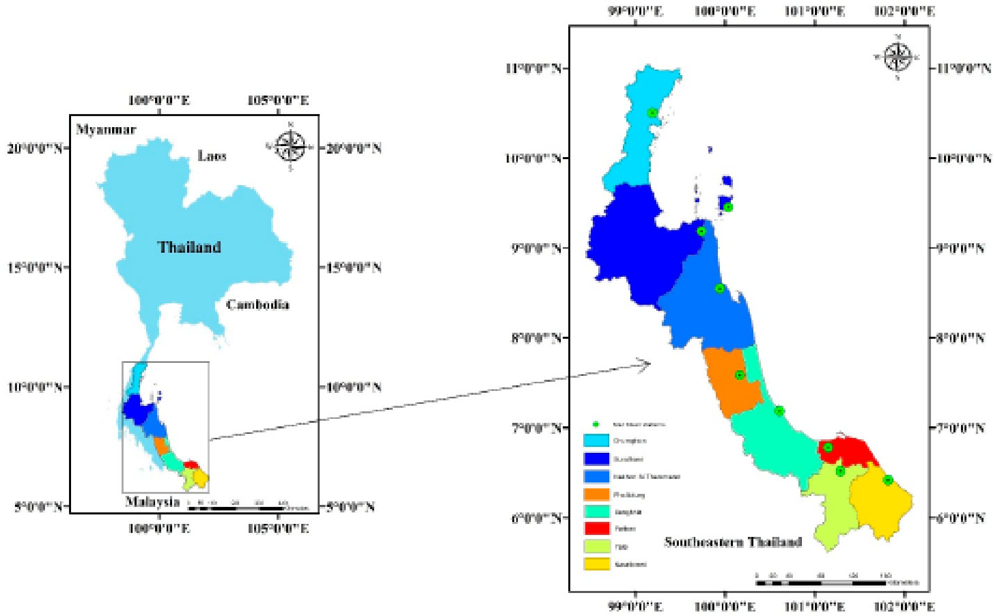


Figure 1. Study area and distribution of meteorological stations in south–eastern Thailand (Source: Kamdar et al. [38]).

2. Material and Methods

2.1. Overview of Methodology

The flow diagram in Figure 2 shows the proposed scheme for siting small–scale wind turbines. The first step, as expected, is the analysis of raw wind data obtained from TMD. In the second step, the WAsP Climate Analyst tool is used to generate an estimate of wind climatology for all nine stations. It uses the 10-min average wind speed recorded at 10 m above the ground level (AGL). The WAsP Climate Analyst estimates wind climatology in the form of a wind rose and a Weibull distribution function. In the third step, the coordinates and topographic information are entered into the WAsP Map Editor tool to create the surface roughness and contour maps for the nine stations. The fourth step mainly involves the use of the WAsP module in terms of mean wind speed, power density, and AEP using the Enercon E–18 wind turbine to conduct a power analysis for the selected sites. The fifth and final step is the estimation of the levelized cost of energy.

2.2. Meteorological Mast and Wind Data Acquisition

The measurement towers in the Southern Meteorological Center (east coast) contain meteorological instruments such as anemometers, wind vanes, barometers, thermometers, rain gauges, and hygrometers. Along with these, the observation items comprise the 10–min average wind speed and wind direction, temperature, rainfall, atmospheric pressure, and relative humidity, which are mainly considered over an international standard period for wind measurement [39]. A description of the various measuring tools is provided in Table 1.

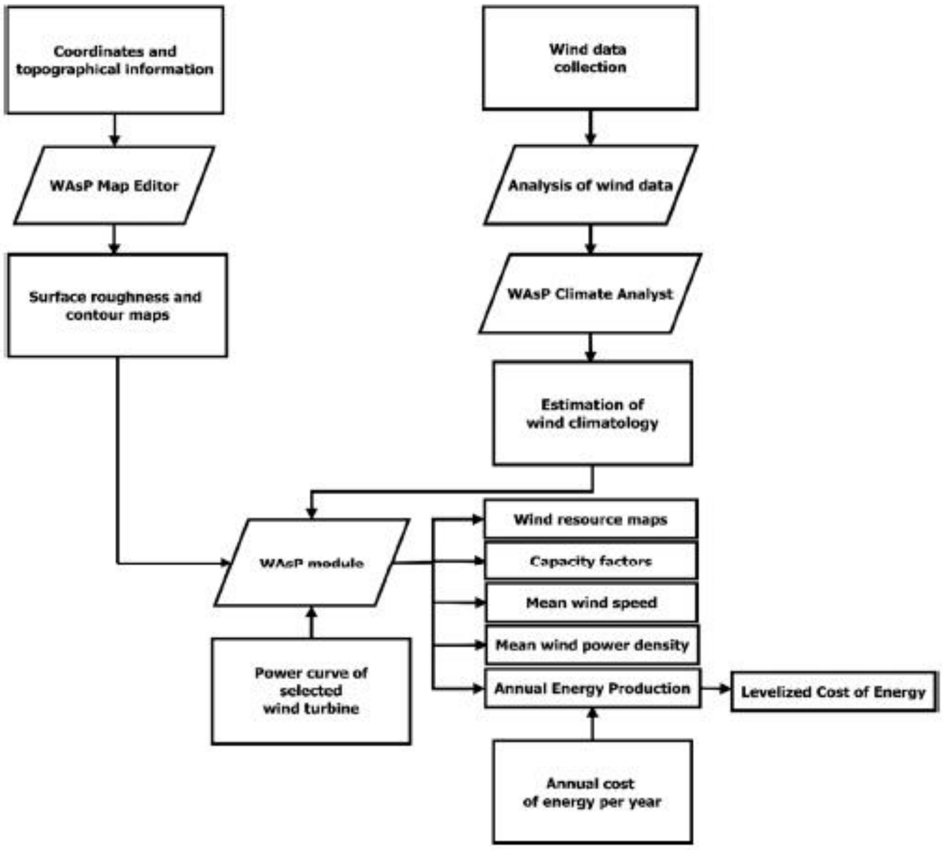


Figure 2. Flow diagram of the proposed scheme.

Table 1. Tool specifications obtained from Thai Meteorological Department [40].

Equipment	Sensor Type	Instrument Range	Accuracy	Height (AGL)
Anemometer	Ultrasonic sensor	0–75 m/s	±2%	10 m
Wind vane	Ultrasonic sensor	0–360°	±2%	
Thermometer	Platinum resistance element	−40 °C to 50 °C	±0.3 °C	
Barometer	Digital	800–1100 hPa	±0.2	
Relative humidity	Thin film	0–100% RH	±2% RH	
Rain gauge	Tumbling cup	0–100 mm/h	2%	

At a minimum, one year of observation data is essential to review the development possibility and to measure the potential wind energy reserve amount [25]. To avoid seasonal bias, this study observed the wind data of nine weather stations located in south–eastern Thailand, at a standard height of 10 m AGL, over a period of 3 years. The geographical coordinates and measurement periods can be seen in Table 2.

Table 2. Geographical coordinates and description of measurement sites in south–eastern Thailand (obtained from Thai Meteorological Department [41]).

Station Name	Latitude (°)	Longitude (°)	Altitude (m a.s.l.)	Measurement Period
Chumphon	10.49	99.18	22	2017–2019
Kanchanadit	9.18	99.73	27	2017–2019
Koh Samui	9.45	100.03	6	2017–2019
Nakhon Si Thammarat	8.54	99.93	5	2017–2019
Narathiwat	6.41	101.81	5.13	2017–2019
Pattani	6.78	101.15	6	2017–2019
Phatthalung	7.58	100.16	4.15	2017–2019
Songkhla	7.18	100.60	6	2017–2019
Yala	6.51	101.28	36.04	2017–2019

Note: a.s.l.: Above sea level.

2.3. *The Weibull Distribution*

Wind speed is the basic factor that must be measured while selecting and designing the wind farm. Its Weibull probability distribution function (PDF) significantly influences the wind turbine performance [34].

The two–parameter Weibull probability distribution is frequently used in calculations to describe the wind speed histogram. It is also utilized in WAsP to study the wind characteristics in every direction as characterized by sectors [32]. The probability distribution function PDF of Weibull distribution is defined by Equation (1) [39,42]:

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

Here, $f(U)$ represents the Weibull probability density function of observing wind speed U (m/s), A defines the Weibull scale parameter in m/s while k indicates the dimensionless Weibull shape parameter. The Weibull shape parameter k has values between 1 and 3 and describes the behavior of wind in accordance with its speed, where small values of k shows variations in wind variables, while large values of k indicate a rather constant wind speed [32,39].

Then, the corresponding cumulative probability function for the Weibull distribution is expressed in Equation (2) [43]:

$$F(U) = 1 - e^{-\left(\frac{U}{A}\right)^k} \quad (2)$$

where $F(U)$ defines the cumulative distribution function of observing wind speed U. The cumulative distribution is the integral of the density or PDF with respect to speed [39].

2.4. *Wind Atlas Analysis and Application Program*

WAsP is a well–established industrial standard as a computer–based program and has been created by the Department of Wind Energy at the Danish Technical University in 1987 [44]. It is a widely used tool for projects related to wind energy and wind engineering [26] in wind resource evaluation, energy yield calculations, and site selection of a wind energy facility.

WAsP uses a linear model composed of a comprehensive collection of individual modules according to the physical characteristics of flows in the planetary boundary layer to predict the vertical and horizontal extrapolation of wind [45]. The WAsP flow model requires the following inputs: (1) Terrain height, (2) surface roughness, and (3) obstacle effects, as can be seen in Figure 3, which is also known as the wind atlas methodology. The WAsP model can calculate the energy production of a single turbine site or of a wind farm, and considers wake losses, layout, and various other factors. The wind atlas provides a hypothetical wind climate for a featureless and preferably planar topography with an even land cover in case the entire computational domain is under the same weather regime [32]. Using wind measurements in actual terrain to study the wind atlas of the region, the WAsP flow model is applied in order to eliminate the regional terrain effects as expressed in Equation (3):

$$W_R = W_A - ORO_A - ROU_A - OBS_A \quad (3)$$

Here, W_R represents the general regional wind climate, W_A defines the recorded wind at the measuring mast, while ORO_A, ROU_A, and OBS_A indicate the properties of orography, roughness, and obstacles at position A, respectively. The orographic effects on the flow are calculated using the spectral BZ (Bessel Expansion on a Zooming Grid) model in WAsP, which is essentially based on the Jackson–Hunt theory. Thus, the WAsP model is primarily in the family of the Jackson–Hunt theory [46]. The internal boundary layer height (h) created under the influence of variations in surface roughness from z'_{01} to z'_{02} in the windward direction is calculated through the roughness model in WAsP by Equation (4):

$$\frac{h}{z'_0}\ln\left(\frac{h}{z'_0}-1\right) = 0\cdot 9\frac{x}{z'_0} \quad (4)$$

where x shows distance to the surface roughness change line and z'_0 is equal to max (z'_{01}, z'_{02}). This study used the newest version of WAsP software, namely WAsP 12 (Version 12.06.0024), WAsP Climate Analyst (Version 3.01.0049), and WAsP Map Editor (Version 12.3.1.54).

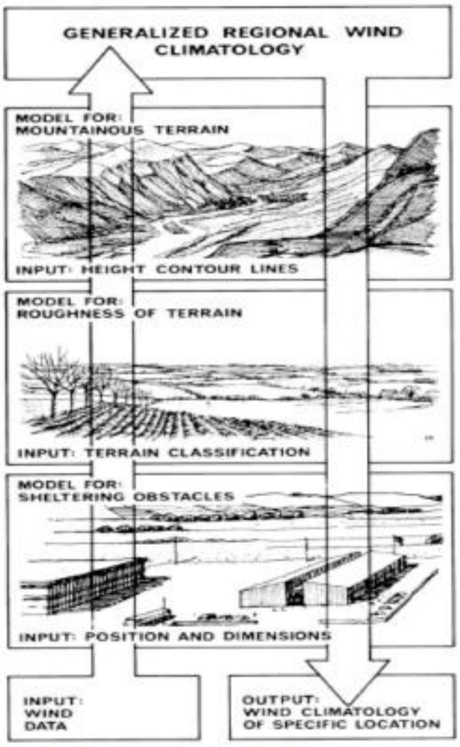
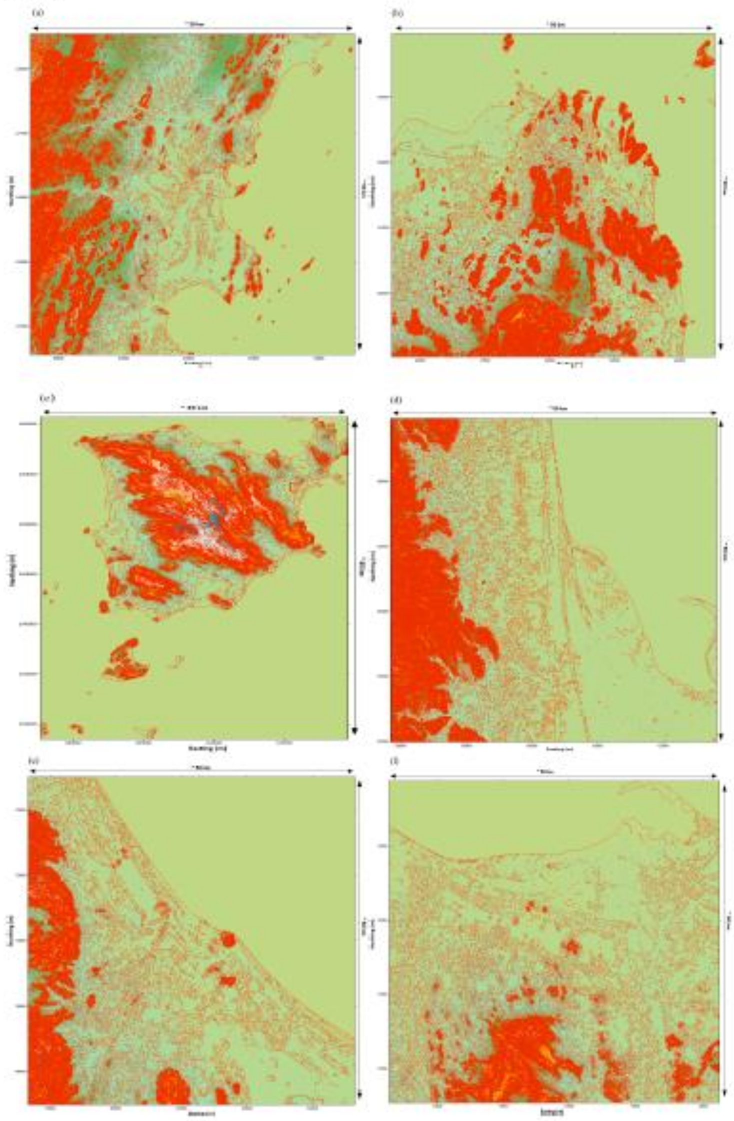


Figure 3. The wind atlas methodology with inputs and outputs. Regional wind climatology is studied to predict the wind climate and resources at specific locations using the wind data from a meteorological model [47].

2.5. Surface Elevation and Roughness Maps

The elevation and roughness maps of south–eastern Thailand are important inputs in the WAsP tool. Therefore, the WAsP Map Editor tool in the WAsP program was used to prepare elevation and roughness maps. The Universal Transverse Mercator coordinate system, Zone 47, along with the datum WGS–1984, was used for the mapping. The maps are a Digital Elevation Model (DEM) developed under the Global Wind Atlas (GWA) Warehouse map server, which uses the Shuttle Radar Topography Mission (SRTM) data and the Viewfinder for regions outside SRTM coverage. The elevation maps of the study area are presented in Figure 4, which has a horizontal resolution of 3 arc–seconds (approximately 90 m).



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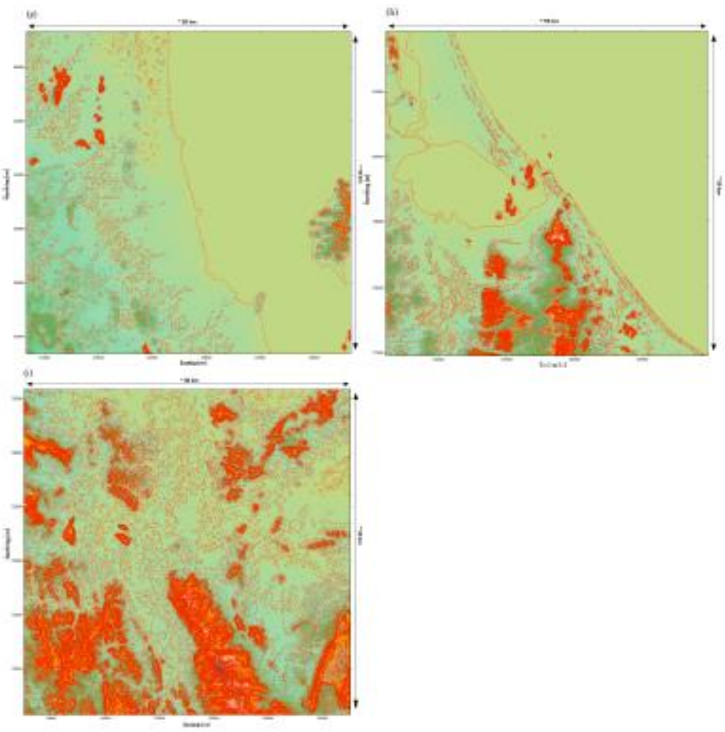


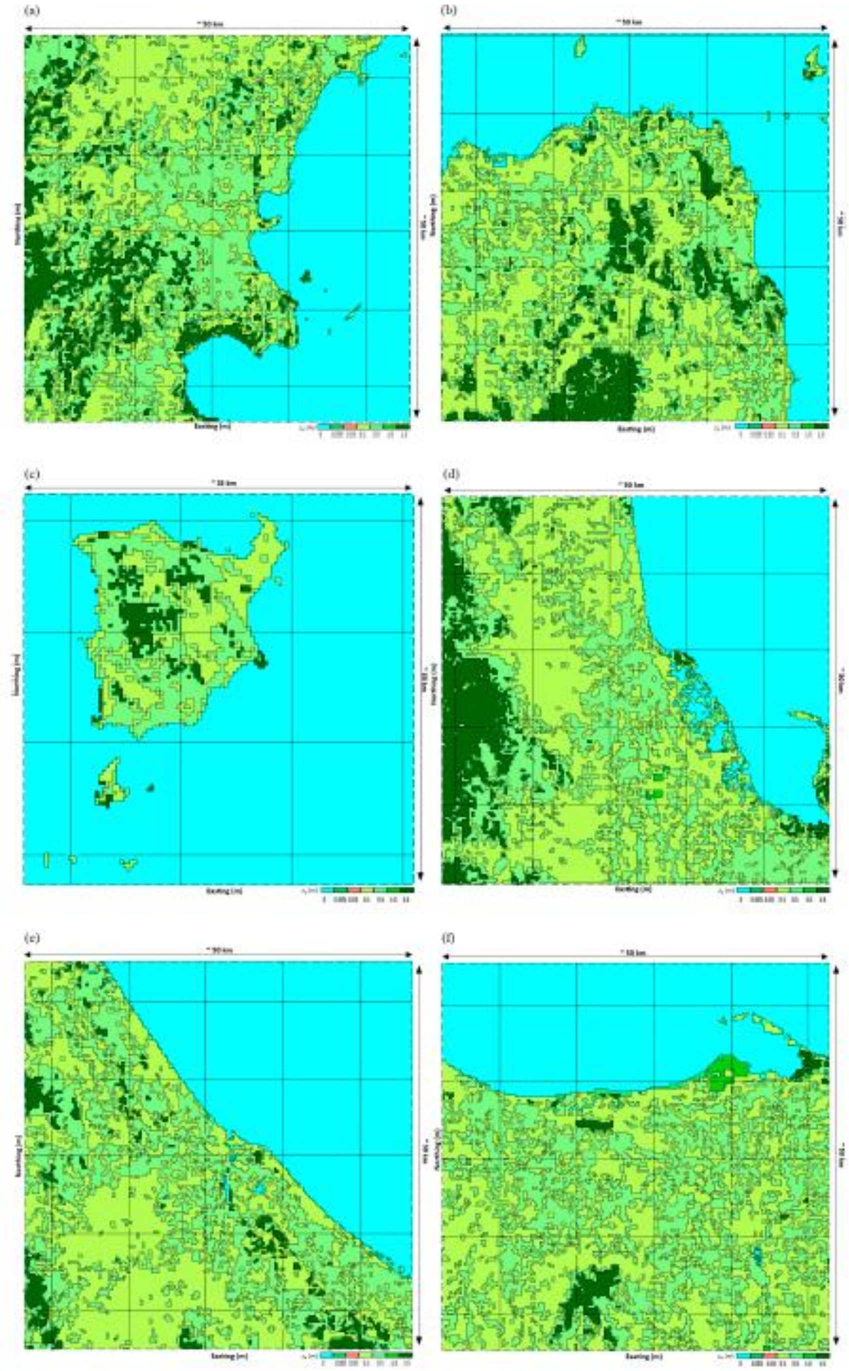
Figure 4. Elevation maps of the study area: (**a**) Chumphon, (**b**) Kanchanadit, (**c**) Koh Samui, (**d**) Nakhon Si Thammarat, (**e**) Narathiwat, (**f**) Pattani, (**g**) Phatthalung, (**h**) Songkhla, (**i**) Yala.

Roughness maps in Figure 5 are formed by using the available data from the GWA Roughness *GlobCover* database provided by the GWA Warehouse map server. The dataset has a 22-class land use classification system and has a 10 arc–seconds (approximately 300 m) resolution. Due to insufficient information related to the surface roughness with high resolution, the surface roughness in south–eastern Thailand can be characterized into seven types: Water bodies, bare areas, grassland, croplands, flooded forest, urban areas, and forests; while the surface roughness lengths in WAsP by default are 0, 0.005, 0.03, 0.1, 0.5, 1.0, and 1.5 m, respectively.

2.6. Economic Analysis

The LCOE is elaborated as a measure of the average net present value of the generated electricity for a particular system over its lifespan [8,28]. The LCOE is computed in \$/kWh or \$/MWh. The details of the input parameters to calculate LCOE are shown in Table 3. LCOE is a suitable method for assessing the viability of energy production for commercial service and specifies its effectiveness compared to other technologies [48]. The summarized form of LCOE is given in Equation (5):

$$\text{LCOE} = \frac{\text{Average total } cost \text{ to build and operate } a \text{ power plant over its lifetime}}{\text{Total power generated by the power plant over that lifetime}} \quad (5)$$



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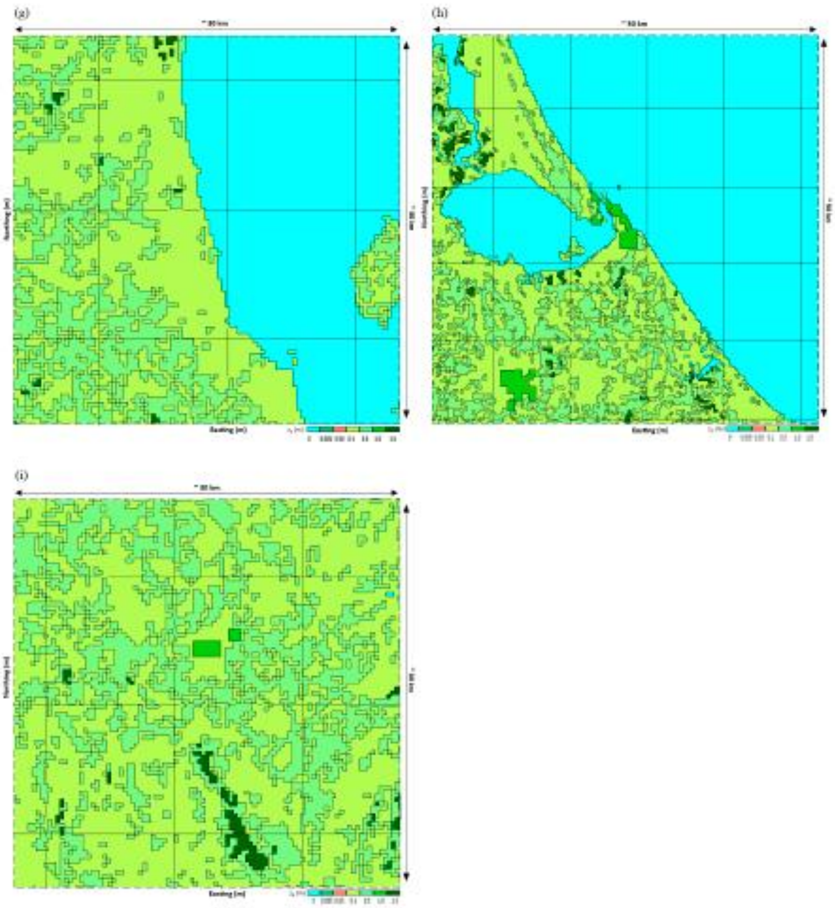


Figure 5. Surface roughness maps of the study area: (**a**) Chumphon, (**b**) Kanchanadit, (**c**) Koh Samui, (**d**) Nakhon Si Thammarat, (**e**) Narathiwat, (**f**) Pattani, (**g**) Phatthalung, (**h**) Songkhla, (**i**) Yala.

or

$$\text{LCOE} = \frac{\text{CAPEX} + \text{OPEX}}{\text{Power production}} \tag{6}$$

where CAPEX represents the construction or capital cost while OPEX shows the operation and maintenance cost of the facility. The detailed mathematical form of Equations (5) and (6) is:

$$\text{LCOE} = \frac{C_t + \left\{\sum_{t=1}^{n} Of_t/(1+d_r)^t + \sum_{t=1}^{n} 0fv_t/(1+d_r)^t\right\} + (FC + HR)}{\sum_{t=1}^{n} P_t/(1+d_r)^t} \tag{7}$$

where C_t is the construction or capital expenditure in terms of tth year in USD, Of_t represents the fixed operation while Ofv_t is the variable operation and maintenance expenditures in terms of tth year USD, d_r denotes the discount rate, FC shows fixed cost, HR indicates human resource cost, P_t symbolizes the energy produced in the tth year in MWh, and n is the plant operation period.

Table 3. Variables for the estimation of the LCOE.

Parameters	CAPEX	Fixed OPEX	Variable OPEX	Capacity Factor	Lifetime
	Million $/MW	$/kW–yr	$/MWh	%	(t) yr
Wind	2.52	10.28–60.0	4.82–23.0	26.0–52.0	25
Exchange rate	31.24 (THB/$)	–	–	–	–
Discount rate	7.5 (%)	–	–	–	–
FiTFix	1.81	–	–	–	–
FiTVar	1.85	–	–	–	–

Adapted from Ref. [8]. Note: LCOE: Levelized Cost of Energy, CAPEX: Capital Expenditures, Fixed OPEX: Fixed Operating Expenses, Variable OPEX: Variable Operating Expenses, Year: yr, THB/$: Thai Baht/Dollar, FiTFix: Fixed Feed–in Tariff, FiTVar: Variable Feed–in Tariff, MW: Megawatt, kW: Kilowatt, MWh: Megawatt hour.

3. Results and Discussion

3.1. Analysis of Wind Speed, Wind Direction, and Wind Power Density

Wind speed is the basic parameter in wind resource assessment for energy production utilizing wind turbines. During proper planning, it is extremely important to consider different periods of variations such as daily, monthly, annual, and seasonal, and the total annual mean wind speed. At extremely high (above 25 m/s) or low (below 3 m/s) wind speeds, possible shutdown periods of the turbine should be identified (when it will be out of service). The capacity factor and predicted power production predominantly depend on the selected wind turbine type, size, and manufacturer [34]. Figure 6 illustrates the monthly average wind speed at 10 m (AGL) for the 3-year period. The average wind speed is lower in the months from May to October, while it is higher from November to April due to the northeast monsoon that brings cold and dry air from the South China Sea, causing strong winds in the Gulf of Thailand and coastal regions of south–eastern Thailand.

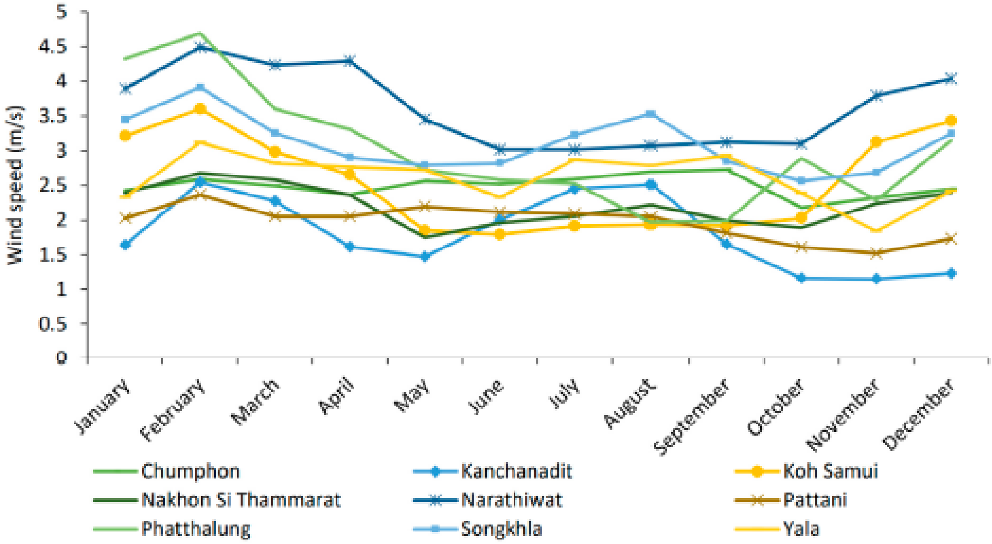
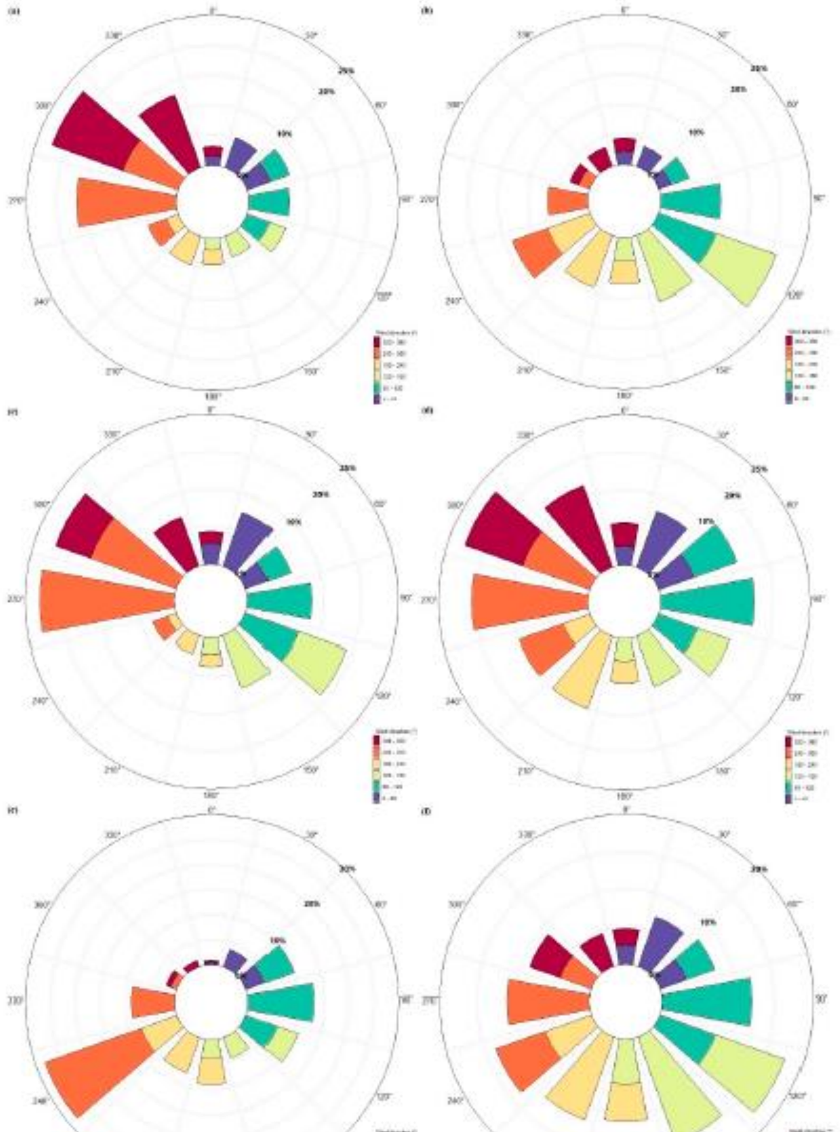


Figure 6. Monthly average wind speed at 10 m AGL.

The dominant wind direction has great importance in the evaluation of a wind energy resource [35]. In order to harness the maximal wind energy, the orientation of the wind generator should be perpendicular to the wind direction [34]. Figure 7, clearly depicts the sector–wise distribution as wind roses for south–eastern Thailand in 12 parts, with discrete 30° intervals.



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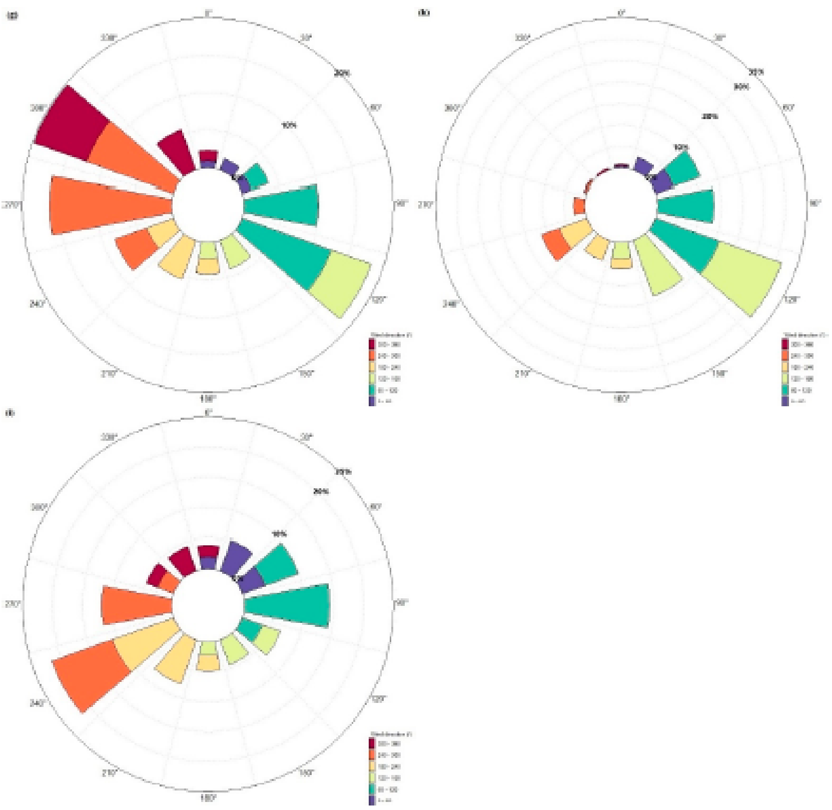


Figure 7. Wind rose diagrams of south–eastern Thailand: (**a**) Chumphon, (**b**) Kanchanadit, (**c**) Koh Samui, (**d**) Nakhon Si Thammarat, (**e**) Narathiwat, (**f**) Pattani, (**g**) Phatthalung, (**h**) Songkhla, and (**i**) Yala.

The wind rose diagrams in Figure 7 show that the dominant wind direction observed over the three years is northwest in Chumphon and Nakhon Si Thammarat, whereas it is southwest in Narathiwat and Yala. Similarly, the southeast direction is dominant in Kanchanadit, Pattani, and Songkhla. The bi–directional northwest–southeast wind rose is more pronounced in Phatthalung, while west is the dominant direction in Koh Samui. Moreover, the occurrence rate of northwest wind direction for Chumphon and Nakhon Si Thammarat is almost 23%, whereas the occurrence rate of southwest wind for Narathiwat and Yala is about 28% and 22%, respectively. Similarly, the occurrence rate of the southeast direction in Kanchanadit, Pattani, and Songkhla is prevailing with 21%, 18%, and 32%, respectively. The occurrence rate of bi–directional northwest–southeast wind in Phatthalung is almost 24% from the northwest and 23% from the southeast, while the occurrence rate of the west direction in Koh Samui is almost 23%.

Wind power density is the maximum available wind power per unit area and can be expressed as [25,49]:

$$P = 0.5\rho v^3 \tag{8}$$

Similarly, the mean wind power density can be measured by using the observed wind data, and is given by [36]:

$$\overline{P} = \frac{1}{2N}\overline{\rho}\sum_{i=1}^{Nobs} n_i v_i^3 \tag{9}$$

where $\overline{\rho}$ indicates the mean air density (kg/m^3) of a specific time interval, v_i is the ith wind speed (m/s), and n_i is the number of occurrences of ith speed (frequency).

The wind power density can be divided into seven categories on the basis of wind speed and annual wind power density, as shown in Table 4 [25,50].

Table 4. Wind power density classification scheme [25,51].

Wind Power Class	Mean Wind Speed (m/s)	Wind Power Density (W/m^2)	Resource Potential
1	3.5–5.6	50–200	Poor
2	5.6–6.4	200–300	Marginal
3	6.4–7.0	300–400	Fair
4	7.0–7.5	400–500	Good
5	7.5–8.0	500–600	Excellent
6	8.0–8.8	600–800	Outstanding
7	Above 8.8	Above 800	Superb

Figure 8 represents the annual mean wind power density in south–eastern Thailand at a 28.5 m hub height. The wind energy resource in south–eastern Thailand varies from station to station as shown in Table 3. For south–eastern Thailand, the annual mean wind power density with the highest value of 802 W/m^2 was found in Phatthalung, which belongs to wind class 7, followed by Yala with 474 W/m^2 and Kanchanadit with 429 W/m^2, and both these stations fall in wind class 4. The minimum annual mean wind power density of 174 W/m^2 was recorded in Chumphon, followed in increasing order by Pattani with 196 W/m^2, and both stations belong to wind class 1; while Nakhon Si Thammarat with 271 W/m^2 falls in wind class 2. Similarly, Narathiwat, Songkhla, and Koh Samui were at 390 W/m^2, 378 W/m^2, and 350 W/m^2, respectively, belonging to wind class 3.

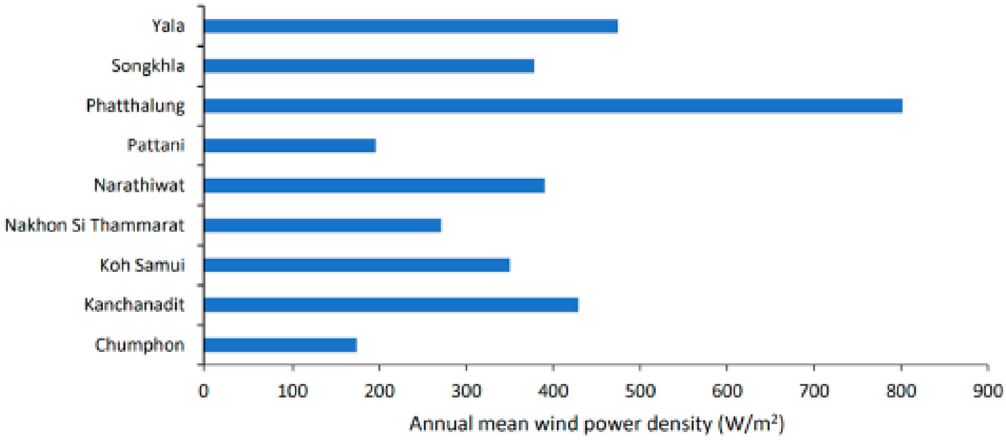
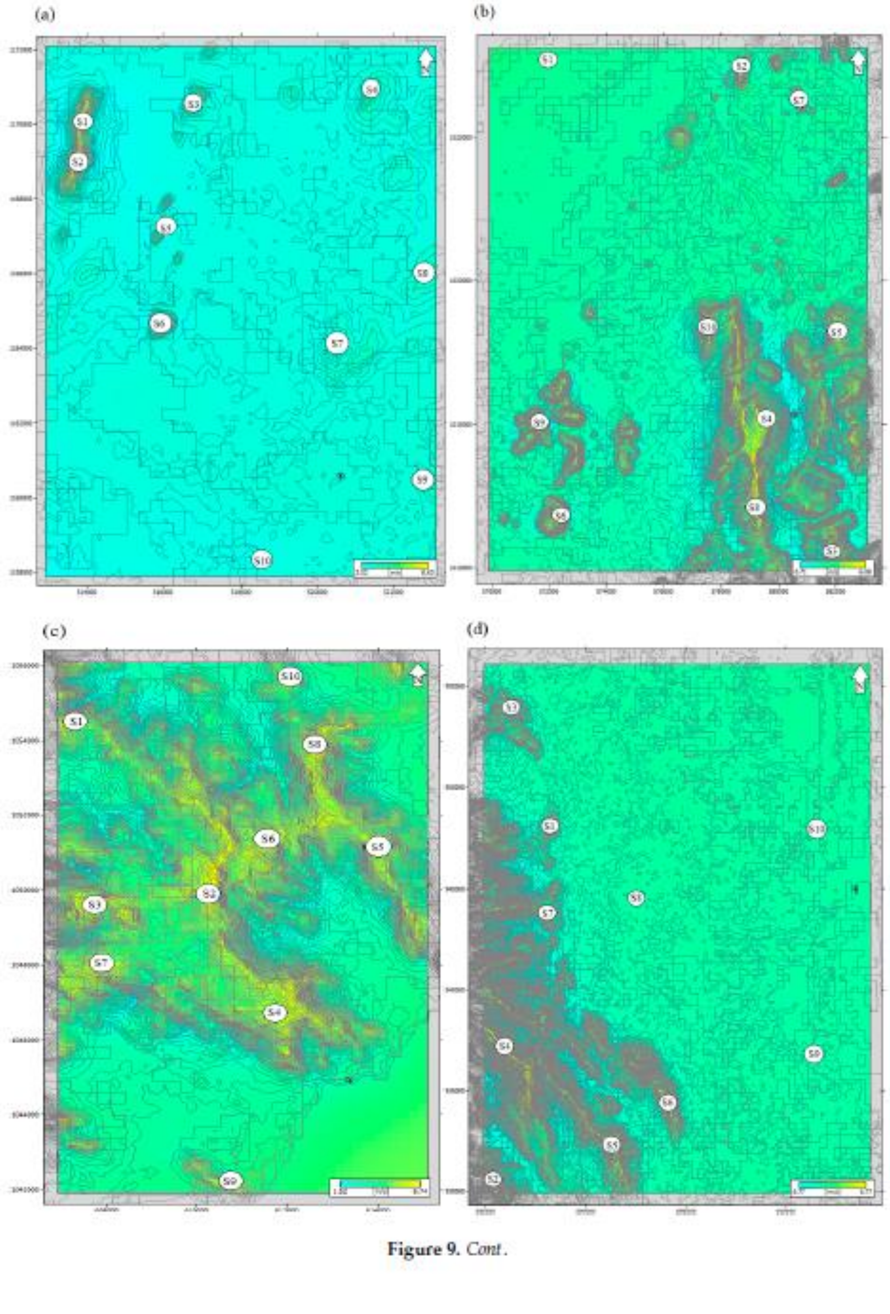


Figure 8. Annual mean wind power density of south–eastern Thailand at 28.5 m hub height.

Yu and Qu [52] reported that good or excellent potential sites are suitable candidates for establishing a wind energy facility, with wind power density exceeding 400 W/m^2 or even reaching 800 W/m^2, and wind speed on average is above 7.0 m/s. Thus, the various sites in south–eastern Thailand inspected using WAsP possess very good potential for wind farm development.

3.2. *WAsP Analysis: South–Eastern Thailand*

The wind resource maps show the mean wind speed extrapolated for a portion of south–eastern Thailand in Figure 10. This study identifies ideal sites in the eight provinces of south–eastern Thailand. WAsP analysis was carried out for the thickly populated, increasing infrastructure and remote areas. Nine stations were inspected by analyzing 3 years of wind data for a prospective wind farm facility. In the next stage, a power analysis was conducted for the selected locations in accordance with the mean wind speed, wind power density, accessibility by using roads, and electrical transmission lines [53].



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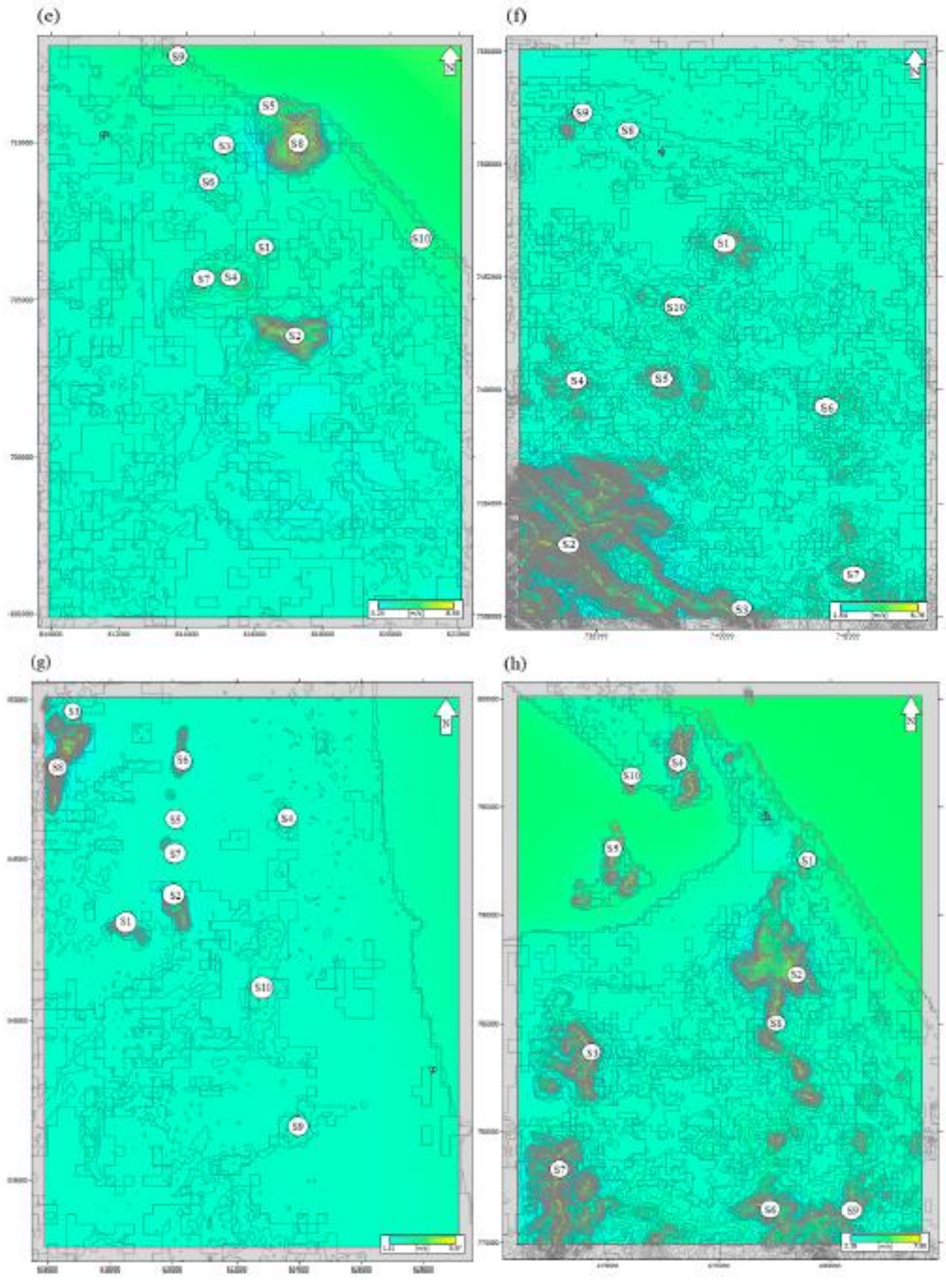

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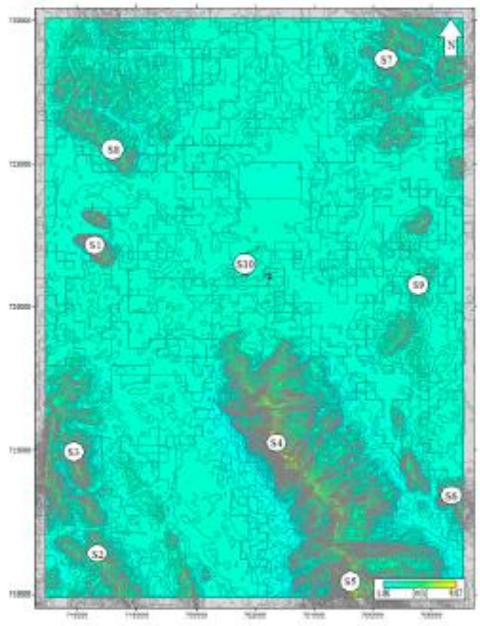

Figure 10. High–resolution wind speed maps of the study area at 28.5 m hub height: (**a**) Chumphon, (**b**) Kanchanadit, (**c**) Koh Samui, (**d**) Nakhon Si Thammarat, (**e**) Narathiwat, (**f**) Pattani, (**g**) Phatthalung, (**h**) Songkhla, and (**i**) Yala.

Wind speed highly varies in direction with respect to different locations; thus, those areas encompassed by the resource grid fall within the WAsP's limits of predictability. Various types of wind turbines can be proposed for the selected sites. However, the wind turbine model for this work is selected on the basis of the availability and reliability of information about the specifications of the power curve. Other types of wind turbine models available in the market may be more appropriate than the one used in this assessment. For instance, there is a wind turbine model that is specifically designed for a low–speed wind regime, but it lacks specifications in the literature. Eight to ten sites in each station of south–eastern Thailand were selected within the resource map plot for power analysis using the wind generator Enercon E–18 with a rated power of 80 kW. These sites were selected based on the mean wind speed, wind power density, accessibility by using roads, and electrical transmission lines.

The 10 m measurement towers installed by the TMD are mounted in relatively exposed areas in south–eastern Thailand. Sites along the ridges, mountain peaks, and coastal ridges show good wind speeds within the resource grid at a 28.5 m hub height.

In south–eastern Thailand, the northern stations such as sites along the northwestern ridges (S1 and S2) in Chumphon and the mountain peaks (S2, S3, and S8) in Kanchanadit, (S2, S3, S6–S9) Koh Samui, and (S2, S4–S6) Nakhon Si Thammarat show good potential for wind farm development with a mean wind speed of 6.0–6.9 m/s, 5.8–6.7 m/s, 6.0–6.7 m/s, and 6.3–6.7, respectively. However, the sites inspected near the coastal side in the south (S10) and east (S7–S9) of Chumphon, northwest (S10) of Kanchanadit, and the eastern part (S9 and S10) of Nakhon Si Thammarat possess less potential for wind farm facility implementation.

In central stations, all sites along the peaks of mountains (S1 to S10) of Songkhla and northwestern ridges (S1, S6, and S8) of Phatthalung in the resource map plot have very good mean wind speeds from 5.9 m/s to 7.1 m/s and from 5.9 m/s to 8.8 m/s, respectively.

These sites have very good potential for wind farms in the future. However, in Phatthalung, sites on the leeward side (S5) and plain areas (S4, S9, and S10) towards the Songkhla lake show less potential for a wind park, because of a mean wind speed of about 3.4 m/s to 4.3 m/s.

The resource maps show great potential on the mountain peaks and ridges in the southernmost stations, in Narathiwat and Yala provinces in south–eastern Thailand. All the sites investigated in Narathiwat and Yala have mean wind speeds around 5.1–8.6 m/s and 5.1–9.4 m/s, except site (S10) close to the meteorological station in Yala, which has very little potential (4.2 m/s). Sites inspected along the ridges (S8 and S5) and towards the northern (S9) and eastern (S10) coast in Narathiwat possess good mean wind speeds of about 5.3 m/s to 8.6 m/s, because of their proximity to the shore. Further investigation regarding offshore wind speed is required around the coastal regions of Narathiwat, which can be expected to have great potential for offshore wind farm facilities in the future. On the other hand, regions (S1, S4–S10) examined on ridges in the Pattani province had less potential for a wind farm facility. However, from the resource, it is apparent that the sites on mountain peaks in the southwest (S2) and south (S3) show some potential for wind farm development as these sites have a mean wind speed of about 5.1 to 6.9 m/s.

The area of south–eastern Thailand is fairly smooth. Regions on the leeward side and plain areas in south–eastern Thailand have much less potential for a wind farm facility, as they are surrounded by many artificial obstacles, for instance high–rise buildings and urban infrastructure, which make airflow highly turbulent and may affect the wind flow. However, mountain peaks and ridges show great potential for a prospective wind farm facility, which are generally located far from the power grid. Hence, small–scale wind turbines can act as a useful power source in such locations [54].

The average power generated by a wind turbine can be computed by applying the following equation:

$$\overline{Pw} = \frac{1}{N}\sum_{i=1}^{N} Pw(U_i) \quad (10)$$

where $Pw(U_i)$ shows the output power, which is defined by the turbine power curve.

Moreover, the energy yield from a wind turbine can be calculated as:

$$E = \sum_{i=1}^{N} Pw(U_i)(\Delta t) \quad (11)$$

where U_i is the wind speed, which is averaged over a time interval Δt, and N is the number of recorded observations.

The Enercon E–18 wind turbine with a rated of 80 kW was used in the power analyses of the identified potential sites. Technical specifications of the turbine are shown in Table 5. The cut–in and cut–out speeds of the Enercon E–18 wind turbine rotor are 2.5 m/s and 25.0 m/s, respectively.

Table 5. Enercon E–18 wind turbine specifications.

Rotor Diameter	Hub Height	Cut–In Speed	Cut–Out Speed	Survival Wind Speed	Rated Power	Rated Wind Speed
18 m	28.5 m	2.5 m/s	25.0 m/s	67.0 m/s	80 kW	12.0 m/s

The wind turbine power curve and a site's wind characteristics can be used to estimate the future energy generation over a specific period [35].

Figure 11 shows the net AEP at the selected sites in each station of south–eastern Thailand. Based on the average net AEP generated by WAsP, Songkhla has the highest potential for prospective wind energy development, followed by Yala and Narathiwat in south–eastern Thailand.

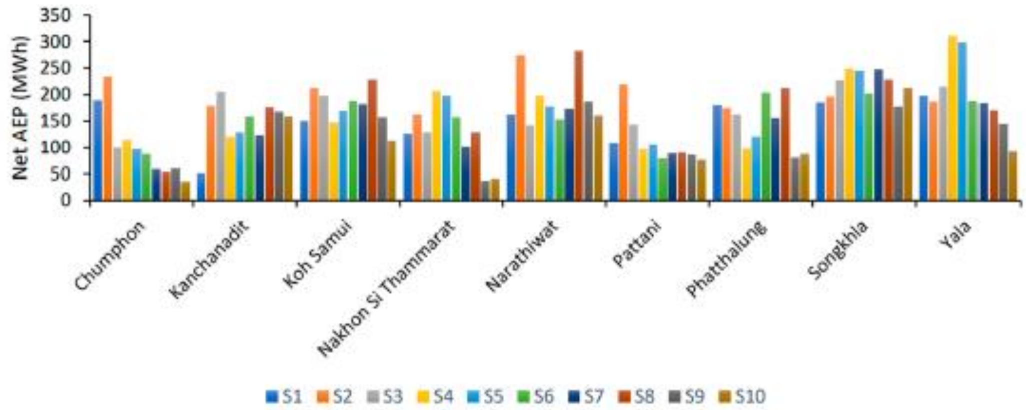

Figure 11. Net AEP of the selected sites in south-eastern Thailand at a hub height of 28 m.

In northern stations, the average net AEP for Chumphon, Kanchanadit, Koh Samui, and Nakhon Si Thammarat is about 102 MWh, 146 MWh, 173 MWh, and 127 MWh, respectively. In Koh Samui, sites (S2, S3, S6–S8) inspected by WAsP have great potential for a wind farm facility with a net AEP of about 180 MWh to 226 MWh. As mentioned previously, Koh Samui is an island and a famous tourist point. Hence, it is linked by an underwater cable to the mainland power plant in Surat Thani. An array of 10 or more 80 kW small–scale wind turbines integrated with other renewables, such as solar, can be used for generating electricity for Koh Samui Island. Furthermore, certain sites in Kanchanadit (S2, S3, and S8), Nakhon Si Thammarat (S4 and S5), and Chumphon (S1 and S2) show a net AEP of about 175 to 204 MWh, 197 to 205 MWh, and 188 to 232 MWh, respectively. These sites have great potential for prospective wind farm facility development.

In central stations, Songkhla and Phatthalung show an average net AEP of about 216 MWh and 146 MWh, respectively. All the sites (S1 to S10) inspected by WAsP in Songkhla show great potential for a prospective wind farm facility with a net AEP of around 177 to 250 MWh, whereas certain sites (S1, S2, S6, and S8) in Phatthalung along the ridges in the northwest display a net AEP around 173 to 211 MWh, and also have very good potential for prospective wind farms.

In the southernmost stations, Yala, Narathiwat, and Pattani depict an average net AEP of about 198 MWh, 190 MWh, and 109 MWh, respectively. Sites along the ridges and mountainous areas in Yala (S1–S6) and Narathiwat (S2, S4, S8, and S9) possess a net AEP around 186 to 311 MWh and 197 to 282 MWh, respectively. These sites show the highest potential for prospective wind farm development. Furthermore, Pattani has only one site (S2) on a mountain peak with a net AEP around 218 MWh, and this site is expected to have good potential for wind farm development in the future.

South–eastern Thailand has a population of more than 7.1 million. It is one of the highest power–consuming regions in Thailand and receives many tourists throughout the year due to popular destinations such as Koh Samui, Koh Pha Ngan, and Koh Tao. As reported by the Electricity Generating Authority Thailand, power demand has been increasing by 5 to 6% in southern Thailand annually, due to the development of services and tourism. Hence, the prospective sites scrutinized by WAsP could reduce the burden on the local power distribution stations and would be sufficient to meet the rising power demand in south–eastern Thailand.

Meanwhile, the capacity factor $\left(C_f\right)$ of the wind turbine is defined as the dimensionless ratio of the average power output (P_{out}) and the rated power output (P_r) over a certain period of time (usually over one year) and can be expressed as [55,56]:

$$C_f = \left(\frac{e^{-\left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_r}{A}\right)^k}}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_f}{A}\right)^k} \right) \tag{12}$$

where V_c, V_f, and V_r are the cut–in wind speed, cut–out wind speed, and rated wind speed, respectively. Similarly, A signifies the Weibull scale parameter and k is the dimensionless Weibull shape parameter. Then, the average power output (P_{out}) can be expressed as:

$$P_{out} = P_r \cdot \left(\frac{e^{-\left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_r}{A}\right)^k}}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_c}{A}\right)^k} - e^{-\left(\frac{V_f}{A}\right)^k} \right) \tag{13}$$

Once the value of the average power output (P_{out}) is known, the average gross energy production (E_{out}) of a wind turbine can be estimated for a specific duration as:

$$E_{out} = P_{out} \cdot T \tag{14}$$

Moreover, $T = d \cdot 24$, where T and d represent the time span in hours and in days, respectively.

The capacity factor mainly depends on the wind resources and wind turbine technology. An annual capacity factor of 17% or greater is considered desirable for wind power [25]. This study computed the annual capacity factors of the nine stations in south–eastern Thailand at the 28.5 m hub height using the WAsP program. The results show that Songkhla, Yala, and Narathiwat have annual capacity factors of 27% or over. Koh Samui, Phatthalung, and Kanchanadit have annual capacity factors ranging between 20% and 25%, whereas Nakhon Si Thammarat, Pattani, and Chumphon have annual capacity factors of 18%, 16%, and 15%, respectively (Figure 12).

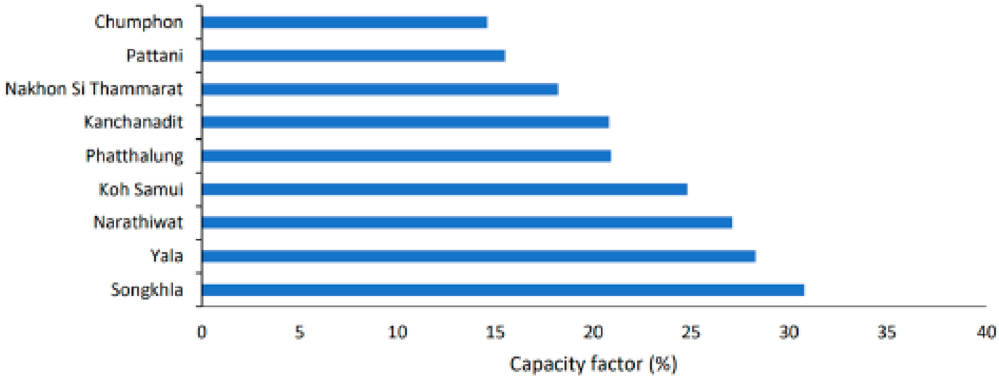

Figure 12. Capacity factors at south–eastern Thailand specific sites assuming Enercon E–18 wind turbine at a hub height of 28.5 m.

3.3. *LCOE Analysis*

In this section, an economic analysis is presented for the installations of the prospective small–scale wind turbines in south–eastern Thailand. LCOE has been calculated for the selected sites using Equation (6) and Table 3, as described in the methodology section, whereas the annual energy yield and capacity factor of the chosen sites were computed using the WAsP module. Using the Enercon E-18 wind turbine model, the lowest LCOE is 92.31 $/MWh to 128.89 $/MWh for Songkhla while the highest LCOE is 189.49 $/MWh to 246.52 $/MWh for Chumphon. Further details of LCOE calculation for the selected sites can be seen in Table 6.

Table 6. Data for the calculation of LCOE.

Sites	AEP (MWh)	CF (%)	LCOE ($/MWh)	
			Fixed and Variable OPEX (Min.)	Fixed and Variable OPEX (Max.)
Chumphon	102.32	14.61	189.49	246.52
Kanchanadit	146.03	20.83	134.35	179.78
Koh Samui	173.71	24.77	113.74	154.84
Nakhon Si Thammarat	127.91	18.25	152.66	201.94
Narathiwat	190.18	27.14	104.23	143.33
Pattani	109.05	15.54	178.44	233.14
Phatthalung	146.87	20.96	133.54	178.8
Songkhla	216.30	30.84	92.31	128.89
Yala	198.24	28.27	100.26	138.52

The principal objective of this study was to analyze the prospects of wind power production at low heights. The geographical positioning of Thailand, like other tropical regions, lacks access to high wind speeds [10]. Therefore, in this study, the low wind profile of the study region was considered. As mentioned earlier, there was no evidence of low–speed wind power studies in southern Thailand. Most of the previous studies [9,10,19–22] were concentrated on making academic contributions rather than taking into consideration the practicality of research with a view to providing a cost–effective renewable wind energy solution.

In addition, the domestic and international investment in renewable wind energy has been a challenge in Thailand because of the associated multi–million–dollar investments in large–scale wind power infrastructures as well as the volatile wind speed at heights. However, the findings of this study suggest the prospect of shifting wind energy strategies to exploit the readily available low–speed wind. Additionally, it is pertinent to note that sites evolved during this research are in proximity to roads and the transmission infrastructure, as both are essential for the transportation of materials and power, whereas building new infrastructure will ultimately increase the overall cost of the project. Furthermore, unlike previous studies, in this study, the approximate cost of the project has also been calculated for the understanding of the energy practitioners, investors, and researchers.

4. Conclusions

In this paper, a wind resource assessment was performed using WAsP software for nine stations in south–eastern Thailand. This study indicates that the regions on the leeward side and plain areas in south–eastern Thailand have poor potential for the establishment of a wind farm facility due to various artificial obstacles such as high–rise buildings and other urban infrastructure that make airflow highly turbulent and may affect the wind flow. However, mountain peaks and ridges show very good potential for the development of small–scale wind power. The maximum average wind speed is found from November to April, with low winds from May to October. The prevailing wind direction observed in Chumphon and Nakhon Si Thammarat is northwest whereas it is southwest in Narathiwat and Yala. Similarly, the southeast direction is predominant in Kanchanadit, Pattani, and Songkhla. The northwest–southeast bi–directional wind rose is very pronounced for Yala, while the dominant direction in Koh Samui is west.

This work used WAsP software for the analyses, to create wind resource maps for south–eastern Thailand with ten sites earmarked around each weather station for wind farm facility implementations in future. The wind resource maps at a 28.5 m hub height indicate the highest annual mean wind power density with a value of 802 W/m^2 was found in Phatthalung, which belongs to wind class 7, followed by Yala with a value of 474 W/m^2 and Kanchanadit with a value of 429 W/m^2 that fall in wind class 4. The minimum annual mean wind power density was recorded in Chumphon and Pattani and both stations belong to wind class 1, while Nakhon Si Thammarat with a value of 271 W/m^2 falls in wind class 2. Similarly, Narathiwat, Songkhla, and Koh Samui had values of 390 W/m^2, 378 W/m^2, and 350 W/m^2, respectively, and belong to wind class 3.

Furthermore, the annual capacity factor of the chosen sites using the Enercon E–18 wind turbine with a rated power of 80 kW was such that Songkhla, Yala, and Narathiwat have annual capacity factors of 27% or over. Koh Samui, Phatthalung, and Kanchanadit have annual capacity factors ranging between 20% and 25%, whereas Nakhon Si Thammarat, Pattani, and Chumphon have annual capacity factors of 18%, 16%, and 15%, respectively. The LCOE calculation shows Songkhla had the lowest cost of 92.31 to 128.89 $/MWh while Chumphon had the highest cost of 189.49 to 246.52 $/MWh. This methodology can be advanced further by using WAsP CFD simulations in complex terrain to maximize production and minimize uncertainty.

The findings of this research are likely to promote the idea that regions near the equator, such as Thailand, can exploit wind energy to decrease their reliance on natural gas, coal, and lignite in the future. The method used in this work is scientific in its approach and is an effective tool for government organizations and stakeholders in prospective small–scale wind farm implementations in south–eastern Thailand. The approach demonstrated could also be used in wind resource assessments for other parts of the world.

Author Contributions: Investigation, Methodology, Data curation and Data analysis, I.K.; Economic analysis, I.K. and S.A.; Resources and Supervision, J.T.; Proofreading, J.T. and H.M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was part of Ph.D. study, supported by Interdisciplinary Graduate School (IGS), Prince of Songkla University. Research was partially funded by Faculty of Engineering, Prince of Songkla University and the Graduate School, Prince of Songkla University with Graduate School thesis research funding.

Data Availability Statement: The data presented in this study are available in this article.

Acknowledgments: The authors would like to acknowledge the Thai Meteorological Department (TMD) for providing wind data for this research. The authors would also like to thank DTU WAsP team for technical support.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX H

Published paper 2 (as a first author)

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 92, Issue 1 (2022) 149-161

SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2811-3950

A Comparative Study of Wind Characteristics Between South-Western and South-Eastern Thailand Using Different Wind Turbine Models

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ARTICLE INFO

Article history:
Received 28 September 2021
Received in revised form 9 January 2022
Accepted 11 January 2022
Available online 5 February 2022

Keywords:
Wind energy potential; Wind characteristics; Wind turbine model; WAsP; Thailand

ABSTRACT

Globally, wind energy has proven to be one of the most sustainable sources of energy. Wind energy assessment plays a critical role on determining installation of wind turbines worldwide. This work presents the technical evaluation of wind energy potential using three available wind turbine models for prospective onshore wind farm in the southern Thailand at Krabi and Songkhla sites. Ten-minute interval wind data over a period of 3 to 4 years obtained from Weather Observing Station is utilized to observe the diurnal and monthly wind speed, as well as frequency distribution. WAsP program is applied for energy yield calculations and wind resource maps. Our results reveal that Krabi and Songkhla has the highest mean wind speed of 4.39 m/s in December and 3.91 m/s in February, respectively. The prevailing wind direction in Krabi and Songkhla are north-east and south-east, respectively. WAsP analyses show that the total net AEP for Krabi is 7163.782 MWh, 7762 MWh and 12731 MWh using 275 kW, 300 kW and 500 kW wind turbine models, respectively. Similarly, the total net AEP for Songkhla is 7116.63 MWh, 7775.245 MWh and 12390 MWh using 275 kW, 300 kW and 500 kW wind turbine models, respectively. The total capacity factor for Songkhla and Krabi is 29.1% and 28.3%, respectively. Our results indicate that Enercon E-40/5.40 500 kW wind turbine model produces the highest total gross AEP and total net AEP for Krabi and Songkhla sites. Besides, the Vergnet GEV MP-C 275 kW turbine model shows slightly higher capacity factor in case of both sites. The findings of this study reflect that small to medium size wind turbines can be utilized to generate electricity at the sites.

1. Introduction

In recent decades, the demand of energy has increased globally as a result of growing population and socio-economic progress. The overall energy consumption will rise up to 6% globally during 2010-2040 as reported by the International Energy Outlook (IEO). Negative impacts of greenhouse gas (GHG) on environment and security of energy supplies have made the government organizations to increase the exploitation of various sources of renewables. Wind energy is one of the clean and

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https://doi.org/10.37934/arfmts.92.1.149161

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inexhaustible sources of renewables and it can be utilized for the generation of electricity by means of wind turbines [1,2].

It is significant to evaluate the wind energy potential technically by knowing characteristics of wind in order to estimate the annual electricity production at potential locations [3]. It provides a pathway for wind energy practitioners with the necessary confidence to study their options to confront the increasing energy demands and mitigating risks [4,5]. To study these wind characteristics, various researchers have used different approaches such as Weibull, Rayleigh and Wind Atlas Analysis and Application Program (WAsP) [6].

Researchers in different countries scrutinized the wind energy potential at specific location using various scientific methods. For example, Adaramola *et al.,* [7] used Weibull parameters to investigate wind energy potential in the coastal parts of Ghana. Solyali *et al.,* [8] inspected wind resource assessment in Cyprus using the Weibull distribution and WAsP. They examined WAsP model more efficient compared to other methods. Wang *et al.,* [9] performed an inclusive study regarding wind statistics along with wind power potential at four localities in China. Promsen *et al.,* [10] and Nouri *et al.,* [11] identified optimal sites for wind turbine installation by using short term wind statistics and WAsP model. Boudia and Guerri [12] used long term wind statistics along with WAsP model to study wind energy potential. Mohammadi *et al.,* [13] used different approaches to measure the Weibull parameters and analyse daily power density in the south part of Alberta, Canada. Sharma and Ahmed [14] studied wind resource assessment using WAsP in the southern island of Fiji.

Detrimental impacts of fossil fuels on climate and high demand of electricity in the southern Thailand which is from 5 to 6% yearly due to tourism industry and socio-economic development [15]. Krabi and Songkhla are located in the south Thailand. Krabi is a significant tourism area in Thailand and millions of tourists visit annually. Similarly, Songkhla hosts thousands of tourists each year due to its border with Malaysia [16,17]. Hence, wind energy is generally more favorable and often recommended for electricity generation.

Few studies on wind energy potential have been considered in the past using different models across Thailand, however, technical evaluation of wind energy potential using WAsP program along with different wind turbine models at selected sites is unknown. Therefore, this study aims to conduct wind energy potential of selected sites using near surface wind data obtained from Weather Observing Stations. The diurnal, monthly and frequency distribution of wind speed and direction are studied. WAsP program is used for energy yield calculations and wind resource maps using three different wind turbine models available in literature.

2. Methodology

2.1 Overview of the Method

The proposed methodology with a schematic diagram for the selected sites is presented in Figure 1. The first step involves the analysis of wind data acquired from Weather Observing Station. This data is further processed through WAsP Climate Analyst tool to generate wind statistics. This study utilizes 10-minutes average interval of wind data from a period of 3 to 4 years recorded at height of 10 m above ground level (AGL). The description of measurement sites and their geographical coordinates can be seen in Table 1.

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Table 1
Geographical coordinates and measurement duration of Krabi and Songkhla sites

Station name	Latitude (°)	Longitude (°)	Height (m)	Measurement duration	Accepted recording (%)
Krabi	8.103	98.975	10	2017-2020	93.87 %
Songkhla	7.18	100.60	10	2017-2019	98.94 %

The second step includes the coordinates and topographical information of the selected sites which are used as an input for WAsP Map Editor to generate elevation and roughness maps. The third step encompasses power curves of selected wind turbine models and site's wind characteristics in WAsP program to estimate energy yield calculations and resource maps of selected sites.

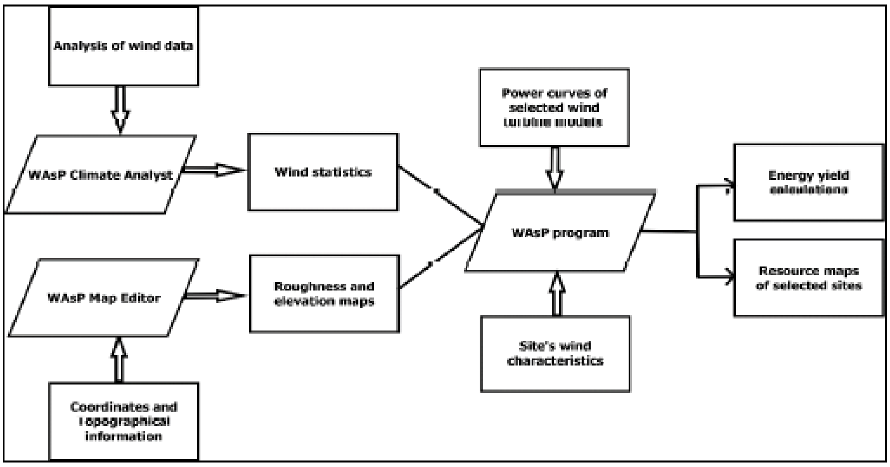

Fig. 1. Schematic diagram of methodology [4]

2.2 Simulation Model

WAsP is a computer-based linear simulation model established by Denmark Technical University (DTU) at Danish Riso National Laboratory. The WAsP model is computed for wind energy potential, site suitability analysis and calculations of energy yield for wind farms. It is used for vertical and horizontal extrapolation of wind data and shows errors less than 10% [4,18,19]. The basic input information that are required for the WAsP program are the terrain height, surface roughness and obstacle effects. The WAsP program can perform all the necessary energy production calculations for a single turbine site or for a wind park along with the wake losses, layout, capacity factor and various other factors [4]. The WAsP model mainly belongs to the family of the Jackson–Hunt theory [20]. Inside WAsP Module there are two important tools i.e., WAsP Climate Analyst and WAsP Map Editor which are explained below.

This study uses the observed wind climatology as a data recording tool for WAsP Climate Analyst to estimate the wind conditions for the selected sites in terms of wind roses and Weibull distribution function. Furthermore, the wind rose is grouped into 12 sectors which signifies the relative frequency of wind direction. The Weibull distribution function is a two-parameter function which defines the

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wind speed histogram. WAsP utilizes this function for evaluation of wind characteristics in each direction by sector wise which can be expressed in mathematical form as [21]:

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

In Eq. (1), $f(v)$ denotes the Weibull distribution function, v means the observed wind speed, A and k signify the scale and shape parameter of the Weibull distribution function, respectively.

WAsP Map Editor is a tool found inside WAsP module which is used to generate elevation and surface roughness maps for the selected sites. The important information of topography and surface roughness have been entered to the servers of Global Wind Atlas (GWA) Map Warehouse-Elevation and Global Wind Atlas (GWA) Map Warehouse-Roughness to complete the elevation and surface roughness maps.

3. Results and Discussion

This section describes the diurnal and monthly wind speed pattern. Besides, a comparative and comprehensive study of wind characteristics of the selected sites has been discussed.

3.1 Diurnal Wind Speed

Figure 2 displays average of wind speed of each hour recorded at 10 m height to show the wind speed diurnal pattern of Krabi and Songkhla sites. It has been observed that both sites examine maximum average wind speed from 2 a.m. to 8 a.m. with minimum average wind speed between 12 p.m. and 10 p.m.

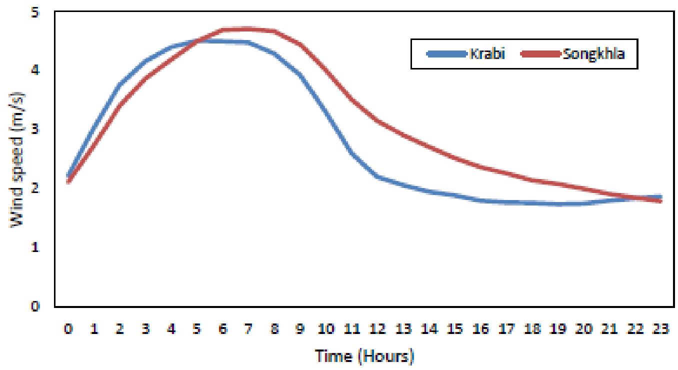

Fig. 2. Diurnal average wind speed for Krabi and Songkhla

3.2 Monthly Wind Speed

Figure 3 shows higher wind speed for Krabi site recorded at height of 10 m AGL which has been observed between October and February with the maximum average wind speed value 4.39 m/s in December. Similarly, the higher average wind speed for Songkhla site is experienced in January, February and August with the maximum average wind speed value 3.91 m/s in February. The lowest

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average wind speed value of 2.02 m/s have been observed in June for Krabi site and 2.56 m/s in October for Songkhla site.

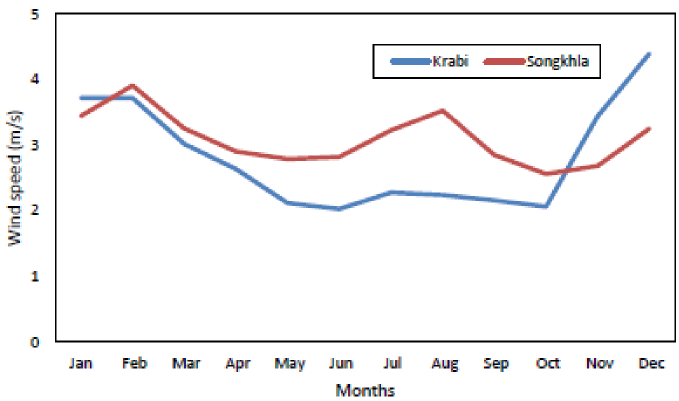

Fig. 3. Monthly average wind speed for Krabi and Songkhla

3.2.1 Frequency distribution of wind speed and wind direction

It is important to consider the frequency distribution of wind speed and wind direction during resource assessment as it gives site specific information.

Figure 4 shows the prevailing wind direction for Krabi which is north-east with a wind speed (3.73 m/s) frequency distribution 22.1%. The values of scale parameter A and shape parameter k are 3.1 m/s and 1.39, respectively.

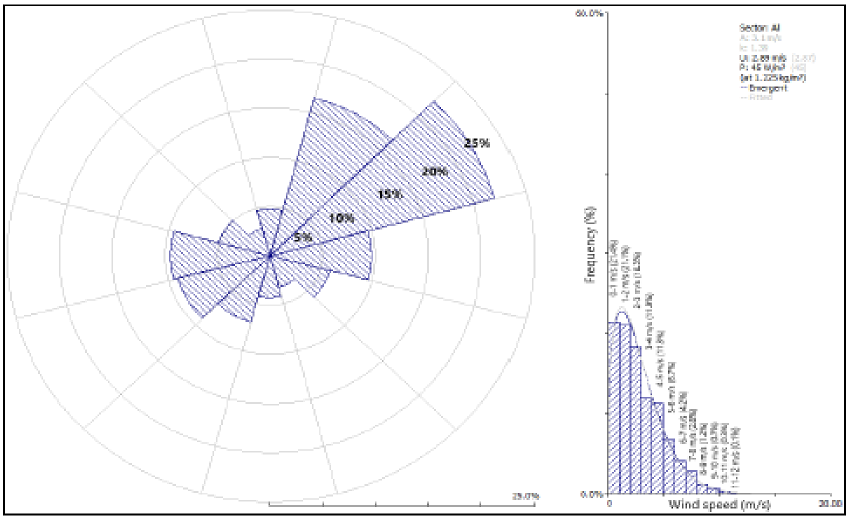

Fig. 4. Wind rose diagram and histogram of frequency distribution of wind speed for Krabi

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Figure 5 presents the prevailing wind direction for Songkhla which is south-east with a wind speed (3.41 m/s) frequency distribution 31.3%. The values of scale parameter A and shape parameter k are 3.5 m/s and 1.60, respectively.

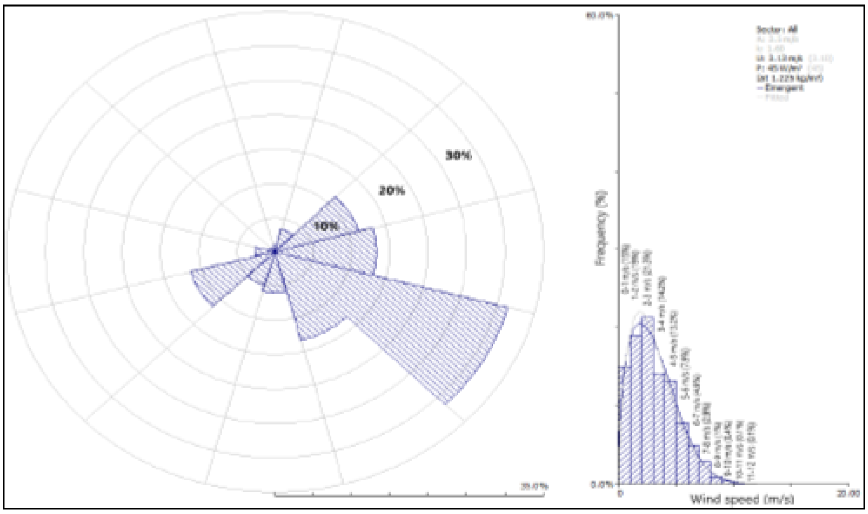

Fig. 5. Wind rose diagram and histogram of frequency distribution of wind speed for Songkhla

3.2.2 Evaluation of wind characteristics

WAsP program is utilized for evaluation wind energy potential and wind characteristics at Krabi and Songkhla sites by using three available wind turbine models in the literature. Technical description and specification of the wind turbine models are given in Table 2.

Table 2
Specification of three wind turbines

Wind turbine model	Rated output (kW)	Rotor diameter (m)	Cut in speed (m/s)	Cut out speed (m/s)	Hub height (m)	Swept area (m²)	Rated speed (m/s)
Vergnet GEV MP-C 275 kW	275	32	3.5	25	55	804	12
Bonus Mk III 300 kW	300	33.4	3	25	30	876	13
Enercon E-40/5.40 500 kW	500	40.3	2.5	25	42	1,275	12

The resource maps of Krabi and Songkhla using WAsP program are displayed in Figure 6 to Figure 11. The AEP estimated for Krabi using 275 kW wind turbine ranges from 35.162 to 964.939 MWh, with 300 kW wind turbine ranges from 0.006 to 1023 MWh and with 500 kW wind turbine ranges from 0.038 to 1748 MWh. Similarly, the estimated AEP for Songkhla using 275 kW wind turbine ranges from 82.620 to 855.898 MWh, with 300 kW wind turbine ranges from 55.879 to 956.283 MWh and with 500 kW wind turbine ranges from 0.125 to 1540 MWh.

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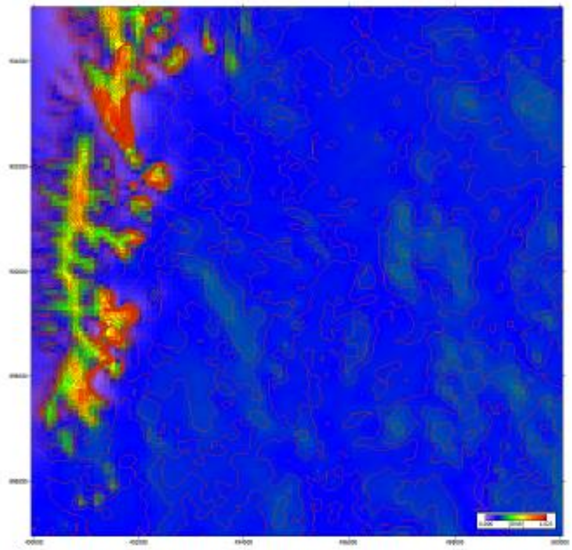
Fig. 6. Mean annual energy production of Krabi at 30 m hub height

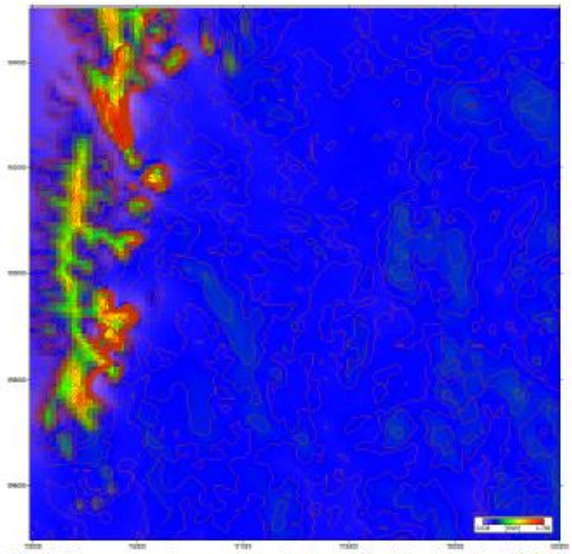
Fig. 7. Mean annual energy production of Krabi at 42 m hub height

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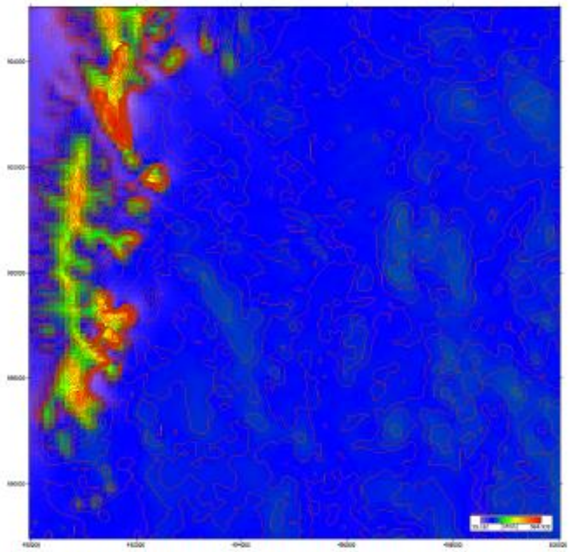

Fig. 8. Mean annual energy production of Krabi at 55 m hub height

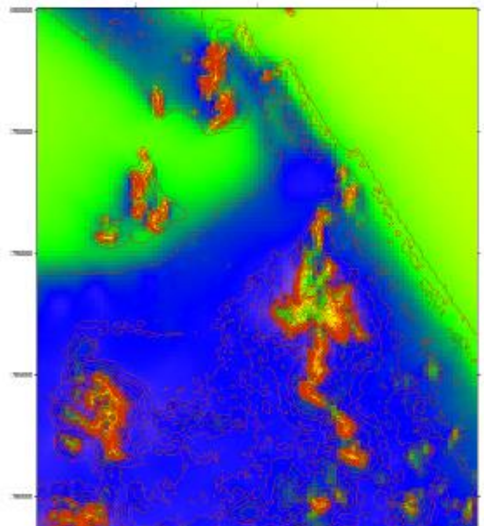

Fig. 9. Mean annual energy production of Songkhla at 30 m hub height

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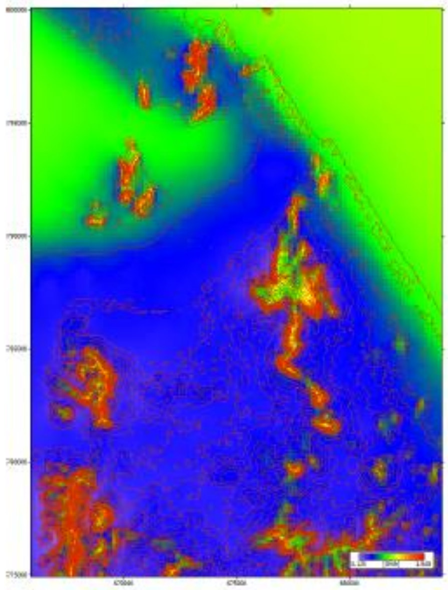

Fig. 10. Mean annual energy production of Songkhla at 42 m hub height

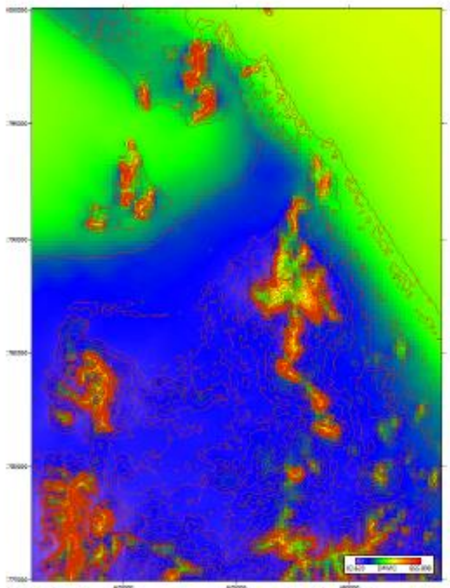

Fig. 11. Mean annual energy production of Songkhla at 55 m hub height

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The statistical analysis of Krabi and Songkhla sites in terms of total gross AEP, total net AEP, proportional wake losses, annual mean wind speed, annual power density and total capacity factor have been evaluated in this study.

The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capacity of 275 kW at 55 m hub height are 7172.545 MWh and 7119.366 MWh, respectively. The mean speed and power density values are 6.85 m/s and 501 W/m^2 for Krabi and 6.75 m/s and 374 W/m^2 for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.8% and 29.5%, respectively. Further details for both sites are given in Table 3.

Table 3
Summary for annual statistics using Vergnet GEV MP-C 275 kW at 55 m height

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	7172.545	7119.366	717.254	711.937	496.618	574.905	955.504	843.985
Total net AEP [MWh]	7163.782	7116.63	716.378	711.663	495.374	574.664	955.014	843.662
Proportional wake loss [%]	0.12	0.04	-	-	0.05	0.03	0.25	0.05
Capacity factor [%]	29.8	29.5	-	-	20.5	23.8	39.6	35
Average speed [m/s]	-	-	6.85	6.75	5.59	6.15	8.48	7.38
Wind power density [W/m^2]	-	-	501	374	260	278	972	477

The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capacity of 300 kW at 30 m hub height are 7768 MWh and 7775.964 MWh, respectively. The mean speed and power density values are 6.87 m/s and 590 W/m^2 for Krabi and 6.55 m/s and 378 W/m^2 for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.1%. Further details for both sites are given in Table 4.

Table 4
Summary for annual statistics using Bonus Mk III 300 kW at 30 m height

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	7768	7775.964	777	777.596	539	644.544	1014	894.461
Total net AEP [MWh]	7762	7775.245	776	777.524	538	644.525	1013	894.316
Proportional wake loss [%]	0.07	0.01	-	-	0.02	0	0.16	0.02
Capacity factor [%]	29.1	29.1	-	-	20.1	24.1	37.9	33.4
Average speed [m/s]	-	-	6.87	6.55	5.28	5.92	9.19	7.13
Wind power density [W/m^2]	-	-	590	378	260	280	1400	488

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The total gross AEP estimated for Krabi and Songkhla using wind turbine with rated capacity of 500 kW at 42 m hub height are 12738 MWh and 12391 MWh, respectively. The mean speed and power density values are 6.85 m/s and 533 W/m² for Krabi and 6.66 m/s and 372 W/m² for Songkhla, respectively. The total capacity factor calculated for Songkhla and Krabi is 29.1% and 28.3%, respectively. Further details for both sites are given in Table 5.

Table 5
Summary for annual statistics using Enercon E-40/5.40 500 kW at 42 m height

Variable	Total		Mean		Min		Max	
	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla	Krabi	Songkhla
Total gross AEP [MWh]	12738	12391	1274	1239	863	998	1732	1468
Total net AEP [MWh]	12731	12390	1273	12390	861	998	1732	1468
Proportional wake loss [%]	0.06	0.01	-	-	0.01	0	0.13	0.02
Capacity factor [%]	29.1	28.3	-	-	19.7	22.8	39.5	33.5
Average speed [m/s]	-	-	6.85	6.66	5.44	6.03	8.76	7.29
Wind power density [W/m²]	-	-	533	373	258	276	1131	475

The results reveal that Enercon E-40/5.40 500 kW wind turbine produces the highest total gross AEP and net AEP for Krabi and Songkhla sites. The annual capacity factor slightly varies for the selected wind turbines as it depends on turbine model and site. The Vergnet GEV MP-C 275 kW shows slightly higher capacity factor for both sites.

4. Conclusion

This study has used the recent meteorological wind data for Krabi and Songkhla sites to study the technical potential of wind energy by using three wind turbine models available in literature. The main points of wind resource analysis of both sites are:

i. Both Krabi and Songkhla sites observe maximum diurnal average wind speed from 2 a.m. to 8 a.m. at height of 10 m AGL.
ii. Krabi site shows maximum average wind speed of 4.39 m/s in December while Songkhla site indicates the maximum average wind speed of 3.91 m/s in February at height of 10 m AGL.
iii. The prevailing wind direction in Krabi is north-east. The Weibull scale parameter A and shape parameter k values are 3.1 m/s and 1.39, respectively.
iv. The prevailing wind direction in Songkhla is south-east with a wind speed. The Weibull scale parameter A and shape parameter k values are 3.5 m/s and 1.60, respectively.
v. The total net AEP estimated for Krabi using 275 kW, 300 kW and 500 kW wind turbine models is 7163.782 MWh, 7762 MWh and 12731 MWh, respectively.
vi. The total net AEP estimated for Songkhla using 275 kW, 300 kW and 500 kW wind turbine models is 7116.63 MWh, 7775.245 MWh and 12390 MWh, respectively.
vii. The value of capacity factor for Songkhla and Krabi is 29.1% and 28.3%, respectively.
viii. WAsP analysis shows that Enercon E-40/5.40 500 kW generates the highest total gross AEP and total net AEP for Krabi and Songkhla sites.

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ix. Regarding capacity factor, the Vergnet GEV MP-C 275 kW turbine model shows slightly higher capacity factor in case of both sites.

The results of the study at various hub heights confirm that both sites can be used to generate wind energy electricity in future. However, further investigation regarding cost analysis for each site would be required.

Acknowledgment
This work was supported by Prince of Songkla University Hat Yai, Songkhla 90112, Thailand, by the grant of an Interdisciplinary Graduate School (IGS), and partially supported by the Faculty of Engineering, Prince of Songkla University and the Graduate School, Prince of Songkla University with Graduate School thesis research funding. The authors acknowledge the help of the Thai Meteorological Department (TMD) by providing the wind data.

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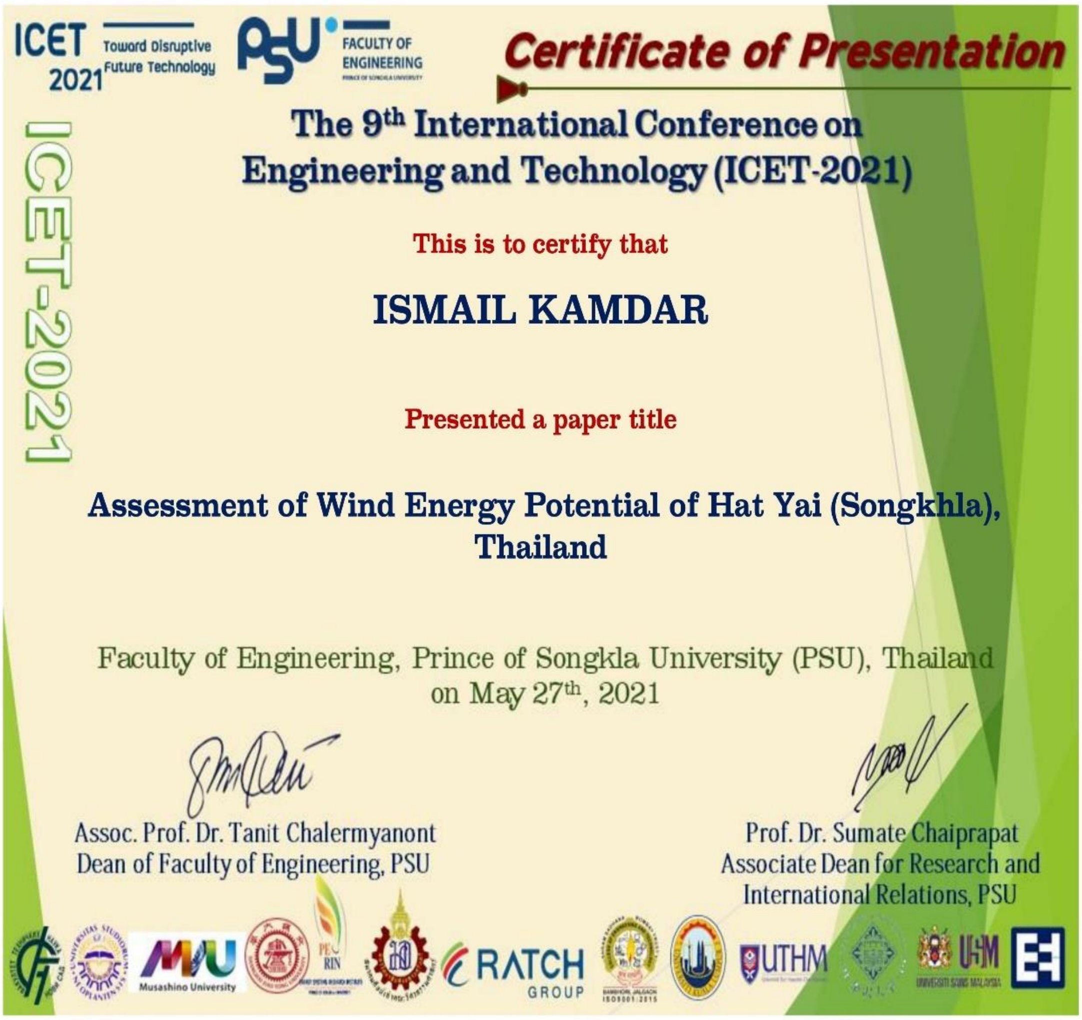
APPENDIX I

Conference certificate



VITAE

Name ISMAIL KAMDAR

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Educational Attainment

Degree	Name of Institution	Year of Graduation
Master of Science Sustainable Energy Management	Prince of Songkla University, Hat Yai, Songkhla, Thailand	2019
Bachelor of Science Electrical (Power) Engineering	COMSATS Institute of Information Technology, Abbottabad, Pakistan	2016

Scholarship Awards during Enrolment

Interdisciplinary Graduate School (IGS) Grant No. IGS Contract no.1-2019/05 │ 2019 – 2022.

Interdisciplinary Graduate School (IGS) Grant No. IGS Contract no.074-282263 │ 2017 – 2019.

Awarded Endowment Fund Scholarship for bachelor's study in Electrical Power Engineering at COMSATS University Islamabad, Abbottabad Campus, Pakistan │ 2012 – 2016.

Work – Position and Address

Trainee Engineer at Islamabad Electric Supply Company (IESCO) June 2016 – May 2017 (12 months).

List of Publication and Proceeding

<u>Journal Publications</u>

(As a first author)

Ismail Kamdar, Shahid Ali, Juntakan Taweekun*, Hafiz Muhammad Ali (2021). Wind Farm Site Selection Using WAsP Tool for Application in the Tropical Region. Sustainability. (Impact Factor 3.251; ISI Web of Science: SCIE). https://doi.org/10.3390/su132413718

Ismail Kamdar, Juntakan Taweekun* (2022). A Comparative Study of Wind Characteristics Between South-western and South-eastern Thailand Using Different Wind Turbine Models. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences. https://doi.org/10.37934/arfmts.92.1.149161

Ismail Kamdar, Shahid Ali, Adul Bennui, Kuaanan Techato & Warangkana Jutidamrongphan* (2019). Municipal solid waste landfill siting using an integrated GIS-AHP approach: A case study from Songkhla, Thailand. Resources, Conservation and Recycling. (Impact Factor 10.204; ISI Science Citation Index Expanded) https://doi.org/10.1016/j.resconrec.2019.05.027

Conference proceedings

Ismail Kamdar, Juntakan Taweekun* (2021). Assessment of Wind Energy Potential of Hat Yai (Songkhla), Thailand. IOP Conference Series: Materials Science and Engineering. DOI:10.1088/1757-899X/1163/1/012001

Ismail Kamdar, Juntakan Taweekun & Kuaanan Techato: “Title: Selection of municipal solid waste disposal site for Ban Phru, Thailand using GIS” at Assuring Sustainability via University with Research: Towards a sustainable development (ASSURE 2018) International Conference, 23 January, Ranong Room Siam Oriental Hotel, Hat Yai, Songkhla, Thailand.