

**OPTIMISATION STUDIES FOR WIND POWER
GENERATION IN MALAYSIA**

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ABSTRACT

This research addresses a gap in the market for harnessing wind energy in Malaysia. While there is a global shift in the quest for renewable energy (RE) sources, non-renewable energy sources continue to dominate Malaysia's electricity production. In recent years, Malaysia has explored alternative RE sources in its national fuel policies and has focused on biomass and solar. A cleaner source of RE-wind has been largely under-explored. Several early studies on Malaysia have exerted a cautionary note due to the low wind speeds prevalent. Moreover, most studies have relied on statistical estimations and very few studies have used wind analysis software to analyse the wind energy potential in Malaysia. There is also evidence in the literature that there is a dearth of initial wind characteristic studies and spatial wind mapping in Malaysia. This study contributes to addresses this gap using robust estimation techniques.

Data on wind speed and wind direction from NCEI for 16 years and 36 sites across Malaysia are used to conduct preliminary statistical analysis. Topographical features from SRTM data and user assigned roughness maps are used to produce more robust estimates. Actual power curves and thrust coefficient curves of commercially available small wind turbines are used to estimate the annual energy production (AEPs) including considering wake loss and performance indicator (dRIX). Geospatial software Google Earth Pro is used to identify sites for micrositeing to produce empirical relevant recommendations. Economic feasibility analysis was conducted using commercially available wind turbines.

Preliminary descriptive statistics indicate that Kudat, Mersing, Kota Bharu, Langkawi, Miri and Penang Island have the highest wind speeds and power density (PD). The wind speeds at these five sites average between 3.9 and 4.2 ms⁻¹, while the mean PD ranges from 58 to 74Wm⁻² at 30 m hub height. These results align with previous

studies on Malaysia, other than Kudat experiences the highest PD when roughness data is not incorporated. However, PD estimations incorporating roughness maps are different from those in the literature. Penang Island, Kudat, Miri and Sandakan are found to have higher PD than Mersing, Kota Bharu and Langkawi. Penang Island is estimated to have the highest PD of 110 Wm^{-2} . Since Kota Bharu is highly congested and Langkawi has high dRIX, both sites were dropped from top 5 consideration.

The top five sites have mean AEPs of 22.7MWh to 83.2MWh, when an Aeolos 50kW turbine of 30m hub height is used. When considering micro-siting, areas in East Malaysia stand-out for their lower mean dRIX (less than 0.3% for Sandakan and Miri), easier access to sites and possibility of placing wind turbines in large wind farms with relatively lower wake loss. Economic feasibility analysis indicate that it is possible to harness wind energy in Malaysia using commercially wind turbines above 20kW. The levelised cost of energy (LCOE) is below RM 0.70 for Penang Island, Kudat, Miri Sandakan and Mersing, when Aeolos 30kW turbines are employed at 30m hub height.

The validity of the WAsP model was assessed by comparing the actual AEP for a live wind turbine to that of the estimated AEP using WAsP. The results indicate that WAsP is likely to underestimate AEP by 13%. However, this deviation may partly be due to data being only available for 17.9 hours a day on average. Overall, the analysis validates that WAsP is a robust and powerful model to estimate the wind AEP when roughness is incorporated. The results from this study demonstrates that there is potential to harness wind energy profitably in Malaysia using small wind turbines. Moreover, given the success of wind energy systems in neighbouring Thailand, with similar mean wind speeds of less than 3 ms^{-1} , Malaysia should consider harnessing wind energy.

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NOMENCLATURE

AEP	Annual Energy Production
ASI	Italian Space Agency
BioGen	Biomass Power Generation & Demonstration Project
CFD	Computational Fluid Dynamics
CO ₂	Carbon di-oxide
Cp	Performance / Power Coefficient of a Wind Turbine
DEM	Digital Elevation Model
DLR	German Aerospace Center ¹
dRIX	Performance Indicator (Difference in Ruggedness Index)
EUR	Euro
EWEA	European Wind Energy Association
FIT	Feed-in Tariff
G-AEP	Gross Annual Energy Production
GWC	General Wind Climate
HAWT	Horizontal Axis Wind Turbines
IBZ	A built-in orographic flow model ²
IEA	International Energy Agency
IMPESA	Industrias Metalurgicas Pescarmona S A
IRR	Internal Rate of Return
KML	Keyhole Mark-up Language
kWh	Kilowatt Hour
lat	Latitude
LCOE	Levelised Cost of Energy
LFR	Line Face Roughness
lon	Longitude
MBIPV	Malaysia Building Integrated Photovoltaic Project
MET	Meteorological Station
MPH	Miles per hour
ms ⁻¹	Metres per second
MWh	Megawatt Hour
MYR	Malaysian Ringgit
N-AEP	Net Annual Energy Production
NASA	National Aeronautics and Space Administration
NCEI	National Center for Environmental Information
NGA	National Geospatial-Intelligence Agency
NIMA	National Imagery and Mapping Agency
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NWP	Numerical Weather Prediction
OMC	Operations and Maintenance Costs
OWC	Observed Wind Climate
OWF	Observed Wind Frequency

¹ In German Language.

² It is not an abbreviation, but just a term used to denote the in-built model.

PD	Power Density
PTM	Pusat Tenaga Malaysia
PWC	Predicted Wind Climate
PWF	Predicted Wind Frequency
R	Roughness
R-Class	Roughness Class
RE	Renewable Energy
RG	Resource Grid
RIX	Ruggedness Index
RL	Roughness Length
RM	Ringgit Malaysia
ROI	Return on Investment
rpm	Rotation per Minute
RWC	Regional Wind Climate
SEDA	Sustainable Energy Development Authority
SREP	Small Renewable Energy Power Programme
SRTM	Shuttle Radar Topography Mission
TNB	Tenaga Nasional Berhad
USD	United States Dollar
UTM	Universal Transverse Mercator Coordinate System
VAWT	Vertical Axis Wind Turbines
W.AVR	Weighted Average
WAsP	Wind Atlas Analysis & Application Program
WCA	Wind Climate Analyst
WGS-84	World Geodetic System 84
Wk	Wake
Wm ⁻²	Watts per metre squared
WRA	Wind Resource Assessment
WTG	Wind Turbine Generator

CHAPTER 1: INTRODUCTION

1.1: Background and Motivation

The ever-rising cost and depletion of fossil fuels, and their detrimental effects on the environment have driven the quest for alternative energy sources. Many countries have begun to invest in the development of renewable energy sources; such as, geothermal, photovoltaic, solar thermal, hydro, wave, tidal and wind energies. These are clean sources of energy that minimise pollution and do not exhaust natural resources by their usage. Business Wire (2016) predicts that the global clean energy market will be worth more than \$777 billion by 2019. Testament to this growth, IEA (2017) indicates that 165GW of renewable power coming online globally accounted for two-thirds of all power capacity added in 2016. Renewable energy investment in the developing world alone accounted for \$116.6 billion in 2016 (FS-UNEP, 2017). In addition to being clean sources of energy, renewable energy sources such as solar and wind are now cheaper per kW of energy produced, compared to non-renewable energy sources such as coal and natural gas (Sauven, 2017). Wind energy is now cheaper than harnessing nuclear energy in some parts of Europe and has experienced rapid growth in continental Europe and is gaining increasing popularity in Asia and sub-Saharan Africa (Carrington, 2017).

Wind energy remains largely under-explored in Malaysia. Few communities in Malaysia are still not connected to the national grid, and conventional energy sources are mainly used to power their households. Favourably most of such communities are islands or coastal areas that have access to relatively good wind speeds. However, the average wind speeds in these regions are still relatively low compared to other parts of the world; such as, Europe, and China. Therefore, the large commercial wind turbines are less than ideal to harness wind energy in Malaysia.

Past Wind energy studies in Malaysia have had limited empirical relevance and therefore hindered policy making (since they have primarily or exclusively relied on statistical analysis). Over the years, while the methods to find potential sites varied, almost all the studies have repeatedly identified Mersing to be the best location for harnessing wind energy, along with a few other sites that have been rediscovered. Most of these studies have relied on statistical estimations and very few studies have used wind analysis software to analyse the wind energy potential in Malaysia. Even among studies that use such software, only a few have presented Micrositing when analysing the potential power; yet no studies have included roughness maps in their analysis (as discussed in the next chapter).

Hence, this study aims to tabulate wind speed, power density and annual energy production (AEP) data that would rank potential sites in Malaysia incorporating roughness maps. This research would, therefore, contribute to improving the regional wind atlases for Malaysia. As can be seen from Figure 1, Malaysia does not have a national wind atlas but is supplemented by regional and/or local wind atlas. This research further aids policy making by analysing the economic feasibility of harnessing wind energy in Malaysia using commercially available wind turbines.

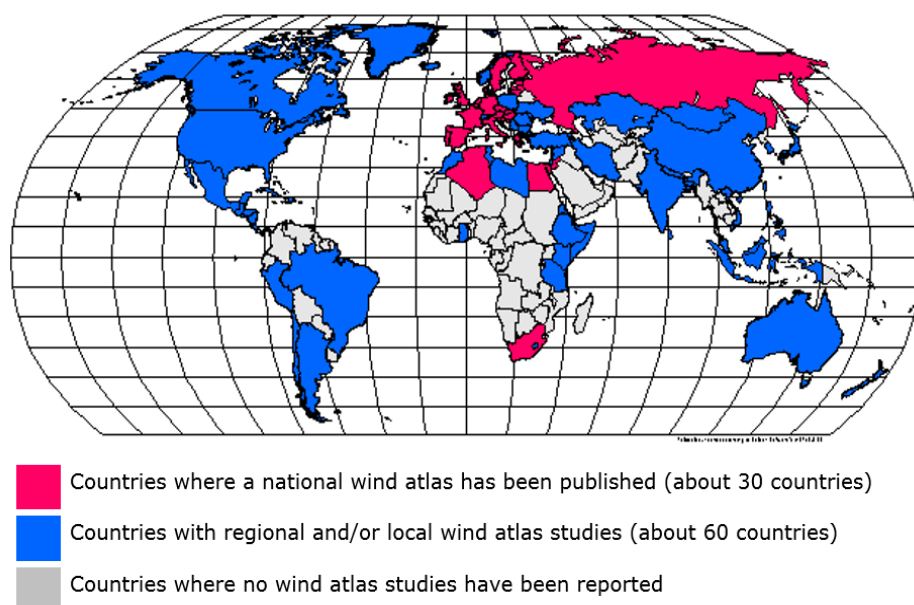


Figure 1: Wind Atlas of Countries

[Source: WASP 12, 2017]

1.2: Energy Sources of Malaysia

Non-renewable energy sources continue to dominate Malaysia's electricity production, with renewable energy contributing only about 10% (Figure 2) over the 36-year period since 1978 for which data is available. Oil was the primary source in electricity generation in Malaysia prior to the "Four Fuel Diversification Policy" that was announced in 1981. This policy focused on having a mix of oil, natural gas, hydropower and coal in energy generation. In order to reduce the reliance on natural gas, the country has been increasing its import of coal (Kettha, 2008). This has resulted in a gradual decline in the usage of natural gas, and a concurrent increase in the share of coal in energy generation.

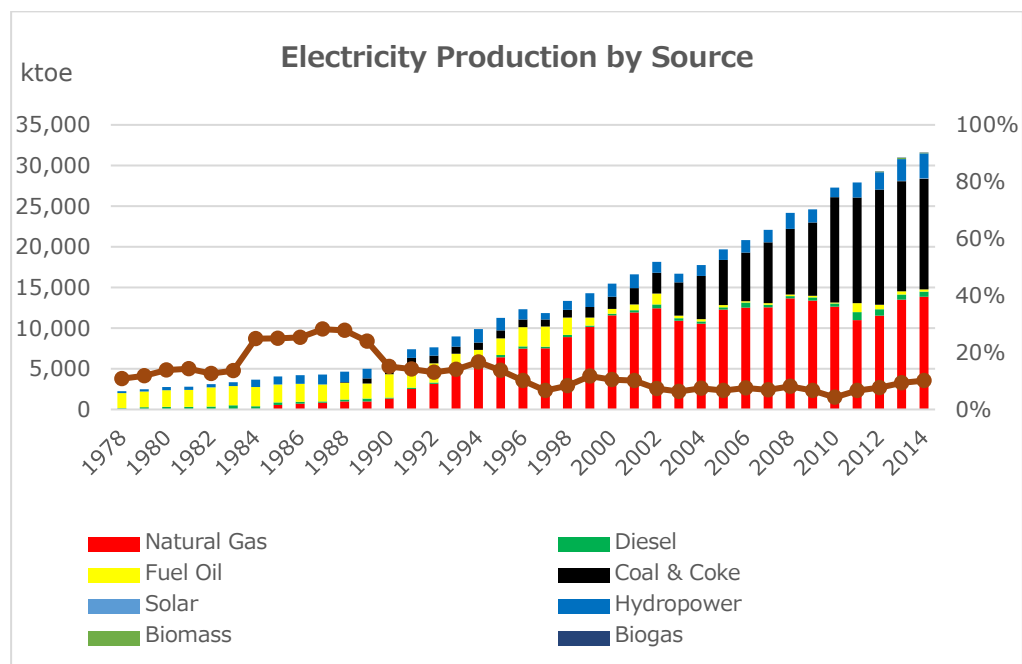


Figure 2: Electricity Production by Source³

[Source: Energy Commission of Malaysia, 2016]

In 2005, Malaysia's crude oil and natural gas reserves were estimated to be sustained for only another 19 years and 34 years respectively (PTM, 2007), highlighting the necessity to diversify the

³ There is a surge in share of RE in 1984, because hydro capacity was almost doubled; while there was linear increase in hydro capacity over the years, there was massive growth in the quantum of non-RE sources used which led to the fall in the share of RE in Malaysia's energy production.

dependence on these two sources of energy for the long-run benefit of the economy. Hence, the "Fifth Fuel Policy of the Eighth Malaysia Plan (2001-2005)" included renewable energy sources such as biomass, biogas, solar and mini-hydro in the production of electricity. Since then, Malaysia has taken an active approach in promoting the use of renewable energy sources, including shifting from the once popular biomass towards solar energy, and introducing initiatives such as the Feed-In-Tariff (TNB, 2014).

Combustion of fossil fuels, such as coal, oil, and natural gas emit environmentally harmful gasses such as carbon dioxide, nitrous oxide, sulphur dioxide, and mercury compounds (Houghton et al, 2001). Since CO₂ emissions from combustion are much larger than that of other gases and its impacts on the environment are adverse, decreasing CO₂ emissions is of greater significance to studies that explore various energy sources. IEA (2017) shows that much of the CO₂ emissions around the globe can be attributed to electricity and heat related use. Therefore, by employing renewable energy sources in the generation of electricity, CO₂ emissions can be minimised.

Malaysia, being one of the fastest growing developing nations, has seen rapid economic growth, coupled with a rapid increase in the emission of CO₂. Figure 3 shows the CO₂ emissions per capita for the Malaysia, China, East Asia and Pacific, Indonesia and World. The graph shows that CO₂ emissions per capita for Malaysia have almost doubled to 8 metric tonnes per person in the 23 years starting 1992 for which data is available. Malaysia's per capita CO₂ emissions have increased steadily over the years and exceed that of China, although China's CO₂ emissions have tripled since 2001. During the same period, the CO₂ emissions per capita for the world as a whole has only modestly increased, and hovers around 4.7 metric tonnes per person. This reflects the necessity for Malaysia to earnestly consider deploying renewable energy sources in its generation of electricity in order to reduce its carbon footprint.

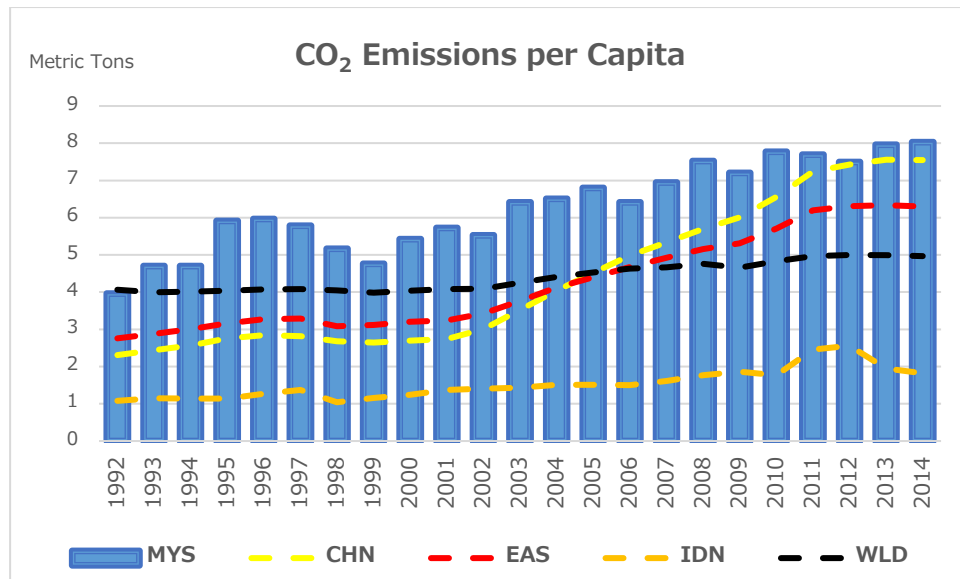


Figure 3: CO₂ Emissions per Capita

[Source: World Bank Group, 2017]

Malaysia has relied on Biomass as a key renewable energy source (PTM, 2007). However, it is not considered clean by many quarters; especially, due to the energy conversion process involved. Although the state and oil palm companies have continuously claimed that the palm oil industry in Malaysia has been environmentally conscious and eco-friendly (Malaysia Palm Oil Promotion Council, 2005), other sources estimate that about 47% percent oil palm agriculture between 1990 and 2002 involved deforestation of rainforests (Brown and Jacobson, 2005). The deforestation of trees affects the photosynthesis process; this process not only naturally removes carbon dioxide from the atmosphere, but also releases oxygen.

Setting fire is a common practice in the deforestation process, which releases vast amounts of carbon dioxide into the atmosphere, causing air pollution and health hazards (Glover and Jessup, 2006). Biomass are used in the boilers, in the same way as fossil fuels. Generating energy from biomass is a continuous combustion process, which adds up a high operating and maintenance cost. The complicated process of biomass energy production entails strict safety precautions. Carbon dioxide, monoxide, nitrogen oxides among other pollutants get released when burning biomass. If these

pollutants are not captured and recycled properly, these could become harmful to those inhaling the polluted air causing health hazards. The level of pollutants released by burning biomass sometimes exceed those released by burning fossil fuels (National Geographic, 2012). A study carried out by the Massachusetts Environmental Energy Alliance shows that burning trees for (biomass) energy generation releases 1.5 times more carbon compared to the combustion of coal, and 3 to 4 times more carbon compared to the combustion of natural gas (Wiles, 2011; Moyer, 2012). Furthermore, biomass power generation requires uninterrupted fuel supply; collecting, storing, transporting residues and disposing wastes need to be done continuously as similar to fossil-fuel production (Bridgwater, 1995; Wu et al., 2002).

A popular source of alternate energy in developing countries is hydro energy (Khan and Iqbal, 2004). In Malaysia, hydropower has been the single largest source of renewable energy (Figure 1). Hydroelectric plants demand higher capital cost but are cheaper to operate (Khan and Iqbal, 2004). However, the adverse impact on wildlife, fisheries and the general ecosystem has gained some adverse attention towards hydroelectricity. In addition, a recent study by Ansar et al. (2014) also concludes that large dams are uneconomical. In particular, the study cites Malaysia's Bakun Dam project as one of the least feasible of the dams in the recent past, with drastic inefficiencies in terms of initial setup costs, and operational inefficiencies. Wave and tidal energy on the other hand are relatively new and are in their nascent stages in energy application.

Solar energy, however, is a serious contender as an alternate energy source in Malaysia; especially, with the blessing of 4 to 6 hours of sunshine every day (TNB, 2014). Nevertheless, two factors favour the use of wind energy over solar energy; one is the land area required and the second reason is the high maintenance. According to TNB (2014), a land area of 100km² is required to generate

1,000MWs of solar energy for one year. This area could otherwise be used for other economic activity; rendering an opportunity cost. This is sometimes not factored in during the evaluation of the feasibility of solar power generation. Wind energy also requires large land masses, but does not disrupt other activities; such as, agriculture and cattle farming. Therefore, wind energy generation can co-habit with other economic activity especially in the agricultural sector. Regular maintenance is another factor that deems solar energy less attractive; for instance, dust and other forms of cloud coverings reduce the efficiency of solar power generation by about 10%, requiring constant supervision (Seely, 2013).

To conclude, wind is a cleaner form of energy with less maintenance and can co-habit with other economic activity reducing the opportunity cost of installing wind turbines. However, one major drawback that has been pointed out in the literature is the high initial setup cost. Despite this, Lantz et al. (2012) and Carrington (2017) point out that the cost of wind turbines has reached an all-time low by the end of the first decade of this century. Given that initial cost or lease payments on them form the major cost component, with a trend of declining prices, wind turbines are likely to be more popular in the future (Lantz et al., 2012). Another significant drawback particularly, in reference to Malaysia, is the lack of sufficient wind speeds for initiation of the wind turbine (cut-in speed). However, with lower power rated smaller Horizontal Axis Wind Turbines (HAWTs), Malaysia may still have the potential to benefit from wind energy. A robust analysis of the wind energy potential at various sites must be developed incorporating elevation, roughness, obstacle and climatic data. The analysis must also incorporate smaller HAWTs to evaluate whether the current technology available makes it economically feasible to harness wind energy at some parts of Malaysia, if not all.

1.3: Research Objective

In the past, during the period of prevalence of cheap oil, renewable energy was not a competitive source of energy, which hindered the direction of renewable energy research. However, with ever rising cost and depletion of fossil-based fuels, and their harmful effects, renewable energy sources are being actively pursued.

The popularity of Biomass and Solar energy have overshadowed research on wind energy since wind speeds are relatively low in Malaysia. Despite the availability of wind data, not many studies have explored in-depth the potential for wind energy in Malaysia. Most studies that did focus on wind energy, focused only on statistical analysis based on wind speed and direction, which is rudimentary in analysing wind energy production.

Due to the unavailability of detailed wind energy potential models in many low speed wind regions, focus on harnessing of wind energy is low. Hence, the aim of this research is to address this gap using the following key issues in harnessing of wind energy in Malaysia:

- To assess if wind energy is an adequate source of energy to be harnessed in Malaysia.
- To identify the most suitable wind turbines for optimal harnessing of wind energy in various parts of Malaysia.
- To develop a wind power potential map of Malaysia that can be used as a reference for future studies on wind energy.
- To evaluate the economic feasibility of harnessing wind energy in Malaysia using turbines identified above.

These four research objectives help produce empirically relevant findings on the economic feasibility of harnessing wind energy across multiple sites in Malaysia.

1.4: Research Contribution

During the past three decades, there has been some discourse in the literature on the potential to harness wind energy in Malaysia (discussed in 2.1). These studies have focused on the same sites in Malaysia and while using alternative methods to assess such sites. Mersing has been repeatedly identified as the site with the highest potential to harness wind energy in Malaysia; this study shows that using more robust wind analysis and Micrositing, this may not be true. This study contributes to the literature in three ways.

First, improved accuracy. This study improves the accuracy of wind power estimations by incorporating a multitude of data. These include, wind speed data from land based meteorological stations and satellite data from National Centers for Environmental Information (NCEI) for 16 years; elevation and orography data from SRTM (Shuttle Radar Topography Mission); user-fed corrections for roughness maps to account for manmade and natural structures at the various sites, accounting for various small HAWTs and hub-heights for installation of these turbines. Previous studies on Malaysia have in most instances ignored elevation and orography data, and in the three studies that have considered this, it was not done accurately (as discussed in section 2.1). Further, none of these studies have accounted for roughness maps at these sites and have not considered precise Micrositing. This study uses the Wind Atlas Analysis & Application Program (WAsP), a tailor-made software for industrial and commercial application, to overcome these issues.

Second, the study considers many sites across Malaysia. This study considers 36 sites across Malaysia, with hourly wind data being analysed for 16 years (2000-2015). The expansion of the analysis to include low wind speed sites that are dispersed across the country, enables to provide a comprehensive analysis that shows how wind energy potential is distributed. Some sites despite lower speeds may experience constant wind flow which may result in higher AEP, thus

even sites with lower wind speeds are considered in this study. A wind energy potential map would be developed to illustrate the power availability in kilo-watt hour (kWh) units to help decision makers and potential investors to locate areas suitable for wind energy harvesting. Previous studies have concentrated only on a handful of sites and have fell short of providing a national level analysis.

Third, the study considers policy effects. The study uses available feed in tariff (FiT) policies of the state (implemented through the national electricity company-Tenaga Nasional Berhad (TNB)) to evaluate the monetary value of the energy produced by each turbine installed at a particular site. Taking into account the market price, transportation and installation cost, maintenance cost and time value of money; the study is able to estimate the return on investment on each turbine at a particular site. This analysis provides policy makers and other stakeholders an avenue for informed policy making. Previous studies that have calculated the economic feasibility of harnessing wind energy have made unrealistic assumptions about the cost of wind turbines, FiTs and have in most instances not accounted for maintenance costs. Using real-world data for these factors makes the study empirically relevant and useful for decision-making.

1.5: Thesis Outline

This thesis is divided into six chapters that explore the motivation, gaps in the literature, methodology, results, discussion of validation of results, policy relevance and limitations.

This first chapter introduces the discussion on the motivation and background for this study and elaborates why the thesis focuses on wind as the key renewable energy source. The chapter then discusses the significance of the research objectives and highlights three key contributions the thesis makes to the literature.

Chapter two reviews the literature in three sub-sections. The first sub-section summarises studies on harnessing wind energy in Malaysia. This includes studies that only use statistical methods and those using wind atlas analysis. The second sub-section focuses more particularly on studies that use wind atlas applications including WAsP. The sub-section summarises the key findings in different parts of the world employing the same WAsP model to tabulate the annual energy production at low wind speed regions. The third sub-section reviews literature on wind turbines. The sub-section discusses the types of wind turbines that have been used in studies on countries with low-wind speeds and their main findings.

Chapter three explains the data and methodology employed in this research. The first sub-section of the chapter discusses the NCEI and SRTM data. The chapter highlights the strengths and weaknesses of these data sources and how the data is employed in the thesis. The second sub-section discusses the wind resource assessment methodologies in incremental robustness; the weighted average wind speed approach, Wind Rose, Weibull distribution and the wind atlas analysis. The third sub-section discusses the power density (PD) estimation and importance of roughness values in estimating a generalised wind climate. The fourth sub-section illustrates some of the anomalies in data from the NCEI database and SRTM maps and

proceeds to discuss roughness corrections as a key element of the wind resource estimation. The fifth sub-section of the chapter discusses power equations and wind turbine characteristics used in estimating the Gross Annual Energy Production (G-AEP). The sixth sub-section discusses Net Annual Energy Production (N-AEP) and identifies three key tools: resource grids, wake loss and the performance indicator (dRIX) in estimating it. The seventh sub-section discusses the robustness of the model introduced in the previous sub-sections. This sub-section compares estimated and actual AEP at a live turbine site to evaluate the robustness of the model. The final and eighth sub-section identifies different tools to evaluate the economic feasibility of wind power projects and the parameters and data used in the analysis. These parameters include the project lifespan, interest rate, inflation rate, exchange rate, estimation of transport and installation costs, estimation of operational and maintenance cost among others. The discussion then focuses on the Levelised Cost of Energy (LCOE) and Internal Rate of Return (IRR) as two tools to appraise the investment in wind turbine technology.

Chapter four discusses the results. The first sub-section of the chapter illustrates the estimations of weighted average annual wind speed for all locations of study. The chapter then proceeds to discuss the resultant wind profiles as the initial screening stage. The third sub-section produces power density calculations and the ranking of Malaysian sites by wind speed and power density with respect to hub heights. It also recalculates the PD incorporating roughness changes and discusses why the PD at some sites had changed. The fourth sub-section discusses the top five mean AEP locations and how they were chosen. The fifth sub-section illustrates the influence of dRIX and wake loss during micro-siting. The sub-section then continues the discussion on N-AEP computation and identification of sites for potential wind farms. The next sub-section discusses the robustness of estimates and validation. The chapter highlights how estimates of the WAsP model were validated using data from an operational wind

turbine with similar climatic and wind profiles. Robust AEP estimates using WAsP are compared to actual AEP generated from the turbine for the calendar year 2017. The deviation in AEP is then calculated and possible reasons for the deviation are discussed in tandem with the implications of the findings. The final sub-section evaluates the economic feasibility of harnessing wind energy in the sites with a ranking of sites presented based on the LCOE and IRR estimates.

Chapter five presents a discussion of the main results identified in chapter four. The first sub-section focuses on the sensitivity analysis of the economic feasibility results. to the sub-section identifies the commercial viability of the sites if AEP were to be lower by 5% and 10% or higher by 5%. The second sub-section discusses the novelty of this study; this study has used (i) topographical data for wind analysis, (ii) robust landcover map, and (iii) google earth to identify locations for the installation of wind turbines. The final sub-section discussion the limitations of the study in greater detail.

Chapter six concludes the thesis by summarising the key findings and contributions. It also presents an outline of how findings in this study could be relevant for decision making by the state and private investors. The chapter concludes by providing a discussion on the extensive future work (minor and major) that can be undertaken to improve our understanding of the potential to harness wind energy in Malaysia.

CHAPTER 2: LITERATURE REVIEW

This section reviews some of the literature that closely relate to the current study. It is divided into three sub-parts: (1) studies in Malaysia that use WAsP and other methods to evaluate the effectiveness of harnessing wind energy in Malaysia; (2) global literature that focus on evaluating the effectiveness of harnessing wind energy at particular sites using WAsP and (3) discussion of the turbine selection literature.

2.1: Review of Harnessing Wind Energy in Malaysia

Malaysia is located in the equatorial region with a 4,675km coastline, and the climate of the country is governed by the northeast and southwest monsoons. The strongest wind is experienced at the east coast of peninsular Malaysia during the northeast monsoon period. Studies by many researchers show that there is good potential to harness wind energy in few islands and coastal areas in the country (Exell and Fook, 1986; Sopian et al., 1995; Chiang et al., 2003; Razali et al., 2009; Islam et al., 2011; Akorede et al., 2013; Nor et al., 2014).

Mersing, a South-Eastern coastal belt, has the most favourable wind speed in Malaysia; recording the highest speed to be 4.5 ms^{-1} to 5 ms^{-1} during December and January, while the average speed is around 2.6 ms^{-1} throughout the year (Sopian et al., 1995; Rosly et al., 2012). Since the wind speed is very low in Malaysia, Sopian et al. (1995) pointed out that small wind turbines can be used at the coastal areas and islands (off-shore) to harness optimal wind energy.

The first wind farm of the nation was set up at Terumbu Layang Layang (Anwari et al., 2012). Following its success in 2005, a hybrid system consisting of solar, wind and diesel was set up in 2007 in Pulau Perhentian (Oh et al., 2010; TNB, 2014). However, this hybrid

system in Pulau Perhentian stopped functioning in 2010 (Rosly et al., 2012). The ministry of rural and regional development installed eight small wind turbines in Sabah and Sarawak for community usage (Ong et al., 2011). In 2012, a 3.3 kW wind turbine was installed by Universiti Malaysia Terengganu in a shrimp farm in Setiu, Terengganu (Albani, 2017). Additionally, the Scientific and Industrial Research Institute of Malaysia has installed wind turbines in Kudat, Kuching, Kuala Perlis, and Kuala Terengganu before 2013. However, no results were published or are publicly available for review of the above-mentioned projects.

Sievert (2010) quotes IMPSA (Sdn. Bhd.) as estimating Malaysia has the potential of generating 500 to 2000MW of wind energy at a cost of 1.8 to 2.5 million USD to generate 1MW. They have identified Kota Kinabalu, Mersing, Langkawi and Kuala Terengganu as the potential sites for wind generation. Albani et al. (2014) and Mekhilef et al. (2012) argue that Malaysia needs to explore the possibility of offshore wind farms, as offshore farms can produce up to 50% more electricity compared to onshore wind farms.

A study conducted in the state of Perlis using data obtained from the weather station in Kangar employing a Davis Vantage Pro2 (instrument) suggests that Perlis has the potential in harnessing wind energy using a vertical axis wind turbine. The stated study is conducted using one-year data (Daut et al., 2012). However, as a general rule of thumb, it is suggested that analysis of wind data should extend to at least 10 years' worth of data to produce robust estimations taking into account variations in wind patterns over time (Fadare, 2008; Maunsell et al., 2004). Therefore, results in this study are likely to be upward biased and need to be treated with caution.

Most wind energy studies in Malaysia exclusively focused on estimating wind power potential using the Weibull distribution. Sopian et al. (1995), Daut et al. (2012) and Razliana et al. (2012) among others show that Mersing, Perlis and Terengganu have the

highest potential for harnessing wind in Malaysia. Siti et al. (2011) using similar statistical approaches evaluate five sites⁴ in Malaysia conclude that Mersing has the highest wind energy potential among sites that they examine. They have estimated the power density to be 62 Wm^{-2} for Mersing. Islam et al. (2011) also use Weibull analysis to study the wind energy potential in Kudat and Labuan and conclude Kudat has the highest wind energy potential among these two sites. However, the authors had not considered the power density at Mersing. Given that several studies have similarly attempted to estimate the potential power density at different individual sites without consistent data, time range, or methodologies, comparison between sites becomes difficult and siting decisions for installation of wind turbines and farms becomes more challenging.

Another study by Islam et al. (2011) analysed the wind power density using Weibull distribution in Mersing, Melaka and Kuantan also claim that Mersing has the highest wind energy density among those three locations. The study also suggests that it is not feasible to harness energy using HAWTs due to higher cut-in speeds and suggests the use of vertical axis wind turbine (VAWT) as the cut-in speeds are lower. However, the study has two key limitations. First, the used Malaysian Meteorological Department (MMD) wind data for only three years from 2006 to 2008, which may not be sufficient to conclude the potential site to harness wind energy to generate energy. Second, mere analysis of power density using Weibull distribution is likely to be misleading as it does not account for geographic characteristics of the sites (discussed in chapter 3).

Jakhrani et al. (2012) studied solar and wind feasibility in Sarawak across five sites⁵ and found that Bintulu has the highest mean wind speed and wind power density among the five sites. However, their

⁴ Langkawi, Penang, Kuala Terengganu, Kota Bharu and Mersing.

⁵ Kuching, Sri Aman, Sibu, Bintulu and Limbang.

study claims that the results are not favourable for large scale wind farms. Based on NCEI data used in this study, the power generated from Bintulu is far less compared to other coastal sites even within Sarawak.

Masseran et al. (2012a) studied hourly wind data of (nearly) three years for ten⁶ wind stations across Malaysia and found these locations to have persistent wind speed. The authors, using unit root and variance analysis, conclude that Chuping has the most consistent wind speed. However, their study, similar to others, points out that Mersing has the highest potential to generate energy at around 18% of the time. This is considered low utilisation and they suggest further research into improving harnessing wind energy. Given that the observed average wind speed at those stations are quite low, the authors also conclude that more effort needs to be made to identify potential wind sites for power generation. Our study attempts to address this gap.

Studies by Masseran et al. (2012a, 2012b and 2013) use various statistical methods of dispersion to evaluate more than 60 sites using MMD wind data for 10 years. Their studies conclude that coastal areas of Peninsular Malaysia and Sabah, Sarawak have the highest potential for harnessing wind energy. These studies also indicate a lack of spatial correlation in harnessing wind energy has curtailed its appeal as a renewable energy source in Malaysia. Our study addresses this gap by producing Predicted Wind Climates (discussed in Chapter 3).

Albani et al. (2011) show that small wind turbines (22kW wind turbines) are able to better harness the wind energy in Malaysian conditions. They also show that Sandakan and Kudat have the highest potential to harness wind energy. Despite the preliminary

⁶ Alor Setar, Bayan Lepas, Cameron Highlands, Chuping, Ipoh, Kota Bahru, Kuantan, Malacca, Mersing and Kuala Terengganu Airport.

efforts in using small HAWTs, the authors study only four sites⁷ in the state of Sabah and rely only using monthly wind observation data for the year 2009. The Inverse Distance Weighted (IDW) method was used to interpolate the spatial wind speed distribution for Sabah without taking into account geographical conditions at the sites.

A more recent study by Ibrahim et al. (2015) attempts to identify the wind power density across Malaysia using Spatial-Temporal Analysis and Wind Potential Geographic Information System. The study concludes at least 1.52 MW or wind energy can be harnessed across Malaysia. This study does not account for wind direction, topographical information, and relies on data for only one year. Further, given the very low wind potential in certain regions being identified in the study, the authors fail to discuss whether harnessing wind energy at those regions is economically feasible.

A common criticism across these studies is that these studies do not factor the difference in data collection, micro-siting⁸ and geographic characteristics of the sites. Most wind data in Malaysia is observed using anemometers set at airports (MMD and NCEI). Wind speeds observed at airports tend to be higher than those observed in the same regions at different locations which leads to overestimating wind power for the region. If wind turbines are to be setup in or around the airport the predicted power densities in the above studies may be applicable; they may be less relevant for locations away from the airport (Ho, 2016). Additionally, most of the above studies calculate the power density or AEP using statistical tools such as Rayleigh distribution, Weibull distribution and unit root analysis and do not factor in topographical or ruggedness characteristics.

⁷ Kota Kinabalu, Tawau, Sandakan and Kudat.

⁸ Choosing appropriate wind turbines and the precise locations to place them, where maximum power production is possible throughout the year.

Mekhilef et al. (2012) use the software HOMER and data from MMD to study six sites along the south china sea coastline since harnessing wind offshore is claimed to be more productive than harnessing onshore wind. The authors claim that the potential for energy harnessing is higher during the northeast monsoon season and the highest resultant annual vector wind speed of 4.1 ms^{-1} is recorded in the east peninsular. Moreover, they used Vestas V-47 and V-80 wind turbines (660kW and 2MW respectively) to calculate the economic feasibility. While a 2MW-rated wind turbine produces the lowest energy cost at RM 0.40, a 0.66MW wind turbine generates a higher net specific production. FiT is an essential factor to ascertain the feasibility of wind energy generation and a FiT greater than the breakeven point certainly would be appealing to investors. The authors propose that energy policies focusing on wind are needed to attract investors; currently Malaysia lacks such policies. While the authors use offshore wind data and economic variables including the maintenance cost to analyse the feasibility of offshore wind farms, the extremely high annual operating cost, ranging in multiples of 1.5 to 14 times that of the cost of the turbine make offshore wind farms highly cost sensitive. Further, the FiT sensitivity analysis of the sample site taken in the study affirms the high volatility and risk associate with offshore wind farms, especially when using large wind turbines in areas with relatively lower wind speeds.

WASP, the wind analysis model and software used in this study has been sparsely employed in the literature on Malaysia; notable exceptions are Albani et al. (2013a, 2013b, 2013c) and Albani and Ibrahim (2014). The use of WASP or other similar wind analysis models improves the accuracy of the power predictions and are able to aid in the production of the generalised wind climates across regions. These are known as Wind Atlas too.

Albani et al. (2013a) study the potential to harness wind energy in Langkawi and conclude that only moderate wind energy can be harnessed at this location. However, the authors only used data for

one year-2009, which falls short of the recommended timeline of at least 10 years. Further, the authors use an arbitrary hub height of 30m in deciding to install the 22kW rate wind turbine. Therefore, AEP estimations are likely to be biased and unreliable. The authors also do not incorporate a roughness map, which is critical for AEP estimations.

Albaniet al. (2013b) conducted a similar study in Kudat, using wind data for 9 years with 6kW, 10kW and 15kW rated wind turbines. This study uses Digital Elevation Maps to account for orographic characteristics of the sites but fails to incorporate a roughness map, this is likely to overestimate power as the default roughness in the DEM is 0.03; a roughness length that is attributed to farmland. For a region having other structures along with trees and forests, a higher roughness length should be assigned (Appendix – C) The authors also identified the potential sites to install wind turbines from resource grid. Micrositing without taking into account the structures and habitants of a particular site is futile as it may not be possible to install wind turbines in highly populated regions or areas with obstructing structures (WAsP 12). Further, Ibrahim and Albani (2014) show that the sites where the turbines are installed in Albani et al. (2013b) fall within a protected forest reserve. Not having accounted for this makes the findings Albani et al. (2013b) empirically irrelevant.

Albani et al. (2013c) study the wind energy power potential at nine sites in Malaysia; four from peninsular Malaysia and five from East Malaysia⁹. Using data for six years from 2007 to 2011, the authors conclude that Kudat has the highest wind energy potential among sites they examine in Sabah and Sarawak while Kota Bharu has the highest wind energy potential in Peninsular Malaysia. The authors use WAsP to create Weibull distribution and WindPro to analyse the AEP

⁹ Kota Bharu, Johor Bharu, Langkawi and Kuala Terengganu in Peninsular Malaysia. Sandakan, Miri, Kota Kinabalu, Kuching and Kudat in Sabah Sarawak.

using a 22kW wind turbine. Kota Bharu is densely populated urban area; hence, choosing a site to install a wind turbine is not a feasible activity even though the site may have the highest potential in Peninsular Malaysia. Moreover, Mersing, which has been rated as the highest wind energy potential in Malaysia for decades, is not included in this study. Furthermore, the use of monthly averages in their studies is likely to impede the power estimations as hourly or daily wind data is preferred for power estimations over weekly or monthly data.

Ibrahim and Albani (2014) study the wind energy potential of Kudat using a 22kW rated wind turbine. Using data for 2013, the authors conclude that Kudat has good potential to harness wind energy. They setup three wind farms of 1km X 1km in size around the protected forest areas of Kudat near its northern tip. The authors conclude that the most optimal zone, Zone 2, produces between 37.5MWh – 43.1MWh. Zone two, is to the right of the protected forest area. The study fails to account of the ruggedness of the terrain and only uses one-year worth of data. Estimations in our study for Kudat show that lower power rated wind turbines can in fact produce higher power than those reported in the study, if micrositeing is considered on a larger area and ruggedness information and wake loss are taken into account.

Albani and Ibrahim (2014) use one-year wind speed data for 2009 and test forty-six wind farms to analyse the potential for harnessing wind energy using turbines of 22 kW to 1.012 MW. This study accounts for topographic information at the site. The results show that four locations have potential for harnessing wind energy with a 22kW wind turbine; these are, Kuala Terengganu, Mersing, Kudat and Langkawi Island. As discussed above, generally, one-year data is not sufficient to estimate the wind power at a site; moreover, a roughness map was not included in the simulation for AEP. To complicate things further, the authors use arbitrary roughness scales for each of the locations. For Kota Bharu the authors use 0.03, and

0.0005 for Mersing, Kudat and Langkawi Island. These values tend to underestimate the roughness of the sites and thus, produce overestimate wind power potential at the sites. For example, a highly populated urban site such as Kota Bharu should take a minimum roughness value of 0.4. Mersing, Kudat and Langkawi have been assigned 0.0005; even flat, smooth land surfaces have a roughness index of 0.005 and therefore the values assigned in the study are misleading (Appendix – C). Assigning a blanket value for the entire area being studied is not recommended (Mortensen, 2016).

Albani et al. (2014) evaluate the economic feasibility of harnessing off-shore wind energy in Kijal (Terengganu) using seven types of wind turbines—110kW, 225kW, 275kW, 600kW, 850kW, 1000kW and 1250kW power rated turbines. They highlight that the 850kW wind turbine produces the most amount of mechanical wind power. Based on investment appraisal techniques—net present value (NPV) and payback period; they also conclude that installation of an 850kW wind turbine would be economically feasible. However, the study uses QuickSCAN data of two readings a day, which is likely to produce biased estimates based on when the reading was taken. For example, if the readings were taken during high wind flow periods of the day, the resulting estimates from WASP are likely to be upward biased and vice versa. Due to this reason, hourly wind data is likely to produce more reliable estimates.

Nor et al. (2014) also evaluate the economic feasibility of harnessing wind energy in Malaysia using multiple turbines. The study uses Numerical Weather Prediction (NWP) to estimate the wind power density across selected regions and then uses NPV analysis to estimate the economic feasibility of harnessing wind energy at those sites. Similar to Albani et al. (2014), Nor et al. (2014) also conclude that if the right power-rated wind turbines are employed, harnessing wind energy is likely to be economically feasible and, in some cases, economically profitable. Nor et al. (2014) however do not account for any topographical or roughness characteristics of the site.

The studies that incorporate Digital Elevation Maps (DEMs) and topographical characteristics of the sites improve the estimation of AEP compared to studies that only use statistical methods. However, they fail to incorporate roughness length maps in estimating the potential wind power at the sites; hence, lead to non-robust AEP estimation. Furthermore, most of the above studies rely on annual data, where they use long time intervals. i.e. the studies use one or two observations of wind speeds per day. This is likely to affect the reliability of the wind power estimations.

This study addresses the gap in the literature by evaluating the potential to harness wind energy across 36 sites¹⁰ incorporating topographical and roughness characteristic of sites. In addition, the study would use rich datasets to produce more robust estimations. This includes the 16-year data from NCEI and 3-arc topographical data. In addition, the study would also use investment appraisal techniques to initiate prudent evaluations of the economic feasibility of installing wind turbines/farms to harness wind energy at the most promising sites across Malaysia.

2.2: Review of WAsP & its Application

It is crucial to efficiently extract wind energy for smooth operation of wind turbines. Thus, precise knowledge of wind energy regimes of the locations is vital prior to any wind turbine installation. Wind resource analysis (WRA) software improves the robustness of wind estimates and power calculations. Software such as WindPRO, WindSIM, HOMER and WAsP are widely used by both researchers and the industry (Nilsson, 2010).

¹⁰ Mersing, Kudat, Kota Bharu, Labuan, Sandakan, Miri, Langkawi, Penang (BL), Butterworth, Kota Kinabalu, Sultan Abdul Aziz S, Malacca, KL Subang, Kuala Terengganu, Sultan Abdul Halim, Bintulu, Johor, Kuantan, Tawau, KLIA, Kuching, Sultan Abdul Shah, Sibu, Sitiawan and Sri Aman.

HOMER is popular in estimating the power of hybrid systems involving Solar and Wind. HOMER uses data on wind speed and direction, solar irradiance and turbine information to estimate the power density and Annual Energy Production. While HOMER is capable of producing estimates for individual wind and solar systems and farms, its model strength is in estimating hybrid system. HOMER produces sensitivity analyses which aid identify a range of resource availability and component costs. These estimates are useful in cost evaluation and feasibility studies; however, since HOMER does not take account of roughness information, it is less than ideal for estimating standalone wind farms.

There are only a handful of software available for wind resource assessment. WRA software such as Wind Farmer, models wind flow with WAsP or an external model (DNVGL, 2018). Other WRA software such as WindSim and Meteodyn WT are based on CFD calculation (WindSim, 2018; Meterodyn WT, 2018). CFD calculations require higher computing power and is generally not favoured for sites with only few rugged terrains as it is both time consuming and expensive. WAsP was developed by the Risø National Laboratory in Denmark as part of the European wind atlas project in order to execute the wind atlas assessment. A wind atlas is the wind climate of a particular region or a country (Troen and Petersen, 1989), and is generally illustrated with tables, maps and graphs. While another WRA software WindPRO allows to download 1arc map directly and allows the user to draw roughness map within the software, WAsP users have to rely on Google earth to create the roughness map. However, both WindPRO and WAsP use the WAsP flow model as their modelling engine (WAsP, 2016). Since WAsP's flow model is the underlying model for both software and WAsP is available free for education purposes, WAsP is used in this study to assess wind resource in Malaysia.

Moreover, Awasthi et al. (2013) state that WAsP is a powerful tool for the assessment of wind data, wind atlases generation and

estimation of power production. WAsP, in particular, has become popular among researchers after the European Wind Atlas Project was disseminated in 1988. The software is found to be generally faster in processing data and is more user-friendly. Supporting this assertion, Khadem and Hussain (2006) point out that WAsP has been used in more than 100 countries and territories worldwide. Further, it has one of the lowest up-side risks in predicting wind speeds among various other methods—within a range of 2.0% to 5.9%—5.9% is the lowest maximum deviation reported among all methods (Prasad et al., 2009).

Troen (1990) points out that the semi-analytical theories for the perturbation of the boundary layer flow developed by Jackson and Hunt (1975) and Mason and Sykes (1979) has led to several models for neutral flow in complex terrains being developed. Unlike previous linearisation of the equations of motions, Troen (1990) developed a model more accommodative of the heterogeneity in surface roughness. Troen's model is integrated in WAsP allowing calculations to be more precise where surface roughness is not homogeneous (complex terrain). The effectiveness of the model has been also tested in Walmsley et al. (1990) and since has been widely employed by studies using WAsP based estimations.

Mortensen and Petersen (1997) point out that the most important factor for the accuracy of WAsP predictions in rugged and mountainous sites is the ruggedness of the terrain. If the reference site and potential site for turbine installation do not share similar ruggedness, wind power estimations are likely to be biased and thus be over- or under- estimated. Singh (2015) highlights that in Bangladesh, wind farms have been developed in rugged forest terrains such as Kutubdia Island using WAsP. Singh proposes that successful utilisation of WAsP in such rugged terrain is testament to its ability work under complex topographical conditions / landscapes. Hence, he highlights that "WAsP is precise, versatile and provides virtually all what is needed for setting up wind farming in any given

landscape". The author also suggests that WAsP has become a reliable and generally accepted standard for micrositeing.

While WAsP has been widely used by the wind exploratory community, its use also bears some limitations. The key among them are the assumptions that the reference and potential sites have similar characteristics along the following dimensions: weather regime, stable weather regime, less rugged terrain and that reference site's data are reliable (Bowen and Saba, 1995; Bowen and Mortensen, 1996). Enforcing these assumptions on the predictions without actually validating them may produce biased estimates. Further, since WAsP uses a linear model to derive ruggedness and power estimates; complex terrains may be beyond its envelope of prediction (Troen, 1990).

WAsP essentially produces a climatic region based on the reference site's wind readings and climatic conditions to be applied on a potential site. Non-standard atmospheric conditions (such as stratification, sea breezes, downslope winds, channelling or blocking valleys) can therefore contribute to errors in the prediction. Furthermore, like other wind models, the assumption in WAsP is that there is high correlation between the predicted and reference sites (ideally correlation is unity). In such circumstances, Bowen and Mortensen (1996) argue that using hourly averages of wind speeds for example is preferable over using 10-minute averages, since the longer period average allows for the wind event to envelope better.

This study uses hourly wind data. WAsP also enforces measured data to fit a standard Weibull distribution and 12-sector Windrose; although this is common across multiple wind assessment models, this simplification may reduce the power of the data and produce marginal errors in the produced estimates. Despite these limitations however, the benefits of using WAsP—its simplicity, linear approximation and ability to work on multiple terrains (with some caveat) has made the model more popular over several other

commercially available wind assessment models. It has also been widely applied in the European, Northern African and to some extent Asian regions for wind assessment and micro-siting procedures, some of which, especially relating to low wind speed, are identified below.

Khadem and Hussain (2006) study the wind power energy potential in Kutubdia Island in Bangladesh, which has about 30% higher average wind speeds at 50m heights compared to the Malaysian average for top 5 sites. They find that at a height of 50m, harnessing wind energy in Kutubdia Island can produce up to 200Wm^{-2} energy and therefore, large wind turbines can be used. The authors also acknowledge that installing large wind turbines at the height of 50 m or above is suitable only for the eastern and southern coastal part of the island while small turbines are suitable for other parts of the island. The authors attribute this conclusion to Kutubdia Island's complex terrain, where the roughness varies throughout the island. Even though several others in the field point out that larger wind turbines are able to produce per unit of power at lower cost (achieve economies of scale), it is also important to choose wind turbines that suit the specific sites in order to generate maximum wind power (Singh, 2015). Khadem and Hussain's (2006) study is testament to this: wind turbines with higher capacity are not necessarily the most efficient and productive—these depend on the available wind speeds and terrain roughness. Their WAsP prediction is also aligned with other study such as Beacon Collision Avoidance System measurement sites, even though they used short-term data for the analysis.

Tanc et al. (2014) test for the wind power efficiency of turbines using a vertical arrangement and the scattered arrangement. The authors used three-hourly daily data for twelve months at the Hatay airport region in Turkey. They conclude that scattered wind turbine arrangements are more efficient due to less shielding of wind. However, since the authors only used a one-year time period of observations, their data unlikely to capture year to year variability in

average wind speed (Landberg et al., 2003; Fadare, 2008; Maunsell et al., 2004). Tanc et al. (2014) also highlight that setting up wind turbines within a proximity of 5 km to the runway of an airport could lead to interferences with electromagnetic communication devices. However, Van der Geest (2009) show that a small wind farm within proximity of the Copenhagen International Airport in Denmark has not faced such adverse issues (especially since they use offshore wind farming).

Mostafaeipour and Abarghooei (2008) study six sites in the Manjil area in Iran to assess their potential for harnessing wind energy. At 10m elevation, three of these sites have about 20% higher wind speeds compared to the top five sites in Malaysia. Interestingly, the authors show that harnessing wind energy at higher elevations increases the captured wind speed by as much as 50% at these three sites. In a similar study, Himri et al. (2009) evaluate the potential to harness wind energy across four sites in Algeria. Two of those sites that bear similar wind speed characteristics to those of the top five Malaysian sites, are found to produce fluctuating wind power across the year. The authors conclude that while these two sites produce lower wind power compared to the other sites they study; the available wind power is still sufficient for harnessing energy with small wind turbines.

To conclude, WAsP is a powerful software used by the industry, which allows to incorporate topographical features alongside wind speed and direction information to produce more accurate estimations of AEP and execute micrositing. As highlighted in the studies summarised above, WAsP has been successfully used to estimated wind power in both high wind speed regions in Europe and even low wind speed regions in the Middle East and East Asia (similar to Malaysia).

2.3: Review of Suitable Wind Turbines

Much of the literature on wind energy focuses on high wind speed regions, such as Europe, where large wind turbine (1MW or higher) are employed. Even ones that focus on Asia (such as on China and India), have also largely employed medium to large wind turbines as relatively higher wind speeds are prevalent in these regions (Sasi and Basu, 1997; Qi, 2010)¹¹. Hence, there is a dearth on studies that employ small wind turbines (<100kW). Given that Malaysia has relatively lower wind speed even compared to most Asian countries, it is not feasible to employ medium or large wind turbines. Previous studies on Malaysia; especially, Sopian et al. (1995) and Abas et al. (2004). Albani et al. (2011) highlight that Malaysia does not support large wind turbines and it is advisable to use small wind turbines for efficient harnessing of wind energy due to the low wind speed availability.

Very few studies focus on onshore wind farms in low wind energy regions such as Malaysia. Even fewer studies focus on Malaysia with commercially available wind turbines being deployed. Studies such as Albani et al. (2014) use seven different medium wind turbines of rated power 110, 225, 275, 600, 850, 1000 and 1250kW. However, the authors do not use any commercially available wind turbines. They produce power estimations based on power curves of non-commercial turbines and also estimate prices based on a linear function of the rated power. Such assumptions hold little empirical relevance and therefore, make the estimations more of a theoretical exercise rather than hold empirical significance. Similarly, Ibrahim and Albani (2014) consider nine wind turbines of 10, 11, 15, 22, 30, 110, 225, 250, and 275 kW power rating (i.e. small to medium power-rated turbines). Again, the authors do not use commercially

¹¹ Information on types of turbines being employed was retrieved from projects registered with the United Nations Climate Change initiative: <https://cdm.unfccc.int/Projects/registered.html>. Further, information of the turbines were also retrieved from turbine operators, such as, Hindustan Petroleum Corporation Limited: <http://www.hindustanpetroleum.com/alternateenergy>.

available wind turbines and conclude that the 22kW turbine is the most appropriate for use given its higher capacity factor based on power curves from non-commercial wind turbines.

As more and more researchers focus on policy-oriented research, recent global studies use commercially available wind turbines to ensure that the estimations are useful for decision making. Studies such as Mohammadi and Mostafaeipour (2013) and Bortolini et al. (2014) use commercially available wind turbines from manufacturers such as Fortis, Ampair, Windenergy Solutions and Enercon among others. Bortolini et al. (2014) extensively studied multiple factors that affect both technical and economic feasibility of small HAWTs. Similar approach is presented in section 3.7.1. for decision making in this study. Al-Hadhrami (2014) use small power rated wind turbines, a combination of Aeolos, Bergey, Fortis and WES wind turbines among others, in his study. His study shows that HAWTs are to be more efficient than VAWTs for low wind speed regions. He also concludes that when the hub height is increased from 10 m to 20 or 30 m, there is a 20% increment in AEP.

In the literature, small wind turbines such as those used in the analysis in this study (and identified in section 3.5.2), have been deemed less profitable than larger wind turbines (Valentine, 2011). This is because small wind turbines require proportionally higher initial investment compared to their rated power. Ozerdem et al. (2006) and Bortolini et al. (2014) show that for wind turbines rated at above 1MW, the cost of the turbine per kW hour energy produced diminishes as the rated power increases. However, both studies also illustrate an inverted-u shaped relationship between rated power and the cost of the turbine per kW hour of energy produced. Both studies indicate that for smaller wind turbines rated below 1MW, the cost of the turbine increases as the power increases. For these reasons, it is important to ascertain whether the wind turbines employed in this study generate sufficient power to justify their instalment. It is also

important to identify the power rating of wind turbines and their hub heights that maximise return on investment.

In light of the above discussion, this thesis only considers small wind turbines with power ratings above 1kW and at or below 50kW since Malaysia experiences lower wind speeds. A detailed discussion of the commercially available wind turbines considered in this study is presented in section 3.5.2 and 3.8.1.

CHAPTER 3: DATA AND METHODOLOGY

This chapter outlines the data and methodology used in this research and how they are analysed. It comprises of seven sub-sections of which two discuss data related issues and the other five discuss methodological approaches in incremental robustness.

3.1: Wind Data

Two datasets are combined in this study to create the wind power estimations. The first set of data contains wind speed, wind direction and climate related information. The second set of data contains topographic information and geographical vector data set related to water bodies to create Digital Elevation Models of the sites. These datasets are explained below.

3.1.1. Wind Speed and Direction Data

A key determinant of the economic viability of a potential site for wind turbine installation is the long-term wind profile—including wind speed and direction. It is a rule of thumb that five to ten years of data is required to establish the long-term wind resource at a particular site for year to year variability in average wind speed to be accurately measured (Landberg et al., 2003; Fadare, 2008; Maunsell et al., 2004). Hence, hourly wind speed and direction data for 16 years across 36 stations in Malaysia are used in this study. Data was derived from the United States National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI). NCEI dataset are historical dataset that are derived from MET data provided the Malaysian met department. The data were collected at the weather stations from Alor Setar, Bintulu, Butterworth, Cameron Highlands, Ipoh, Johor Bahru/Senai, Kerteh, Kota Kinabalu, KLIA, Kuala Lumpur Subang, Kuala Terengganu, Kuantan, Kuching, Kudat, Labuan, Langkawi, Malacca, Mersing, Miri, Muadzam Shah, Penang/Bayan Lepas, Petaling Jaya, Sandakan,

Sibu, Sitiawan, Sri Aman/Simanggag, Subang/Sultan Abdul Aziz Shah Airport, Kedah/ Sultan Abdul Halim Airport, Perak/ Sultan Azlan Shah Airport, Tawau, and Temerloh. A map of these stations is presented in Figure 4 below. The combined database consists of 3,294,210 hourly observations. Wind speed data from the source files were in 'Miles per hour' and they were converted into 'metres per second' for comparison with regional literature.

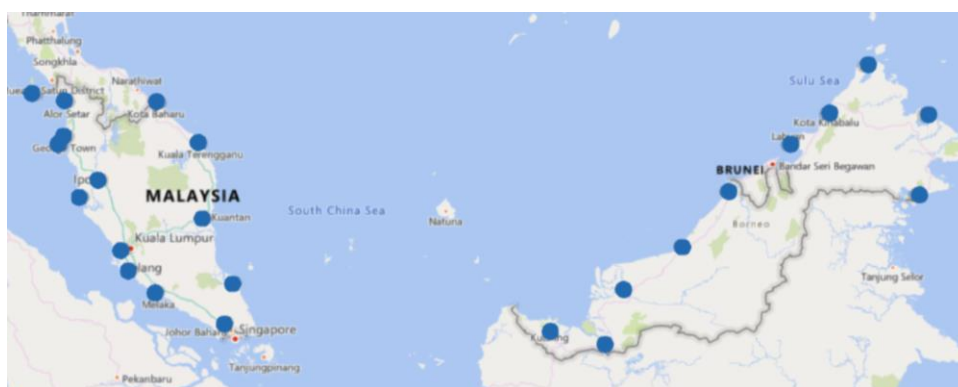


Figure 4: Study Sites of Malaysia

3.1.2. Topographical Information & Digital Elevation Models

Latitude, longitude, elevation from the sea level and topographical (both natural and man-made) features influence the wind speed available at a specific region (Khadem and Hussain, 2006). Although historical wind speed data can be used to estimate the available wind power at a specific region as discussed in section 2.1; accounting for topographical information provides more prudent estimates.

Topography captures three key land and terrain related information: the horizontal and vertical dimensions of the terrain (relief), three-dimensional surface quality information, and the landform(s). Geomorphometry uses such topographical information to produce digital elevation models (DEMs); a map of the land using contour lines and the roughness change lines (the boundaries), among others to represent the topographical data.

In DEMs, height contours and roughness lines form the key components for the digitising process. Digitising here refers to defining a roughness parameter on both sides of the contour. The opposing sides could be a combination of left and right or up and down. The two lines — roughness line and roughness-change line are critical for digitising. The roughness line provides roughness at either side of the contour line; whereas, the roughness-change line accounts for the roughness differences within the sites. It is also important that these lines end in a closed loop or node or at the end of the map boundary to ensure consistency in the roughness length (Singh, 2015). Roughness length is critical in estimating AEPs.

Data produced by the Shuttle Radar Topography Mission (SRTM) project was used in producing DEMs for this study. SRTM was launched with the intention of obtaining RADAR data of the Earth's land surface in order to create high resolution topographic maps. The SRTM data sets are generated using radar interferometry¹² (Farr and Kobrick, 2000; Rosen et al., 2000; Farr et al., 2007). The SRTM data sets were produced jointly by the space agencies of the USA, Germany, Italy and the National Geospatial-Intelligence Agency (NGA) of the USA.

The first version of SRTM data were produced with data from the STS-99 mission in 2000, covering more than 3/4 of the land surface of the Earth¹³. The first version was sampled at 30 arc-second; however, the data were not processed to remove voids. Moreover, areas with flat water surfaces and coastlines were reported to have

¹² The SRTM instrument consisted of the Spaceborne Imaging Radar-C (SIR-C) hardware set modified with a Space Station-derived mast and additional antennae to form an interferometer with a 60-meter long baseline (Kobrick, 2006).

¹³ The STS-99 was a radar imaging mission as part of the then newly created SRTM project. The SRTM project was headed by the National Imagery and Mapping Agency and NASA, with participation of the German Aerospace Center DLR.

errors (Farr and Kobrick, 2000)¹⁴. An improved version (Version 2) was released in 2005. The water body data were corrected in the second version, but it still had some voids. SRTM v2.1 was released as an improvement on version 2 by filling the voids. Version 2.1 is also sampled at 3 arc-second for both US and non-US regions. The latest is the 1 arc-second data (Version 3), which was extensively released for the US regions, while non-US regions contained noise and errors. While more detailed maps are available for the US at 1 arc-seconds (30m), the most detailed maps for other regions are still at 3 arc-seconds (90m). Thus, this study uses the consistent and complete SRTM v2.1 data. SRTM data developed by NASA is the one of the commonly used data in the wind industry. It produces the most complete (except for some voids) and highest-resolution DEMs of the Earth; hence, become more reliable (Farr et al., 2007).

WAsP is based on the World Geodetic System 1984 (WGS-84) for its geospatial analysis. WGS-1984 is a right-handed, three-dimensional Cartesian coordinate system with its origin at the mass-centre of the Earth (Figure 5). It is a widely used standard to define exactly where a set of coordinates are on the earth.

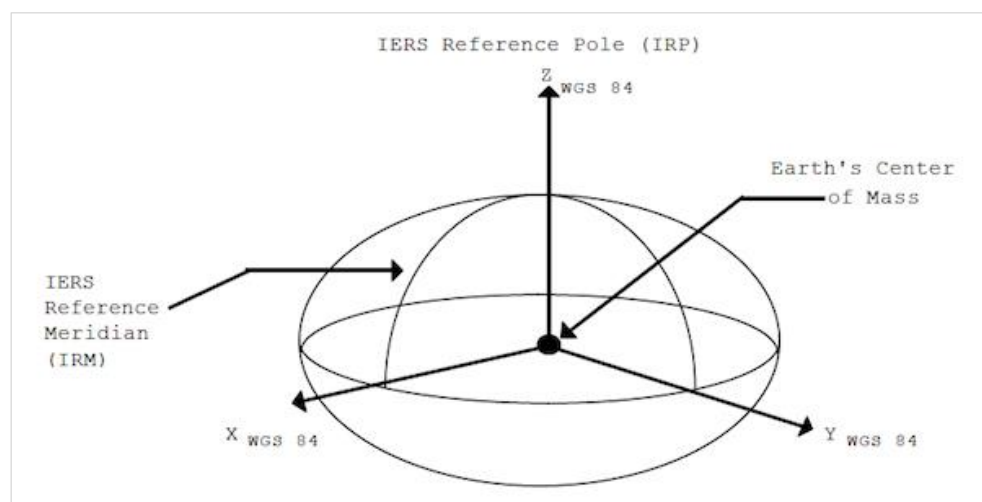


Figure 5: World Geodetic System 1984 (WGS-84)

¹⁴ An arc-second of longitude equals $30.87 \text{ meters} * 0.6561 (\cos 49^\circ)$ or 20.250 meters. A 3-arc second measures 60.75 meters along its north side and 92.60 meters along its east and west sides.

It is important that a widely used geodetic system is used since the earth is not a perfect sphere and therefore, the location of a point on the earth and its height can vary from system to system. Site descriptions are now fed in a Universal Transverse Mercator (UTM) Coordinate System. UTM is a 2-dimensional Cartesian coordinates system that states the distance of a location in meters to the East and North. These distances are referred to as the Easting and Northing, respectively. The earth is partitioned into sixty zones in the UTM system and each zone includes six degrees of longitudes. However, the latitude from only 80S to 84N is included as part of the UTM, as a different system¹⁵ is used for Polar Regions. Since Malaysia lies closer to the equator, the entire country falls within the UTM geodetic system. DEMs are extracted for individual sites from Zones 47 (lon 96 to 102), 48 (lon 102 to 108), 49 (lon 108 to 114) and 50 (lon 114 to 120).

DEMs downloaded from the SRTM project, are used to construct vector maps. A vector map generally consists of elevation (orography) and landcover (surface roughness) of an area. However, vector maps created using SRTM data only, contain height contours to illustrate surface elevation and roughness change line (only at the boundary). DEMs only contain roughness values for boundaries, which is not sufficient for wind potential analysis. User-fed roughness information for land surfaces (as discussed in section 3.3.2) is important to obtain robust estimations.

A good vector map contains Digital Elevation Maps (DEM) and SRTM Water Body Data (SWBD) with user corrections for obstacles and roughness. Adding roughness changes lines manually (landcover map) allows WAsP to understand differences in the structures on the landscape of the site (as discussed in section 3.3.2). This allows for more robust estimation of the AEP.

¹⁵ Universal Polar Stereographic (UPS).

3.2: Wind Resource Assessment

Four different methods are combined in this study to evaluate the wind power potential of 36 sites across Malaysia. Standard weighted average based statistical analysis is combined with Wind Rose analysis (to identify the direction of wind flow), Weibull analysis (to identify the shape of the wind distribution) and Wind Atlas Analysis (to account for topographical information in estimating wind power). These methods are discussed in further detail below.

3.2.1: Weighted Average Wind Speed

The percentage of available wind speeds (measured categorically in 1 ms^{-1} intervals) is used to estimate the power available, rather than the mean value, to improve the accuracy of the analysis. A crude estimation of mean is likely to lose valuable information and therefore a more detailed analysis of the percentages is presented below. The weighted average approach (W.AVR) is used to find out the average annual wind speed (see Figure 22 for graph depicting the distribution of wind speeds for Malaysia).

$$\text{Weighted Average} = \frac{\text{Sum of Weighted Terms}}{\text{No.of Terms}} \quad (3.1)$$

The weighted average approach provides a more accurate depiction compared to a simple arithmetic mean. W.AVR lines are indicated in ms^{-1} at a height of 10 metres. This initial descriptive analysis is used as a screening exercise. Data relating to stations with less than 70,000 hourly observations were removed for consistency. Stations, where production of meteorological information has been discontinued since 2005, were also removed. After the elimination of eleven such sites, the analysis was conducted for 24 stations.

While the above approach improves accuracy over using a crude measure of mean, it does not account for wind direction, this is where Wind Rose is useful.

3.2.2: Wind Rose

Wind rose is a widely used diagram to illustrate wind data (especially speed and direction) of a particular site / location. The Wind rose is divided into sectors, and each sector is depicted by a spoke. The European Wind Atlas project recommends that Wind rose is divided into twelve sectors of 30° each, which is the default-setting for WAsP. The length of each spoke represents the relative frequency of time that the wind blows from that particular direction (sector). Spokes with more than one colour indicate wind speeds from more than one wind speed class being present in a direction.

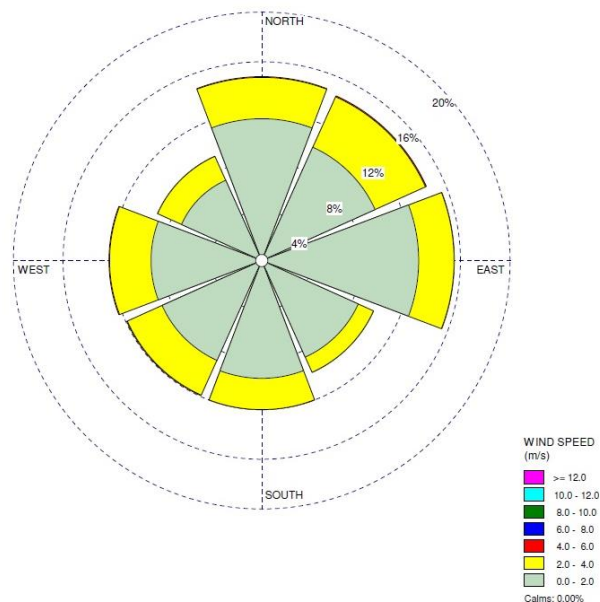


Figure 6: Ten-year Windrose for Malaysia

For Malaysia, the dispersion of wind speeds is not significantly large and therefore, spokes for most sites are within two bands (Figure 6). Wind rose is an easy tool to comprehend wind pattern and is also useful in comparisons across sites, as data are standardised for the constructions of the spokes. Nevertheless, the wind rose does not account for microclimates of a particular site. Microclimates refer to differing weather patterns at one particular site compared to the region surrounding it. Wind rose does not account for topographical information and thus, may not be useful in determining potential

sites for projects. Despite its limitations, wind rose is widely used as preliminary tool to represent wind data.

Heni et al. (2015) study the wind power density in reference to wind direction at Karbala Site in Iraq using wind rose. The study shows scientifically that wind direction does not change with height. Despite many studies taking this relationship for granted, this finding allows us to estimate wind power production at various sites – without compromising on wind direction anomalies.

3.2.3: Weibull Distribution

Weibull distribution is a theoretical frequency distribution of wind speeds. There are three types of Weibull distribution; 1-parameter, 2-parameter and 3-parameter Weibull distribution. In a three parameter Weibull distribution, the three parameters--scale (A), shape (k) and location (μ) are present. In the 2-parameter Weibull distribution, the location parameter (μ) is assumed to be zero. In the 1-parameter Weibull distribution, the location parameter (μ) is assumed to be zero and the shape parameter (k) is assumed to be a constant. A two-parameter Weibull distribution is used in the literature to assess the locations for the installation of wind turbines (Fadare, 2008). The scale parameter A indicates the average speed and the shape parameter k indicates the dispersion of wind speeds from the mean. The shape parameter k takes higher values for lower dispersions from the mean and vice versa. In regions with consistent wind speeds; such as islands, the dispersion of each wind speed observation from the mean is likely to be low. Therefore, the value of k is likely to be high (Figure 7 & Table 1).

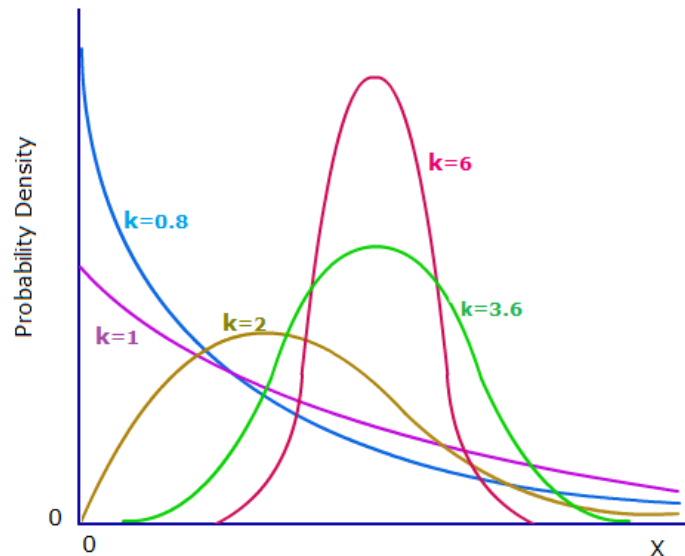


Figure 7: Weibull Distributions with Varying k Values¹⁶

[Source: Engineered Software.Com, 2016]

Table 1: Variations in shape parameter K in relation to land morphology

Value of k	Ground Morphology	Wind Typology
1.2 – 1.7	Mountain Sites	Highly variable
1.8 – 2.5	Land Plains (Hills)	Variable
2.5 – 3.0	Open Countryside	Less variable/ almost regular
3.1 – 3.5	Sea Coasts	Regular ¹⁷
3.5 – 4.0	Islands	Very regular

[Source: ABB ,2011]

One of the main attractions of the Weibull distribution is its ability to incorporate the variability of wind speeds in the prediction (van Donk et al., 2005). This becomes important in power calculations as the arithmetic mean is likely to underestimate the power potential of a turbine in regions with large wind speed dispersions (ABB, 2011). Unlike Wind Rose and histograms, the Weibull fit is able to account for the variability in wind speeds arising from varying morphological conditions. Table 1 above, summarises different classes of the k parameter in relation to various morphological conditions and wind

¹⁶ Note: If $k=1$, the Weibull distribution is an Exponential distribution. If $k=2$, the Weibull distribution is a Rayleigh distribution and if k is between 3 and 10, the Weibull distribution approximates the normal distribution.

¹⁷ Regular refers to wind speeds being similar throughout the period.

variability. Wind speeds tend to not follow a normal distribution as highlighted above. Therefore, most empirical studies have used the Weibull analysis to account for the varying dispersions of the wind speed and morphological conditions. Several studies also use the special case of Weibull distribution—the 'Rayleigh distribution' to identify the dispersion of wind speeds (Seguro and Lambert, 2000; Lun and Lam, 2000; Dorvlo, 2001; Celik, 2004; Akpinar and Akpinar, 2004). The Rayleigh distribution is particularly attractive in identifying the power potential of a region as it depicts a linearly increasing failure rate. Studies have used this increasing failure rate to consider the risk of failure of a turbine over its lifetime.

In the literature, Weibull distributions have been deemed popular in evaluating the wind energy harnessing potential of specific sites. It is a continuous distribution as opposed to static distributions such as chi-squared and particularly popular for its ability to model skewed data – both left and rightward (Rinne, 2010). Weibull distribution also supports varying speeds (i.e. phases), which introduce an additional flexibility in analysing the data. This distribution has been used in studies such as Fadare (2008) and Fagbenle (2011) on Nigeria, and Islam et al. (2011) and Akorede et al. (2013) on Malaysia, among others. Another tool that is also popular among wind energy analysts is 'Numerical Weather Prediction' (NWP). The NWP uses mathematical models to simulate future weather including future wind speeds. NWP was also used in Nor et al. (2014) in their study on the feasibility of wind energy resources in Malaysia.

3.2.4: Wind Atlas Analysis

WASP is utilised to estimate both vertical and horizontal extrapolation of wind climate statistics. It has five core calculation blocks to conduct the wind resource assessment (WRA); analysis of raw data, generation of wind atlas data, estimation of wind climate, estimation of wind power potential and calculation of wind farm production. WASP comprehend wind climate at a potential site based

on profile of wind climate of an observed station as shown in Figure 8. In-built models in WAsP estimate the Generalised Wind Climate (GWC), Predicted Wind Climate (PWC), Gross Annual Energy Production (G-AEP) and Net Annual Energy Production (N-AEP). It also automatically calculates Wake loss (Wk) during micro siting.

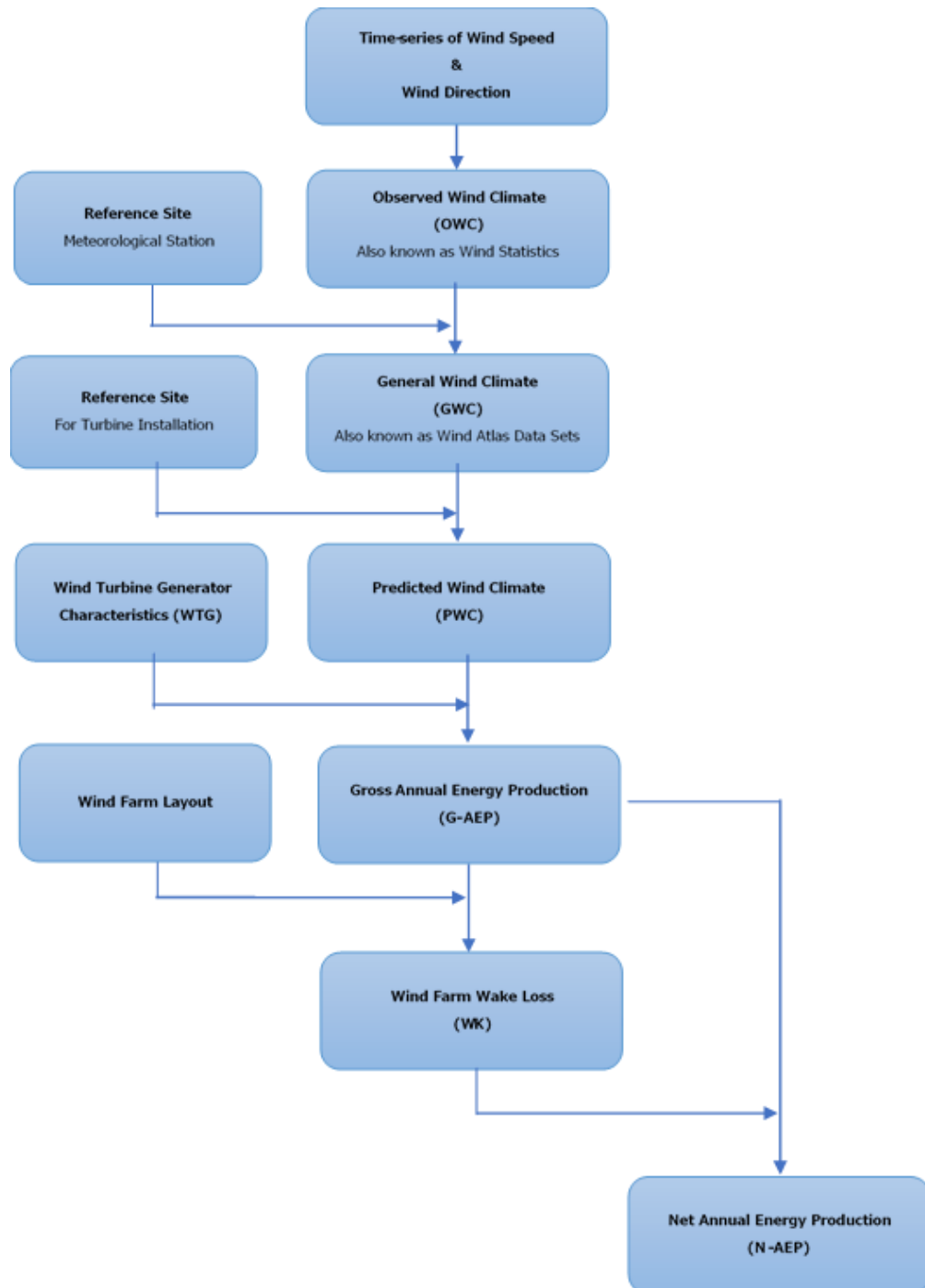


Figure 8: Wind Atlas Methodology

The Observed Wind Climate and Observed Wind Frequency are generated using WAsP Climate Analyst (WCA). Site descriptions such as, the height of the anemometer (above the ground level), latitude and longitude are fed into WCA along with the wind data to generate OWCs. WCA generates a very comprehensive summary of the wind data across four graphs. These four graphs are discussed in chapter 4.2 with Langkawi as a case study.

The met station only consists of its location in a map - as UTM coordinates, anemometer height and user-corrections (if applicable). It does not contain any wind speed or direction data in it. On the other hand, OWC is an xml-based format that contains a summary of recorded wind data at a met station; such as wind rose and wind speed frequency distribution for each sector and as a whole. Once, the OWC of a particular site is fed in to the met station (without a vector map), WAsP estimates the wind climate at the met station. Most met station data are collected at the airport and are mostly prone to get influenced by surrounding buildings and trees. Given the met station coordinates, WAsP is able to predict such influences and adjust the OWCs. Such self-predicted potential deviation for a met station (Sandakan) is given in Figure 27.

After removing sites where reliable data was unavailable, raw wind data were used to generate OWC for 24 sites. Vector maps were integrated with their respective OWC to generate GWC as discussed in section 3.3. The GWC comprises of roughness effects, obstacle effects, orographic effects, observed wind frequency (OWF), predicted wind frequency (PWF) and power density (PD). The distribution of wind energy at different wind speeds is calculated as the power of each wind speed times the probability of that wind speed from the Weibull.

3.3: Generalised Wind Climate (GWC)

A vector map met station information, and an OWC are used to generate a GWC for a location. WASP adjusts wind data by removing the influencing effects of the collection site itself. Thus, GWC of a particular site becomes a site independent wind climate for the vicinity and this can be used to predict the wind climate in nearby areas. GWC provides a summary of the wind speed and power density at 5 default roughness classes as shown in Figure 29. In addition to estimating speed and power density for five different roughness classes, speed and power density are also estimated at five different heights. Wind speeds at different heights are calculated using the logarithmic wind profile law¹⁸ as shown below:

$$U_z = U_{ref} \left[\frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{ref}}{Z_0}\right)} \right]; \quad (3.2)$$

where,

U_z = Wind speed at height Z above ground level

U_{ref} = Wind speed at reference height (anemometer)

Z = Height above the Ground level at which the wind speed needs to be calculated

Z_{ref} = Anemometer height at reference site

Z_0 = Roughness length.

($\ln$ is the natural logarithm function)

[Source: Danish Wind Industry Association, 2003]¹⁹

¹⁸ The model assumes that the area is at neutral atmospheric stability conditions.

¹⁹<http://drømstørre.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/shear.htm>

In reality however, atmospheric conditions are less likely to be neutral and stable. A more refined version of the mathematical model used in WAsP, is given below:

$$U_{(z)} = \left(\frac{U^*}{K} \right) \left[\ln \left(\frac{z}{z_0} \right) - \varphi \right]; \quad (3.3)$$

where,

U^* = Friction Velocity

K = Von Karman Constant (≈ 0.4)

z_0 = Roughness Length

φ = Stability-dependant Function (+ve for unstable & -ve for stable conditions)

[Source: Petersen et al., 1997]

It is vital to extrapolate the wind speed for available hub heights of the potential wind turbines because any installation of wind turbines would be at a higher elevation than the standard height at which observed raw wind data are measured; the observed raw wind data are measured at standard 10 m heights.

Although the default heights for GWC analysis were 10m, 25m, 50m, 100m and 200m; these heights do not suit small wind turbine application. Hence, smaller reference heights of 10m, 18m, 24m, 30m and 36m were used. This is executed to reduce compounding losses during extrapolation, as WAsP estimates the wind power density and speed at different heights sequentially. The chosen hub heights also are in accordance with commercially available towers used to assess AEP in this study.

An example of GWC is given in Figure 29 for Sibü. The upper section of the figure shows the tabulated mean wind speed (parameter U , measured in ms^{-1}) and mean power density of wind (parameter P , measured in Wm^{-2}) for five different roughness classes (including zero roughness length) and five different heights. The bottom-left section displays the Wind rose, while the bottom right section displays the Weibull distribution with Weibull parameters A and k of a particular sector.

WAsP uses the geostrophic wind to estimate PD (P in the GWC window). Geostrophic wind is the theoretical wind that is calculated to conduct the assessment. WAsP uses the latitude to calculate the Coriolis parameter; a parameter used in calculating the geostrophic wind speeds. As the roughness class increases from 0 m to 0.4 m, the wind flow above the surface reduces and this can be observed by the decreasing wind speeds presented in Figure 37 and Figure 38. Decreasing wind speeds also reduce the potential power in the region as evident in Figure 39 and Figure 40.

3.3.1: Estimating Power Density

Average kinetic energy flux per unit area at 90 degrees to the wind flow is known as the power density. Estimates of such power density across multiple sites in Malaysia was produced using the above discussed methodology. Examining multiple Windrose in GWC, it can be noted that in some instances the size of Windrose spokes corresponding to wind speed and power density diverge (Figure 36). This is because, even though the OWF of higher speeds are very small, the energy produced by the higher wind speeds is very large (and much larger than the energy produced by lower speeds). The power density spokes even within the same region may differ due to topographical condition. WAsP also predicts wind climate for neighbouring regions. A turbine site or a reference site can be placed anywhere on the vector map and WAsP would predicts the wind speed and powder density for the respective location.

However, such predictions by WAsP may be affected by three factors: (1) local terrain outside WAsP's operation envelope, (2) local climate being outside WAsP's operation envelope and (3) lack of cross-correlation between wind speeds at reference and potential sites (Bowen and Mortensen, 1996). While the local terrain and climate conditions across most sites in Malaysia are within the operating envelope of WAsP, the similarity between potential sites and the

meteorological stations need examination by reference to the difference in ruggedness between the sites.

It is vital to carry out a thorough study throughout the nation to create a wind atlas for Malaysia as in Singh's (2015) proposal for Fiji. This would assist the various stakeholders—researchers, commercial enterprises and policy makers to ascertain the potential for wind energy across the country, and the wind turbines suitable to be employed. Given that Malaysia exhibits persistent but low wind speed, it may still be possible to harness wind energy in a cost effective and feasible manner.

3.3.2: Importance of Roughness Corrections

Wind speeds near²⁰ the surface of the earth is affected by the friction (roughness) against the surface of the earth. Hence, landscape characteristic such as Roughness classes and Roughness lengths are used in assessing wind conditions at a potential site. Roughness length is the height above the ground at which the theoretical wind speed is zero and is measured in meters. The Roughness Class is a defined value in terms of the roughness length and is dimensionless. Lettau (1969) presents a simple empirical relationship between roughness elements and roughness length:

$$z_0 = 0.5 (h \cdot S) / A_H \quad (3.4)$$

where,

z_0 = Height where the mean wind speed becomes zero

h = Height of the roughness element

S = Cross-section facing the wind

A_H = Average horizontal area (measuring density) of several elements distributed evenly over an area.

This equation 3.4 provides reasonable estimates of z_0 when A_H is larger than S . However, it tends to overestimate z_0 when A_H is of the order of S . This is because, when the roughness elements are close

²⁰ Less than 1 km.

together, the flow is 'lifted' over them. Then only a fraction of S and h contributes to the roughness. Furthermore, the lifting of the flow requires measurement of the displacement length. The displacement length is the height above ground from somewhere between the top of the roughness elements and half the height of the elements. It is important to take note of the displacement height on sites with forests, cities, and tall vegetation (WAsP 12). Finally, the equation assumes that the porosity is approximately zero, i.e. the roughness elements are solid. For porous roughness elements, z_0 from the equation above must be reduced by a fraction equal to the porosity.

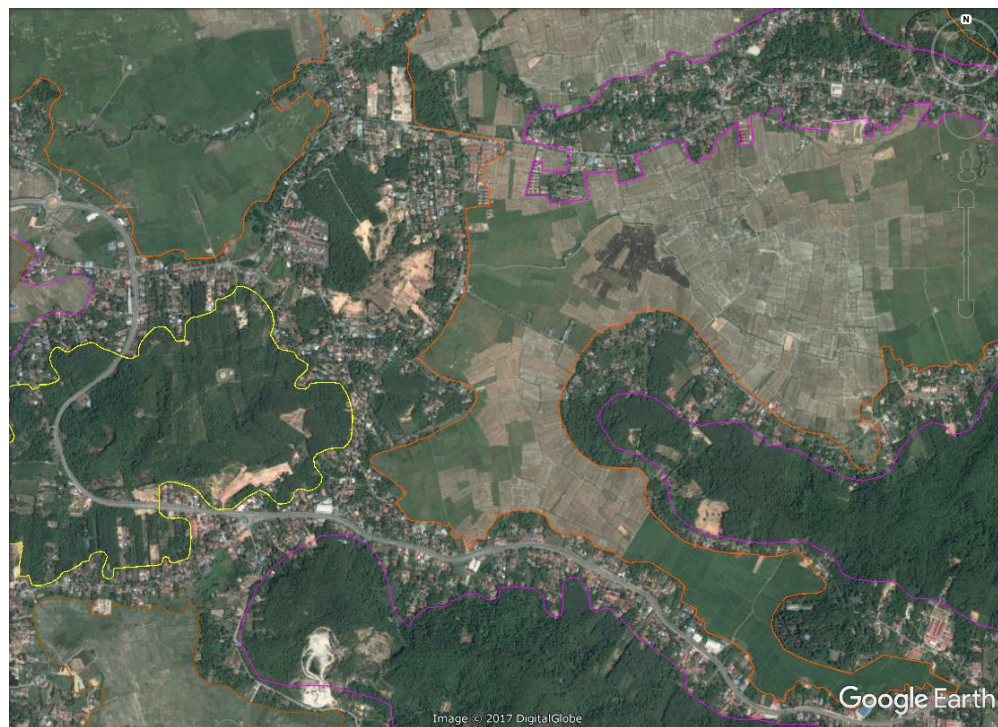


Figure 9: Roughness Contours drawn for Langkawi²¹

In order to account for the roughness length, aerial photos of the sites on Google Earth were carefully assessed to manually draw roughness class polygons as precisely as possible (see Figure 9). All the user-fed roughness/landcover maps used in this study were drawn on Google Earth Pro. Using Google Earth Pro to create a KML file is comparatively easier to scanning and recreating a landcover

²¹ The map was zoomed in and the change in colour of the lines indicate the change in roughness.

map from a paper map or a picture. Similarly, it is also easier to zoom, identify and even locate sites on Google Earth Pro compared to drawing the roughness lines on WAsP map editor. However, given that Google Earth Pro does not have a high-resolution satellite view nor 3-D view of Malaysia, it becomes difficult to identify the details of specific sites. The street view function is also not supported for most parts of East Malaysia; hence, assessing few sites and creating perfect landcover (KML) maps becomes challenging. Moreover, creating a KML file with carefully drawn-out roughness lines is a very tedious and time-consuming process.

The roughness class polygons drawn on Google Earth Pro are then exported as KML files.²² These KML files are then imported into WAsP and added onto the SRTM topographical map. The roughness polygons are then assigned roughness length values (in metres) based on the Table in Appendix – C. For instance, water surfaces are smoother than the land; thus, the wind speeds are not affected significantly on water surfaces. On the other hand, forests, hills and large buildings significantly slow down the wind speeds. For example, large towns and cities with extensive built-up areas can (such as those covered in the purple colour polygons below) only experience 24% of the relative energy ($RL=0.4m$). Likewise, for Miri, open green spaces (which is typical of most areas in Miri) would be assigned a roughness length of 0.0055m. Based on the Table 2, this corresponds to between 52% to 73% of the potential energy in that area.

²² Keyhole Markup Language (KML) is an XML notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers.

Table 2: Roughness Class & Energy Index

Roughness Class	Roughness Length (in m)	Energy Index (%)
0	0.0002	100
0.5	0.0024	73
1	0.0300	52
1.5	0.0550	45
2	0.1000	39
2.5	0.2000	31
3	0.4000	24
3.5	0.8000	18
4	1.6000	13

[Source: Danish Wind Energy Association, 2003]

It is also important to incorporate obstacles near the met station or turbine sites. Significant obstacles such as tall building, huge trees, forest, taller hedges, etc. can affect the wind flow. These obstacles can be included as an individual obstacle map with three dimensional boxes (with coordinates) or treated as roughness length lines. The decision on which method to employ depends on two factors; the distance between the turbine or anemometer site and any obstacle, and the difference in relative heights between the turbine / anemometer and the obstacle. If the distance between the site and the obstacle is less than 50 obstacle heights, then the obstacle should be treated as a sheltering obstacle. Similarly, if the height difference between the turbine / anemometer and the obstacle is smaller than 3 obstacle heights, then the obstacle should be treated as a sheltering obstacle (WAsP 12). If otherwise, the obstacle could be treated as a roughness element.

Google Earth Pro was extensively used to identify the structures in around the met station and around the feasible turbine installation sites. In most cases in this study, the met station or wind farm sites are very far away from obstacles. Hence, they were treated as roughness elements - with a very high value of RL (0.8 to 1) based on the landcover map. GWCs were created again with a combined vector map (SRTM and landcover map) to assess the wind profile.

3.4: Data Anomalies

An integral part of the wind energy estimation is the topographical and ruggedness data. Publicly available data pertaining to these two components were found to have errors in some instances. These are discussed below alongside the user corrections to remedy these errors.

3.4.1: NCEI Data Anomalies

A few met station coordinates had some errors in NOAA/NCEI data. For instance, when the met station in Mersing was located on Google Earth using the NOAA data coordinates, the met station was located inside the sea (Figure 10). Google Earth Pro was used to locate the anemometer and extract the correct coordinates to use in the analysis. To avoid such inaccuracies in the future, the Malaysian Meteorological Department in particular, may want to review the publicly available geographical coordinates of the met stations. Inaccurate coordinates when employed in estimations produce unreliable wind power estimations and may impede the estimations of researchers who do not verify the location of the met stations.

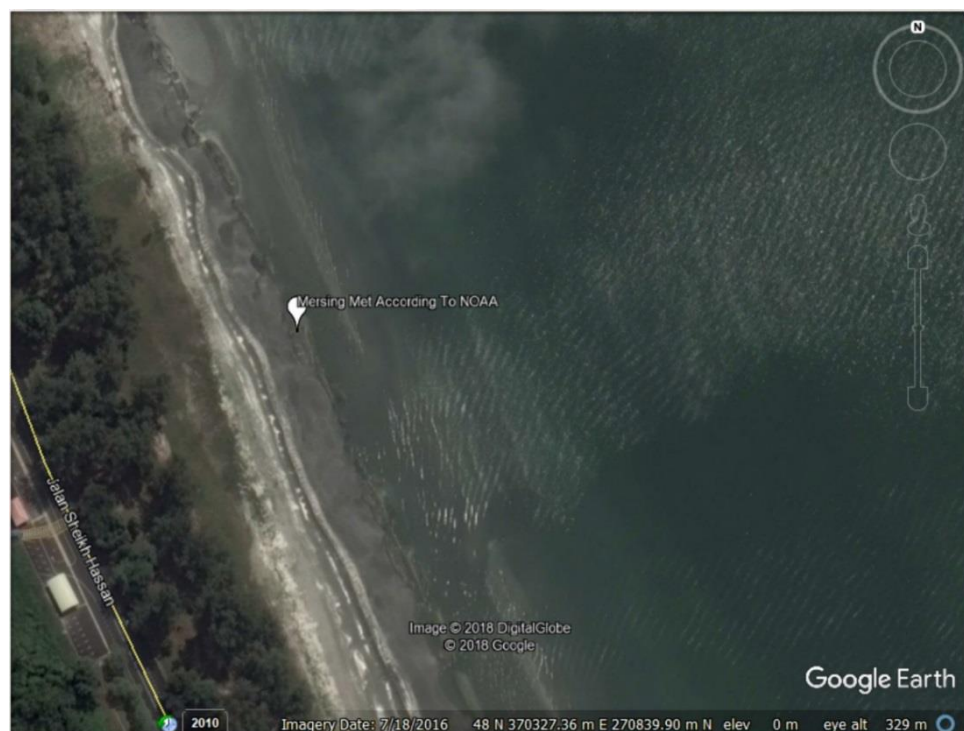


Figure 10: Mersing Met Station According to NOAA (NCEI)

Another issue was incorrect conversion from latitude-longitude (lat-lon) to UTM. Multiple engines were used to convert the lat-lon coordinates to UTM and the coordinates generated for Miri were not anywhere closer to Miri. Hence, the anemometer was searched via Google Earth Pro to find the correct coordinates. As evident in Figure 11 and Figure 12, the Northing coordinates are in the range of one-hundred and sixty thousand in SRTM, but the corresponding site (the Miri airport) in Google Earth presents UTM coordinates in the range of eight hundred thousand northing. The latter values in Google Earth are identical to those obtained using UTM conversion engines, and therefore, the errors in northing values can be attributed to SRTM data.

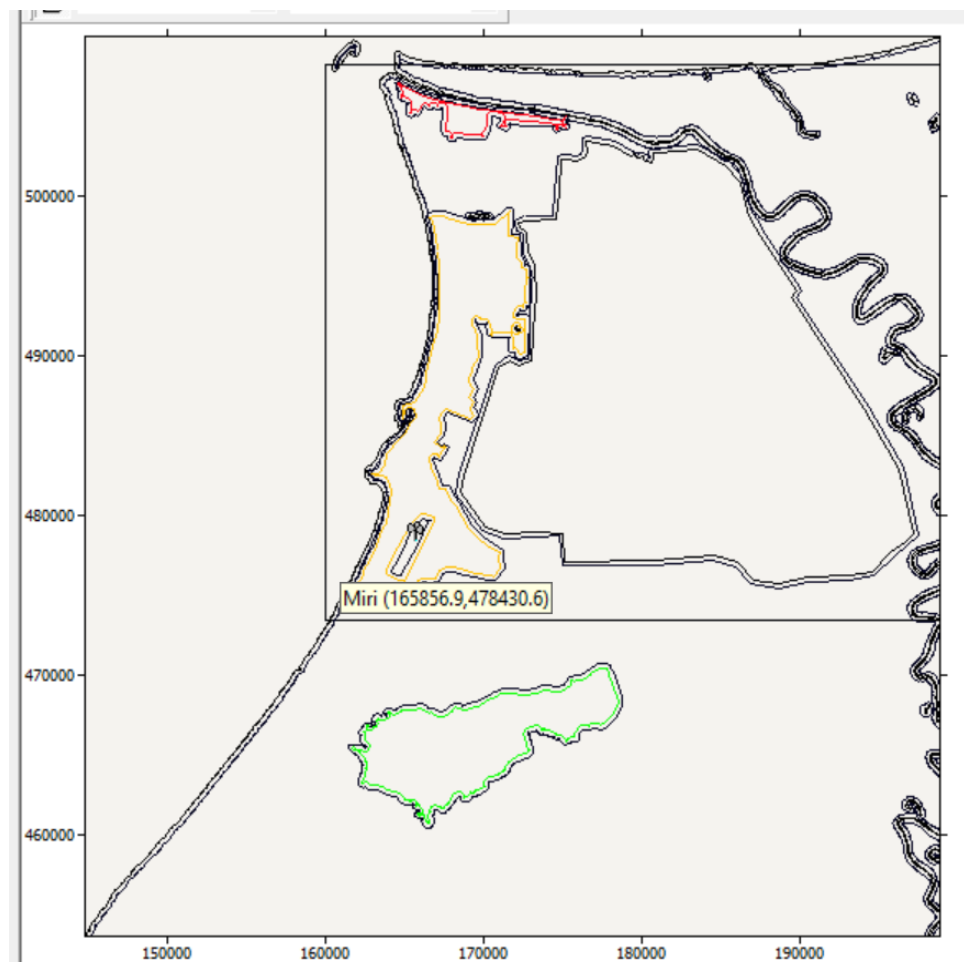


Figure 11: Miri Met Station Coordinates in SRTM



Figure 12: Miri Met Station Coordinates in Google Earth Pro

Places like Tawau have many airports and the main passenger airport is not the airport at which the anemometer is located. In addition to the identification of airports with Google Earth Pro, other issues with the NOAA data had to also be tackled. These include change in the site at which the wind data was collected, without a change in the station ID or name. For example, a change in the airport at Tawau resulted in the newer airport being used to record wind data since 2012, which exhibited higher wind speeds (and by extension higher power density); without attributing this shift in speeds to the change in the location of the anemometer reading, any results produced as if they belonged to the same station would produce upward biased estimates (overestimate, since the wind speeds are shown to improve). Hence, all the site anemometer locations were checked with the help of Google Earth Pro to ensure that human errors are minimized and the predicted values in the thesis are more reliable.

3.4.2: Topographical Data Anomalies

It is important to check for inconsistencies in the downloaded SRTM maps. Inconsistencies can arise due to incorrect roughness lengths in the downloaded SRTM maps, cross-points and Line Face Roughness errors (LFR). Maps downloaded from the SRTM server sometime contain errors—(i) primarily swapped roughness length for water bodies and land surfaces (ii) additional incorrect roughness line and (iii) void data. This study uses void-filled SRTM 3-arc data therefore the third concern is less severe.

For the first concern, this can only be rectified by manual intervention of the user to swap the roughness lengths. Moreover, these errors can be more prominently identified when user-fed roughness maps are incorporated. Incorporating the user fed roughness maps lets WAsP check for LFR errors. The LFR errors help identify which roughness lines and polygons have incorrect roughness lengths. Studies that do not incorporate roughness maps are likely to not identify SRTM map errors and any estimations that use incorrect swapped roughness lengths are likely to overestimate the wind power potential (since the land area will be accounted as water bodies where the $RL=0$).

Large differences in the topographical conditions between the turbine site and anemometer sites is likely to make prediction more difficult for the WAsP model. The Annual Energy Production (AEP) estimates are influenced by the topographical condition (including elevation and roughness) at the site of the anemometer and the site where the wind turbines will be installed. It is therefore imperative to use reliable good quality topographical data to improve the accuracy of the AEP predictions.

With regards to the second concern, despite the completeness of version 2.1 of the SRTM data, downloading SRTM data for a particular

geographical area can sometimes have additional roughness lines. Figures 13 and 14 below illustrate some of these errors.

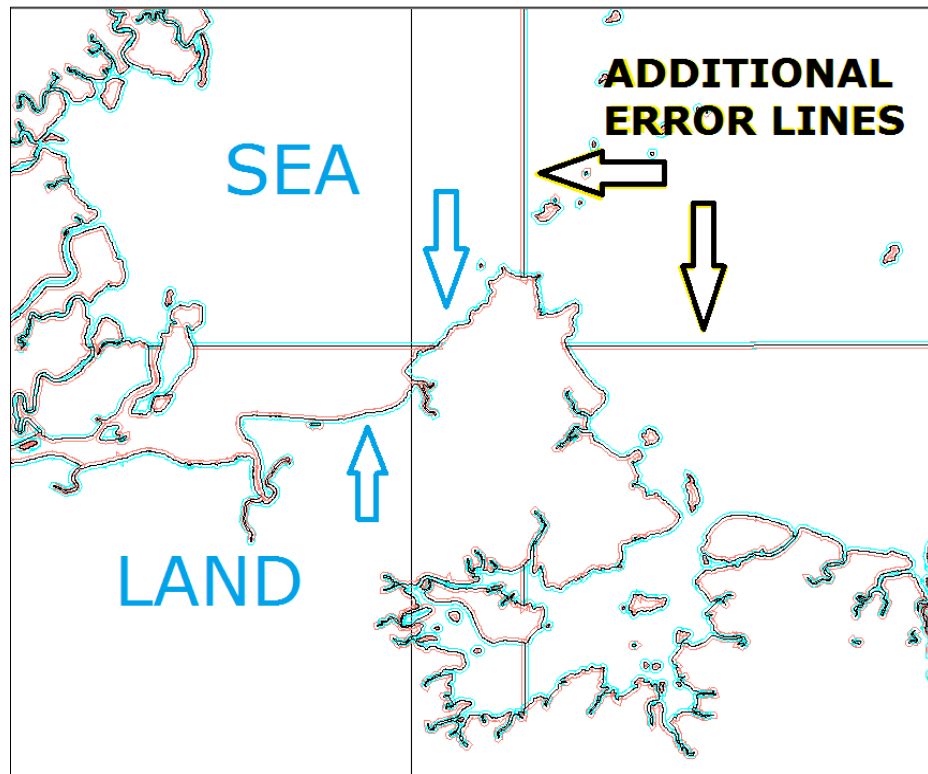


Figure 13: SRTM Errors (Swapped RL & Additional Lines)

The blue arrows indicate an incorrect swap in roughness lengths (Figure 13 and Figure 14). While the water and land areas are identified accurately in the roughness lines to the right of the graph (blue outside, red inside), they are swapped (incorrectly) to the left of the graph in Figure 13. To the left, the maps identify land areas as water bodies and water bodies as land areas. These need to be manually swapped; ignoring such errors are likely to produce highly inaccurate predictions of wind profile and hence AEP. Similarly, the linear lines indicated by black arrows in Figure 13 are the additional roughness lines that are inaccurately coded by SRTM and need to be removed. Ignoring these lines (i.e. not removing them) would lead to having dead ends in the vector map and produce biased estimates.

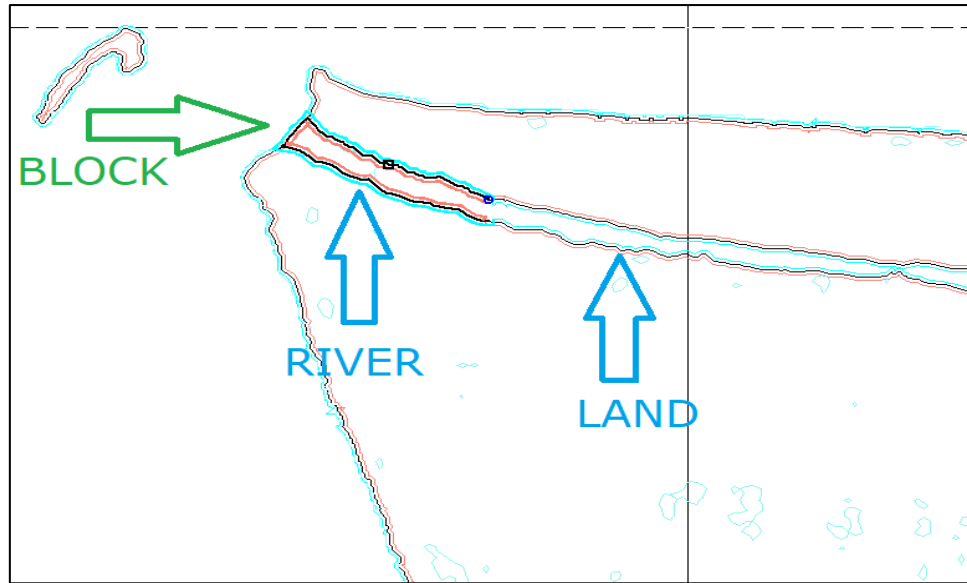


Figure 14: SRTM Errors (Swapped RL & Blocks)

Figure 14 shows a blockage at the river in the SRTM data, while there are no such blocks in the geographic space (verified via Google Earth Pro and Google Maps). These additional lines (blockage) in SRTM need to be manually removed before using the SRTM for wind assessment. Hence, the blockage is removed by splitting the lines and deleting additional lines present. The bold lines also indicate a swapped roughness lines; the land and river lines have been swapped. These inaccuracies in roughness length have to be corrected before they can be used for any wind assessment estimations.

3.5: Gross Annual Energy Production

WAsP estimates G-AEP of wind turbines when wind turbines are placed on the vector map. Multiple wind turbines can be placed on a map to estimate G-AEP— both as part of a wind farm or as an independent wind turbine. If the wind turbines are not cluttered under a wind farm, WAsP ignores the other wind turbines when estimating the G-AEP of a particular wind turbine. This leads to overestimation of AEP since wake loss is being ignored. The WAsP AEP estimation model and selection of wind turbines are discussed below.

3.5.1: Power Equations

Wind turbines use the kinetic energy of the wind and produce electrical energy. The blades collect the kinetic energy in wind and convert it into mechanical energy. The mechanical energy then turns the shaft that connects the blades and the gear box. The energy is then transmitted from the gear box through the drive shaft to generator that produces electrical energy. Kinetic energy is a function of mass and velocity. Thus, the theoretical energy available in the wind for a wind turbine to harness is given by:

$$P_m = \frac{1}{2} C_p \rho A V_{wind}^3; \quad (3.5)$$

where,

P_m = Mechanical output power of the turbine (W)

C_p = Performance / power coefficient of the wind turbine

ρ = Density of Air (kgm^{-3})

A = Swept area (m^2)

V_{wind} = Wind speed (ms^{-1})

Power coefficient is a mechanical ratio between the power harnessed by wind turbine and the available power in wind (Gevorkian, 2009). A German physicist, Albert Betz discovered that an ideal turbine can have the maximum (theoretical) power coefficient of 0.5956²³. The overall efficiency of wind turbines would be much lesser than the theoretical value due to the losses in mechanical and electrical devices in them.

In Figure 15, the area²⁴ under the grey curve (topmost) represents the amount of available power per square metre wind flow of the particular site. Area under the blue curve (middle) gives the amount of theoretical mechanical power that can be harnessed. The area under the red (bottom) curve shows the amount of electrical power that can be generated by the turbine at the particular site.

²³ Actual value is $\frac{16}{27}$.

²⁴ Area under the curve is all the way to the axis at the bottom.

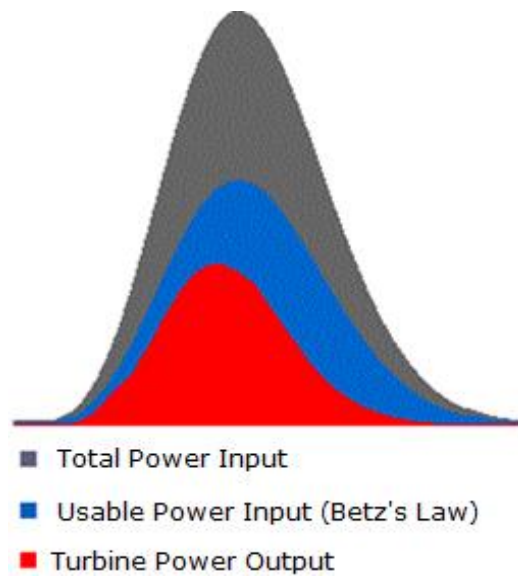


Figure 15: Sample of a Power Density Function

[Source: Danish Wind Industry Association, 2003]

The power coefficient is not a constant value; it varies with the bladed parameters, wind speed and the blade speed. Density of air decreases with the increasing temperature and altitude. Based on the wind power equation (3.5), available wind power is proportional to the cube of the wind speed. Therefore, a 20% increase in the wind velocity increases the available power by 73%, in theory (Kreith, 1998).

Electrical generators within the wind turbines are capable of handling a range of wind speeds, upon which the power output reaches its optimum. This optimum wind speed is known as the rated output (wind) speed, and the output at this speed is referred to as the rated output power. Figure 16 illustrates a typical power curve of a wind turbine. When the wind speed increases above the cut in speed, the electrical power swiftly increases till its rated output power. Then the output of wind turbine remains constant till the speed of the turbine reaches the cut-out speed. In large wind turbines, adjusting the blade angles help to maintain the generated power constant when the speed exceeds the rated output wind speed. The wind turbine shuts down during high wind speeds as turbine blades are destructive in high wind speeds.

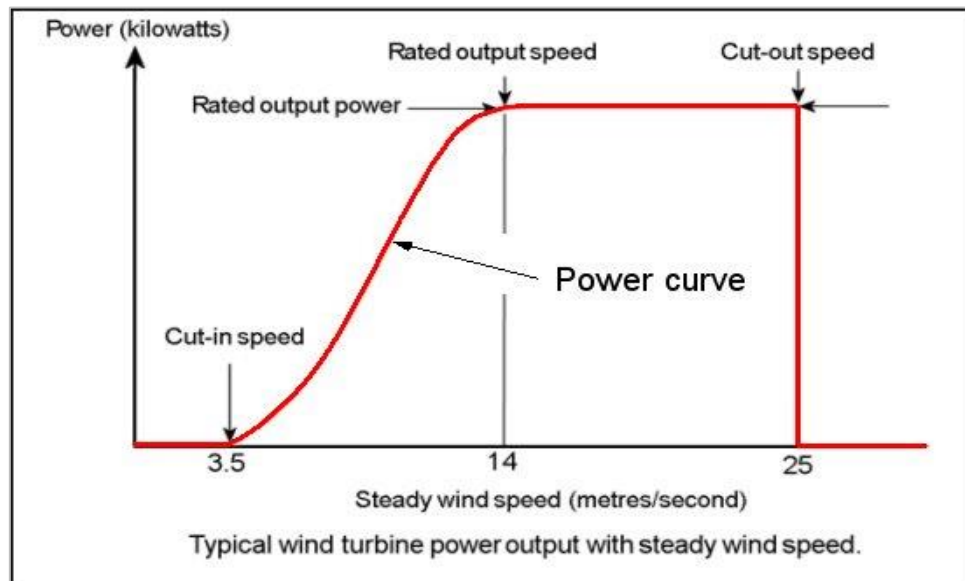


Figure 16: Power Curve of a Wind Turbine

[Source: Wind Power Program, 2015]

WAsP uses the power curve of wind turbines to calculate the power. An advantage of using this power curve and thrust coefficient curves is that even with the small increases in the wind speed, predicted AEP remains fairly constant. In contrast, other methods using the Boyle's AEP, overestimate energy production even for the small increment in wind speeds due to the cube (of velocity) in the formula. In addition, Boyle's predictions do not account for turbine type, specifications or wake effects in wind (Singh, 2015).

Omni-directional power production in WAsP is the sum of sector-wise power production. Mean power production can be assessed incorporating probability density function of the wind speed at a particular hub height and the power curve of a wind turbine. Thus, the following mathematical model is used in calculating the mean power generation in WAsP:

$$P = \int_0^{\infty} \text{Pr}(u)P(u) du; \quad (3.6)$$

where,

P = Mean Power Production

$\text{Pr}(u)$ = Probability Density Function

$P(u)$ = Power Curve

In studies, where a siting-procedure is used to derive the probability density function (as opposed to using measured data at a potential site), the probability density function can be approximated using a Weibull function. Therefore,

$$\text{Pr}(u) = \frac{k}{A} \left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^k\right); \quad (3.7)$$

where,

A = Weibull Scale Parameter

k = Dimensionless Weibull Shape Parameter

U = Wind Speed

Hence, from equations (3.6) and (3.7);

$$P = \int_0^\infty \frac{k}{A} \left(\frac{u}{A}\right)^{k-1} \exp\left(-\left(\frac{u}{A}\right)^k\right) P(u) du \quad (3.8)$$

However, integrating the equation (3.8) is not possible based on the general integration rule (analytically); thus, numerical methods are used by WAsP to compute this mathematical model. It could be noted from the wind speed distributions across sites in Malaysia that there are discontinuities in wind speed. Therefore, the power curve would also reflect such discontinuities causing jumps from one power level to another. Such intervals in the power curves are accounted for in the mathematical model below:

$$(P_{i+1} - P_i) \exp(-\alpha_i^k); \quad (3.9)$$

where $\alpha_i = \frac{U_i}{A}$

U_i = Wind Speed before the Discontinuity

P_i = Power before the Discontinuity

P_{i+1} = Power after the Discontinuity

3.5.2: Wind Turbine Selection

Selection of the appropriate wind turbines is crucial to understanding the wind energy potential at a given site. The power curves, cost and performance of the turbine affect their profitability. In selecting wind turbines for use in this study, three key criteria were deployed. (i) Availability of power curve and price. (ii) Reliability of turbine producer (known history of products and experience). (iii) Applicability to conditions in Malaysia (wind profile, air density, elevation, terrain etc.)

Based on the capacity factor, cost and power curves produced in Al-Hadhrani (2014), this study uses Aeolos wind turbines as it meets the three criteria set in this research. (i) Aeolos has the power curves and the prices made available which is vital for accurate estimations. (ii) Aeolos also has been an active industry player for more than 30 years and has operations in Europe (origins) and in Asia (via manufacturing plant and distribution hub in China). (iii) Further, Aeolos has experience in installing small wind turbines in countries such as Pakistan, Philippines and even Malaysia. Aeolos supplied two 5kW wind turbines, and a 10kW and 20kW wind turbine each, for a government funded project in Malaysia. These turbines were fitted on 12m hydraulic towers in housing areas. Given the experience and maintenance activity involvement of Aeolos in Malaysia, their 5kW, 10kW, 20kW, 30kW and 50kW turbines are used in this study.

While turbines such as those from Bergey have a lower cut-in speed, they are proportionately more expensive and thrust coefficient curves are not available for them. Therefore, Bergey wind turbines were not used in analysis. However, the 20kW Libellula wind turbine at 21m hub height was used in analysis regardless of the price since the power curve and thrust coefficient curves looked promising.

To improve the accuracy of estimates in academic studies such as this, wind associations and their members (who are manufacturers)

may want to consider making their power curves and indicative prices publicly available. This will promote more research on wind applications and wind energy systems across the globe. This is also likely to produce more reliable AEP estimates using multiple turbines from multiple manufacturers and may in turn help commercial manufacturers to explore new markets through research-led policy making. It is also imperative to have power curves from manufacturers certified by external bodies to assure their reliability.

Once the suitable wind turbines are selected, wind turbine generators (WTG) are created in Turbine Editor using power curves, thrust coefficient curves, hub height, rotor diameter, noise level, rotation per minute (rpm), cut-in speed, cut-off speed, density as show in Figure 17. Resource grid needs a WTG to estimate the AEP of a site. Similarly, WTGs are needed to estimate the above said parameters in wind farms. If different types of wind turbines are used in different wind farms, then these WTGs should be added to the farms, but if one type of turbine is used to all farms, then the WTG can be added to the project directly.

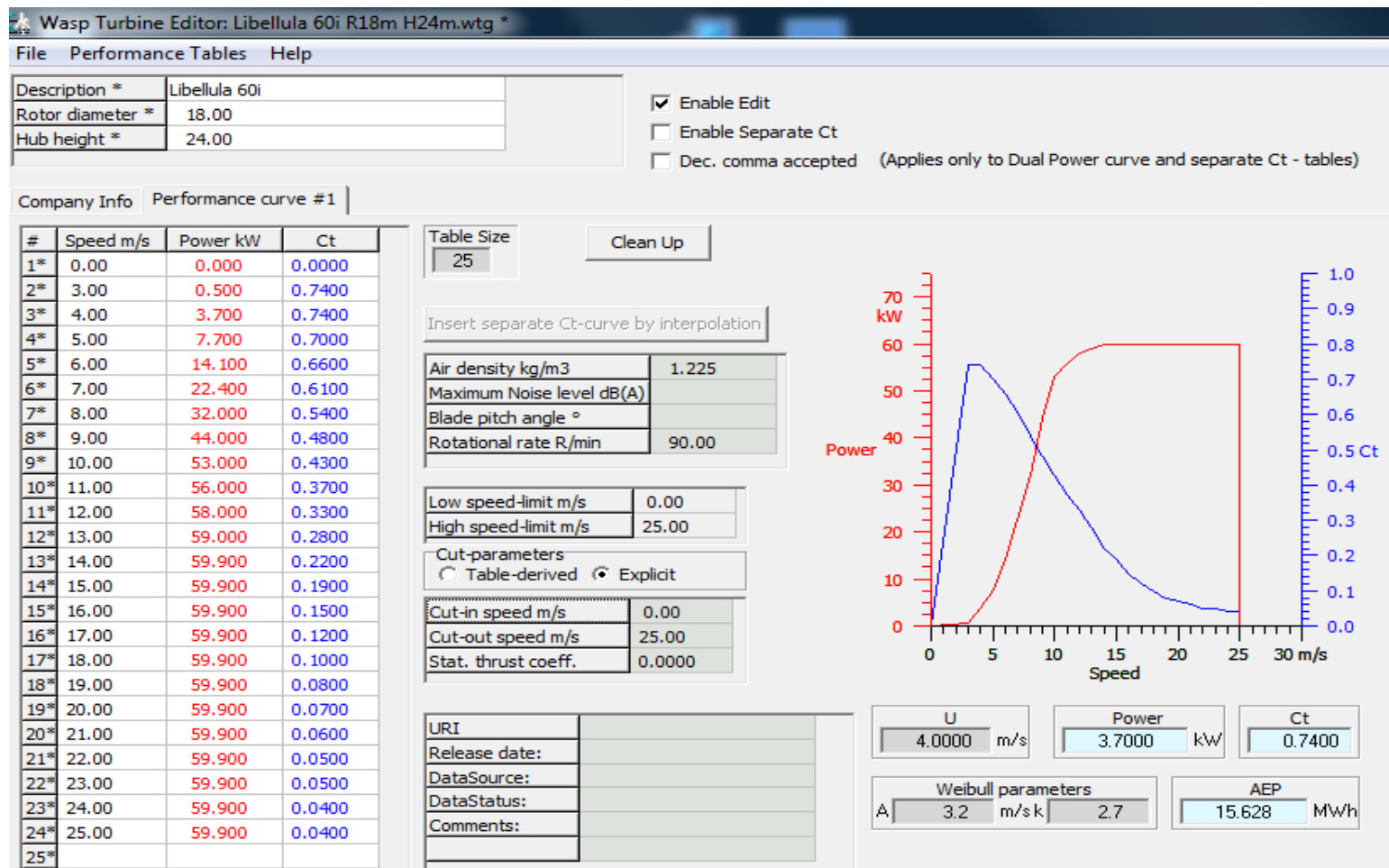


Figure 17: WTG Created using Power & Thrust Curves in Turbine Editor

3.6: Net Annual Energy Production

G-AEP estimation does not provide the most accurate prediction of N-AEP since wake loss is not considered in G-AEP estimation. Hence, it is vital to cluster the wind turbines in a farm to calculate the actual AEP. Wind turbines need to be placed in the most suitable location. Resource grid is useful in identifying such potential locations (micrositing). Subsequently, it is vital to assess the differences in the RIX (dRIX) to ensure that the estimations are within WAsP's operational envelope. These are discussed in further detail in the sub-sections below.

3.6.1: Resource Grid and Micrositing

A reference site or a turbine site can be used to predict the wind climate of an area near the met station. Reference site estimates the PWC by using a GWC of an area to a particular location by altering the effects of the terrain features at the site itself. On the other hand, the turbines sites predict AEPs of a location since turbines sites use WTGs as part of the estimation without the wake loss.

Wind farm models are used to calculate the net AEP in WAsP. These wind farms consist of a reference site, multiple turbines sites and WTGs. WAsP is capable of analysing several hundreds of turbines. Turbines here refer to the combination of a turbine sites and WTGs. Location characteristic from the turbine sites, power curves and thrust coefficient curves from the WTGs, and wake decay constant are used to calculate the net AEP of a wind farm.

During micrositing, it is useful to use a resource grid (RG) to analyse the wind climate rather than a reference site or a turbine site as it covers predictions for a larger area. Each point in a resource grid works as a turbine site. Resource grids can be layered over a vector map at a particular height to predict the AEP of a site. RG analyses the wind profile at a certain height incorporating GWC, vector map

and a wind turbine generator. When the height increase, the AEP increase at shown in Figure 18 below.

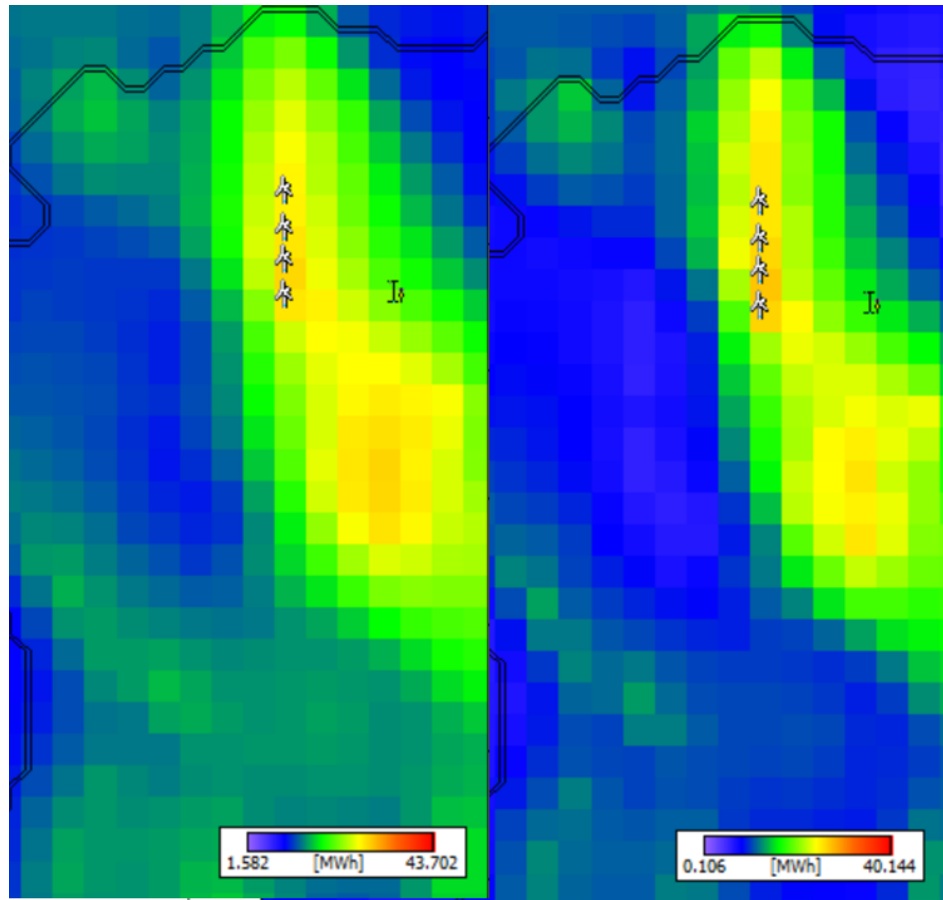


Figure 18: RG (Left H=30m & Right H = 12m)

A better practice is to use the turbine height as the resource grid height to reduce the extrapolating corrections. Once the RG is set, it calculates the following: AEP, PD, mean speed, Weibull factors A and K, Sector frequency and Elevation with colour coded maps. The colour coded maps aid in quick visual comprehension of the wind resource over the area. By default, RG shows the results for all sectors; however, individual sectors can be chosen from the dropdown menu to further explore wind profiles. Further, the statistics tab in resource grid provides quantifiable statistic for the above discussed maps. These statistics are classified by sector, mean, min and max values with its location detail.

In general, the resource grid is a rectangular grid, though it allows polygon / node property / elevation mask to check the AEP given different conditions. For example, Figure 19 shows AEPs in the RG masking / excluding areas with elevation above 50 m and 100 meters respectively. The white pixels illustrate that areas with elevation above 50 m and 100m are eliminated in the AEP estimation on a resource grid.

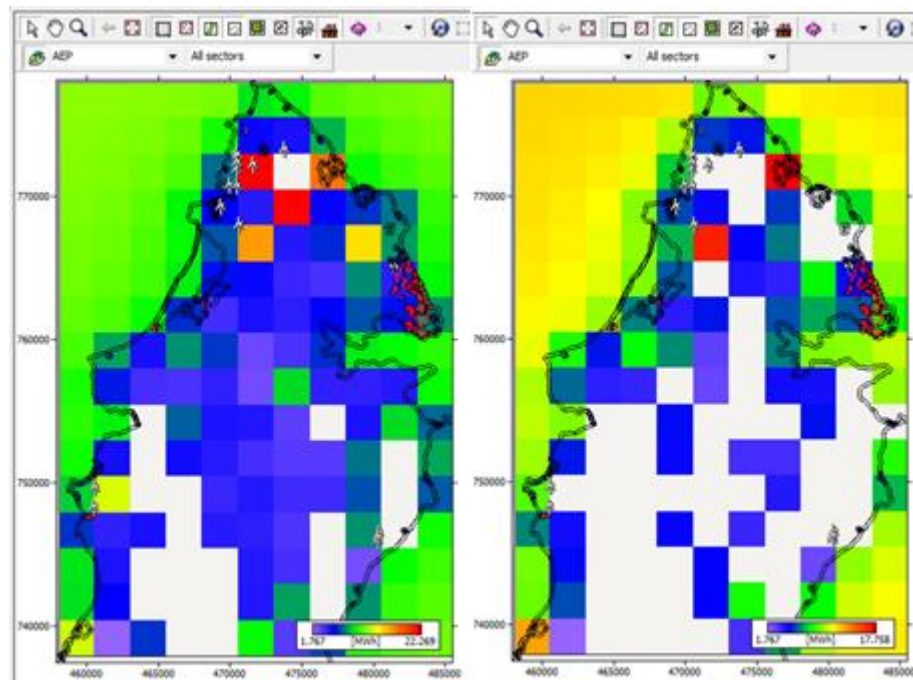


Figure 19: Masking Elevation above 50 m (left) & 100 m (right) in RG

Resolution of the RG is very important for microsites. In WAsP, the resolution refers to the size of land area covered by a pixel on the RG. If the resolution is set to 50, then each pixel on the grid represents 50m x 50m ground area. Therefore, reducing the resolution in WAsP makes microsites more precise as it is more microscopic. As evident in Appendix D 1-3, decreasing the resolution from 200 to 50 improves the precision of locating areas with higher AEP.

While more accuracy is preferred, initial screenings of the sites could be assessed using higher resolution RGs as they take less time to process. The 200-m resolution for Kudat depicted in Appendix D-1,

contains 27,064 sites (grids) and therefore takes about 3mins to calculate. However, the 50-m resolution depicted in Appendix D-3, contains 429,013 sites (more than 18 times that available in the 200m resolution, for the same geographic) and takes more than half an hour to process.

Once the micrositing is done, it is important to synchronise the wind farms with Google Earth Pro to ensure that the proposed locations are available for installing wind turbines.

3.6.2: Wake Loss

Efficiencies of wind farms play a key role in the investment decision. Wind speed reduction in wakes from upwind turbines results in reduction in AEP of wind farms. Such loss in power is known as wake loss or array loss. Reducing the wake / array loss as much as possible, should be one of the priorities during micrositing. Wind turbines should be set-up with adequate distance, where the turbulence caused by the upwind turbines becomes closer to undisturbed / smooth flow for the downwind turbines.

Although, placing turbines at the highest wind resource grids is vital, placing them closer to each other would cause a significant loss in net AEP due to wake loss. WASP 8 recommends maintaining a distance of 4 times the rotor diameter to reduce the wake effect. Wake loss is minimal when there is only one row of wind turbines at 90 degrees of the predominant wind direction. Likewise, wake loss gets higher if turbines are set-up in a straight row aligned in the same direction as the wind flow. Hence, it is also vital to consider the wind direction before placing turbines as a grid or arc. Moreover, if there are many arrays, the actual AEP might be lesser than calculated AEP because of the effect of the turbines on the general roughness description for the vicinity.

WAsP uses Park model, a model based on the Jensen's wake model, to calculate wake loss. This model is capable of estimating the wake loss quickly; an advantage of using WAsP for WRA. The model assume that the wake expands linearly behind the rotor. Hence, the positioning of turbines, the thrust coefficient curve of the wind turbines used in the wind farm and the wake decay constant²⁵ are used to estimate the wake loss. A flow field utilized within the WAsP model to estimate the output of a wind turbine is given below.

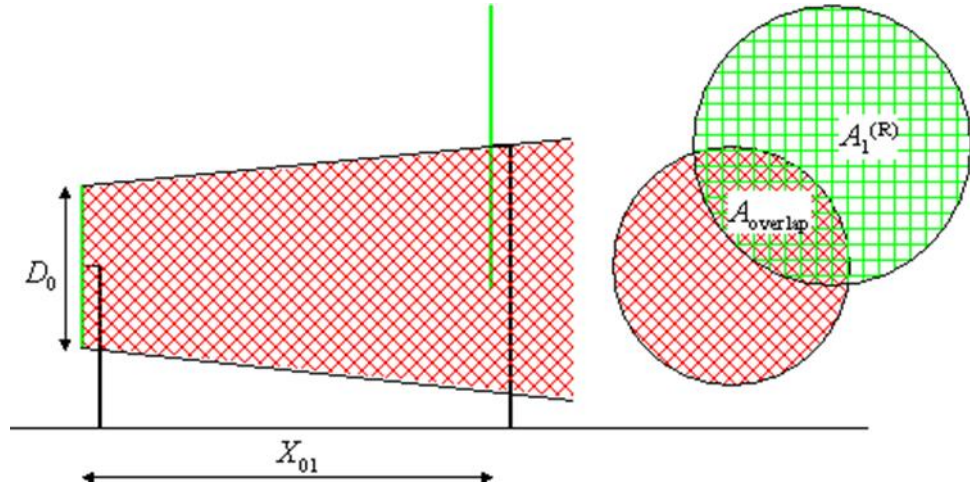


Figure 20: Output of Turbine Model in WAsP

The effective wind speed reduces at the down-wind wind turbine (Turbine-1) is estimated using the following equation:

$$\delta V_{01} = U_0 (1 - \sqrt{1 - C_t}) \left(\frac{D_0}{D_0 + 2kX_{01}} \right)^2 \left(\frac{A_{\text{overlap}}}{A_1(R)} \right) \quad (3.10)$$

where,

U_0 = Undisturbed wind speed at the up-wind turbine (Turbine-0)

D_0 = Rotor diameter

X_{01} = The downwind horizontal distance between the wind turbines

k = Wake decay constant

C_t = Thrust coefficient

²⁵ Rate of expansion (break-down) of the wake.

The thrust coefficient in equation 3.10 is given by,

$$C_t = \left(\frac{2F_t}{\rho \frac{\pi}{4} D_0^2 U_0^2} \right) \quad (3.11)$$

where,

F_t = Thrust Force

ρ = Density

U_0 = Undisturbed wind speed at the up-wind turbine (Turbine-0)

D_0 = Rotor diameter

If speed reduces from U_0 to V when wind passes the rotor plane, then the relation to C_t can be shown as below.

$$(1 - C_t) = \left(\frac{V}{U_0} \right)^2 \quad (3.12)$$

The default wake decay constant in WAsP is 0.075, an adequate value for most lands (WAsP 12, 2017). Wake loss can be estimated only when turbines sites are organised / laid within a wind farm. For instance, if two wind farms are added, wake effects from one wind farm would not affect the turbine performance in the other wind farm; a drawback of WAsP. Once the wind farms are set (if only one type of WTG is used), the turbine sites can be extracted, combined and loaded as a one big farm. In this way, wake effects of all the turbines can be estimated. Turbines sites can be manually moved or removed if the wake loss is high when all turbine sites are combined as one. If different types of WTGs are used, then it is important to assign WTGs to each turbine sites. At this stage, N-AEP of the proposed farms would be finalised. However, this would not be adequate by itself because it is important to also evaluate the characteristics of the potential sites; such as, dRIX, access to sites, economic feasibility, etc.

3.6.3: The Ruggedness Index

Topographical differences affect wind power estimation. The term 'complex terrain' is widely associated in defining landscapes with hilly or mountainous terrain which are steep. However, there is no widely accepted measure of terrain; such as, a threshold beyond which

terrain would be considered complex or otherwise. One well-known measure of terrain complexity (or steepness) is relative relief, i.e. the difference between the highest and lowest elevations within unit areas of 100 km² (Rutkis, 1971; William-Olsson, 1974). This was used as a means for judging the influence of the mountains and thereby the degree of reliability of the results presented in the European Wind Atlas (Troen and Petersen, 1989).

WAsP uses an alternative measure for the complexity of the terrain; the Ruggedness Index (RIX). The RIX is defined as the fractional extent of the surrounding terrain that is steeper than a critical slope. RIX measures how fast the slope of a terrain accelerates using the contour map (topographical map). WAsP calculates RIX for the potential sites identified by the user. It also estimates the RIX for each sector (direction); this produces more nuanced details to understand the ruggedness of a terrain. A flat site has a RIX of 0%, and sites with accelerating elevation have a higher RIX. For instance, a 20% RIX indicates that about one fifth of the terrain is steeper than the critical slope. The RIX values are used by WAsP to model the wind flow over the area. The index was proposed as a more refined measure of the flow separation, and by extension a measure of whether a terrain violates the assumptions of linearised flow models (Bowen and Mortensen, 1996).

Figure 21 illustrates the ruggedness of the Miri landscape. The graph on top shows the colour coded height classes. The red lines in the bottom graph are contour lines which indicate a change in the terrain height. In Miri, the contour lines in the centre of the graph represent forest areas, where the steepness rapidly changes; as evident by the close proximity of the contour lines.

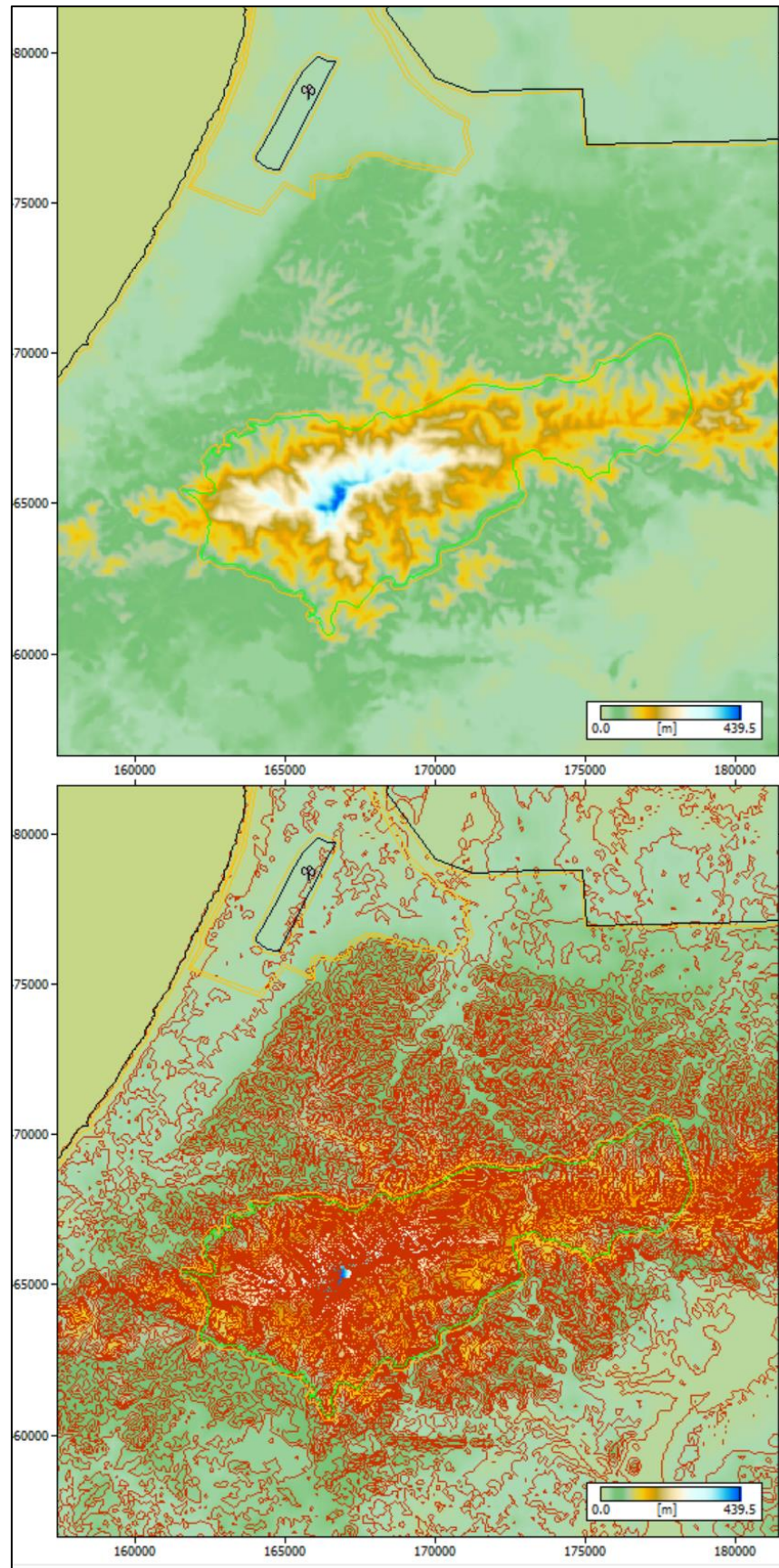


Figure 21: Elevation Without (Top) & With (Bottom) Contour Lines

Differences in the RIX (dRIX)²⁶ is measured as a percentage change of RIX and the accuracy of the WAsP AEP estimates are affected by this. It is important that the dRIX between the observed met site and the potential site for turbine installation is small. If the observed site is more rugged than the potential site, the wind power is underestimated. Likewise, if the observed site is less rugged than the potential site, then the power is overestimated. The dRIX would be small when both sites have low RIX or when both sites have high RIX. If the two sites are quite similar, then the prediction errors are observed to be small. In such instances, WAsP predictions are reliable. WAsP evaluation is highly reliable for dRIX less than 10% and relatively reliable for dRIX less than 20%.

WAsP prediction errors are larger if one of site (observed or predicted) has low RIX and the other site has high RIX (Mortensen and Petersen, 1997). WAsP predictions become unreliable for sites with dRIX larger than 20% as its calculations are beyond its prediction envelope. In such instances, the errors can be reduced using two methods. First, employing user correction to wind speed data to adjust the variations in the ruggedness²⁷. User corrections need to be employed with caution since incorrect adjustments to the wind speeds are likely to add additional bias to the estimations. Second, utilisation of WAsP CFD analysis. WAsP CFD analysis is more accurate in estimating wind power in highly rugged terrain. Using CFD models helps to develop a steady-state, time-independent solution for the wind and turbulence field (Berge et al., 2006). However, it requires higher computing power and is generally not favoured for sites with only few rugged terrains as it is both time consuming and expensive.

Smaller dRIX sites are preferred as WAsP predictions are more likely to be accurate. Hence, it is important to choose sites with low dRIX

²⁶ dRIX is sometimes referred to as performance indicator.

²⁷ As noted in Mortesen et al. (2008).

when choosing sites for turbine installation. Studies that do not assess the dRIX when micro-siting may underestimate or overestimate the AEP of the wind turbines. In this thesis, the dRIX is utilised as an important tool in assessing the sites for installing wind turbines. WAsP tends to overestimate wind speeds at sites near extensive forests (Dellwik et al., 2006). In Malaysia, such forests are visible in Penang, Kudat and Langkawi. Therefore, it is important to assess the dRIX before proposing the potential sites.

3.7: Robustness of the WAsP model

It is important that the proposed WAsP model's estimates are validated independently using a live wind turbine for comparison of estimated and actual AEP. For this purpose, several operators of live wind turbines were approached locally and internationally. Due to data constraints and commercial confidentiality clauses, it was difficult to find appropriate live wind turbine data in Malaysia. Hence, data from a live wind turbine in Udappu, Sri Lanka has been used with the permission of the turbine operator.

Sri Lanka is a tropical island nation like Malaysia and is located in the Indian Ocean within 6° to 10° north and 79° to 82° east. Actual wind speed and power data of the S88 wind turbine system located in Udappu, Puttalam of Sri Lanka is used to validate the WAsP model. The operator of the wind turbine had agreed to share data for the calendar year 2017 on the basis that it is only used for academic purposes.

The data consists of measured wind speed, wind direction, temperature, pitch angle and the energy generated at ten-minute intervals. The annual data was then cleaned to ensure no duplicates were present and was also investigated for consistency of records. The wind speed data and direction were not found to have any extreme or suspicious values. Out of the over 47,000 data points,

just over 9,600 data points had to be removed due to duplication. The final dataset consists of 38,516 observations (at 10 min intervals). On average, after discounting for missing observations, each day has 17.90 hourly observations: with some hours recording zero observations and some hours recording a maximum of six observations—due to the 10minutes interval of the data.

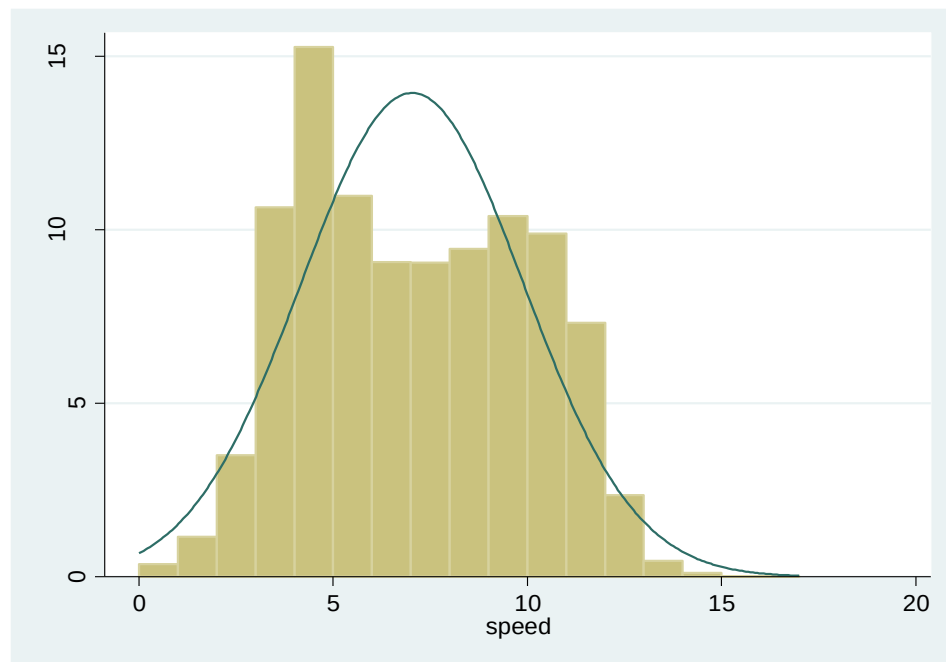


Figure 22: Wind Speed Distribution at Udappu

Figure 22 indicates that the site has relatively good potential for harnessing wind energy. This is because, the site record wind speeds of more than 2ms^{-1} for more than 95% of the time. The average wind speed at the site was 7.08ms^{-1} at 80m hub height in 2017 and had a maximum speed of 16.8ms^{-1} . The mean speed of Udappu is more than 35.4% of the mean speed of Penang²⁸, which has the highest wind speed among the Malaysian sites. Penang experiences mean speeds of 5.23ms^{-1} at 80m hub height of same roughness class as Udappu. These wind speeds are considered to be low compared to European wind speed profiles. Hence, these speeds are classified as low wind speeds and share similar profile to those in tropical regions

²⁸ This is after the landcover map was incorporated.

such as Malaysia, Indonesia, and even parts of the African continent closer to the equator. The average temperature at the site was 35.44 degree Celsius, which is similar to the temperature profile across most sites in Malaysia. Further, the wind turbine in Udappu is located at a coastal site, and most Malaysian sites considered are also coastal. For these reasons, the site and turbine being studied are found to be a suitable comparison for validating the WAsP model estimates for Malaysia.

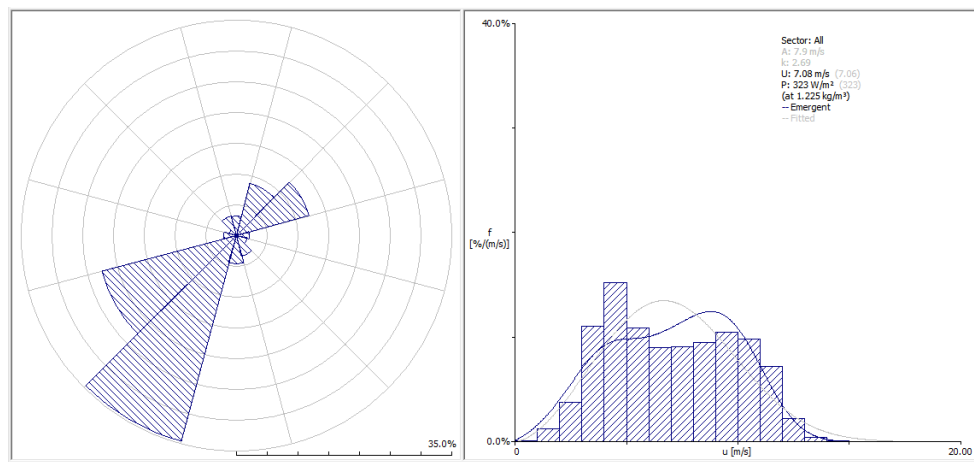


Figure 23: Wind Rose & Weibull distribution Estimated by WAsP for Udappu

The Wind Rose and Weibull distributions for the Udappu site (Figure 23) show that there is good potential to harness wind from the south-westerly direction i.e. facing the sea (see Figure 24). More than 80% of the wind energy generation is attributed to just two of such south-western sectors on the Wind Rose. The Weibull distribution indicates the PD to be 323 Wm^{-2} .

The wind turbine deployed at the site is a 2.1MW rated S88 system manufactured by Suzlon Energy limited based in India. The system, manufactured for low to medium wind regions has a cut-in wind speed of 4 ms^{-1} , rated wind speed of 14 ms^{-1} and a cut-out wind speed of 25 ms^{-1} . The installed system has a hub height of 80m.

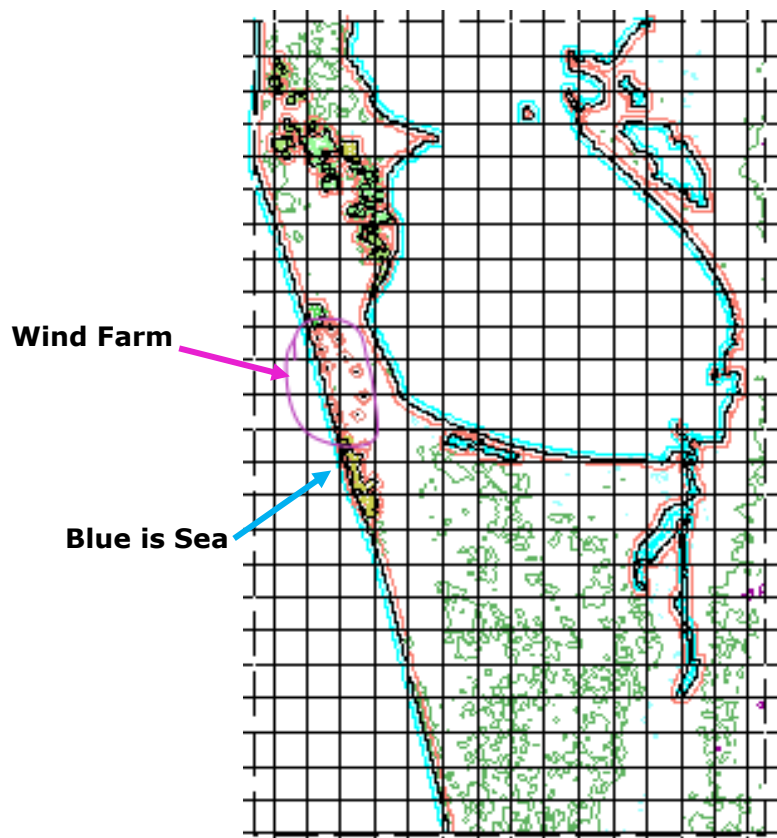


Figure 24: Vector map of Udappu (SRTM & Roughness Map)

In addition to the data from the turbine operator, SRTM maps for Udappu, Sri Lanka were downloaded from the SRTM v2.1 database and roughness maps were created manually in Google Earth Pro. The merger, cleaning and checking of accuracy of data were done similar to the process identified for the Malaysian data. The combined vector map is presented in Figure 24. The pink circled area indicates the windfarm site. Each pink diamond with a black dot inside indicates a wind turbine in the farm²⁹. As evident from the vector map there are no large residential or commercial areas near the wind farm. There is a cluster of housing and a small town to the north of the wind farm (identified as patches of green) and a small agricultural area to the south (identified by a brownish yellow patch). There are no residences, agricultural or commercial sites to the south east of the

²⁹ Figure 25 presents a zoomed Google Earth view of the wind farm with the wind turbine being studied clearly distinguished from the rest of the wind turbines.

wind farm. Additionally, the terrain is relatively flat with the highest elevation being only 20m.



Figure 25: The actual Wind Farm in Udappu

Since the data was collected at the same site as the turbine, the turbine site is marked as both the anemometer and potential turbine site on WAsP. A check on Google Earth (and prior information from the wind farm operator) shows that there are other wind turbines within the same locale (see Figure 25). In the figure, the wind turbine being studied is marked with a star on its right and the adjacent turbines are marked with circles. To account for the seven adjacent turbines in the wind farm, the turbines were duly cluttered in a wind farm in the vector map so that the wake loss for the chosen wind turbine is accurately computed³⁰.

An analysis of the resource grid for the area (Figure 26) shows that the wind turbines are located in ideal locations as identified by WAsP to have the highest potential energy. The red shade indicates the highest potential energy while blue indicates the lowest potential. The wind turbine being studied in this section is identified as 'WT1(S2)' and marked as Udappu for easy reference.

³⁰ One of them is not visible due to zoom scales but is identified in Figure 25.

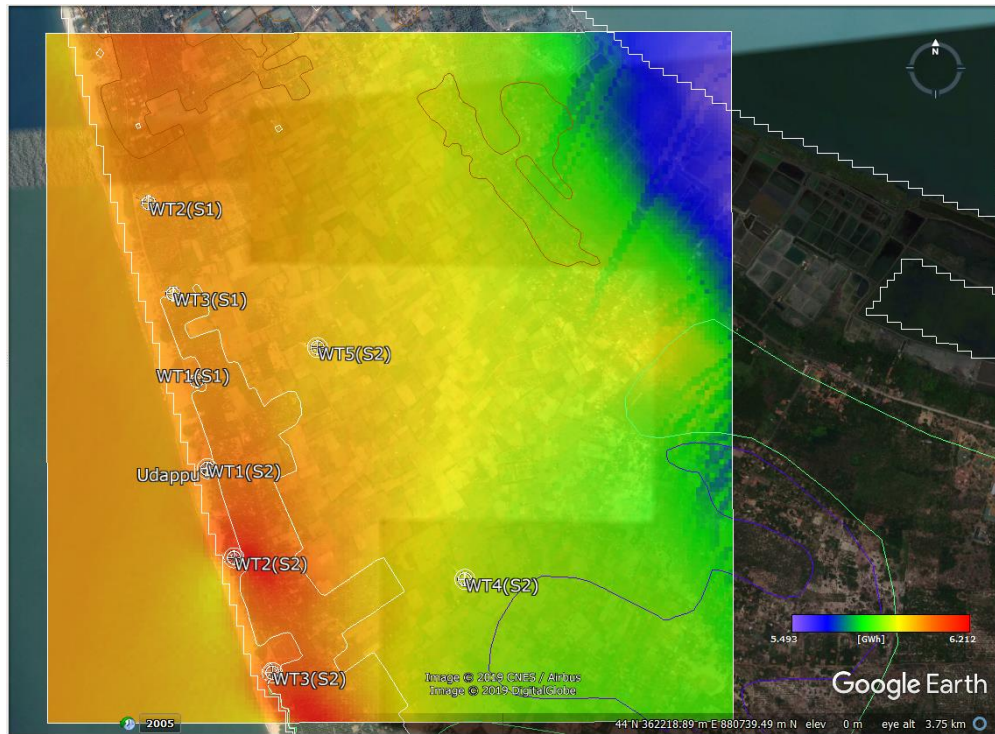


Figure 26: Resource grid for Udappu

Based on the data, WAsP model predicts the N-AEP to be 5.958GWh with a 1.57% wake loss (see Table 3). The WAsP estimation is based on 24 hourly observations per day. The actual data (as discussed earlier) only consists of 17.90 hourly observations; therefore, to make the comparison more sensible, the predicted N-AEP was converted to kW³¹. Thus, the power generation estimated by the WAsP model for the wind turbine WT1(S2) in Udappu is 680.137kW. This is similar to the actual mean power generated by the turbine, shown in Figure 27.

³¹ This meant that for the AEP predicted by WAsP, the energy in GWh was divided by 8760 hours (24hrs per day times 365 days) to arrive at the kW power generated. For the actual power data, the turbine operator had made the power data available in kW.

Table 3: AEP estimates for wind farm in Udappu, consisting of 7 WTs.

Site	Location [m]	Turbine	N-AEP [GWh]	Wake loss [%]
WT1(S2)	(360191, 881896)	Suzlon S88	5.958	1.57
WT2(S2)	(360306.3,881508.1)	Suzlon S88	6.061	1.43
WT3(S2)	(360473.4,881008.1)	Suzlon S88	6.009	1.28
WT4(S1)	(360145.7,882278.2)	Suzlon S64	2.982	1.71
WT4(S2)	(361316.7,881411.6)	Suzlon S88	5.695	3.41
WT5(S2)	(360674.7,882421.3)	Suzlon S88	5.281	11.69
WT2(S1)	(359937.3,883052.4)	Suzlon S64	3.017	0.32

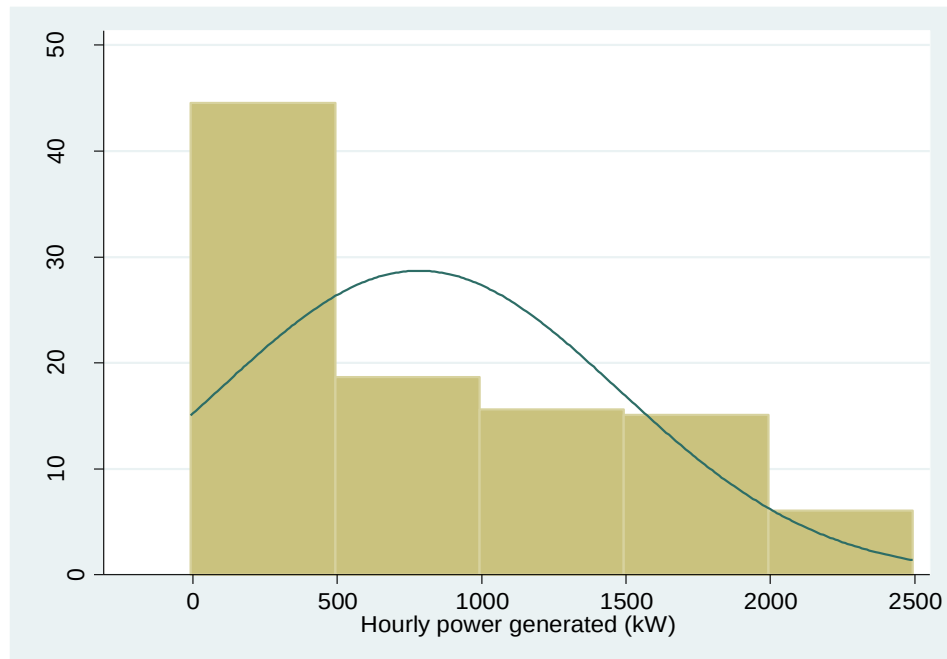


Figure 27: Actual Hourly Power Generated by the WT in Udappu

Figure 27 illustrates that the actual mean hourly power generated by the turbine is 782.619kW, with a maximum power generated of 2120 kW based on data for 2017. Based on the comparison of the predicted and actual power for the turbine in 2017, the deviation in the WASP

model prediction is found to be relatively small at about -13%. In other words, the WAsP model is found to have underestimated the power generated by about 13%. One of the reasons for the deviation could be data issues—as a rule of thumb, it is important to use at least 5 to 10 years of wind data for reliable predictions. Further, the missing hourly observation could have biased power estimates downwards if those missing observations recorded at relatively lower wind speeds.

Although there is a deviation in the estimated power, it is important to note that the WAsP model has not overestimated the N-AEP. This leads to further credibility of this study's findings from the subsequent chapter that there is potential to harness wind energy in Malaysia at least in 3-5 sites. Given that the study has used prudent estimates, it is possible that actual power generated at the identified Malaysian sites could be higher.

An advantage of using WAsP is that sensitivity of WAsP is very high. Every time a workspace is opened, WAsP checks if the files (vector maps, OWC, met stations, etc. discussed earlier) used in the workspace has changed. Such checks reduce the human errors, which is vital when dealing with millions of data and multiple files from different software are incorporated to estimate N-AEP. WAsP also performs remarkably well in complex topographical conditions; even if it is slightly outside the envelope (Sveinbjornsson, 2013). Hence, WAsP predictions are reliable for wind resource assessment in Malaysia.

3.8: Economic Feasibility

From an economic standpoint, the question of whether harnessing wind energy is feasible, is imperative. It is important to note that the economic feasibility of a wind turbine is sensitive to several factors; these include, cost of turbine, exchange rates, transportation and

installation cost, maintenance cost and of course power production. This study uses four methods to evaluate the feasibility of installing different wind turbines at several sites; these investment appraisal techniques include: IRR, Payback, LCOE and NPV, inclusive of ROI and sensitivity analysis. The following section describes the parameters necessary to employ these methods and how they are constructed.

3.8.1: Parameters for Evaluating the Economic Feasibility

(a) Cost of Wind Turbines

Wind turbines are commercially available from multiple manufacturers and vendors. It is important to be prudent in estimating the cost of the turbine, as this forms the largest expense in harnessing wind energy. For example, a 10kW horizontal axis wind turbine can be purchased from China based manufacturers for as low as USD 2000 but can also be bought from European manufacturers for USD 25000³². In determining the cost of the wind turbines and the poles, this study used the prices quoted in official Aeolos and Libellula documents (identified in section 3.5.2)³³. The Libellula wind turbine under consideration produces approximately the same wind power as a 30kW Aeolos wind turbine. However, the Libellula costs significantly more than any Aeolos wind turbine under 50kW. Given these factors, when the NPV and IRR were computed (Appendix E & F), this study uses the Libellula wind turbine as comparison to Aeolos, to determine what class of wind turbines are appropriate for Malaysia. The list of prices (in USD) of the wind turbines and poles are provided in the table below.

³² Based on searches on Alibaba.com, ebay.com and the ecommerce websites of the largest wind turbine manufacturers as at 6th January 2018.

³³ In instances where this information was not available, i.e. for 50kW turbines, the cost of these turbines was based on estimates in line with Aeolos's peers' pricing and industry data on incremental pricing for rated power.

Table 4: Cost of Aeolos Wind Turbine System

Rated Power of Turbine	Height of Pole	Price of Pole	Price of Turbine	Total Price
5kW	12m	1,627.00	8,328.00	9,955.00
5kW	18m	1,742.00	8,328.00	10,070.00
10kW	12m	4,950.00	14,820.00	19,770.00
10kW	18m	9,600.00	14,820.00	24,420.00
10kW	24m	13,200.00	14,820.00	28,020.00
10kW	30m	16,800.00	14,820.00	31,620.00
20kW	12m	4,950.00	26,200.00	31,150.00
20kW	18m	9,600.00	26,200.00	35,800.00
20kW	24m	13,200.00	26,200.00	39,400.00
20kW	30m	16,800.00	26,200.00	43,000.00
30kW	12m	4,950.00	36,680.00	41,630.00
30kW	18m	9,600.00	36,680.00	46,280.00
30kW	24m	13,200.00	36,680.00	49,880.00
30kW	30m	16,800.00	36,680.00	53,480.00

The transportation and installation costs associated with the turbines used in this study are expected to be minimal since the poles and turbines come with easy assembly. Based on the sites studied and an exploration of the literature on wind farms, this study assumes that on average, about 50 wind turbines will be installed in windfarms in each of the sites. Locations such as Miri, with vast swathes of flat land can host 100 wind turbines or more, while more densely populated areas and/or areas with thick forests such as Langkawi can host about 30 wind turbines. Therefore, a fixed transportation cost of RM 1000 is estimated for each turbine (it is expected that for each site the transportation cost of turbines would be about RM 50,000 on average), which includes both transnational transport (from China) and ground transport (from the disembarkation port in Malaysia).

Additionally, the installation cost is assumed to be a function of the energy output of the turbine at 2.5% of the cost of the turbine (Bortoloni et al., 2014). Therefore, larger turbines and those that need to be attached to taller poles will bear more installation cost than those with lower-rated power and attached to shorter poles. A 30kW 30m wind turbine that costs RM 218,000 is assumed to have a transportation and installation cost of RM 6,450 (comprising of RM 1,000 transportation cost and RM 5,450 installation cost, which is 2.5% of the turbine cost).

In assessing the economic feasibility of wind turbines, it is important to note the useful lifespan of wind turbines. In general, most wind turbines have a lifespan of over 20 years, however, in the literature 20 years is assumed to be the general lifespan of a wind turbine (Mohammadi and Mostafaeipour, 2013). The Aeolos wind turbines referred to in this study have a manufacturer warranty of 5 years and can be safely assumed to operate for 30 years and above. The shorter lifespan of 20 years is considered to provide more conservative estimates.

Wind turbines like other mechanical devices are prone to efficiency loss over time. EWEA (2009) and Milborrow (2013) indicate that wind turbines are likely to deteriorate in efficiency no more than 0.7%. Therefore, in this study, we use discount annual energy production by 0.7% i.e. presenting a compounded effect. Wind turbines are likely to lose operational efficiency much faster after the first 20 years (Milborrow, 2013)³⁴; however, in the first 5 years there is likely to be almost negligible operational efficiency. Therefore, the 0.7% loss in annual operational efficiency is an average figure for the first 20 years based on experience in other regions where onshore applications have been available.

³⁴ Still this is likely to be less than 2%.

(b) Economic Indicators

One of the key factors in assessing the feasibility of any project is the opportunity cost and revenue generation. In the case of wind technology, the alternative is to consider solar energy for comparison. In Malaysia, the energy commission does not provide a Feed-in-Tariff (FiT) for Wind Energy output. The closest clean energy comparison would be solar energy; therefore, the solar energy FiT in 2017 was used as the basis for calculating the revenue generation from the wind turbines. The Sustainable Energy Development Authority (SEDA) Malaysia's tariff table for Solar PV (Non-individual (≤ 500 kW)) (21 years from FiT Commencement Date) indicates the FiT for 500 kW and lower rated systems to be RM 0.7424 per kWh of power; this rate is applied in the study.

Additionally, other macroeconomic indicators such as the exchange rate, interest rate and inflation rate are also important to assess the economic feasibility as they are components of the investment appraisal techniques. The three indicators are derived from Bank Negara Malaysia and are derived from the annual average for 2017. The exchange rates are MYR 4.08 per USD and MYR 4.80 per EUR; the interest rate used here is the average lending rate of commercial banks in Malaysia, which is 3%; the inflation rate for 2017 based on official figures is 2.1%. The real interest rate, which is the interest rate adjusted for inflation is therefore 0.88%.

(c) Maintenance Cost

The operational and maintenance cost (OMC) is likely to be a significant consideration in the decision to invest in wind turbine technology. In general, the OMC of wind turbines is much smaller than that of solar and other renewable technology (Seely, 2013). The OMC consists of rental for land (which is assumed to be a relatively small and nominal sum in this study, given that wind turbines can co-exist with activities such as agriculture), service and spare parts, insurance, administrative and other miscellaneous expenses. In the

literature, the total annual OMC is estimated to be 0.6-07 Euro cents per kWh (Blanco, 2009; Bortolini, 2014).

Given the smaller power rated wind turbines explored in this study a combined fixed plus variable cost approach is taken towards the OMC. RM 500 is estimated to be the fixed component of the annual OMC and the variable component is calculated as 0.6-euro cents per kWh of energy produced by the turbine. This approach of using a fixed plus variable cost approach allows to apportion costs such as administrative costs, land rental etc. more appropriately as these costs are likely to be relatively stable regardless of the kWh of energy produced by the turbines. In other words, each site is estimated to bear RM 25,000 of annual fixed cost (to cover some basic rental and administrative cost) and between RM 4,320 and RM 122,400 variable cost per year³⁵. The total OMC is estimated to be between RM 29,320 and RM 147,400 per year per site.

3.8.2: Levelised Cost of Electricity

The levelised cost of electricity (LCOE) takes into consideration the life cycle costs of an energy technology project (this could be for solar, wind, tidal or even hybrid systems), and therefore is a useful way to compare different energy systems. The LCOE captures the initial costs (costs of wind turbine, transportation and installation costs etc.), annual costs such as maintenance, and the energy produced by the turbine through its useful life. The LCOE can be thought of as a break-even value denoted as RM per kWh that illustrates the cost of each kWh of energy produced by the turbine/system. Comparison of this value to the FiT will enable us to understand whether a wind turbine at a particular height can be operated at costs below the FiT to be economically feasible.

³⁵ $(0.006 \times 4.8 \times 3000 \times 50)$ and $(0.006 \times 4.8 \times 85000 \times 50)$, respectively.

Formally, the LCOE can be denoted as:

$$\text{LCOE} = \frac{\text{Total Life Cycle Cost}}{\text{Total Lifetime Energy Production}} = \frac{I + C - S}{E} \quad (3.13)$$

where,

I = Initial investment (cost of turbine + transportation + installation cost)

C = Annual Cost (OMC)

S = Salvage Value

E = Total Energy Production

The salvage value is assumed to be zero in this study, to be more prudent. Market rates for used Aeolos 20-year old wind turbines are not commercially available and are likely to be led to higher profitability estimations. Equation 3.14 below expands these terms to illustrate how the computations were performed for each site and turbine. The effective annual real interest rate for discounting energy production values and the costs is 0.88% as discussed in section 3.7.1 (b); this rate captures both the market interest rate and adjusts this for inflation.

$$\text{LCOE} = \frac{I + \sum_{t=1}^T \{C_t \gamma^t\} - S \gamma^T}{\eta \sum_{t=1}^T \{\gamma^t x_t\}} \quad (3.14)$$

where,

γ = Time – Value of Money i.e $\left[\frac{1}{1+r} \right]$

η = Energy Production

T = Life-cycle of the Project (assumed to be 20 years)

C_t = Operating Cost in Year 't'

X_t = System Degradation in Year 't'

3.8.3: Net Present Value

The net present value (NPV) is one of the most critical project investment appraisal techniques used in finance and engineering (Mathew, 2006). The NPV is able to illustrate the net cash flows from an investment (engineering, construction, acquisition etc.) in today's

currency value. NPV's ability to convert future cash flows in today's terms is the major attraction of this investment tool. The NPV discounts each cash flow by the real interest rate. Given that the real interest rate used in this study is 0.88% as discussed in section 3.7.1 (b); we could use this to identify the value of RM 1 at a time in the future. For example, RM 1 would only be worth RM 0.876653 in 15 years' time (Appendix – E). The year in which the turbine is purchased is denoted as Year 0, revenue and maintenance cost are assumed to from Year 1. The cash flows (revenue minus cost) for each year are multiplied by their discount factor and summed-up to derive the NPV. This is formally denoted in the equation below:

$$NPV = \sum_{t=1}^T \frac{C_t}{(1+r)^t} - C_0 \quad (3.15)$$

where,

C_0 = Initial investment

T = Life-cycle of the Project (assumed to be 20 years)

t = Year

C_t = Operating Cost in Year 't'

r = effective real interest rate i.e $\left[\frac{1+r}{1+i} \right]$, where 'i' is the rate of inflation.

As a general rule of thumb, NPVs above zero are considered to be economically feasible and higher NPVs are preferred over lower ones (Mathew, 2006). An NPV of zero indicates that after taking into account the cost of borrowing (interest rates) and also factoring-in the inflation rate (which lowers the purchasing power of money).

The discounted Return on Investment (ROI) is obtained by dividing the NPV by the cost of the turbine. This allows to more easily compare the turbines of different power rating at different hub heights. The ROI can be expressed as follows:

$$\text{Discounted ROI} = \frac{NPV}{\text{Cost of a Turbine}} \quad (3.16)$$

The IRR is the discount rate (real interest rate, i.e. interest rate adjusted for inflation) at which the NPV is zero (break-even).

$$\sum_{t=0}^T \frac{CF_t}{(1+IRR)^t} = 0 \quad (3.17)$$

where,

T = Life-cycle of the Project (assumed to be 20 years)

t = Year

CF_t = Cash Flow in Year 't'

The IRR is a useful way to identify whether the cost of borrowing (or the opportunity cost of investment, where borrowing is not necessary) is met by the project. It also presents a quantifiable rate up to which the project can produce positive returns.

CHAPTER 4: RESULTS

Employing methodology discussed in the previous chapter, this chapter presents results and stepwise discussion of arrival towards the economic feasibility from wind speed analysis, wind profiles, power density to gross and net annual energy production.

4.1: Weighted Average of Annual Malaysian Wind Speed

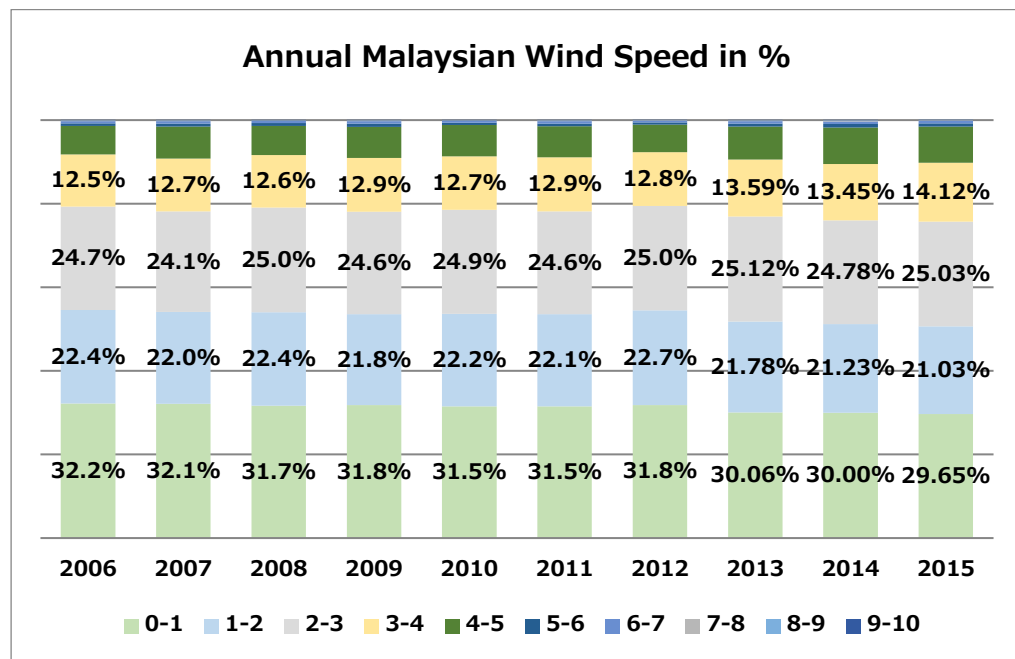


Figure 28: Annual Malaysian Wind Speed Distribution in Percentage

The above graph shows the annual wind speed in 1 ms^{-1} blocks across Malaysia. Over the 10-year period from 2006, the wind speed spread has been fairly constant with the nation recording less than 4 ms^{-1} for more than 80% of the time. This warrants research into HAWT that are capable of harnessing this lower wind speeds. Station-wise analysis (Appendix – A) presents a refined picture on identifying stations that have the potential for harnessing wind energy on a larger scale.

Sultan Abdul Halim, Sitiawan, Johor Bahru, Sri Aman and Subang experience wind speed less than 1 ms^{-1} more than 40% of the time, while Mersing experience the same speed for less than 10% of the

time. All stations experience 1 to 2 ms^{-1} speed for 15% to 30% of the time. Most places experience wind speeds of 2 to 3 ms^{-1} for 20% to 30% of the time, Mersing and Kota Kinabalu get this range of speed more than 30% of the time. 10% to 15% of the time most places experience wind speed of 3 to 4 ms^{-1} . Penang (Bayan Lepas), Butterworth, Mersing, Miri, Kudat and Sandakan experience this range of wind speed more than 15% of the time. Mersing, Kudat, Butterworth, Kota Bharu, Sandakan, Miri and Penang (BL) experience wind speed of 4 to 5 ms^{-1} for 10% to 15% of the time. From the above observations, it is evident that Mersing, Labuan, Kudat, Kuching, Kota Kinabalu, Penang (BL), Butterworth and Sandakan attract relatively stable and higher wind speed percentage relative to the other locations.

Moreover, most stations except Mersing, Kudat and Sandakan, experience wind speed below 2ms^{-1} for more than two-thirds of the time. This indicates that even though the speed is low, wind energy is available throughout the year to be harnessed by small wind turbines. It also can be seen from the twenty-four figures of wind speed statistical analysis (Appendix-A) that weighted average wind speeds for most places have not changed much over the years (except Tawau). Such pattern is promising to further assess the wind resource as the wind speeds have been relatively stable for over a decade. Moreover, when the weighted average wind speeds do fluctuate slightly in Kota Bharu, Kuala Terengganu, Kota Kinabalu, Kudat, Mersing, Tawau and Miri, the pattern of fluctuation is similar.

4.2: Wind Profile

A summary illustration of the WCA is presented for Langkawi below to understand how the wind profile for each site was analysed and subsequently used to understand the power density estimates. The WCA is presented across four different graphs. Similar findings are made for other sites across Malaysia as initial assessment.

Mean Year

The full line on the mean year graph describes the seasonal variation (by month) in the measured wind speed while the dotted line presents the cube of wind speed (when reading the dotted line, it needs to be multiplied by a factor of 25). All data associated with the same calendar month are averaged by WCA and the results plotted at the midpoint in each of the indicated monthly intervals. The y-axis is the wind speed; for the full line, the unit is ms^{-1} and for the dotted line the unit is m^3s^{-3} . The x-axis is the months in a year. A sample mean year from the OWC report of Langkawi is shown below. It can be seen that in Langkawi, the wind flow is higher during the months of November to March, where the average monthly wind speed is above 2ms^{-1} . The wind speed is lowest in May, with generally lower wind experienced during the rest of the summer months.

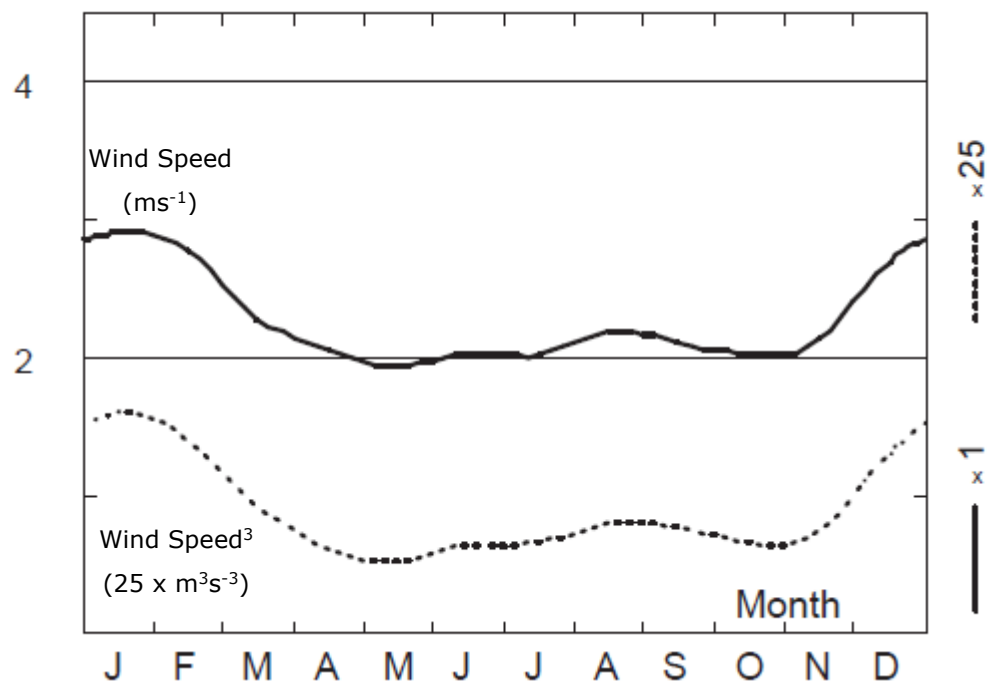


Figure 29: Mean Year in OWC Report of Langkawi

Mean Days

Mean days graphs below show the average daily variation in wind speed across the 24-hour time period. WCA uses the daily averages for each of the hourly intervals for two months—January and July, this is to ascertain any variations in the wind flow across time mid-year. Data from all months of January (July) associated with the same time of day are averaged. The full line is the mean wind speed for each of the corresponding hour intervals while the dotted line illustrate the cube of the average wind speed (when reading the dotted line, it needs to be multiplied by a factor of 25). The y-axis is the wind speed; for the full line, the unit is ms^{-1} and for the dotted line the unit is m^3s^{-3} . The x-axis is the hour intervals in a day. A sample of mean days from the OWC of Langkawi is shown in Figure 30. The wind speeds are higher during the night, especially from 3 to 6 am in January, where average wind speeds exceed 4 ms^{-1} . In July, higher wind speed is experienced from 2 to 10am, but the average wind speed is only between 2 to 2.5 ms^{-1} .

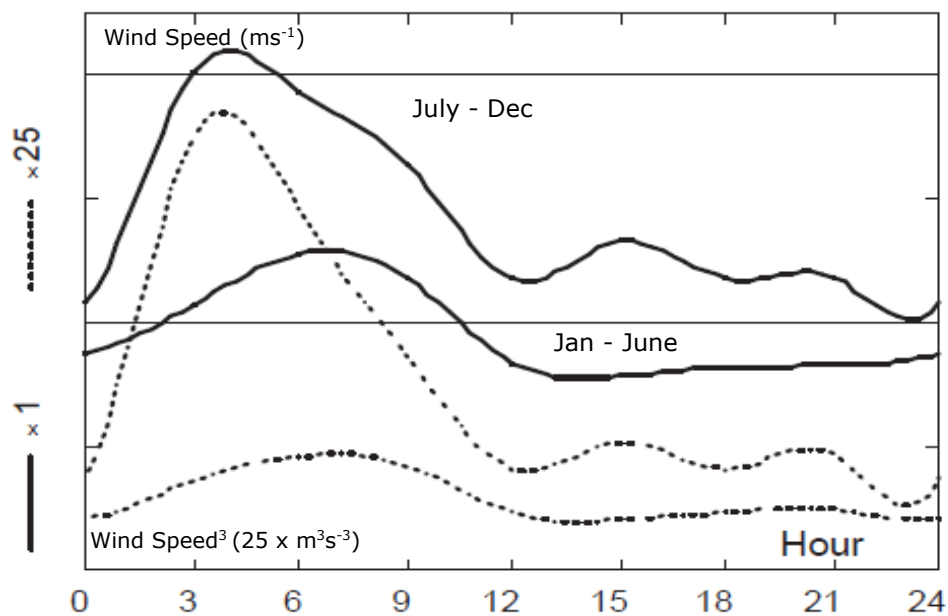


Figure 30: Mean Day from the OWC Report of Langkawi

Wind Rose

Wind rose graph in OWC report illustrates the relative frequency of wind flow direction. WCA plots the wind rose for 12 sectors, where the thick lines depict the frequency. The sectors from 1-12 indicate wind direction intervals of 30° each. That is, longer spokes indicate higher relative frequency. The lighter shade (grey) lines indicate the contribution of each sector to the total mean speed. For example, in Langkawi, wind flows relative more often in sector 3 (Figure 31). However, sector 2 contributes more to the mean wind speed than sector 3—this is because the wind speeds experienced in sector 2 are higher than those experienced in sector 3. This analysis is crucial in micro-siting decisions, as it is important to identify sectors in which relatively stable wind flow is available (such as those experienced in sectors 2,3,9 and 10) and at the same time have relatively good wind speeds (such as those experienced in sector 3).

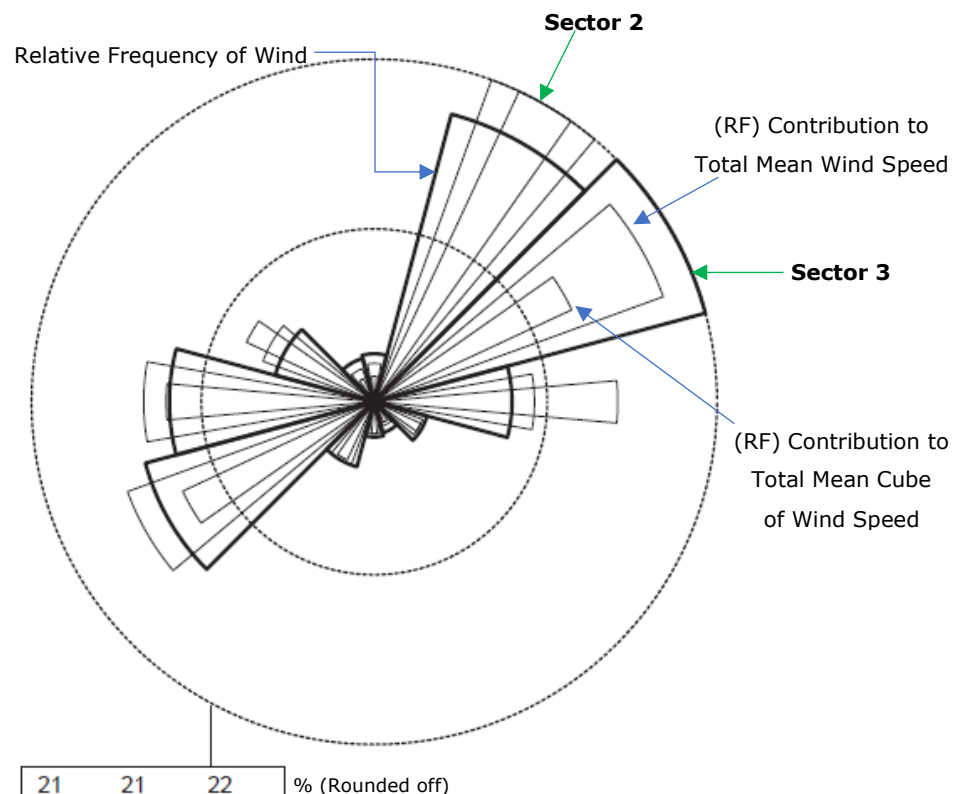


Figure 31: Wind Rose from the OWC Report of Langkawi

Time Prints

The time prints graph shown below illustrates the monthly deviation in average wind speeds over the years in relation to those illustrated in mean year (Figure 29). The x-axis is the calendar years; 6 is 2006 and 15 is 2015. The dotted line is the cube of the difference in wind speeds by month in a given year in relation to the mean wind speed for the month across all the year. From Figure 32, it can be seen (blue shaded area) that the wind speed discrepancy in January 2011 was about 0.3ms^{-1} and the deviation in cubic speed was $0.8\text{m}^3\text{s}^{-3}$. This leads to the high average wind speed in January across the 10 years, at 2.9ms^{-1} . Similarly, the green shaded area shows that wind speed discrepancy in June 2015 was about 0.4ms^{-1} and the deviation in cubic speed was $0.6\text{m}^3\text{s}^{-3}$, which leads to the lowest average wind speed in June across the 10 years. Generally, lower discrepancies are preferred, and a discrepancy larger than 5% is attributed to large fluctuations in wind speeds such as those arising from monsoons (WAsP, 2014). This analysis is very important in understanding the changing wind patterns across months over the years (partly attributed to El-Nino). Similarly, the open circles show the relative deviation of the mean cube of speed for each calendar year. In the graph below, the average wind speed in Langkawi for 2010 and 2013 did not vary much from the 10year average wind speed. The graph also shows that the average annual wind speed has been on a downward trend since 2011.

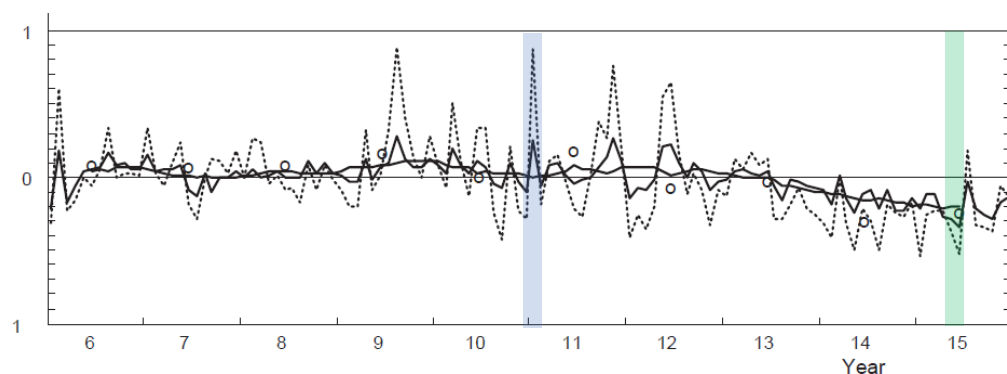


Figure 32: Time Prints from the OWC Report of Langkawi

A sample of self-prediction of met stations to identify potential deviation of the predicted wind profile from that of the observed wind profile is shown Figure 33. The highest frequency of wind flow is experienced in Sector-3. The data observed at the met station indicates that wind flows along the direction of sector 3 (60° to 90°) about 13.1% of the time. However, WASP's estimations based on long-term data and deviation patterns estimate the corresponding value to be 13.8% of the time. The resultant Weibull is shown on the right. Pre-calculated Weibull parameters A and K, the fitted wind speed average 'U' and predicted power P are displayed in the graph. The darker line is the predicted Weibull, while the lighter shaded line is the observed Weibull for the site. It also can be seen that for Sandakan, the average wind speed is 3.44 ms^{-1} in the direction of Sector 3.

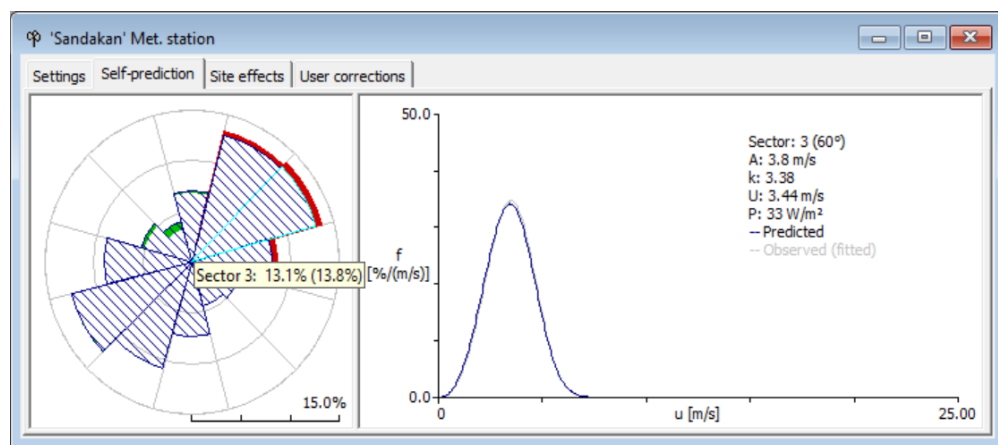


Figure 33: Sandakan Met Station Window in WASP

For comparison, the self-identified deviation in wind rose and Weibull distribution for Miri are presented in the top panel of Figure 34. The red border in the Windrose depicts that WASP's fitted spokes are higher than those observed. On the other hand, the green border indicates that WASP's fitted values are lower than those observed. In the lower panel of Figure 34, the fitted Windrose and Weibull distributions are presented. These fitted values are then used by WASP to generate GWCs.

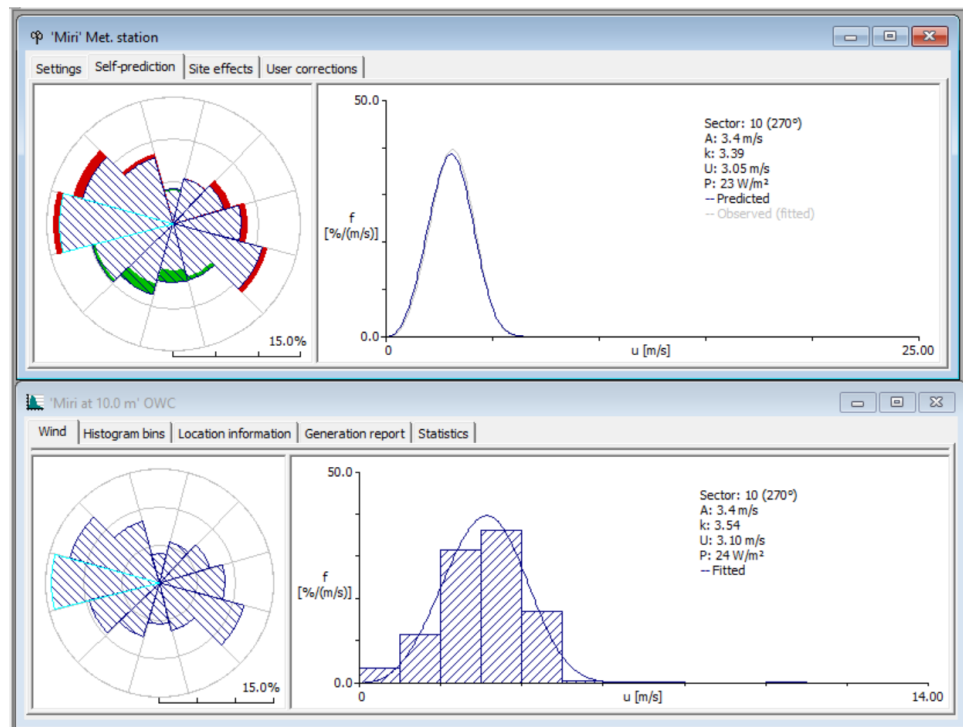


Figure 34: Comparison of Met Station & OWC Window of Miri

A sample of GWC is shown in Figure 35 for the site, Sibü. The figure shows how the wind speed and PD are affected by roughness and height. Wind speeds and thus PDs decrease with increasing roughness. For example, at a height of 10m, a very flat smooth land surface area in Sibü has the potential to harness 24 Wm⁻². At more highly concentrated land spaces, such as housing areas (assigned roughness class 4), only 3 Wm⁻² of PD is available at the same height.

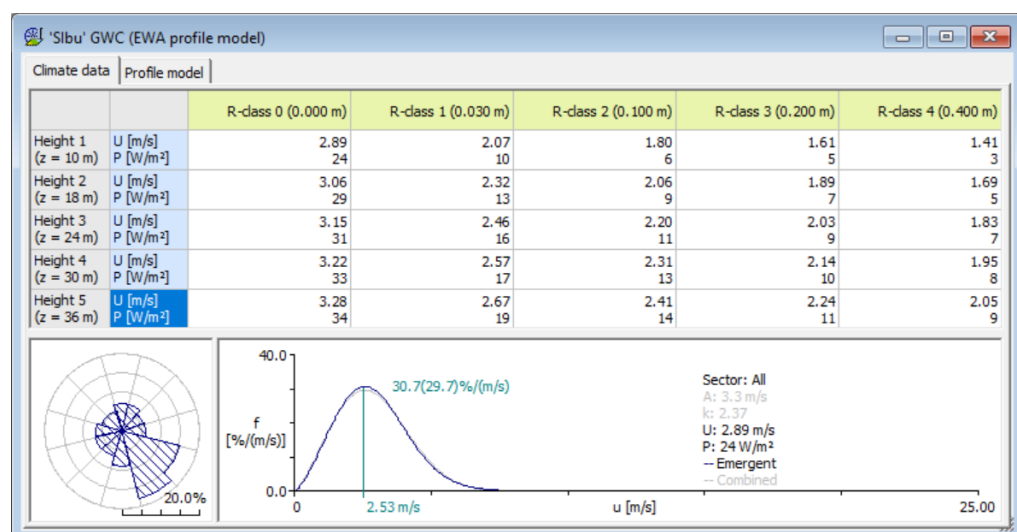


Figure 35: GWC Window of Sibü

At the same time, increases in the hub height at the same roughness class enables the turbine to experience higher wind speeds and subsequently higher PD. As evident from the GWC of Sibu, when moving from 10m hub height to 36m hub height, both the wind speed and PD increase considerably. Moreover, in highly concentrated housing areas (R-class 3) of Sibu, only 5 Wm^{-2} of power can be harnessed at a height of 10m, but at the height of 36 metres, the available PD increases to 11 Wm^{-2} .

Further, the frequency of high wind speeds can significantly affect PD. For example, examining multiple Windrose of GWCs, it can be noted that in some instances, the size of Windrose spokes corresponding to wind speed and PD diverge (Figure 36). This is because, even though the OWF of higher speeds are very small, the energy produced by the higher wind speeds are very large. It is also much larger than the energy produced by lower speeds, which has higher OWFs.

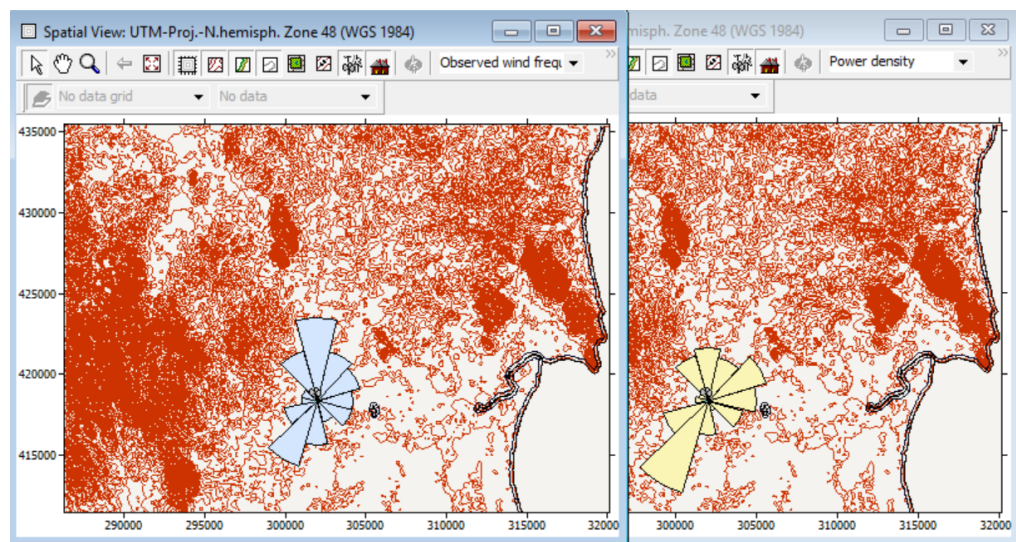


Figure 36: OWF & PD of Kuantan

4.3: Power Density Estimates

Summary graphs presented below, pertain to wind speeds (Figures 37 and Figure 38) and PD (Figure 39 and Figure 40) from the GWC output of all sites. It is a common practice to identify a potential site based on the highest available average wind speeds. However, the wind speed assessments show that the highest available wind power is not generated at the site with the highest average wind speed.

For instance, the Figures (37 – 40) indicate that although Mersing experiences the highest average speed, more power is available at Kudat. At the height of 10 m, the mean wind speed is 3.78 and 3.77 ms^{-1} for Mersing and Kudat respectively (when $R=0$). However, the available PD at the same height for Kudat is 54 Wm^{-2} while it is 44 Wm^{-2} for Mersing. Similarly, Mersing shows an average speed of 4.30 ms^{-1} at a 36m height, while Kudat experiences an average speed of 4.28 ms^{-1} . Yet, at the height of 36 m, Kudat has a PD of 77 Wm^{-2} ; whereas, Mersing has 63 Wm^{-2} . Therefore, higher windspeeds do not necessarily lead to higher PDs.

Further, when the GWCs of Mersing and Kudat were compared (Figure 41 and Table 5), it was noted that the Weibull distribution shows a higher right skewed wind speed dispersion for Kudat compared to Mersing. This demonstrates that there are higher wind speeds that are above the average, which enables more wind power to be generated in Kudat. The numerical values of wind speeds and PDs at different heights and roughness for Kudat and Mersing from the GWC are tabulated in Table 5 for ease of comprehension. Further analysing the GWCs of Kudat and Merisng shows that when the turbine hub height is at 36 m, it produces almost 50% more power than that produced at 10 m height.

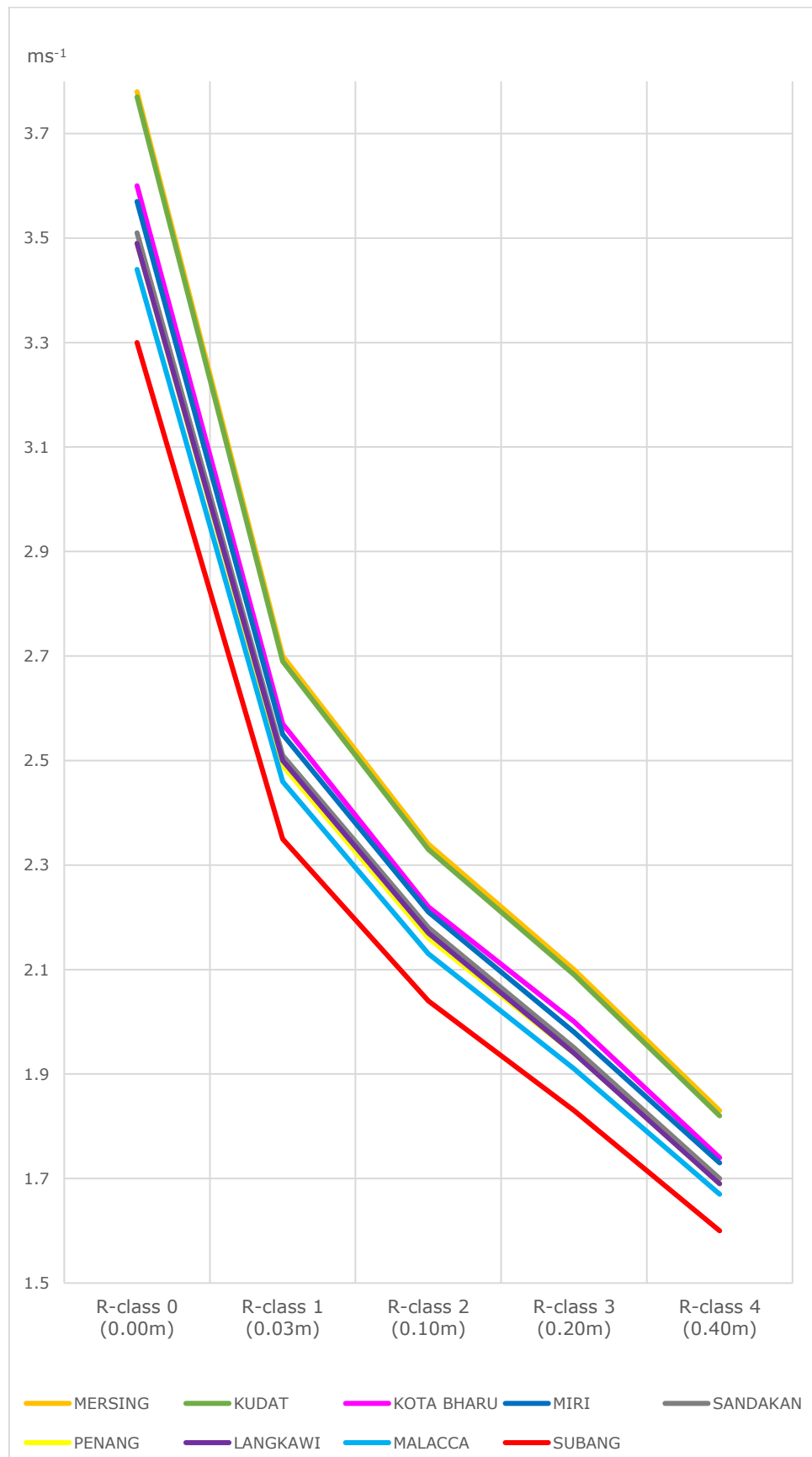


Figure 37: Mean Wind Speed at 10m Height

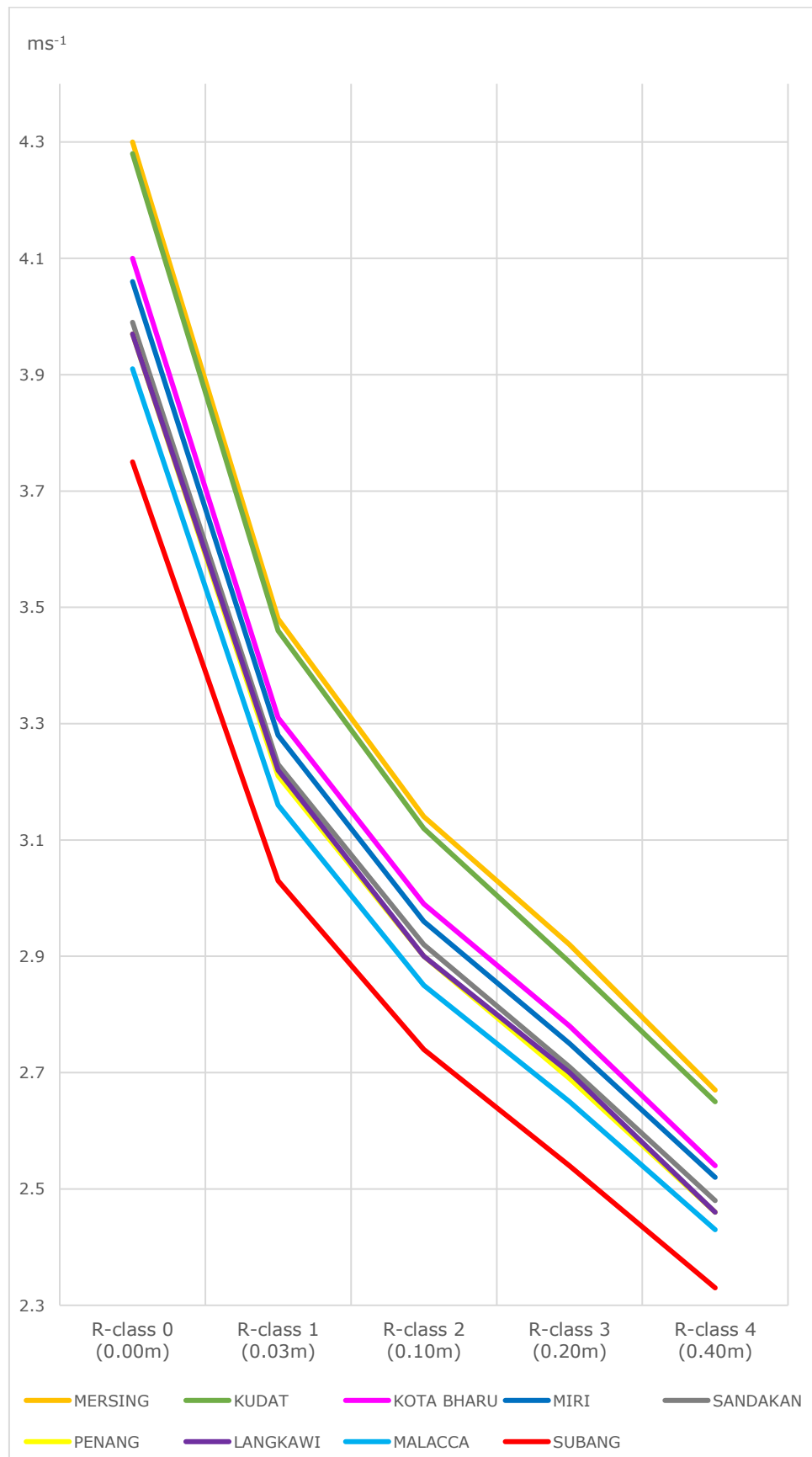


Figure 38: Mean Wind Speed at 36m Height

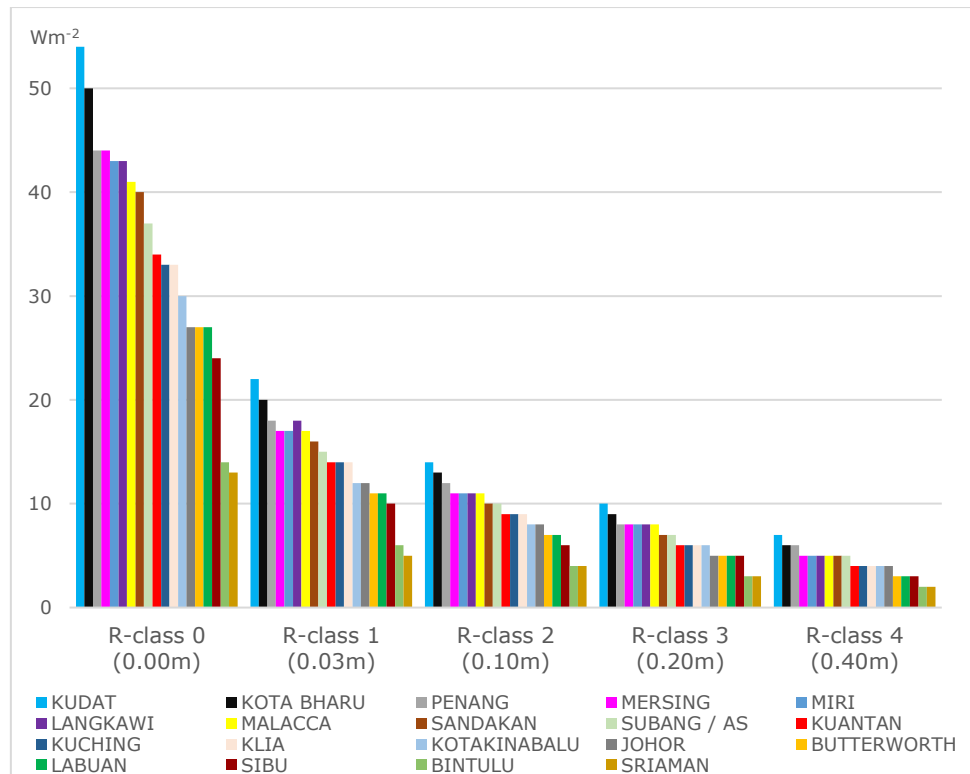


Figure 39: Power Density at 10m Height

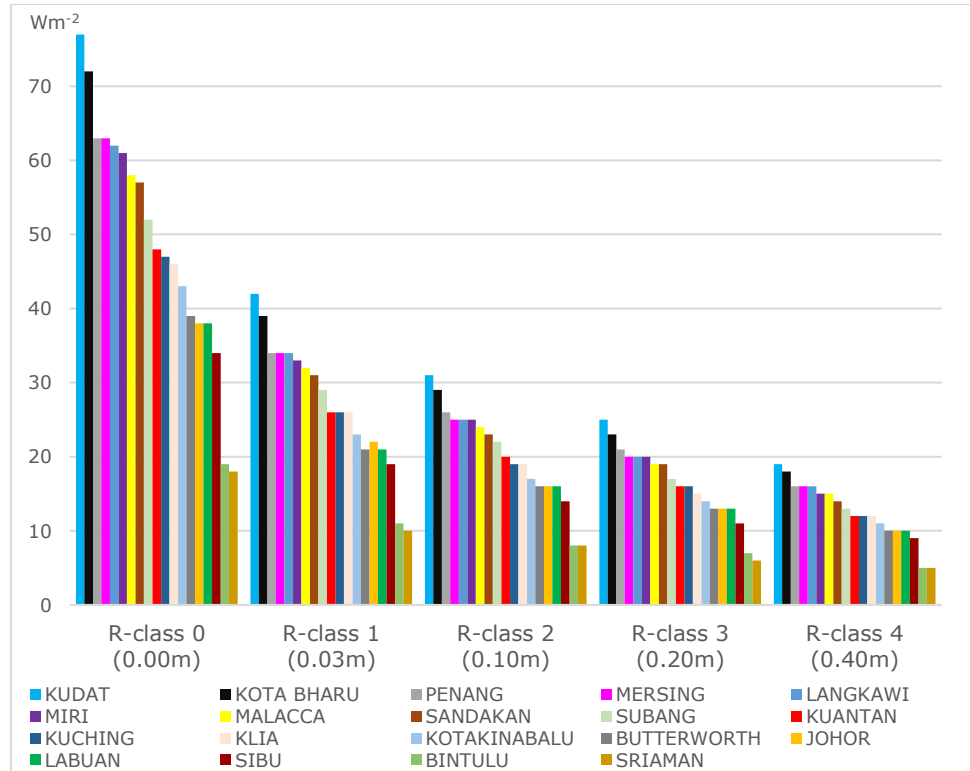


Figure 40: Power Density at 36m Height

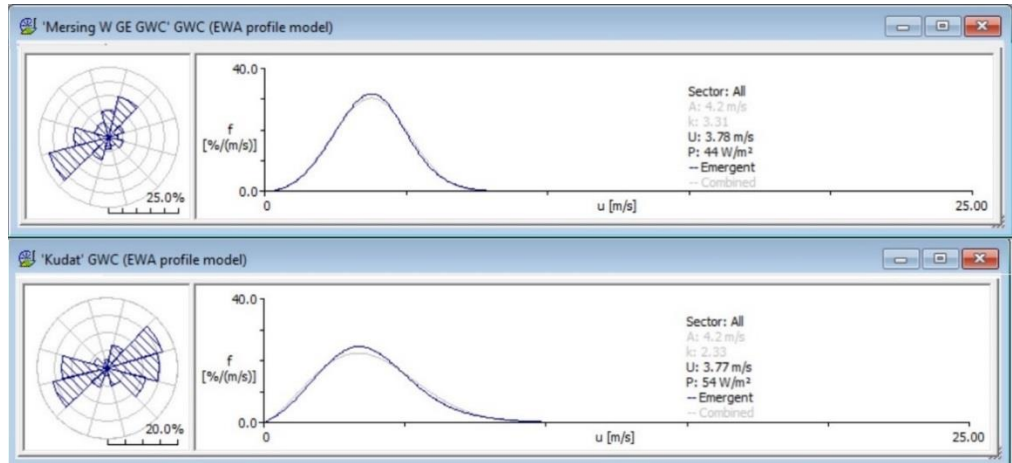


Figure 41: GWC of Mersing (Top) & Kudat (Bottom)

Table 5: Comparison of GWCs of Kudat (K) & Mersing (M)

Z ↓	R →	(0.0 m)	(0.03 m)	(0.10 m)	(0.20 m)	(0.40 m)
(10m)	M (ms^{-1})	3.78	2.7	2.34	2.1	1.83
	M (Wm^{-2})	44	17	11	8	5
	K (ms^{-1})	3.77	2.69	2.33	2.09	1.82
	K (Wm^{-2})	54	22	14	10	7
(18m)	M (ms^{-1})	4.01	3.03	2.68	2.46	2.2
	M (Wm^{-2})	52	24	16	13	9
	K (ms^{-1})	3.99	3.01	2.67	2.44	2.18
	K (Wm^{-2})	64	30	21	16	11
(24m)	M (ms^{-1})	4.12	3.2	2.86	2.64	2.39
	M (Wm^{-2})	57	28	20	15	11
	K (ms^{-1})	4.11	3.19	2.85	2.62	2.37
	K (Wm^{-2})	69	34	25	19	14
(30m)	M (ms^{-1})	4.22	3.35	3.01	2.79	2.54
	M (Wm^{-2})	60	31	23	18	14
	K (ms^{-1})	4.2	3.33	2.99	2.77	2.52
	K (Wm^{-2})	74	38	28	22	17
(36m)	M (ms^{-1})	4.3	3.48	3.14	2.92	2.67
	M (Wm^{-2})	63	34	25	20	16
	K (ms^{-1})	4.28	3.46	3.12	2.89	2.65
	K (Wm^{-2})	77	42	31	25	19

Figure 39 and Figure 40 also illustrate that Kota Bharu has the 2nd highest power density of 50 Wm^{-2} and 77 Wm^{-2} at 10 m and 36 m heights, respectively. Although Kota Bharu experiences the 3rd height wind speed (see Figure 37 and Figure 38), it has higher power density compared to Mersing (see Figure 39 and Figure 40). Most studies in the literature that analyse wind speeds in Malaysia without incorporating topographical characteristics conclude that the best site to harness wind energy is Mersing³⁶, while the results above show otherwise. Incorporating topographical characteristics at sites affect the amount of wind power available. In fact, Kota Bharu and Penang have the 2nd and 3rd highest PD among the sites assessed and Mersing is placed 4th.

These resultant power densities are different from those presented in Siti et al. (2011) and Islam et al. (2011). Siti et al. (2011) estimated that the PD for Mersing at 10m as 62 Wm^{-2} , while this study estimated it to be 44 Wm^{-2} . Islam et al. (2011) estimated PD for Kudat and Labuan at 100m as 67.4 Wm^{-2} and 50.8 Wm^{-2} , respectively, while this study estimated PD for Kudat to be 97 Wm^{-2} and Labuan to be 65 Wm^{-2} at the same height. Since these two studies did not take account of topographical conditions, the results are unreliable (Sveinbjornsson, 2013). Albani et al. (2013), and Albani and Ibrahim (2014) among others who use WAsP incorporating topographical data produce similar PD ranges for the sites as those presented in this study when landcover / roughness maps are not incorporated. However, when the landcover map got added to the vector map, the PD ranges are not the same.

A comparison of PD using vector map incorporating SRTM only, and a vector map incorporating both SRTM and landcover map is given in Table 6. From the table, it could be seen that the power density increases even after adding the landcover map in some instances. A common mistake is to assume that feeding in roughness values

³⁶ Sopian et al. (1995); Masseran et al. (2012); Akorede et al. (2013)

would reduce the PD. This notion is true if the roughness length of the majority areas surrounding the anemometer site, is higher than the airport (anemometer site). Airports with buildings take a roughness length of 0.02 and Miri has a vast area of flat smooth land, which takes a lower roughness value (0.0055) than the airport. Hence, PD increases when the landcover / roughness map is added to the SRTM. Since the wind speed in Miri is almost 4ms^{-1} (at 10m hub height), and given that Miri has vast swathes of flat land, it is an ideal candidate for consideration to install huge wind farms for grid connectivity. In contrast, densely populated sites like Kota Bharu, Mersing and eastern Penang Island do not have sufficient land to setup wind farms, despite having relatively better PD. It also needs to be noted that the western parts of Penang island has flat land areas to support wind farms.

Table 6: Comparison of GWC of Miri with and without Landcover Map

GWC with SRTM Only						
Z ↓	R →	0.00m	0.03m	0.10m	0.20m	0.40m
10m	U (ms^{-1})	3.55	2.53	2.2	1.97	1.72
	P (Wm^{-2})	42	17	11	8	5
18m	U (ms^{-1})	3.76	2.84	2.52	2.3	2.06
	P (Wm^{-2})	50	23	16	12	9
24m	U (ms^{-1})	3.87	3.01	2.69	2.47	2.24
	P (Wm^{-2})	54	27	19	15	11
30m	U (ms^{-1})	3.96	3.14	2.82	2.61	2.38
	P (Wm^{-2})	57	30	22	17	13
36m	U (ms^{-1})	4.03	3.26	2.94	2.73	2.5
	P (Wm^{-2})	60	33	24	20	15
GWC with SRTM & Landcover Map						
10m	U (ms^{-1})	3.97	2.83	2.45	2.2	1.49
	P (Wm^{-2})	58	23	15	11	3
18m	U (ms^{-1})	4.21	3.18	2.81	2.57	1.89
	P (Wm^{-2})	68	32	22	17	7
24m	U (ms^{-1})	4.34	3.36	3	2.76	2.09
	P (Wm^{-2})	74	37	26	20	9
30m	U (ms^{-1})	4.43	3.52	3.16	2.92	2.26
	P (Wm^{-2})	79	41	30	24	11
36m	U (ms^{-1})	4.52	3.65	3.29	3.06	2.4
	P (Wm^{-2})	83	45	33	27	13

Albani et al. (2013c) claim that Kudat has the highest power density of 21Wm^{-2} . This thesis also estimates similar power density when estimated with just the DEM. However, the power density increases for Kudat once the landcover map is used (similar to Miri).

4.4: Gross Annual Energy Production Estimates

The Annual Energy Production (AEP) estimates are influenced by the topographical condition (including elevation and roughness) at the site of the anemometer and the site where the wind turbines will be installed. Large differences in the topographical conditions between these two sites is likely to make prediction more difficult for the WAsP model as discussed in 3.6.3.

After assessing sites for dRIX, sites with high dRIX were eliminated even if they had high G-AEP. For instance, Langkawi which had PD and G-AEP similar to Mersing was dropped since it had a maximum dRIX of 38%. From the remaining sites, the top 5 were selected for micrositing. It should be noted that these selected sites have dRIX that are within WAsP's operational envelope.

The mean G-AEP estimations for top 5 sites is produced in Figure 42. The figure indicates that Penang has the highest mean G-AEP among the five sites. Utilising a 50kW Aeolos wind turbine with a hub height of 30m can yield mean AEP of 83.2MWh in Penang. The same turbine in Kudat can generate a mean AEP of 53.2MWh. From the figure it is also evident that higher rated wind turbines and taller hub heights yield higher mean AEP. Among the two, it is evident that the turbine capacity plays a larger role in influencing the mean AEP compared to the hub height. During commercialisation, it is therefore important to focus on the right power rating of turbines.

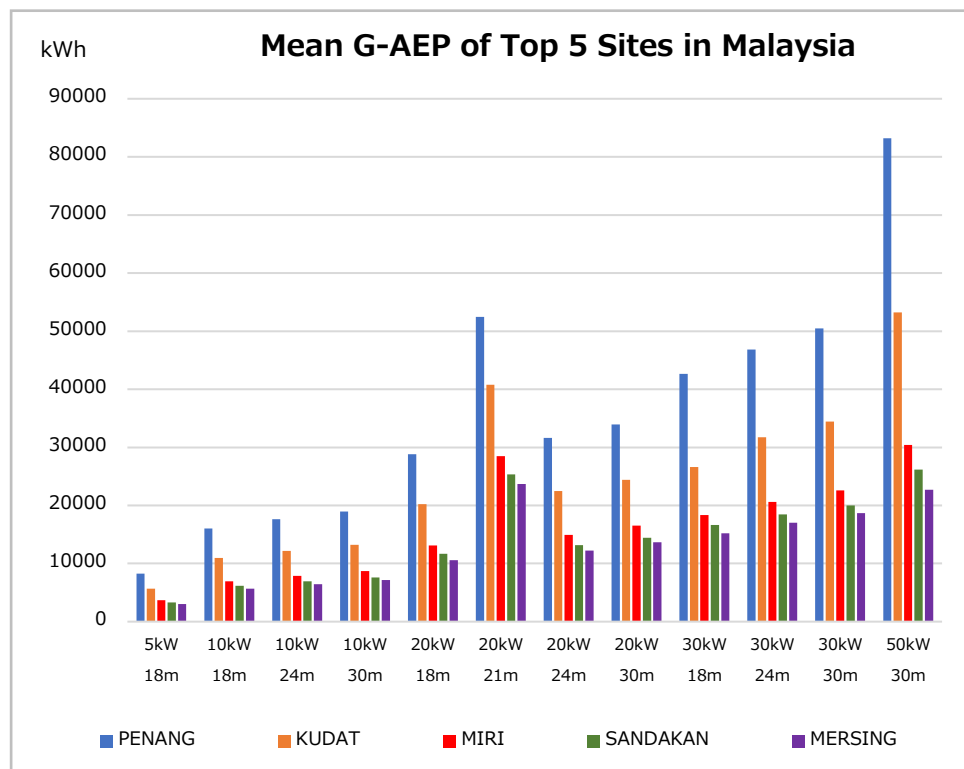


Figure 42: Mean G-AEP of Top 5 Sites in Malaysia

If the roughness maps were not incorporated and one were to purely analyse the PD, Kudat was ranked first and Penang Island was ranked third. Once the roughness maps were added, the PD for Penang was ranked first and Kudat was ranked second. This is similar to the mean AEP ranking and emphasises the importance of accounting for roughness maps to make precise estimates. Failing to incorporate roughness information is likely to oversee Penang as a potential site.

Many authors often describe sites or areas by wind class ranking, average wind speeds or PD. However, these studies fail to incorporate topographical information and assessing roughness characteristics of the anemometer site and potential wind farm site. Focusing solely on statistical values; such as, average wind speeds and PD could mislead the findings. Therefore, it is important to focus on AEP incorporating roughness maps because it is more robust.

4.5: Net Annual Energy Production Estimates

When analysing the wake loss (with the aid of RGs) for various sites in Malaysia, some higher AEP regions seem to have more wake loss due to the wind flow direction. Hence, turbines were not put at the highest gross AEP region shown in the resource grid. Instead, the turbines were placed, where the wake loss is less at the same time the AEP is closer to the highest gross AEP region. Initially, four different wind farms located in separate sites with different arrays was tested in Miri. Subsequently, the turbines were combined into one site for comparison of AEP and wake loss. The results of this exercise are presented in Table 6. For all micrositing exercises, the wake loss percentage was kept below 1% as possible.

Table 7: Output of a Wind Farm in Miri (30kW 30m Turbine)

	Net AEP of all Turbines (MWh)	Gross AEP of all Turbines (MWh)	Average Net AEP Per Turbine (MWh)	Average Gross AEP Per Turbine (MWh)	Wake Loss (%)
4 Wind Farms as 1 Site	1575.691	1576.367	23.172	23.182	0.04
4 Wind Farm Sites	1601.612	1602.282	23.343	23.352	0.0375

From Table 7, it can be seen that the change in wake loss is very small in Miri. This is because the vast land space available in Miri allows to place turbines 10 to 20 times their diameter apart. In other areas in Malaysia, where land space is smaller, such spacing would not be feasible. Hence, the wake loss could be higher in other areas.



Figure 43: Congested Kota Bharu

Google Earth Pro is extensively used in this study to evaluate the feasibility of the potential wind turbine sites. Although some places in Malaysia have very high potential to harness wind energy, setting up a wind farm in those places may not be practical. Place like Kota Bharu is a congested city and installing a wind turbine farm in a congested city is not feasible (Figure 43). Even though roof mounted turbines and micro / small turbines are developed for such congested sites, setting up wind farms to connect to the grid is not possible in those cities. Hence, after a thorough assessment with the help of Google Earth Pro, the site was dropped from micro-siting. For similar reasons, Mersing was also dropped from micro-siting.

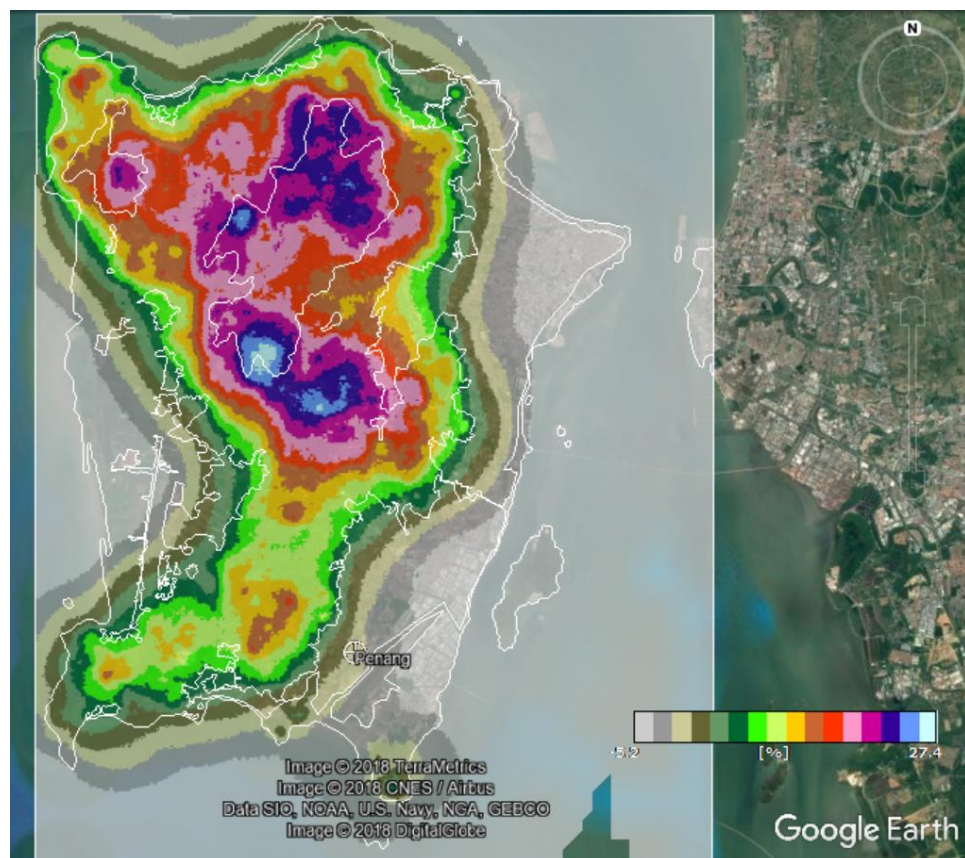


Figure 44: High Rugged Terrains (Penang)

Places like Penang and Langkawi demonstrate very high AEP when resource grid is used to estimate the AEP. However, those high AEPs are available at very high terrain, which are mostly not easily accessible. Additionally, the dRIX is very high in Langkawi and slightly more than 20% in Penang. One of the limitations in WAsP is

overestimation / underestimation due to high dRIX. Hence, it is vital to choose AEP with lower dRIX in order to estimate the AEP within WAsP's operational envelope to increase the precision of the estimation. Although Penang has a slightly higher dRIX (more than 20%), the site is not dropped from the analysis since the East of Penang island has a long flat empty land area (10 m elevation) with good wind potential (Figure 44).

The use of Google Earth Pro has made site assessment more convenient; in the past site assessment need more manpower and perhaps physical inspections to inspect the sites. However, exploring places like Miri (Figure 45) in east Malaysia (with vast flat lands) has become easier after Google Earth Pro became free to the public in 2015.

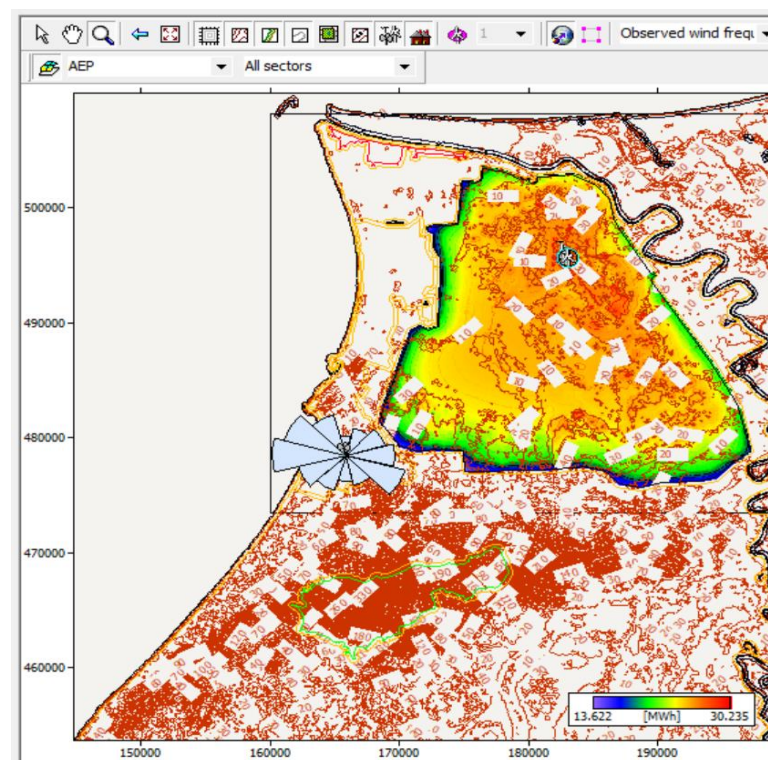


Figure 45: Vast Flat Land in Miri with an Elevation of 10m

Recent updates in WAsP allows to synchronise the resource grid and the vector map to Google Earth Pro. This synchronisation process helps to assure that the proposed wind farms are not created in

protected forest areas or high terrain areas (Figure 46). Moreover, the visibility of roads on Google Earth Pro, helps to assess the distance of the potential wind farms from residential areas. This is crucial as accessibility of the wind farms via road (which can be measured using the Google Earth Pro ruler tool) has implication for cost of maintenance. It is also crucial to have easy access to the sites for any repair work. When microsites, assessing the potential sites on Google Earth Pro helps to provide locations that are feasible rather than merely recommending turbines be installed on grids with high AEP values.

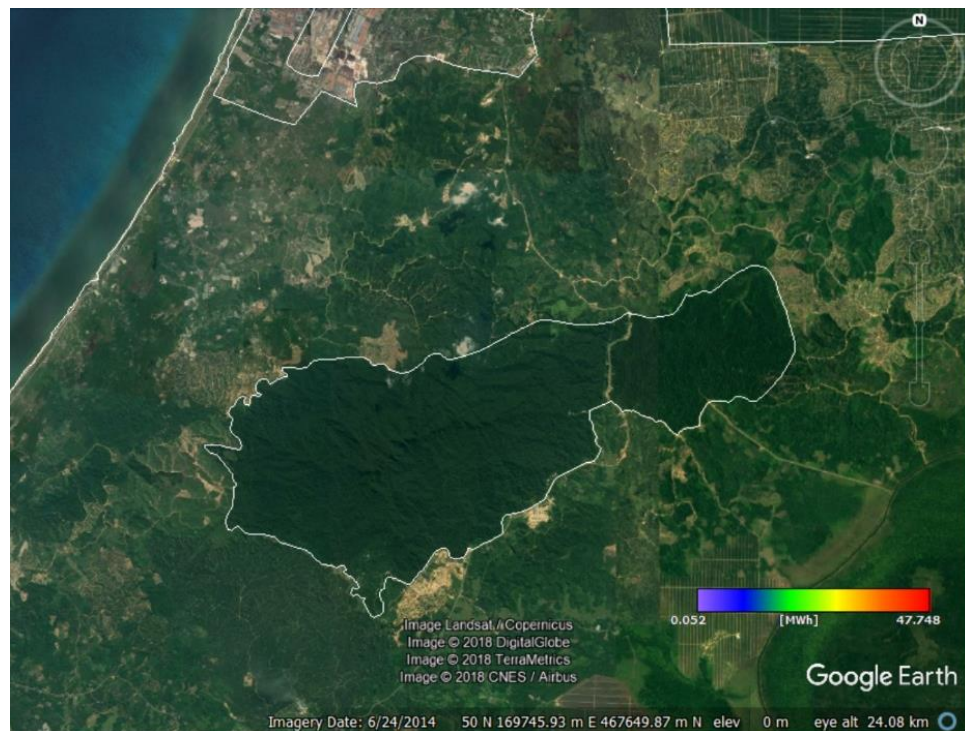


Figure 46: Forest Area is marked in Landcover Map

To summarise, in identifying potential sites to install wind turbines (microsites), it is important to account for dRIX, wake loss, space availability and access to potential wind farms. Results from this research indicate that some sites; such as, Kota Bharu and Mersing which have relatively high AEP may still not be ideal for microsites. This is because of the dense population and lack of flat terrain in these sites. In Langkawi, on the other hand, despite relatively high wind speed, the highly rugged terrain in lieu of the forest areas make

some parts of the island less suitable for setting up wind farms. Locations in the east in specific; such as Kudat, Miri and even Sandakan have large swathes of land that are ideal for setting up wind farms despite some of them having relatively lower wind speeds. Not checking for these land characteristics either physically or on Google Earth may mislead researchers to suggest installing turbines in locations that are not in fact available for setting up wind farms.

4.6: Economic Feasibility Analysis

The above sections have illustrated that at least some sites across Malaysia have the potential to harness wind energy in excess of 3 MWh per year, and in some cases, up to 85 MWh per year. It is important to then assess whether harnessing of such wind energy is economically feasible. The three key tools used for evaluating the economic feasibility of sites are the LCOE, NPV and IRR. A discussion of the results across these tools and sites is presented below.

To start off, the LCOE graph for Mersing is presented in Figure 47 as it is a good illustration of how use of different power rated turbines can lead to oscillation between economical and non-economical harnessing of wind energy.

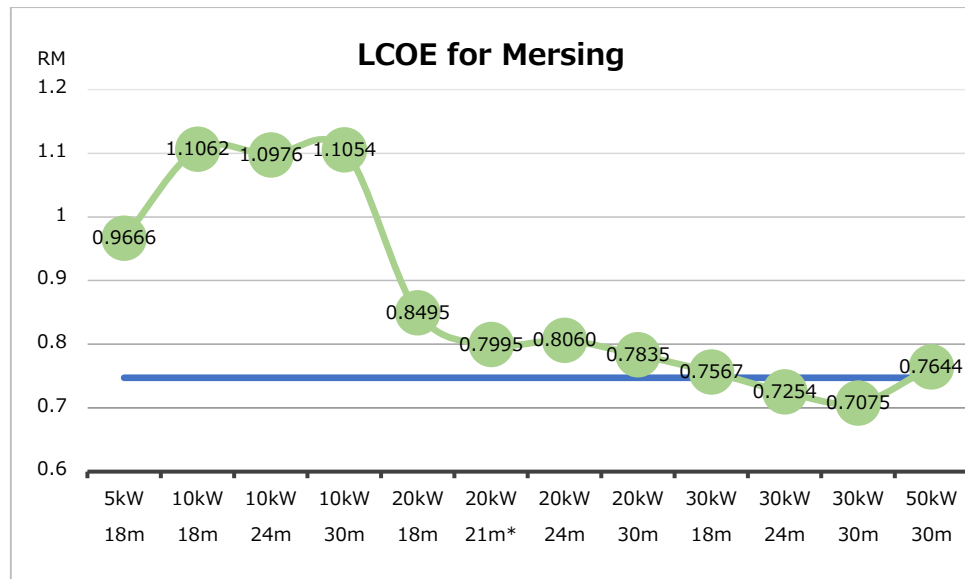


Figure 47: LCOE for Mersing

The green line in Figure 47, indicates that the LCOE for Mersing using wind turbines at different rated power and different heights. A 10kW Aeolos wind turbine installed at 24m height in Mersing costs RM 1.0976 per kWh of energy produced. Given that the FiT rate in Malaysia is RM 0.7474 (indicated by the blue line), energy produced from the above discussed wind turbine is not economically feasible, as it costs more to produce the energy than it would draw in as revenue. Therefore, from the above graph we can conclude that wind turbines of 30kW power rating and hub heights of 24m and 30m can feasibly harness wind energy in Mersing.

However, for turbines with lower rated power, it is not economically feasible. In fact, as Valentine (2011) highlights, there seems to be a quadratic relationship between rated power, height and economic feasibility. The LCOE for 10kW turbines are higher than that of 5kW turbines, and the LCOE seems to increase as the height increases (despite higher energy production). However, for turbines rated 20kW and higher, the LCOE decreases as hub height and rated power of turbines increase. The lowest LCOE in Mersing is experienced by 30kW turbines installed at 30m hub heights. It generates RM 0.0399 of profit (RM 0.7474 – 0.7075) per kWh of energy produced.

In Kudat all wind turbines explored in this study operate at LCOEs below the FiT (Figure 48). This; therefore, presents a case to install small wind turbines to harness energy. Further, the 50kW turbines at 30m hub heights have the lowest LCOE. LCOE for the hub height of 24m and 30m for the 20kW is almost the same. Similar pattern can be seen for the hub heights of the 30kW turbine.

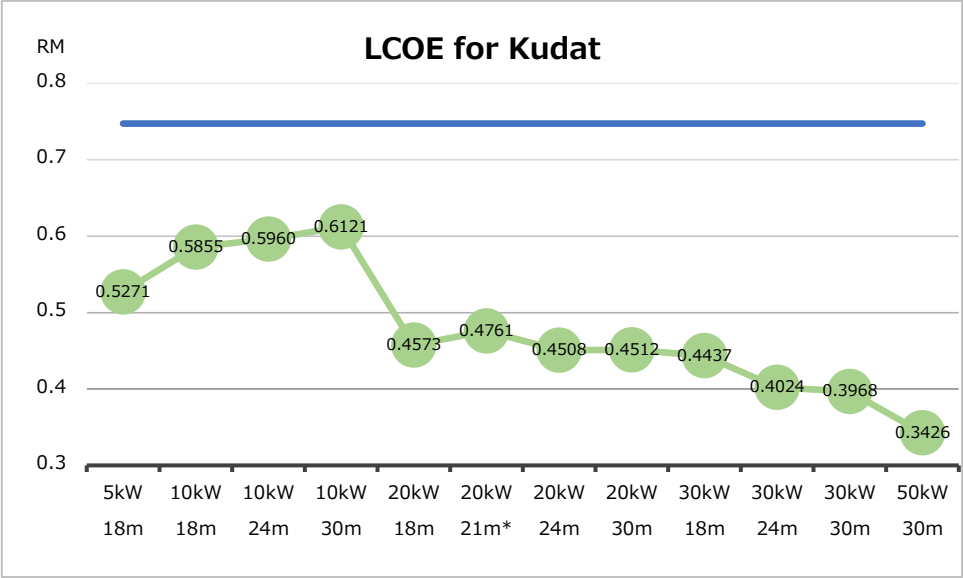


Figure 48: LCOE for Kudat

Figure 49 illustrates that only turbines rated at 30kW and higher generate positive NPVs in Sandakan and are therefore economically feasible. A 30kW Aeolos wind turbine installed at a hub height of 24m generates RM 6,117.27 over 20 years in net revenue. Higher rated turbines at higher hub heights are likely to generate larger positive NPVs (up to an optimal turbine power capacity). To make the NPVs comparable, it is important to account for the cost of the turbines and hubs. Two ways to do these are the discounted ROI and IRR.

The discounted ROI for Sandakan is also presented in Figure 49. The findings indicate similar results to those identified via LCOE (not presented here for brevity). While the discounted ROI values seem small -3.5% to 1.5%, it is important to note that the discounted ROI already factors in the cost of borrowing (the commercial interest

rate). Therefore, the discounted ROI presents surplus earnings after factoring in cost of borrowing and inflation.

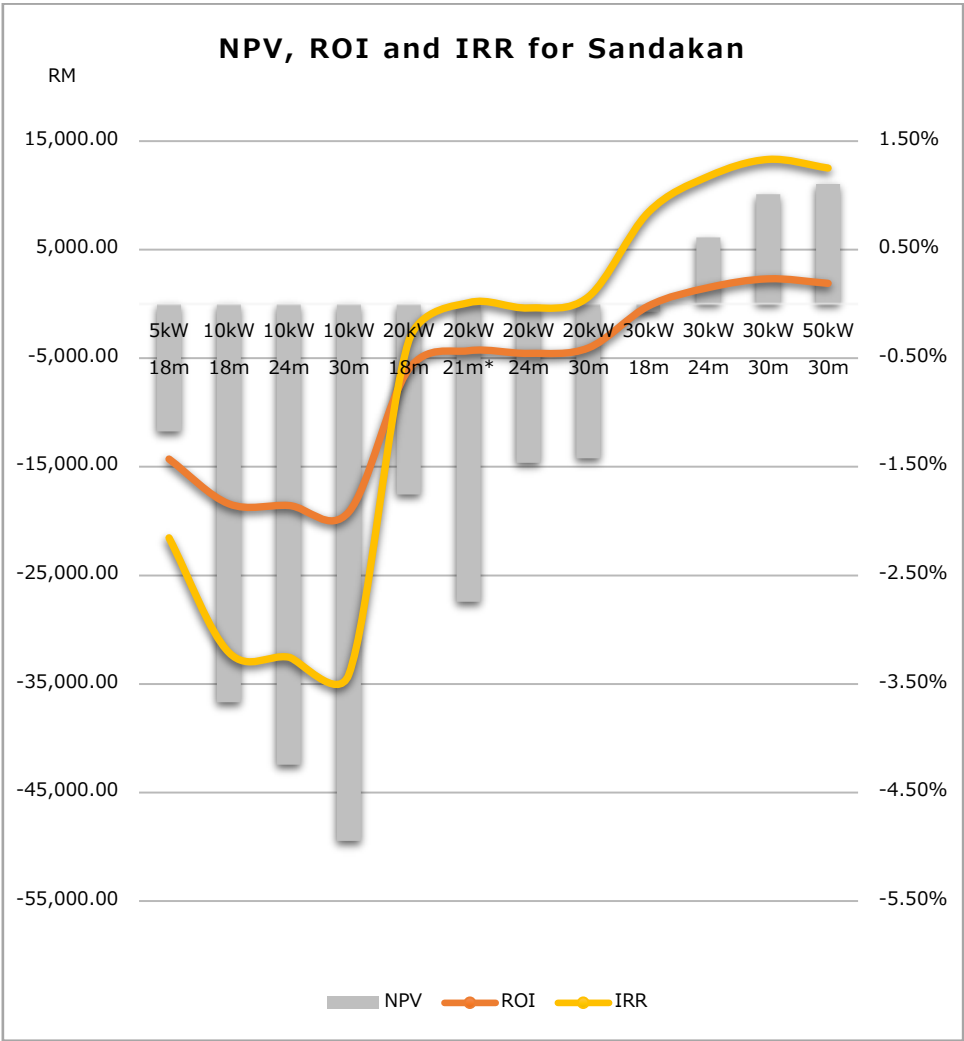


Figure 49: NPV, ROI and IRR for Sandakan

Additionally, a 50kW turbine installed at 30m hub height can produce a return of about 1.25% in Sandakan. Given that the real interest rate in Malaysia (for 2017) is 0.88%, the turbine produces a premium of 0.37%. For 5kW and 10kW turbines, the rate is negative, which indicates that investments in these turbines will only be productive if the real interest rate is negative (i.e. instances where the inflation rate is higher than the interest rate).

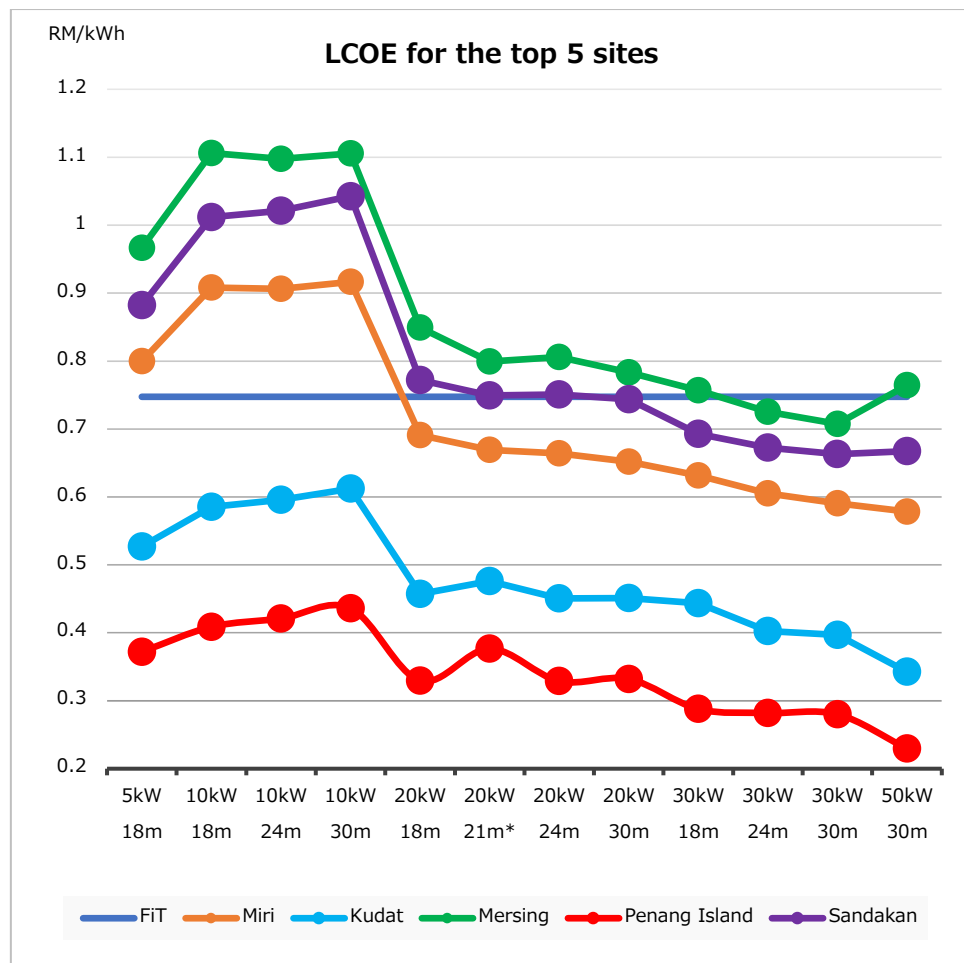


Figure 50: LCOE for the Top 5 Sites

The LCOE and discounted IRR for the five identified sites is summarised in Figures 50 and Figure 51 respectively. From both figures, it is evident that Penang and Kudat have the highest economically feasible potential to harness wind energy, as they have the highest returns on investment. Further, Penang, Kudat, Miri and Sandakan are able to profitably harness wind energy for 30kW and 50kW turbines, while Mersing is able to do so for 30kW turbines only (Figure 50). From both Figures 50 and Figure 51, it is also evident that wind turbines with higher rated power installed at higher hub heights are more profitable than lower power rated turbines and turbines installed at lower hub heights.

Among a handful of studies that used WAsP in Malaysia and conduct economic feasibility analysis, Albani and Ibrahim (2014) are among the closest to this study. The AEP estimates in this study are likely to

be overestimated as the study applies a blanket roughness class value for each site. In reality, these sites do not represent flat smooth surfaces as Albani and Ibrahim (2014) claim (See Figure 9, for instance).

Despite these drawbacks in their study, Albani and Ibrahim (2014) is the only study to present comparable NPV and IRR computations with a WAsP based AEP computation. In their economic feasibility analysis, the authors claim that turbines less than 100kW cost between USD 3000 to 8000 per kW of installed capacity. Their estimates are based on US and European large turbines and do not reflect the cost of commercially available wind turbines in Asia. For example, the European wind manufacturer, Aeolos, has a different pricing strategy for Asia using their production and distribution facilities in China³⁷. They also used arbitrary assumptions on the power curves of the turbines. Further, they also do not account for transport cost, maintenance cost, etc. Hence, the economic feasibility analysis from Albani and Ibrahim study may not represent empirical relevance.

While Albani and Ibrahim (2014) estimate that the cost of electricity in Mersing and Kudat are similar and are likely to be about 85 to 87 cents Malaysian per kilowatt, this thesis estimates the cost to widely vary between the two sites. The LCOE for Kudat is only between 35 to 60 cents Malaysian per kilowatt and that for Mersing is RM 0.70 to RM 1.10 per kilowatt. The unrealistically high characterisation of wind turbine costs in Albani and Ibrahim's study is likely to have depicted the higher FiT requirement.

Moreover, Albani and Ibrahim estimated the cost of harnessing wind energy in Langkawi to be between RM 1.15 to 1.28 based on WAsP

³⁷ In fact, China is now one of the largest wind turbine manufacturers and provides a market for competitively priced wind turbines that are suitable for using countries like Malaysia (Aeolos turbines are already used in Malaysia and other parts of ASEAN).

AEP predictions. Even though Langkawi has huge potential, not accounting for the high dRIX in Langkawi would lead for an overestimation of AEP. Given that dRIX is way higher than 20%, AEP estimates for Langkawi are unreliable as they are beyond WASP calculation envelope and require WASP CFD computations. For these reasons, this thesis did not include Langkawi in economic feasibility estimates.

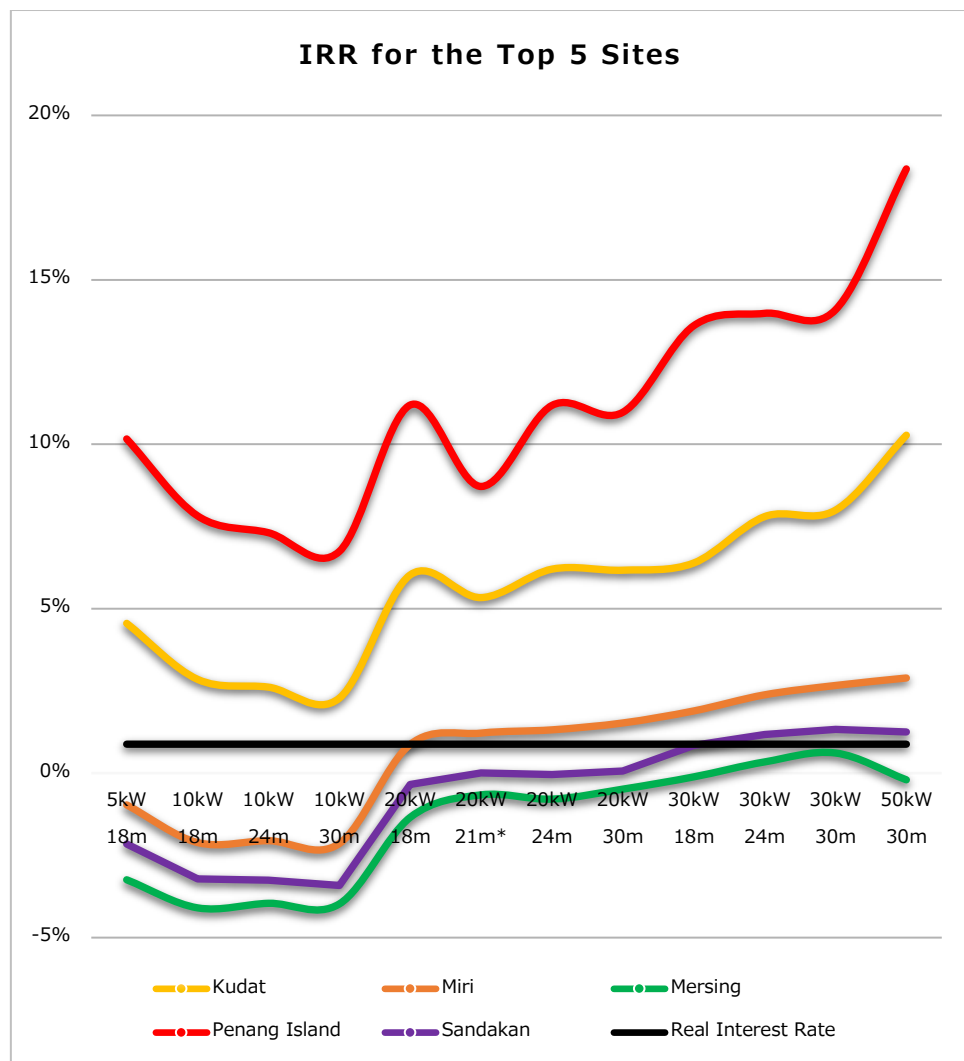
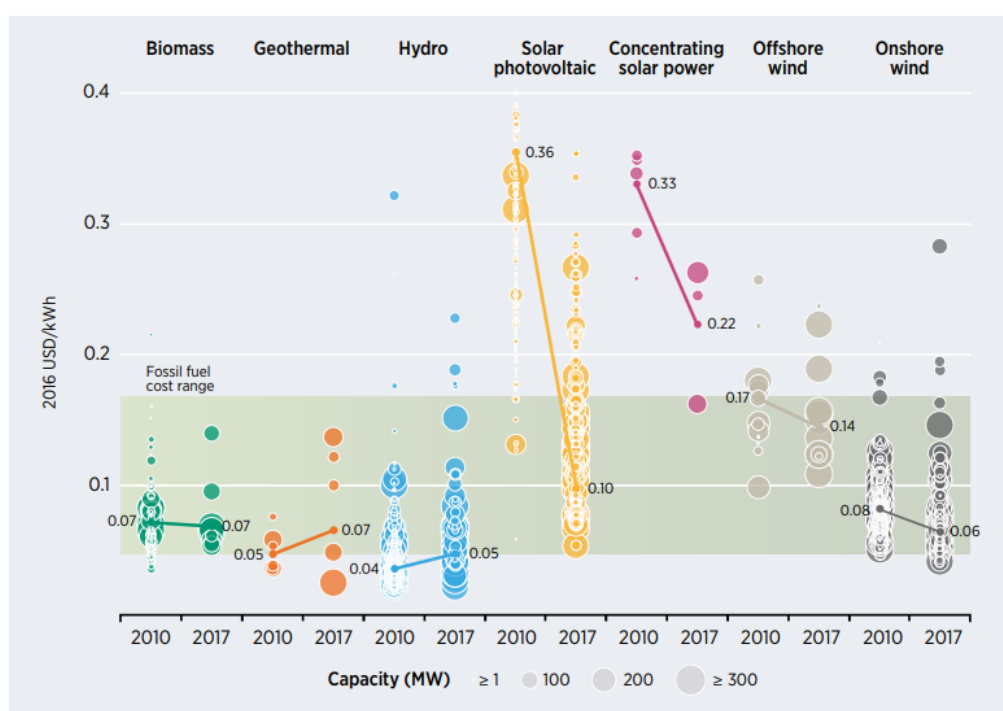


Figure 51: IRR for the Top 5 Sites

The LCOEs for the top 5 sites (Figure 50) also are comparable if not marginally cheaper than solar energy applications for Malaysia as estimated by Baharum et al. (2018). The authors estimate that the LCOE (MYR/kWh) for solar energy production in Malaysia is RM 0.70 in 2015. Estimates in our study indicate that the LCOE for the top 5

sites with 30kW turbines is likely to be lower than RM 0.70. In fact, for Penang and Kudat the LCOE is low as 30-40 cents (Figure 50). Baharum et al. (2018) further estimate that the LCOE for solar is likely to decrease to RM 0.49 by 2020 given declining prices of solar systems. Given the reducing cost of wind turbines, there will be similar reductions in LCOE for wind power generation. A global study by IRENA (2018), indicate that onshore wind energy is cheaper than solar and be comparable to biomass and hydro (Figure 52).



Source: IRENA Renewable Cost Database.

Note: The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE value for plants commissioned in each year. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

Figure 52: Comparison of LCOE for RE at a Global Scale

Findings from this chapter indicate that turbines rated at 20kW or higher are able to harness wind energy in an economically feasible manner. However, there is also some indication at certain sites that turbines rated 50kW or higher may produce lower returns than 30kW rated wind turbines. Therefore, among the turbines that are able to produce positive returns across these sites, the 30kW rated turbine can be seen as optimal. Further, sites in Penang Island, Kudat and

Miri are identified to have the potential to harness wind energy with commercially available wind turbines and being able to make profitable returns over a 20-year period at the prescribed FiT rates. The cost of producing electricity at these sites with 30kW rated wind turbines is found to be even cheaper than solar energy.

For the past few decades, most studies on wind energy in Malaysia have been focusing merely on statistical analysis and/or have not conducted robust analysis of available AEP and concluded that wind energy is not suitable for Malaysia. The economic feasibility analysis in this chapter illustrates that there is a huge potential to harness wind energy in Malaysia in the sites identified above. Therefore, commercial investors and policy makers may further explore investment in wind energy as alternative source of renewable energy, given that the LCOE is lower than FiT in several sites.

CHAPTER 5: DISCUSSION

This chapter evaluates the robustness of the results presented in the previous chapter. The first sub-section of the chapter discusses the sensitivity of the economic feasibility computations to deviations in AEP. The second sub-section highlights the novelty of this study, in particular, the significance of the results. The third and final sub-section evaluates the limitations of the results.

5.1: Sensitivity Analysis of Economic Feasibility

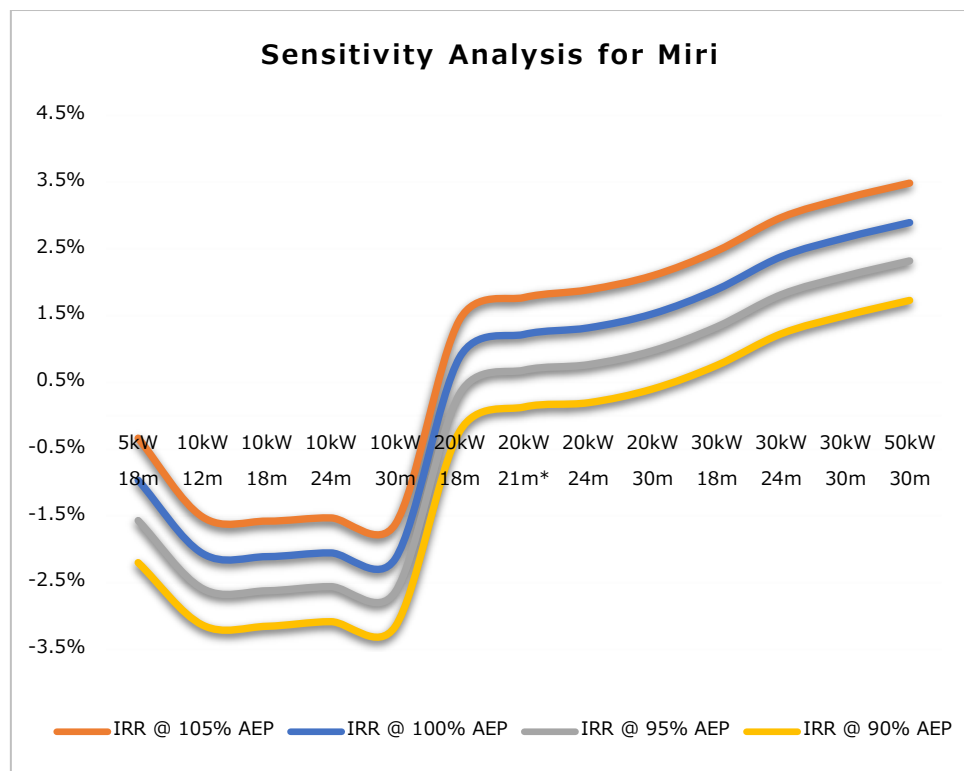


Figure 53: Sensitivity Analysis for Miri

To account for possible deviations in actual AEP, a sensitivity analysis is conducted to ascertain the changes in the net annual returns (using IRR) in response to changes in AEP. These could be due to change in climatic conditions, mechanical failures, data issues etc. (Ozerdem, 2006; Mortensen, 2010). A sensitivity analysis for Miri is shown in Figure 53.

Three different scenarios of fluctuations in energy production are evaluated at +5%, -5% and -10%. The sensitivity analysis illustrates that the lower AEPs (at 95% and 90% of the predicted AEP) lowers the IRR significantly. For a 10% drop in AEP the IRR falls by about 1.5 percentage points (or about half of the full AEP IRR value). On the other hand, if the AEP were to increase by 5%, there is evidence of increase in the IRR by about 0.5 percentage points (or 17%). Given that section 3.7 of the chapter highlights that WASP possibly underestimates AEP (albeit marginally), any increases in AEP is likely to make wind energy much more attractive to investors.

5.2: The Novelty of this Study

Since the study has used (i) topographical data for wind analysis, (ii) robust landcover map, and (iii) google earth to identify locations for the installation of wind turbines. Hence, this study can be used as a preliminary reference for future analyses by researchers and commercial users.

Wind energy has been discarded as a non-suitable renewable energy source in Malaysia. Most studies in Malaysia did not use the topographical information for wind resource analysis and have merely done statistical analysis as stated in the literature review. Topographical analysis is crucial because there are sites that exhibit good wind speed but are surrounded by dense forest or rugged terrain (RL values are high). In such cases, not including topographical data would overestimate the wind resource available at the site as discussed in the methodology and literature review chapters. Even, when the topographical information is not used for power estimation in previous studies, the wind speeds and power were estimated at 10m heights. These estimations at a 10 m height from the sea level do not account for reality, i.e. that the land is not a flat 10 m surface. Hence, estimating wind speeds at 10 m would

lead to the conclusion that the wind speed is not sufficient for harnessing energy.

Not only is topographical information used in wind resource analysis, but also landcover maps with precise RL values are used in the calculation to ensure that the N-AEP generated is not overestimated. There are only a handful of studies that used WAsP in analysing wind potential in Malaysia. However, as discussed in the literature, these studies used RL value of a smooth surface to the entire vector map and estimated the power availability in Malaysia. In this study, a precise landcover map is integrated with appropriate RL values to estimate the wind potential in Malaysia.

Moreover, Google Earth (or other GIS software) was not used to make decisions in the handful of studies that argued that Malaysia should consider wind as the renewable energy. As mentioned in the literature, Albani et al. (2013b) proposed wind farms over protected forest area. Thus, utilising Google Earth becomes essential in micrositeing. Moreover, utilising Google Earth helped to conclude that Mersing and Kota Bharu are not suitable for wind turbine installation, though they are in the top 10 sites in Malaysia in terms of wind speeds. This study identifies locations that are unsuitable for harnessing wind energy due to complex terrain, topographical conditions, or inadequate space to install turbines etc. Thus, further analysis is not feasible in those locations even if alternative methods to this study are used. Eliminating such sites that do not have the potential to host wind farms despite the wind speeds being good helps future researchers and commercial enterprises to focus their resources on sites with the potential to host wind farms.

Lastly, the WAsP model follows a similar approach used for commercial projects. Since there are many commercial projects that have used WAsP as discussed in Chapter 2 and Chapter 6, the estimates from this study are more empirically relevant compared to statistical models that are sparsely used by the industry. This study

also tested the sensitivity of the projects by forecasting scenarios of producing lower AEP, and yet demonstrated that considering wind energy is still profitable at certain sites even if the AEP turns out to be about 10% lower than predicted by the study.

5.3: Limitations

The results in this study are affected by certain limitations:

(1) The results in this study are affected by the NCEI and SRTM data used in this study. While extra care has been taken to correct errors identified with met station locations (in NCEI data) and roughness line errors (in SRTM data), any unidentified errors with the data are likely to impede the conclusions drawn in this study.

(2) The WAsP modelling employed in this study is likely to overestimate wind power in highly rugged terrain. Sites where dRIX was more than 20% were avoided; however, there is still likely to be some (minimal) deviation in the power estimations. To account for these, a sensitivity analysis with a potential for up to 10% loss in power was incorporated in 5.1.

(3) The roughness length assignment and micrositing procedures are based on data captured in Google Earth Pro, the timeliness and accuracy of these data also affect the conclusions drawn. Google Earth Pro data for some sites is about 2 years old. This may pose some restrictions on the inference drawn here, if tall buildings or man-made structures inhabit the proposed turbine wind farm sites.

(4) Micrositing in certain areas was impeded by the lack of anemometer sites in areas closer to suitable sites for setting up medium to large scale wind farms. New met stations or anemometer sites away from urban areas will likely improve estimations.

(5) The selection of wind turbines in this study is partly also based on availability of power curve and cost data for turbines. While there may be other turbines that cost less per kWh of wind energy harnessed or those that harness wind energy more efficiently, lack of information³⁸ on them impedes their utilisation in this study.

³⁸Turbine manufacturers do not make thrust curves available unless the turbines are ordered from them.

CHAPTER 6: CONCLUSION & FUTURE WORK

This thesis studies the potential to harness wind energy in Malaysia using robust estimation techniques. It contributes to the literature by improving the AEP estimation using user-fed roughness data and micrositeing procedures that are more empirically relevant.

NCEI dataset are more reliable since they are derived from the MET data provided by MMD. PD calculations using NCEI data for 16 years and 36 stations indicate that most sites in Malaysia have PDs more than 20 Wm^{-2} , at 10m hub height. Sites such as Kudat, Mersing, Kota Bharu, Penang and Langkawi have higher power densities among other tested sites. However, most of these sites experience wind speeds of less than 3ms^{-1} across 60% of the time measured at 10m hub height. Given that most commercially available wind turbines have cut-in speeds of 3ms^{-1} , statistical analysis of wind speed and PD indicate that the ability to harness wind energy in Malaysia is low when not accounting for topographical information.

Refined PD and AEP are calculated at several sites using topographical data from SRTM Maps and user-fed roughness map. These refined results indicate that Kudat and Kota Bharu have power densities more than 50Wm^{-2} , and at least 6 more sites have power densities above 40Wm^{-2} at 10m hub height. Therefore, it can be concluded that there is high potential to harness wind energy in Malaysia. PDs estimated at roughness class of 0.03 (which is the default roughness) indicate Kudat can generate over 30Wm^{-2} , while the next top four sites can generate between 15 and 30Wm^{-2} .

Given errors in the SRTM Maps, this study corrected these errors pertaining to sites in Malaysia prior to its use. Studies that do not make these corrections are likely to produce biased estimates. It should be noted that WAsP and other wind engineering models assign higher power production to more elevated sites. For instance, forest areas (which are highly elevated) will record higher power production

capabilities. However, thick forests reduce wind flow and in fact record lower power production capabilities. Not accounting for these roughness features and landcover is likely to produce estimates that are not useful for micrositing exercises. Therefore, this study incorporates user-fed roughness classes to areas such as forests, densely populated housing areas and even flat land to ensure that more robust AEP estimates are produced.

One of the key contributions of this study is the more precise AEP estimations accounting for landcover maps and correcting for errors in SRTMs. Previous studies on Malaysia that have not made corrections for such features had partially led to failed attempts in setting up wind turbines; such as, in Pulau Perhentian (Ho, 2016).

Aeolos wind turbines in the range of 5kW to 30kW power rating indicate that, AEP increases with hub height and power rating in an almost linear fashion. Larger wind turbines are not used in this study due to the high cost and high cut-in speed. Penang Island shows higher AEP in these estimations even compared to Kudat. The higher AEP in Penang can be attributed to the terrain in Penang. These higher terrains in the Centre-West coastal areas of the island enables a higher wind flow and thus higher power generation. Places like Miri show potential of harnessing good wind energy across large swathes of land.

Micrositing exercises indicate the importance of analysing the terrain and obstacles of each site. Access to wind farms further away from housing areas makes the cost of maintenance and even connectivity to power utilisation more expensive. Access to road networks is also vital for the feasibility of efficiently maintaining wind farms. Additionally, when considering sites to install turbines, it is important to take note of land area that is sufficient to house at least 50 turbines to make the farms economically feasible. Taking these factors into account when installing wind turbines, makes some sites such as Langkawi with large forest areas less feasible than sites like

Miri. Some previous studies have recommended sites that are in the middle of dense forests and dense cities without having checked if the lands are in fact suitable for installation. Therefore, another important contribution of this study is that the sites proposed are suitable for setting up wind farms.

Economic feasibility analyses illustrate that only wind turbines rated 20kW and higher can profitably harness wind energy in Malaysia. In some sites like Mersing, only 30kW power rated wind turbines can achieve this. The levelised cost of energy in Penang, Kudat and Miri are lower than the FiT for most applications, and therefore justify investment. The IRR in these sites is also higher than the effective real interest rate, which indicates that harnessing wind energy in these sites is able to produce profitable returns even after accounting for cost of borrowing. Most previous studies do not account for the cost of borrowing and make unrealistic assumptions or do not take account of transportation and maintenance costs. By accounting for these parameters, this study contributes to producing more robust feasibility analysis that would help commercial investors to make informed decisions.

The results indicate that Aeolos 30kW wind turbines installed at 30m hub height produce the most economically feasible returns when harnessing wind energy in Malaysia. The returns to installing wind turbines in Kudat and Penang are positive for all wind turbines. Harnessing wind energy in these areas produces LCOEs that are below the FiT and IRRs that are higher than the real interest rate.

6.1: Policy Implications

Findings from this study indicate that there is potential to economically harness wind energy in some sites in Malaysia. Malaysia, which has been lagging its regional peers Thailand, Vietnam and Philippines in wind energy adoption (Ho, 2016), may

want to explore at least the top 3 sites. Thailand, which has similar mean wind speeds of no more than 3ms^{-1} , has wind turbine systems ranging from 10kW to 2.3MW and is ranked as the top wind energy producer among ASEAN nations (Major et al., 2008; Chingulpitak and Wongwises, 2014; Sawyer et al., 2018). In 2018, Thailand had an installed wind capacity of 1,189MW (Sawyer et al., 2018). Given similarities in wind, climatic and terrain profiles; it may be useful for Malaysia to study Thailand's success in harnessing wind energy.

Hence, given that wind is a cleaner energy source and the cost of wind turbines are on a significant decline, the Government of Malaysia, in particular the energy commission, may want to consider introducing FiTs for Wind power (at least similar if not higher to solar power). The government may also wish to actively support wind power systems by initiating state-led or public-private partnership (PPP) projects. Such initiatives on a large scale may help reduce the cost of these projects and make harnessing wind energy profitable even in other sites³⁹.

Private investors may also wish to explore PPPs as a potential avenue to explore wind farms in Malaysia with positive returns in an industry experiencing declining costs. This study provides investors details on the highest potential sites. It also informs investors locations within those sites that could yield the best returns given space availability, access to sites and available power⁴⁰. While this study demonstrates Aeolos wind turbines can profitably harness wind energy, investors may wish to explore other small wind turbines as well, if data pertaining to other wind turbines is available.

³⁹ Estimations of economic feasibility using dealer prices for AEOLUS wind turbines return profits in all 5 sites.

⁴⁰ Data and results from this study for the top 5-sites are available upon request to assist commercial explorations at these sites.

6.2: Future Work

This study has identified sites that are suitable and not suitable for wind energy projects in Malaysia with the aid of robust estimation techniques and the use of GIS software for micro-siting. For example, while Mersing and Kota Bharu have been identified as being among the top 10 sites in Malaysia for wind energy potential in previous studies, our study illustrates that these sites are not suitable for wind energy projects due to lack of space to set up wind farms. Even if alternative methods are used, these sites would not be ideal sites for wind energy projects due to lack of space. Hence, future researchers and commercial enterprises can focus their resources on exploring sites with the potential to host wind farms and not deplete their resources on sites such as Mersing and Kota Bharu that are severely congested.

While significant effort has been dedicated towards identifying suitable sites for wind turbine installation, there is still potential for improvement. To understand these possible improvements, it is important to first focus on the different elements of this study. This study encompasses several independent but interconnected elements as part of the model in estimating the availability of wind resources. The resultant model is comprised of (i) NOAA time series data of wind speed and direction alongside the data pertaining to the locations of meteorological stations, (ii) Digital Elevation Maps of sites in Malaysia from the SRTM project, (iii) user-created landcover maps, (iv) resource grids that take account for micro-siting (v) wind turbine generator files, (vi) wind farm layout files and (vii) user-formulated spreadsheet that computes the economic feasibility of harnessing wind energy using different turbines and different hub heights.

Minor Elements of Focus for Future Work:

The wind speed and wind direction files were reconstructed from the raw data files extracted from NOAA. The data required extensive cleaning: removing blanks, rearranging the columns, combining the hourly data to create a single file with 10-year data. Therefore, researchers working with this data do not need to work on cleaning or improving these files. However, researchers may update the data to include more recent years when they become available. Such addition needs to carefully account for data cleaning to ensure consistency. The MET station files are created using the latitude, longitude and elevation from NOAA and require no further update (unless the data collection sites are changed). Moreover, studies that are able to install their own anemometers before conducting the micro-siting exercises in areas such as Penang, Kudat and Miri may provide more nuanced findings.

Errors in the DEMs were rectified as discussed in Chapter 3. Landcover maps were created manually on Google Earth. It was created as precisely as possible with over a million points per site to account for structures, obstacles and other topographical information. Landcover maps were not only created as precisely as possible, the values assigned to various landcovers (roughness) were audited for accuracy. Two complex terrain maps were sent to researchers at DTU (Denmark) for verification and advice. These measures ensured that the integrity of the landcover maps met stringent requirements to be used for N-AEP estimations. In the future, researchers may modify existing landcover maps to account for new information. For example, a dense forest may now be less dense due to cutting down of trees for new construction, vegetation, natural reasons, etc. Moreover, there could also be new constructions in bare lands, increase in density of locales, etc. In these efforts of updating the landcover maps, crowdsourcing may prove important. Crowdsourcing helps in keeping the database up to date and also allows for independent verifications by third parties.

Although the software could run the estimation once the model is built, the crucial part comes down to human ability. Human error in identifying the roughness class could cause a deviation in wind power estimation. As discussed in Chapter 2, some studies gave values of smooth surface areas for higher RL class locations. A peer reviewed crowdsourced database engaging the academic, industry and state agencies would eliminate guesswork, distortion and potential for errors. This helps with polishing the estimates of wind resource availability in Malaysia and ensuring the correct sites for wind turbine installation are identified.

The resource grid is created with high resolution such that each grid is 50 m x 50 m in size. It is layered on wind turbine hub height and when different turbines are used, WAsP automatically recognises the difference and asks if a change in the height of the RG is required as the hub height. The RG will then compute the N-AEP for each grid at that particular height. This study already identified the optimal locations for micro-siting based on structures visible on Google Earth. In the future, researchers may identify different locations on the already computed RG if new structures were to emerge in the locations proposed in the study.

Researchers in the future may also consider developing an interactive map that can be created using the results of this study. This would enable the wider public, commercial users, and researchers to engage with the wind resource availability in Malaysia. The following section highlights major elements of focus.

Major Elements of Focus for Future Work:

Researchers in the future can focus on three major elements to enhance the understanding of the potential to harness wind energy in Malaysia: turbines, CFD and developing suitable wind turbines.

(i) Turbine Selection:

The turbines employed in this study were chosen based on two criteria: (1) turbines with operating speeds that suit Malaysia and (2) availability of turbine datasheets (especially thrust curves and prices). Only a few turbines were tested in this study due to a lack of data sheets availability. Researchers in the future could test for different wind turbines if datasheets are available.

To test different turbines, researchers / commercial operators have to just create a new Wind Turbine Generator (WTG) file in WAsP with the data and replace the existing WTG in the model or change the existing WTG files with the new data file. The wind farm files already identify the ideal locations within a site at which wind power potential is highest. Therefore, researchers just need to modify the WTG and WAsP will then automatically estimate the N-AEP based on the model designed in this study. The height of the resource grid has to be changed to the same height as the hub height to estimate the N-AEP available at the height for a specific wind turbine.

The economic feasibility estimations have also carefully accounted for important parameters such as maintenance cost, transportation cost, and salvage value. It also accounted for economic parameters such as interest rates and inflation. Subsequently, researchers can evaluate the economic feasibility of the new turbines by modifying the spreadsheet with integrated formulas to arrive at NPV, IRR, and LCOE. For new turbines, researchers have to just insert the N-AEP estimates from WAsP and edit costs values for the turbine (the cost of the turbine, and the hubs). The spreadsheet would then automatically compute the NPV, IRR and LCOE.

It is possible to expand the application of this research to other commercially available wind turbines. In order to enable this, the 'Wind Farm' files for the locations in Malaysia and the economic efficiency tabulation spreadsheets would be made available via an online repository. These measures allow for wider adoption of the

models presented in this study and enhance the approach towards identifying sites and turbines that are suitable for harnessing wind energy in Malaysia.

(ii) Estimating Wind Power in Rugged Terrains:

The WAsP IBZ model used in this study is similar and superior to the CFD model for dRIX less than 20% (see, WAsP, 2017). However, for some applications, such as, rugged terrain with dRIX more than 20%, the WAsP CFD model may prove more efficient. Studies that are able to employ CFD models in their calculations may be able to identify air flow dynamics more accurately and the effects they have on the wind power generation in rugged terrain areas, like Langkawi. Langkawi is an island and has relatively high wind speed and power. It also has vast areas to place wind turbines. Although the WAsP IBZ model can run the estimation of N-AEP, due to the high dRIX at some places in Langkawi, CFD calculations are needed. CFD calculations are quite expensive and not necessary for sites with dRIX less than 20%. In the future, researchers may conduct CFD calculations to explore the wind resource at sites with high dRIX (i.e. $dRIX > 20\%$); such as, Langkawi.

(iii) Developing New Turbines:

As mentioned in the background section of the study, Europe is building bigger wind turbines that are suitable for high wind speeds prevalent in the region. Even in Asia, the major wind turbine manufacturers and projects mostly associate with high-power rated wind turbines. When there is no necessity, the major manufacturers may not focus on developing small wind turbines. Although the small power rated turbines tested in this study are suitable (i.e. financially feasible) to harness wind energy in Malaysia, the country may have to consider developing their own wind turbines to optimise the harnessing of the prevalent wind speeds in this part of the world.

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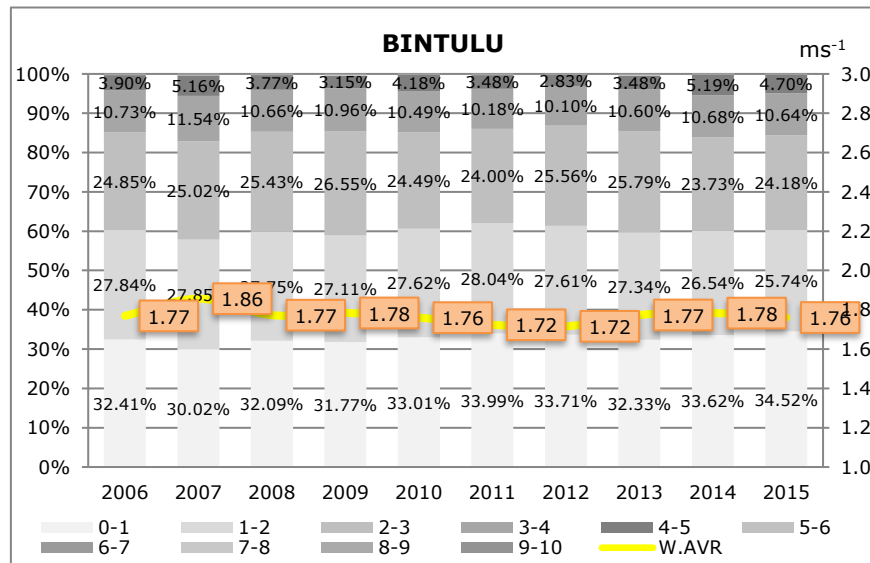
⁴¹ <https://www.pfpi.net/781>

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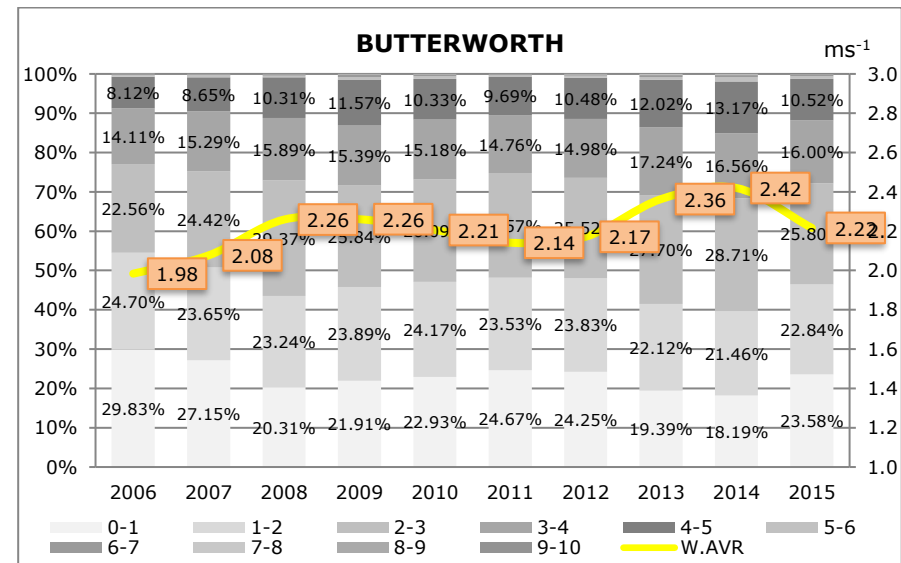
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APPENDICES

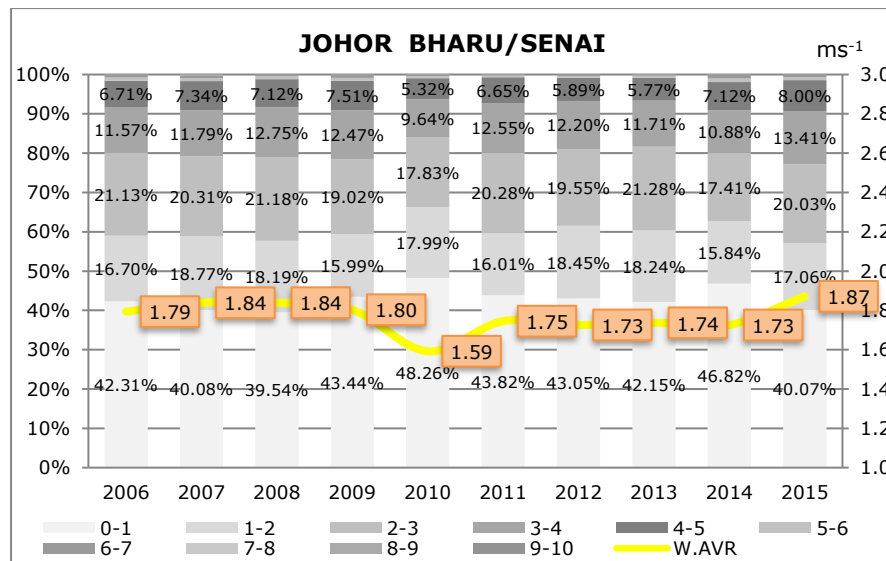
Appendix – A: Descriptive Statistics of Wind Speed by Stations



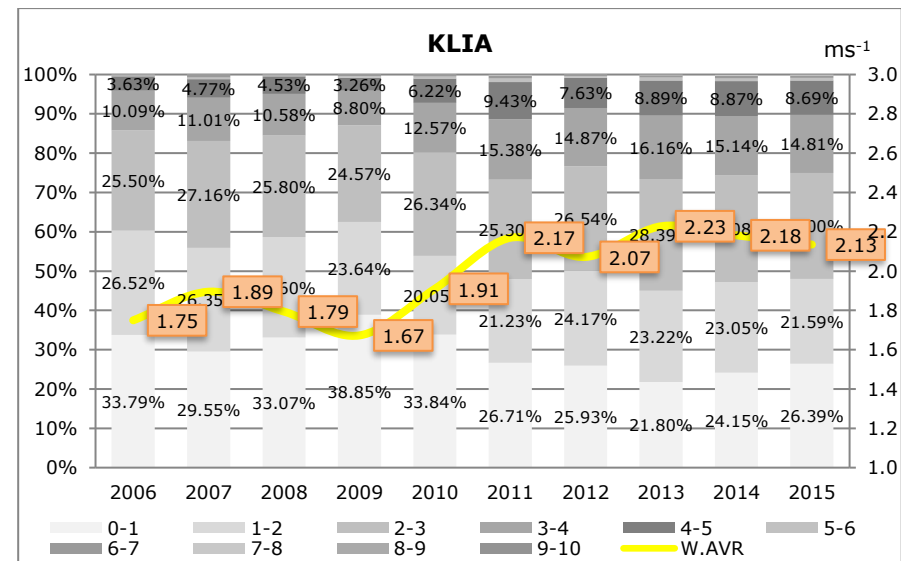
Appendix – A01: Annual Bintulu Wind Speed in Percentage



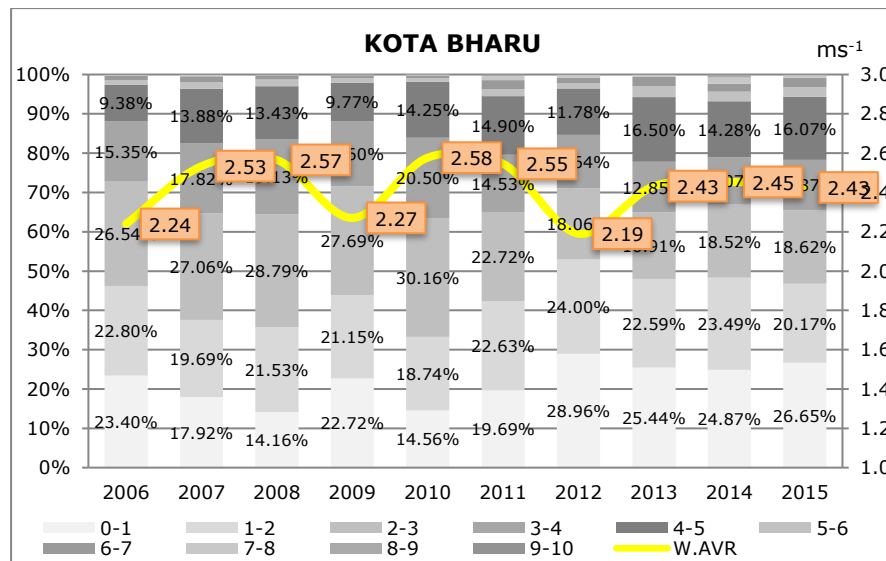
Appendix – A02: Annual Butterworth Wind Speed in Percentage



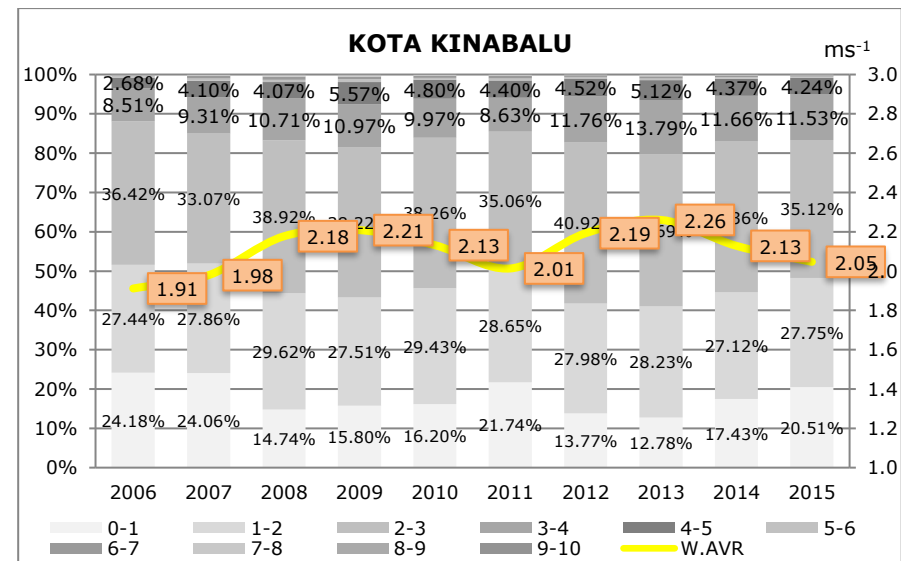
Appendix – A03: Annual Johor Bahru Wind Speed in Percentage



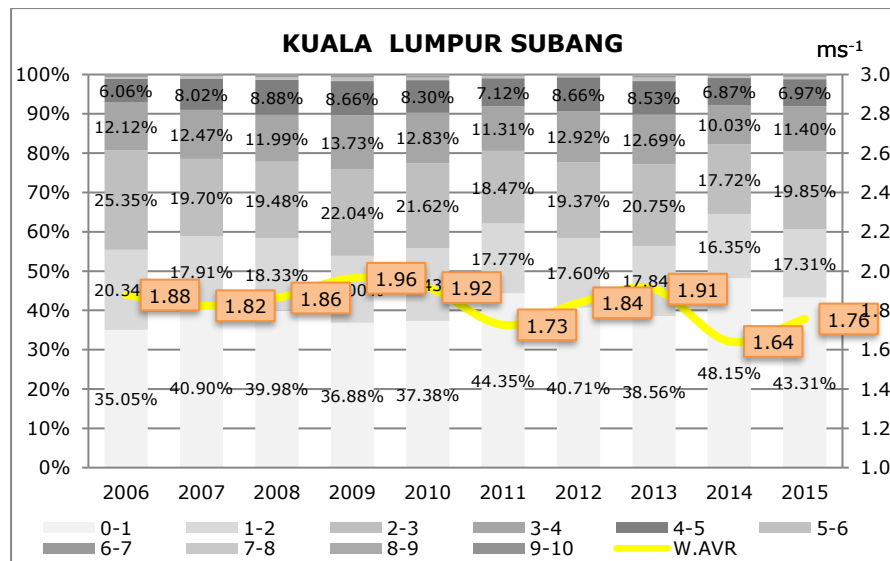
Appendix – A04: Annual KLIA Wind Speed in Percentage



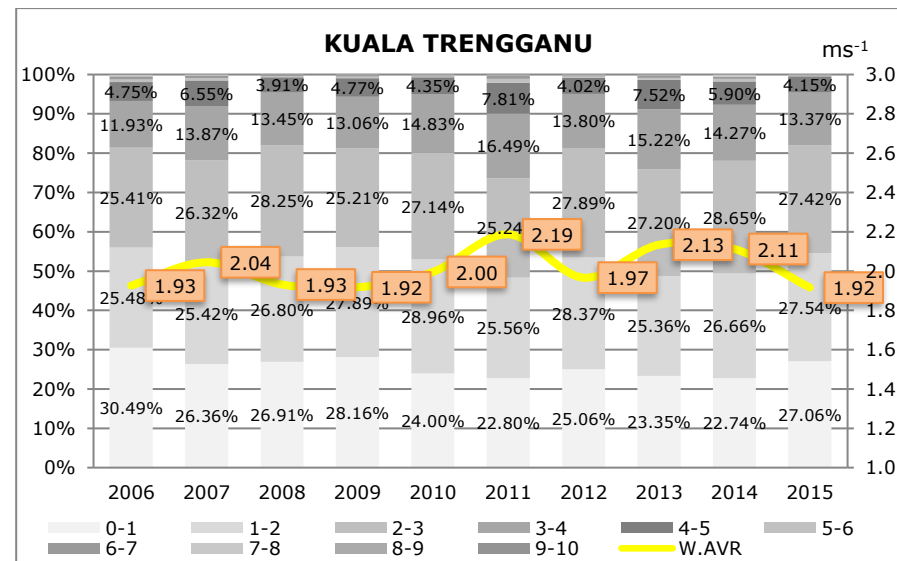
Appendix – A05: Annual Kota Bharu Wind Speed in Percentage



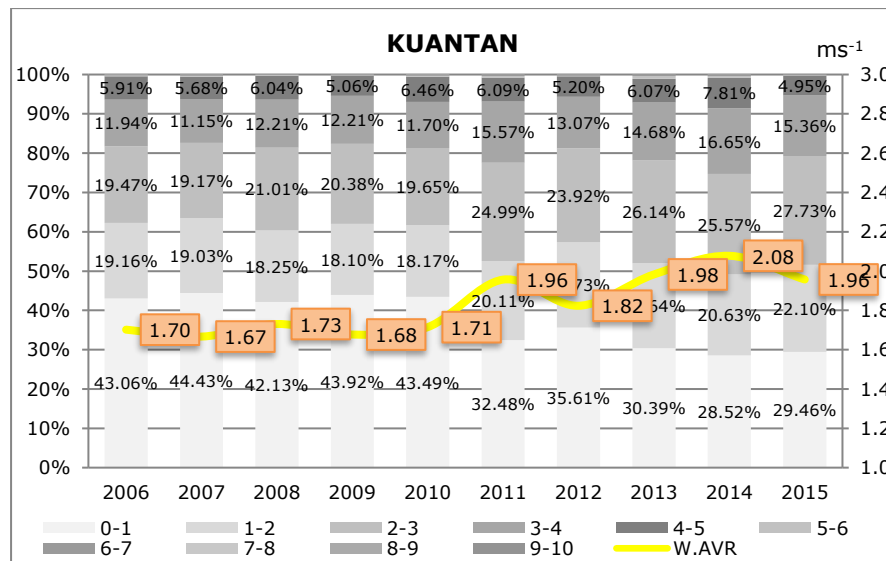
Appendix – A06: Annual Kota Kinabalu Wind Speed in Percentage



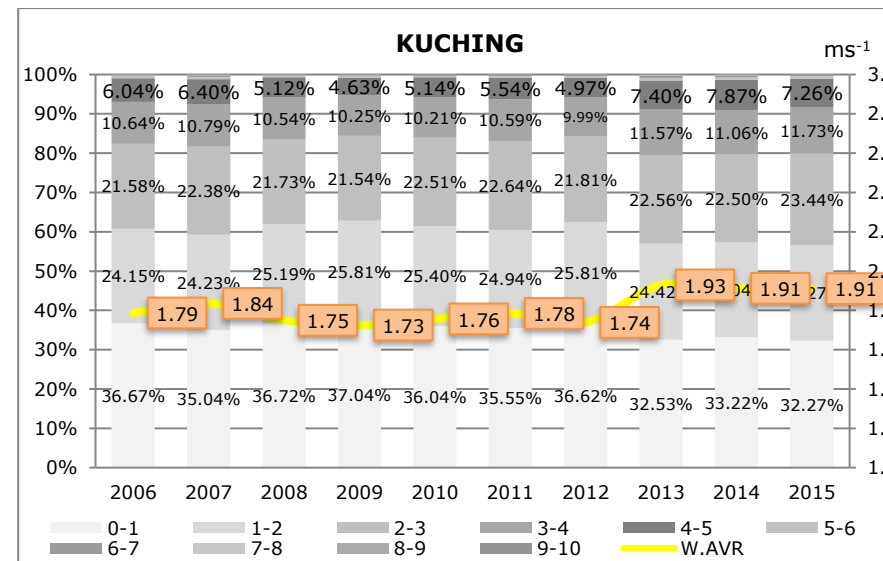
Appendix – A07: Annual Subang Wind Speed in Percentage



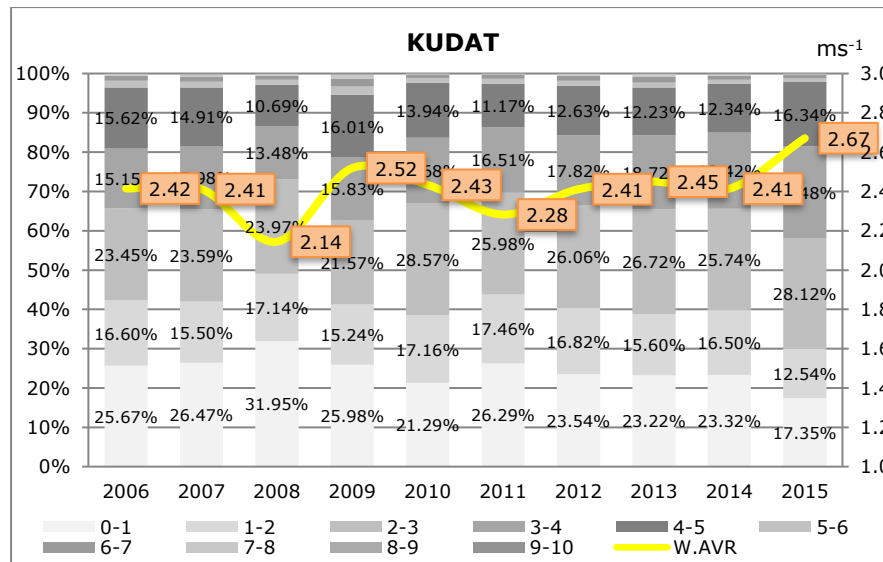
Appendix – A08: Annual Kuala Terengganu Wind Speed in Percentage



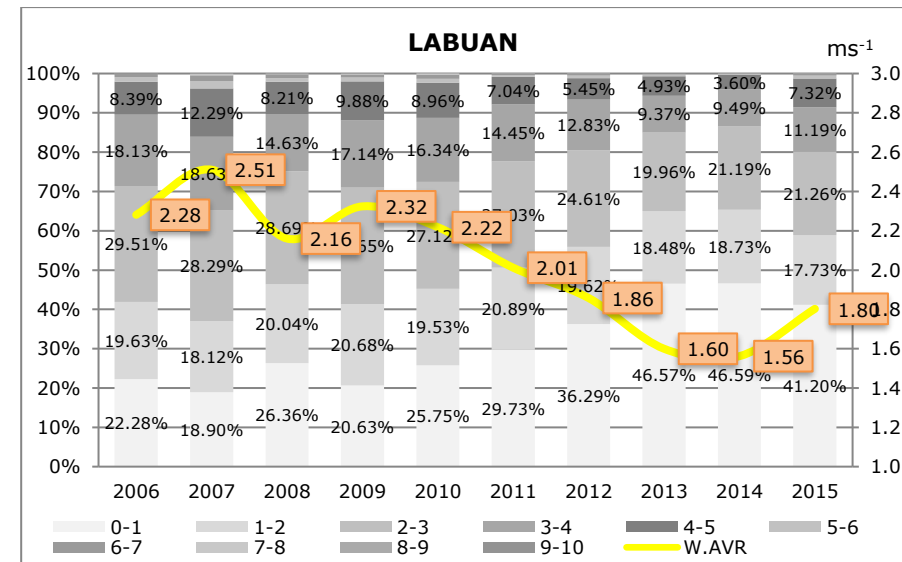
Appendix – A09: Annual Kuantan Wind Speed in Percentage



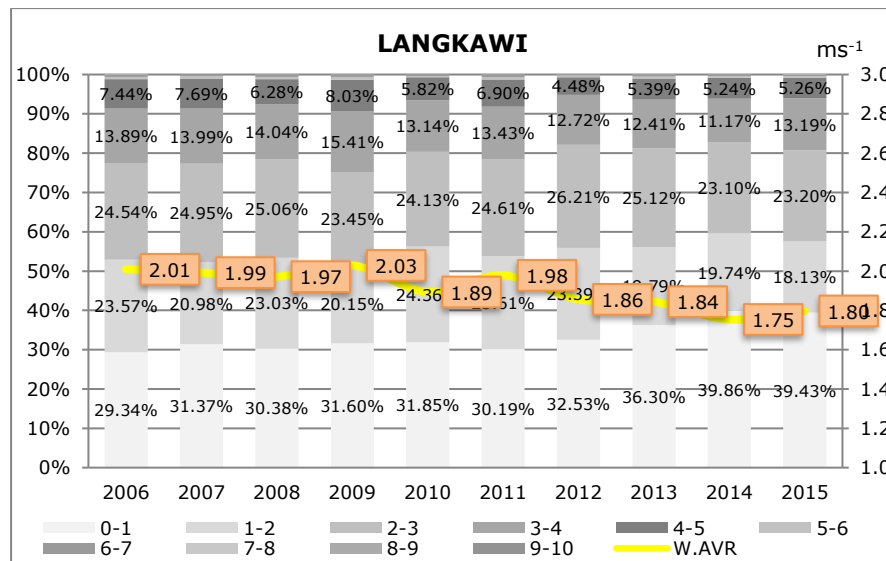
Appendix – A10: Annual Kuching Wind Speed in Percentage



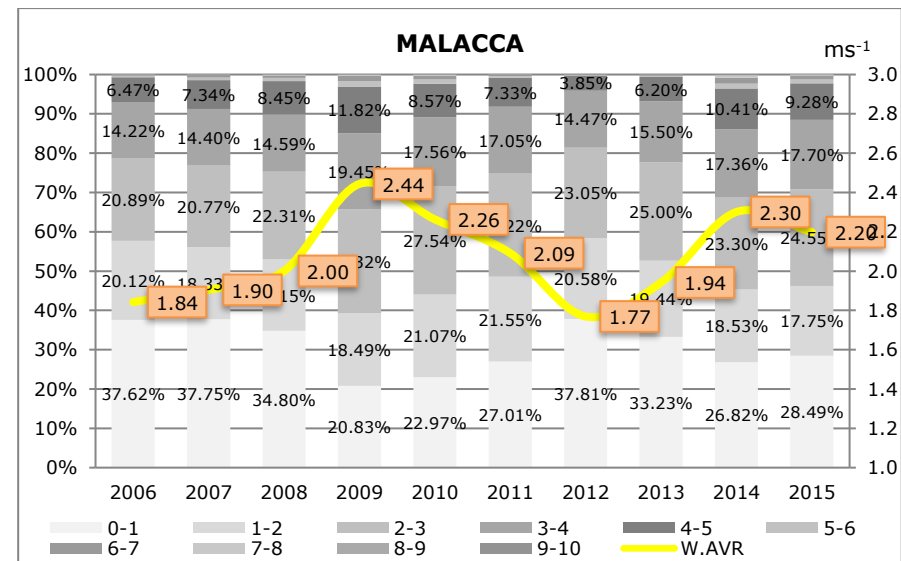
Appendix – A11: Annual Kudat Wind Speed in Percentage



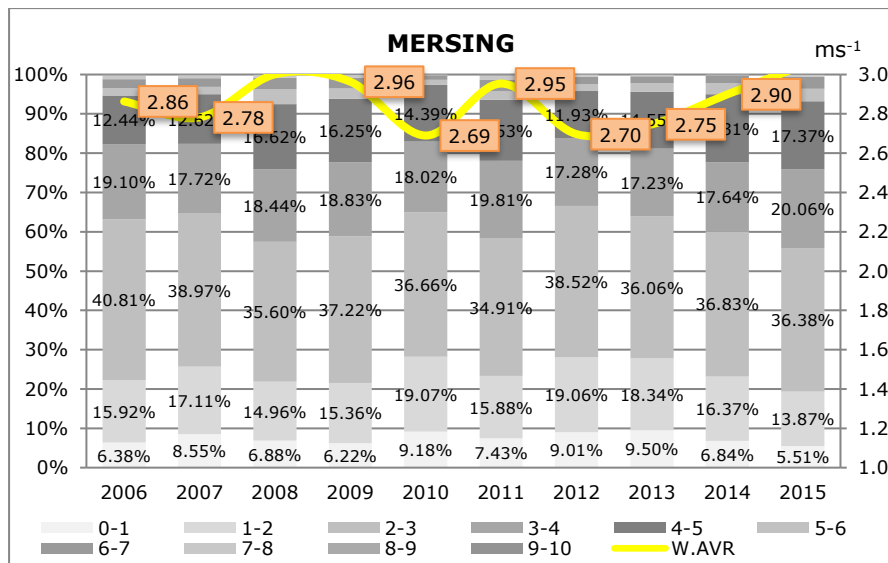
Appendix – A12: Annual Labuan Wind Speed in Percentage



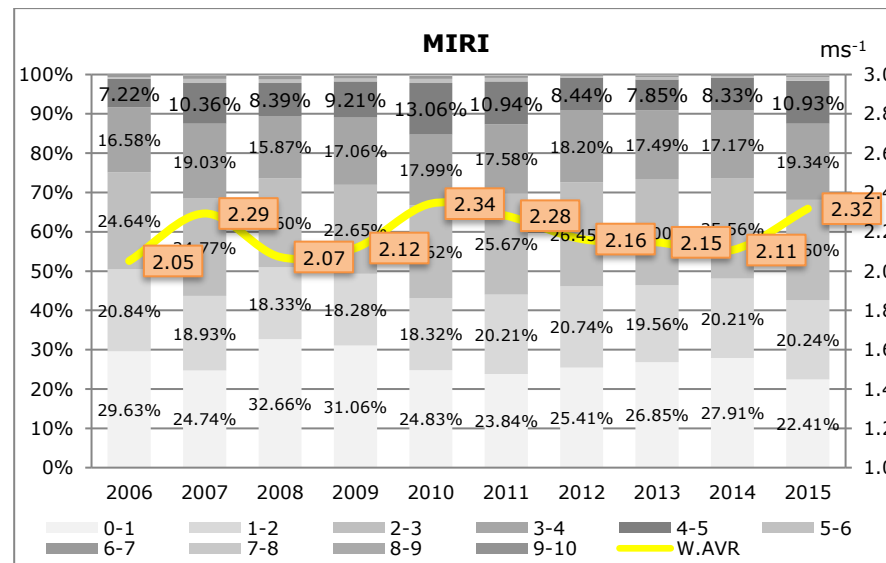
Appendix – A13: Annual Langkawi Wind Speed in Percentage



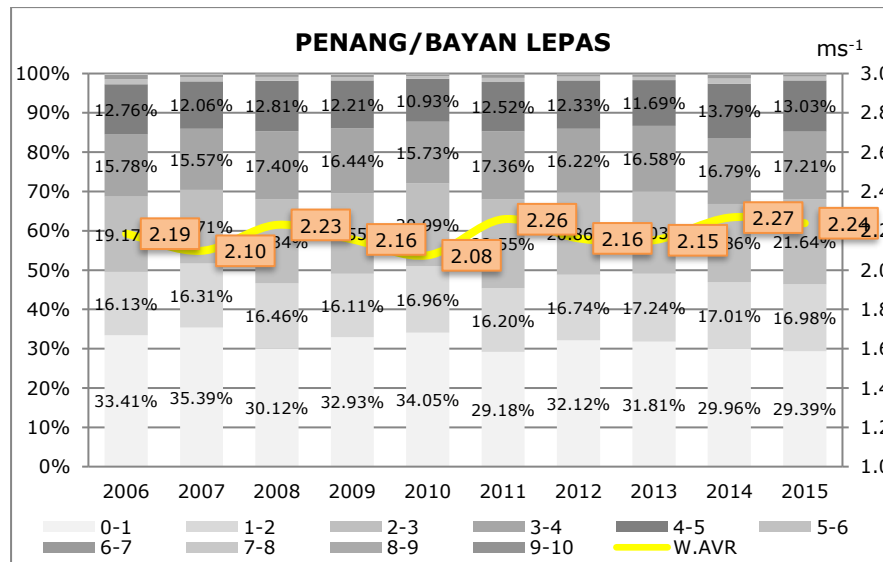
Appendix – A14: Annual Malacca Wind Speed in Percentage



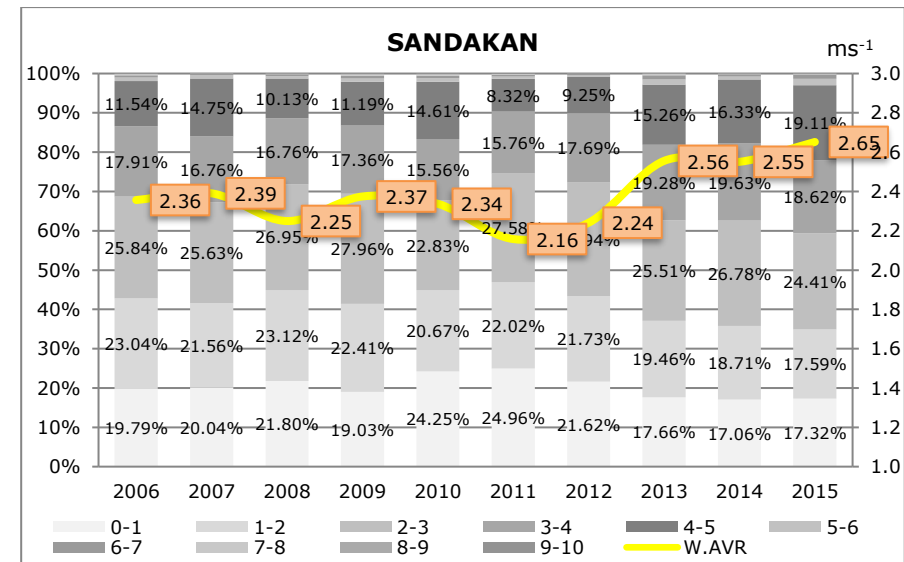
Appendix – A15: Annual Mersing Wind Speed in Percentage



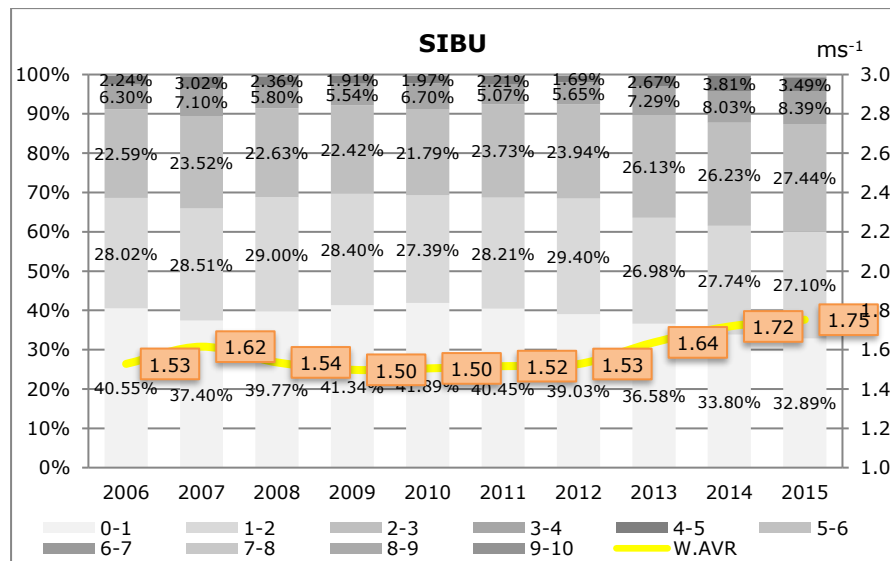
Appendix – A16: Annual Miri Wind Speed in Percentage



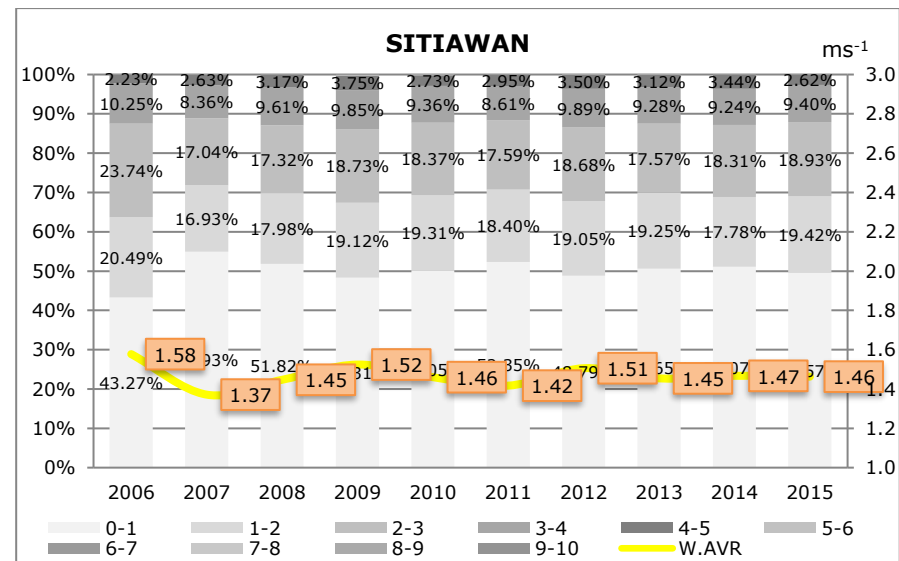
Appendix – A17: Annual Penang Wind Speed in Percentage



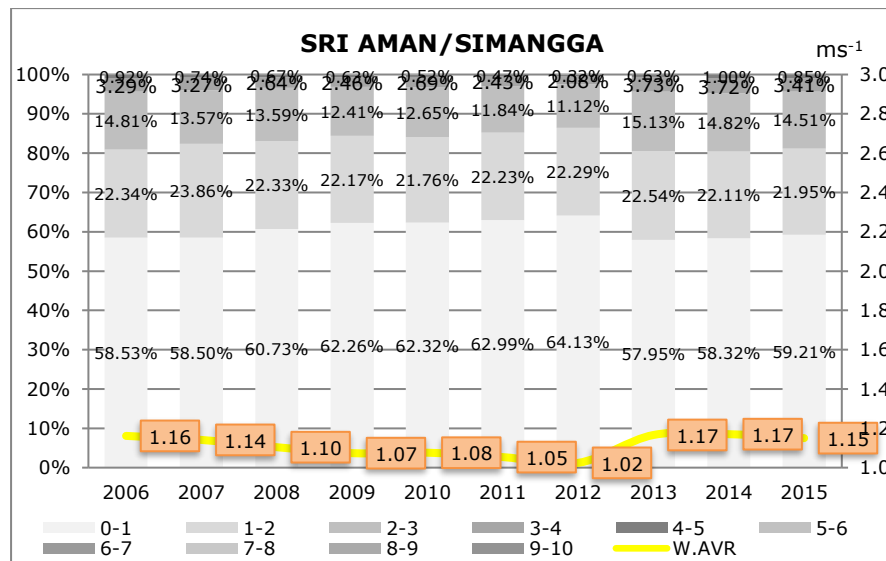
Appendix – A18: Annual Sandakan Wind Speed in Percentage



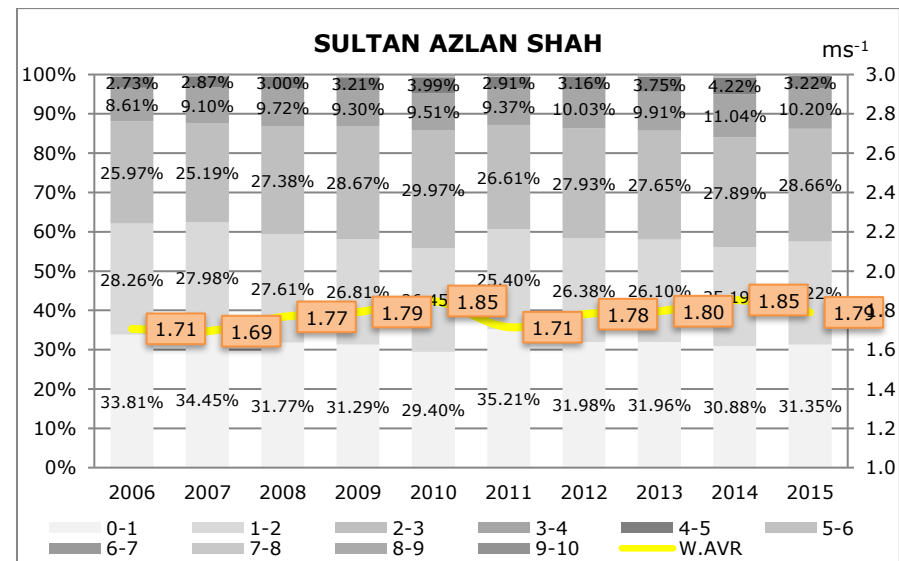
Appendix – A19: Annual Sibu Wind Speed in Percentage



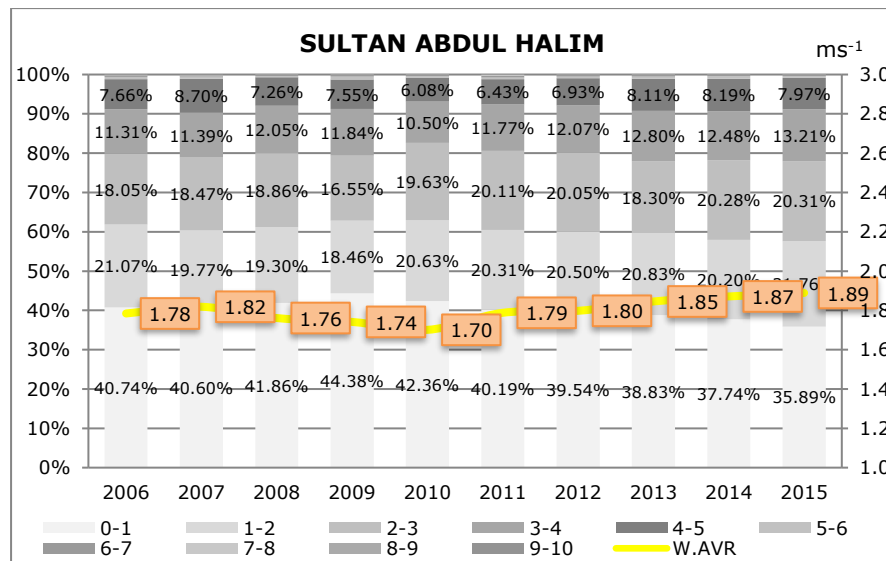
Appendix – A20: Annual Sitiawan Wind Speed in Percentage



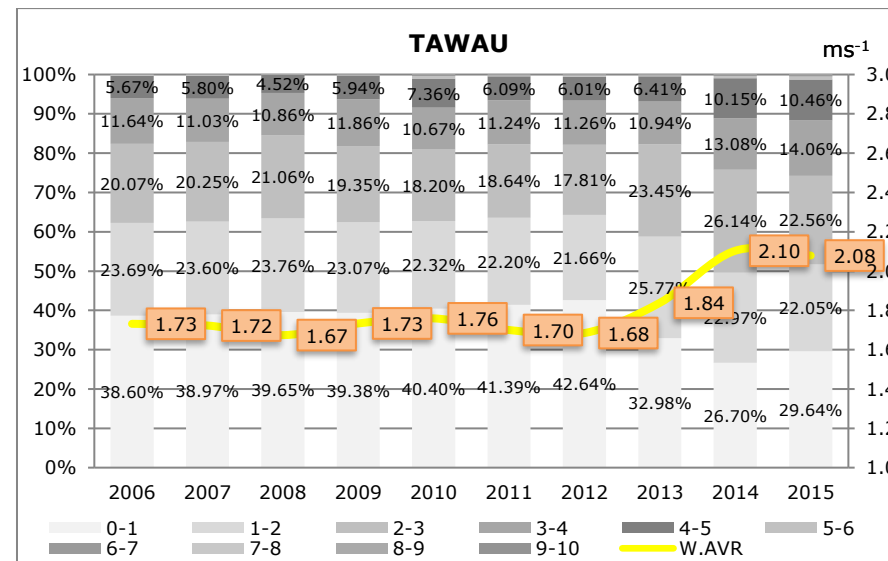
Appendix – A21: Annual Sri Aman Wind Speed in Percentage



Appendix – A22: Annual Sultan Azlan Shah Wind Speed in Percentage



Appendix – A23: Annual Sultan Abdul Halim Wind Speed in Percentage



Appendix – A24: Annual Tawau Wind Speed in Percentage

Appendix – B: Weibull Parameters, Mean Wind Speed & Mean Wind Power at 10m height

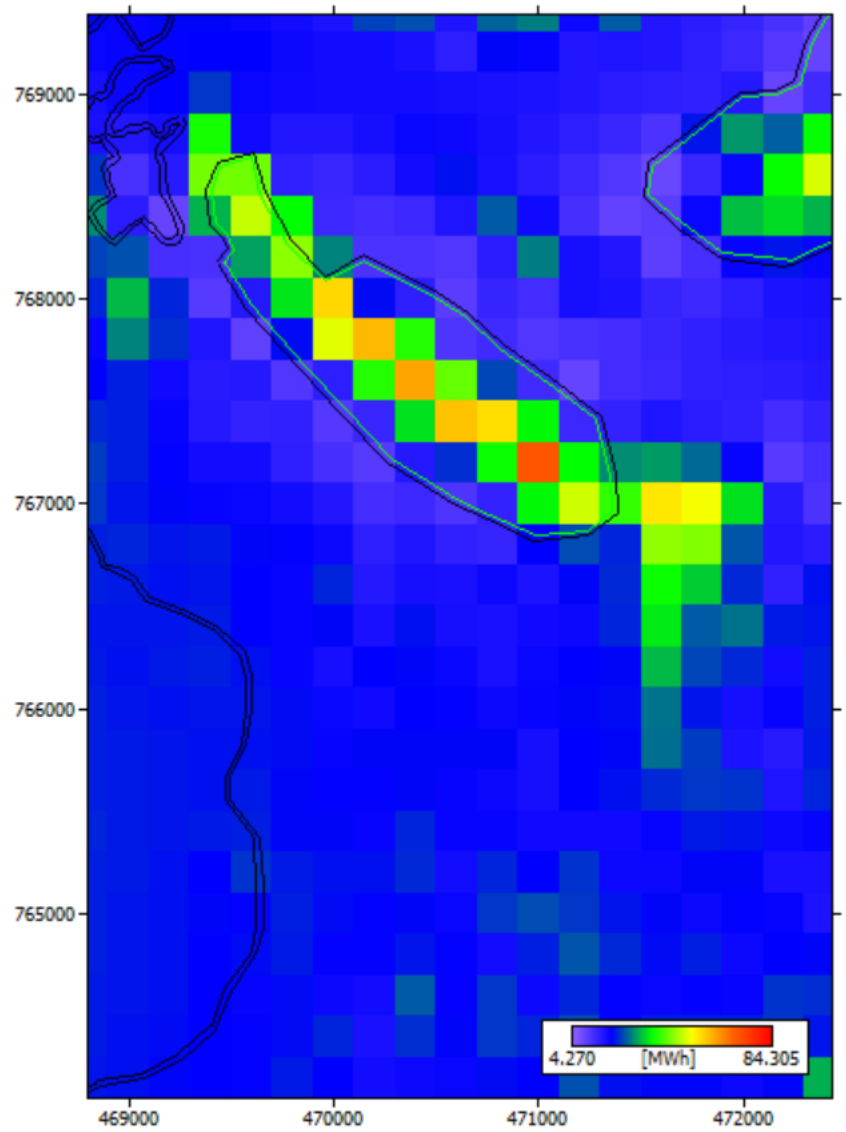
	A	K	U (in ms⁻¹)	P (in Wm⁻²)
Mersing	3.1	1.91	2.93	26
Kudat	2.8	1.70	2.50	23
Kota Bharu	2.7	1.73	2.44	20
Labuan	2.7	1.77	2.43	19
Sandakan	2.6	1.70	2.27	17
Miri	2.5	1.67	2.18	16
Langkawi	2.4	1.57	2.09	16
Penang	2.3	1.52	2.07	15
Butterworth	2.5	1.73	2.18	14
Kota Kinabalu	2.5	1.98	2.20	13
Sultan Abdul Aziz S	2.0	1.30	1.85	13
Malacca	2.1	1.53	1.92	12
KL Subang	2.0	1.42	1.80	11
Kuala Terengganu	2.3	1.73	2.00	11
Sultan Abdul Halim	1.9	1.35	1.76	11
Bintulu	2.2	1.70	1.92	10
Johor	1.6	1.15	1.55	10
Kuantan	1.9	1.36	1.73	10
Tawau	2.0	1.45	1.81	10
KLIA	2.0	1.55	1.83	10
Kuching	1.9	1.42	1.72	9
Sultan Abdul Shah	1.9	1.59	1.71	8
Sibu	1.8	1.46	1.61	7
Sitiawan	1.1	0.97	1.22	5
Sri Aman	0.9	1.00	0.97	3

Note: Constructed from the OWC results of Stations

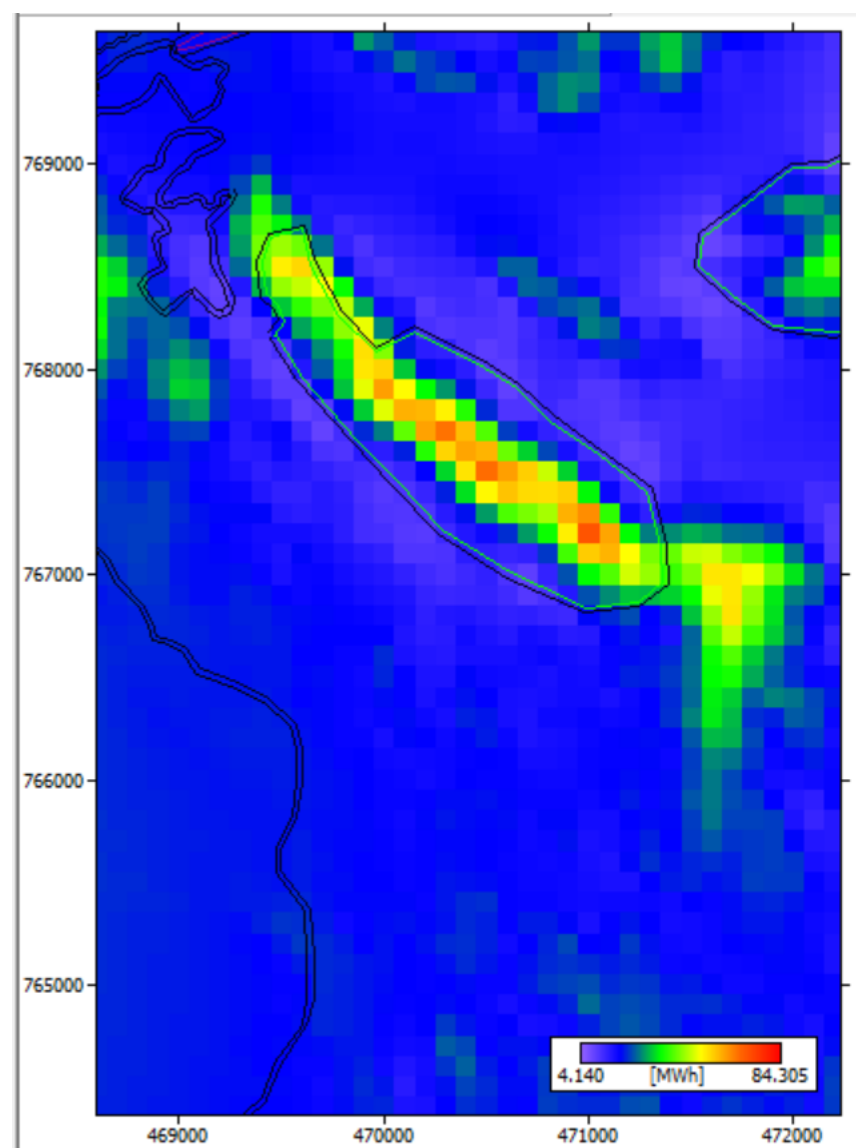
Appendix – C: Roughness Length Table

Physical z_0 [m]	Terrain surface characteristics	Roughness Class	z_0 specified in WASP [m]
1.5		4 (1.5 m)	1.5
> 1	tall forest		> 1
1	city		1
0.8	forest		0.8
0.5	suburbs		0.5
0.4		3 (0.40 m)	0.4
0.3	shelter belts		0.3
0.2	many trees and/or bushes		0.2
0.1	farmland with closed appearance	2 (0.10 m)	0.1
0.05	farmland with open appearance		0.05
0.03	farmland with very few buildings/trees	1 (0.03 m)	0.03
0.02	airport areas with buildings and trees		0.02
0.01	airport runway areas		0.01
0.008	mown grass		0.008
0.005	bare soil (smooth)		0.005
0.001	snow surfaces (smooth)		0.003
0.0003	sand surfaces (smooth)		0.003
0.0002	(used for water surfaces in the Atlas)	0 (0.0002 m)	0
0.0001	water areas (lakes, fjords, open sea)		0

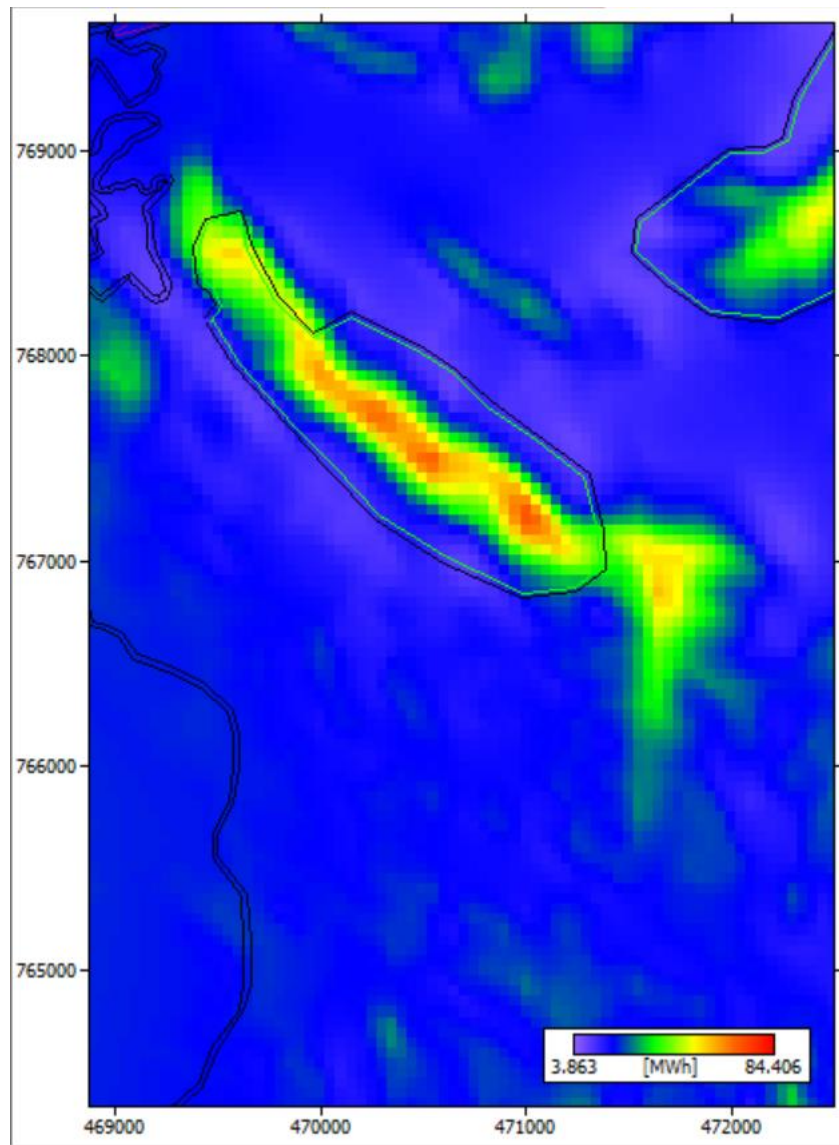
Appendix – D: Resource Grid at Different Resolution Values



Appendix – D1: Resource grid at Resolution = 200m



Appendix – D2: Resource grid at Resolution = 100



Appendix – D3: Resource grid at Resolution = 50

Appendix – E: Present Value Discount Factors

Year	Discount Factor
0	1.000000
1	0.991262
2	0.982601
3	0.974015
4	0.965504
5	0.957068
6	0.948705
7	0.940415
8	0.932198
9	0.924053
10	0.915978
11	0.907975
12	0.900041
13	0.892176
14	0.884381
15	0.876653
16	0.868993
17	0.86140
18	0.853873
19	0.846412
20	0.839016

Appendix – F: Investment Appraisal of the Top 5 Sites

Appendix F-1: Investment Appraisal for Miri

Rated Power	5kW 18m	10kW 18m	10kW 24m	10kW 30m	20kW 18m	20kW 21m	20kW 24m	20kW 30m	30kW 18m	30kW 24m	30kW 30m	50kW 30m
Turbine Model	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Libellula	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos
Energy output per year (kW)	3677	6927	7872	8702	13101	28485	14936	16540	18339	20590	22578	30405
Annual revenue (RM)	2729.80	5142.60	5844.17	6460.36	9726.18	21147.26	11088.49	12279.30	13614.87	15286.02	16761.91	22572.67
Revenue generation over 20-years (discounted at k) (in RM)	51113.51	96291.34	109427.66	120965.39	182115.32	395966.34	207623.42	229920.42	254928.09	286218.95	313853.89	422656.01
Cost price in USD	10070.00	24420.00	28020.00	31620.00	35800.00	78000.00	39400.00	43000.00	46280.00	49880.00	53480.00	71240.00
Cost of turbine (RM)	41085.60	99633.60	114321.60	129009.60	146064.00	318240.00	160752.00	175440.00	188822.40	203510.40	218198.40	290659.20
Setup cost (RM)	2027.14	3490.84	3858.04	4225.24	4651.60	8956.00	5018.80	5386.00	5720.56	6087.76	6454.96	8266.48
Maintenance cost per year (RM)	605.90	699.50	726.71	750.62	877.31	1320.37	930.16	976.35	1028.16	1092.99	1150.25	1375.66
Maintenance cost (in RM) over 20-years (marked up at m)	12117.95	13989.95	14534.27	15012.35	17546.18	26407.36	18603.14	19527.04	20563.27	21859.84	23004.93	27513.28
Net Present Value (RM)	-7408.87	-27791.93	-31324.34	-36259.00	-100.88	11002.40	7218.86	11721.92	19940.93	32333.14	41518.47	62684.10
Annual Return on Investment	-0.90%	-1.39%	-1.37%	-1.41%	0.00%	0.17%	0.22%	0.33%	0.53%	0.79%	0.95%	1.08%
Internal Rate of Return (IRR)	-1%	-2%	-2%	-2%	1%	1%	1%	2%	2%	2%	3%	3%
Levelised Cost of electricity	0.7997	0.9082	0.9064	0.9165	0.6908	0.6694	0.6641	0.6519	0.6314	0.6051	0.5906	0.5785

Appendix F-2: Investment Appraisal for Kudat

Rated Power	5kW 18m	10kW 18m	10kW 24m	10kW 30m	20kW 18m	20kW 21m	20kW 24m	20kW 30m	30kW 18m	30kW 24m	30kW 30m	50kW 30m
Turbine Model	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Libellula	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos
Energy output per year (kW)	5688	10939	12178	13241	20236	40788	22480	24395	26627	31758	34462	53249
Annual revenue (RM)	4222.77	8121.11	9040.95	9830.12	15023.21	30281.01	16689.15	18110.85	19767.88	23577.14	25584.59	39532.06
Revenue generation over 20-years (discounted at k) (in RM)	79068.16	152061.64	169284.82	184061.44	281298.04	566988.76	312491.60	339111.77	370138.52	441463.89	479051.85	740207.53
Cost price in USD	10070.00	24420.00	28020.00	31620.00	35800.00	78000.00	39400.00	43000.00	46280.00	49880.00	53480.00	71240.00
Cost of turbine (RM)	41085.60	99633.60	114321.60	129009.60	146064.00	318240.00	160752.00	175440.00	188822.40	203510.40	218198.40	290659.20
Setup cost (RM)	2027.14	3490.84	3858.04	4225.24	4651.60	8956.00	5018.80	5386.00	5720.56	6087.76	6454.96	8266.48
Maintenance cost per year (RM)	663.81	815.04	850.73	881.34	1082.80	1674.69	1147.42	1202.58	1266.86	1414.63	1492.51	2033.57
Maintenance cost (in RM) over 20-years (marked up at m)	13276.29	16300.87	17014.53	17626.82	21655.94	33493.89	22948.48	24051.52	25337.15	28292.61	29850.11	40671.43
Net Present Value (RM)	17112.11	21128.10	21180.55	19086.96	86899.22	161018.13	99206.07	107501.29	121000.05	168509.33	186425.15	341230.74
Annual Return on Investment	2.08%	1.06%	0.93%	0.74%	2.97%	2.53%	3.09%	3.06%	3.20%	4.14%	4.27%	5.87%
Internal Rate of Return (IRR)	4.56%	2.85%	2.62%	2.28%	6.03%	5.34%	6.20%	6.17%	6.39%	7.80%	8.00%	10.28%
Levelised Cost of electricity	0.5271	0.5855	0.5960	0.6121	0.4573	0.4761	0.4508	0.4512	0.4437	0.4024	0.3968	0.3426

Appendix F-3: Investment Appraisal for Mersing

Rated Power	5kW 18m	10kW 18m	10kW 24m	10kW 30m	20kW 18m	20kW 21m	20kW 24m	20kW 30m	30kW 18m	30kW 24m	30kW 30m	50kW 30m
Turbine Model	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Libellula	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos
Energy output per year (kW)	3023	5654	6464	7176	10569	23679	12211	13657	15183	17038	18690	22723
Annual revenue (RM)	2244.28	4197.53	4798.87	5327.46	7846.43	17579.29	9065.45	10138.96	11271.86	12649.01	13875.46	16869.56
Revenue generation over 20-years (discounted at k) (in RM)	42022.34	78595.53	89855.24	99752.66	146918.31	329158.75	169743.55	189844.21	211056.94	236843.06	259807.30	315869.51
Cost price in USD	10070.00	24420.00	28020.00	31620.00	35800.00	78000.00	39400.00	43000.00	46280.00	49880.00	53480.00	71240.00
Cost of turbine (RM)	41085.60	99633.60	114321.60	129009.60	146064.00	318240.00	160752.00	175440.00	188822.40	203510.40	218198.40	290659.20
Setup cost (RM)	2027.14	3490.84	3858.04	4225.24	4651.60	8956.00	5018.80	5386.00	5720.56	6087.76	6454.96	8266.48
Maintenance cost per year (RM)	587.06	662.84	686.16	706.67	804.39	1181.96	851.68	893.32	937.27	990.69	1038.27	1154.42
Maintenance cost (in RM) over 20-years (marked up at m)	11741.25	13256.71	13723.27	14133.38	16087.75	23639.11	17033.54	17866.43	18745.41	19813.89	20765.44	23088.45
Net Present Value (RM)	-15383.37	-43314.16	-48492.69	-54866.17	-30974.63	-47599.21	-26008.23	-23431.73	-18541.52	-10977.91	-5889.57	-30985.80
Annual Return on Investment	-1.87%	-2.17%	-2.12%	-2.13%	-1.06%	-0.75%	-0.81%	-0.67%	-0.49%	-0.27%	-0.13%	-0.53%
Internal Rate of Return (IRR)	-3.24%	-4.10%	-3.96%	-3.98%	-1.34%	-0.66%	-0.79%	-0.48%	-0.11%	0.34%	0.61%	-0.20%
Levelised Cost of electricity	0.9666	1.1062	1.0976	1.1054	0.8495	0.7995	0.8060	0.7835	0.7567	0.7254	0.7075	0.7644

Appendix F-4: Investment Appraisal for Penang

Rated Power	5kW 18m	10kW 18m	10kW 24m	10kW 30m	20kW 18m	20kW 21m	20kW 24m	20kW 30m	30kW 18m	30kW 24m	30kW 30m	50kW 30m
Turbine Model	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Libellula	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos
Energy output per year (kW)	8252	16025	17608	18958	28823	52449	31605	33967	42629	46846	50456	83185
Annual revenue (RM)	6126.28	11896.96	13072.18	14074.42	21398.20	38938.14	23463.55	25217.10	31647.77	34778.47	37458.53	61756.54
Revenue generation over 20-years (discounted at k) (in RM)	114709.99	222761.47	244766.55	263532.73	400664.83	729086.83	439337.06	472170.92	592580.27	651200.24	701382.39	1156344.03
Cost price in USD	10070.00	24420.00	28020.00	31620.00	35800.00	78000.00	39400.00	43000.00	46280.00	49880.00	53480.00	71240.00
Cost of turbine (RM)	41085.60	99633.60	114321.60	129009.60	146064.00	318240.00	160752.00	175440.00	188822.40	203510.40	218198.40	290659.20
Setup cost (RM)	2027.14	3490.84	3858.04	4225.24	4651.60	8956.00	5018.80	5386.00	5720.56	6087.76	6454.96	8266.48
Maintenance cost per year (RM)	737.66	961.52	1007.11	1045.99	1330.10	2010.53	1410.22	1478.25	1727.72	1849.16	1953.13	2895.73
Maintenance cost (in RM) over 20-years (marked up at m)	14753.15	19230.40	20142.21	20919.81	26602.05	40210.63	28204.48	29564.99	34554.31	36983.30	39062.66	57914.57
Net Present Value (RM)	48376.06	83143.86	87390.86	88796.78	191604.18	303205.68	210471.09	224216.77	316119.27	352483.75	381446.82	706253.16
Annual Return on Investment	5.89%	4.17%	3.82%	3.44%	6.56%	4.76%	6.55%	6.39%	8.37%	8.66%	8.74%	12.15%
Internal Rate of Return (IRR)	10.16%	7.82%	7.31%	6.74%	11.19%	8.72%	11.18%	10.97%	13.60%	13.98%	14.09%	18.37%
Levelised Cost of electricity	0.3722	0.4088	0.4210	0.4362	0.3296	0.3766	0.3289	0.3321	0.2879	0.2820	0.2800	0.2296

Appendix F-5: Investment Appraisal for Sandakan

Rated Power	5kW 18m	10kW 18m	10kW 24m	10kW 30m	20kW 18m	20kW 21m	20kW 24m	20kW 30m	30kW 18m	30kW 24m	30kW 30m	50kW 30m
Turbine Model	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Libellula	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos	Aeolos
Energy output per year (kW)	3322	6197	6960	7620	11669	25334	13144	14413	16645	18440	20002	26170
Annual revenue (RM)	2466.25	4600.65	5167.10	5657.09	8663.07	18807.96	9758.11	10700.21	12357.25	13689.86	14849.48	19428.61
Revenue generation over 20-years (discounted at k) (in RM)	46178.70	86143.70	96750.07	105924.64	162209.27	352164.69	182713.06	200353.27	231380.01	256332.08	278045.24	363785.82
Cost price in USD (Aeolos)	10070.00	24420.00	28020.00	31620.00	35800.00	78000.00	39400.00	43000.00	46280.00	49880.00	53480.00	71240.00
Cost of turbine (RM)	41085.60	99633.60	114321.60	129009.60	146064.00	318240.00	160752.00	175440.00	188822.40	203510.40	218198.40	290659.20
Setup cost (RM)	2027.14	3490.84	3858.04	4225.24	4651.60	8956.00	5018.80	5386.00	5720.56	6087.76	6454.96	8266.48
Maintenance cost per year (RM)	595.67	678.47	700.45	719.46	836.07	1229.62	878.55	915.09	979.38	1031.07	1076.06	1253.70
Maintenance cost (in RM) over 20- years (marked up at m)	11913.47	13569.47	14008.96	14389.12	16721.35	24592.39	17570.95	18301.89	19587.52	20621.44	21521.15	25073.92
Net Present Value (RM)	-11737.54	-36693.13	-42444.75	-49452.29	-17561.86	-27419.09	-14631.76	-14213.50	-714.73	6117.27	10108.20	11044.94
Annual Return on Investment	-1.43%	-1.84%	-1.86%	-1.92%	-0.60%	-0.43%	-0.46%	-0.41%	-0.02%	0.15%	0.23%	0.19%
Internal Rate of Return (IRR)	-2.15%	-3.21%	-3.25%	-3.41%	-0.34%	0.01%	-0.04%	0.07%	0.84%	1.17%	1.33%	1.25%
Levelised Cost of electricity	0.8822	1.0118	1.0214	1.0426	0.7721	0.7491	0.7508	0.7439	0.6927	0.6724	0.6630	0.6675