ONSHORE AND OFFSHORE WIND RESOURCE ASSESSMENTS FOR THAILAND

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SUMMARY

In Thailand, renewable energy is poised to play a key role in the attainment of sustainable development objectives. In application to the development of wind energy in Thailand, this research presents wind resource assessments, using 3-D atmospheric and computational fluid dynamics numerical models and climate data, in several onshore and offshore parts of Thailand, with a main focus in the Gulf of Thailand (GoT).

The main objectives of this research were (1) to assess the onshore wind energy potential in Thailand using the Regional Atmospheric Modeling System (RAMS), (2) to investigate the offshore wind energy potential in the GoT using the Mesoscale Compressible Community (MC2) model, along with the Modern-Era Retrospective Analysis for Research and Applications (MERRA) climatic database, and to propose a method to apply universal climatic data into atmospheric models where measured data are limited; and (3) to present the offshore wind resource assessment of the Gulf of Thailand using the Weather Research and Forecasting (WRF) atmospheric model, along with the NCEP/NCAR R2 reanalysis climatic database and computational fluid dynamics microscale wind flow modeling.

Presented under the format of a “Thesis by Publications”, the first publication of the thesis, published in Energy Procedia in 2014, assesses the onshore wind energy potential in Thailand by using the Regional Atmospheric Modeling System (RAMS) at a 9 km resolution. In this work, a wind resource map at 120 m elevation above ground level (agl) is produced based on the NCEP reanalysis database for the three year period of 2009-11. The onshore wind resource map is validated by comparing the modeling results to measured wind data at 100 m agl. The mean square error (MSE) is the main criterion to evaluate the modeling. The annual mean wind speeds at 120 m agl are in the range of 1.60 to 5.83 m/s. The maximum annual mean power density is approximately 200 W/m^2, which corresponds to a wind power density of Class 2. The windy regions are in the mountain areas of western, southern and eastern part of Thailand. While needing further analysis to optimize its development, this wind resource could be developed and exploited in order to achieve the national renewable energy policy targets of Thailand.

The second publication, published in the International Journal of Renewable Energy in 2016, presents an assessment of the wind energy potential in the northern part of the GoT, which is an important process in the development of wind power projects. The MC2

atmospheric model, along with the MERRA climatic database, are used in order to investigate the mean wind speeds and the technical power potential of the territory. Moreover, the comparison has been made using the Weather Research and Forecast (WRF) atmospheric modeling, along with MERRA climatic database. The results show that the annual mean wind speeds are in the range of 2.3 to 7.5 m/s. The technical power potential, over an area of 1,500 km^2, is in the range of 2,500 MW. In comparison, the measured/predicted ratio (M/P) and the percent mean relative error (PMRE) are in the range of 0.70 to 0.96, and 4 to 42%, respectively. Regional outcomes from this study can be applied to develop offshore wind power projects in the northern part of the Gulf of Thailand.

In the last publication, published in Energy (Elsevier) in 2017, the Weather Research and Forecasting (WRF) atmospheric model, along with the NCEP/NCAR R2 reanalysis climatic database, are applied to create wind resource maps at 80 m, 100 m, and 120 m above mean sea level (amsl) to identify the potential surface areas for the development of offshore wind power plants in the GoT. The predicted wind speeds are validated using observed wind speeds obtained from 13 met masts installed along the coastline of the GoT. Results show that the average annual mean wind speeds reach the range of 5.5 to 6.5 m/s in specific areas of the Bay of Bangkok, situated in the northern part of the GoT. Based on the results of the wind resource assessment and using computational fluid dynamics microscale wind flow modeling, a wind power plant optimization is performed. The technical power potential and a priority zoning for offshore wind power development are performed using wind turbine generators of 3.3 to 8.0 MW capacity. Depending on the wind turbine generator selected, it is found that 642 to 924 MW of capacity could be installed in the short-term planning; 2,658 to 3,825 MW of additional capacity could be added in the medium-term planning, and 2,864 to 4,120 MW of additional capacity in the long-term planning. These wind power plants would have an annual energy production in the order of 5.6 to 8 PWh in the short-term, an additional 23 to 33 PWh in the medium-term, and an additional 25 to 36 PWh in the long-term, respectively, thus avoiding CO_{2eq} emissions in the order of 3 to 4.5 million tonnes CO_{2eq} per year in the short-term, 13 to 18 million tonnes in the medium-term, and 14 to 20 million tonnes in the long-term. In total, depending on the wind turbine generator selected, wind power plants in the GoT could have a total installed capacity of 6,000 to over 8,000 MW, would generate between 50 and 75 PWh of energy per year, while avoiding emissions of 30 to 40 million tonnes CO_{2eq} per year.

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NOMECLATURE

ABL	Atmospheric boundary layer
ADAS	Atmospheric data assimilation system
AEDP2015	Alternative Energy Development Plan in 2015
AEP	Annual energy production
agl	Above ground level
amsl	Above mean sea level
ARW	Advance Research Weather Research and Forecasting
CF	Capacity factor
CFD	Computational fluid dynamics
DEDE	Department of Alternative Enegy Development and Efficiency
DEM	Digital elevation model
EECD	Eastern Economic Corridor Development
EGAT	Electricity Generating Authority of Thailand
EHIA	Environment health impact assessment
EIA	Environment impact assessment
GDP	Gross domestic product
GEOS-5	Goddard Earth Observing System model version 5
GoT	Gulf of Thailand
GTS	Global Telecomunication System
GW	Gigawatt
GWEC	Global Wind Energy Council
JDA	Joint Development Area
LiDAR	Ligth dectection and ranking
M/P	Measured/Predicted
MC2	Mesoscale Compressible Community
MCDA	Multiple-criteria decision analysis
MERRA	Modern-Era Restrospective Analysis for Research and Applications
MM5	5th generation Penn State/NCAR mesoscale model
MSE	Mean square error
MSL	Mean sea level
MSW	Municipal solid waste
MW	Megawatt
NASA	National Aaronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NRCT	National Research Council of Thailand
PDP2010	Power Development Plan in 2010
PCD	Polution Control Department
PEA	Provincial Electricity Authority
PMRE	Percent mean relative error
PWh	Petawatthour
QuikSCAT	Quik Scatterometer
RAMS	Regional Atmospheric Modeling System
RE	Renewable energy
RSM	Respond surface method
SPP	Small power producer
TPP	Technical power potential

WAsP	Wind Atlas Analysis and Application Program
WEST	Wind Energy Simulation Toolkit
WGS	World Geodetic System
WRF	Weather Research and Forecasting
WTG	Wind turbine generator

CHAPTER 1

General Introduction

Renewable energy can provide benefits to society, as shown in Figure 1.1. In addition to the reduction of carbon dioxide CO_2 emissions, governments have enacted renewable energy policies to meet a number of objectives, including the creation of local environmental and health benefits, facilitation of energy access, particularly for rural areas, advancement of energy security goals by diversifying the portfolio of energy technologies and resources, and improving social and economic development through potential employment opportunities [1].

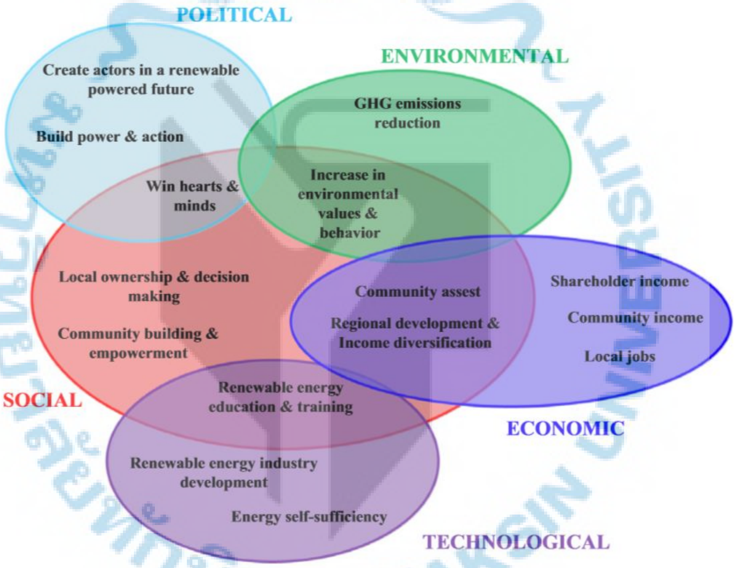

Figure 1.1 The global benefits of renewable energy production.

Thailand’s economic growth (3.2% per-capita GDP growth in 2000-15) is linked to the per-capita electricity consumption. In 2016, the growth in per capita GDP was better than the Southeast Asian countries and the global average. According to the Southeast Asia Energy Outlook 2017, renewable energy contributed 6% of the primary energy demand in Thailand, which amounted to 643 Mtoe in 2016, as shown in Figure 1.2 [2]. It can be seen that the primary energy demand in Thailand has increased by approximately 70% between 2000 and 2016, with coal accounting for the largest share of the growth. Figure 1.2 also shows the ratio of power generation in 2016. In Thailand, renewable energy deployment contributed 6.2% of a total of 199,567 GWh of power generation in 2016 [3].

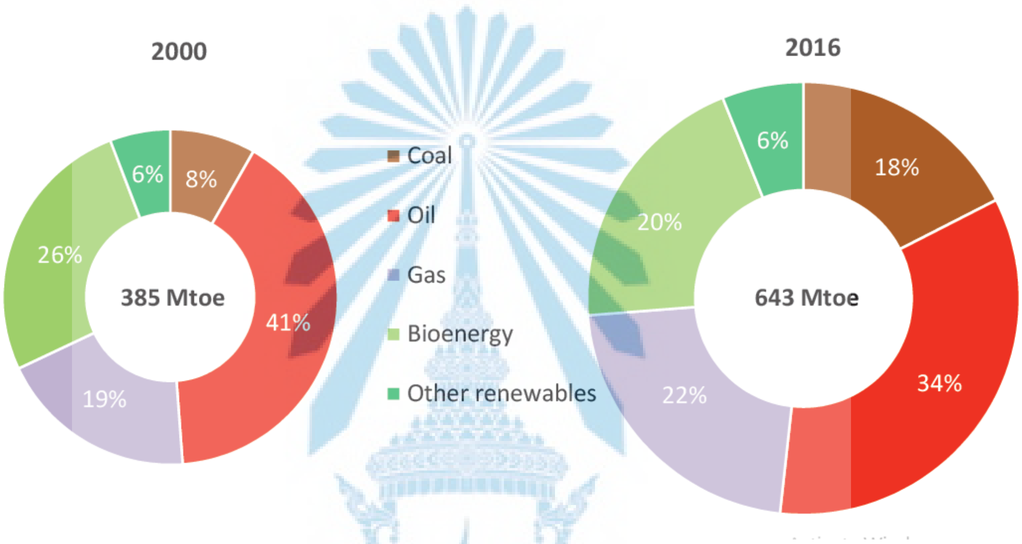

Figure 1.2 Primary energy demand in Thailand in 2000 and 2016 [2].

Figure 1.3 presents the domestic power generation ratio attributed by fuel type in 2016, where the power generation from fossil fuel was over 63% in Thailand [3]. This raises environmental concerns due to the high proportion of fossil fuel-based enery resources needed in the energy portfolio of the country. For its part, the Renewable Energy Development Plan for the 15-year period of 2008-22 presents strategic plans and policies [4]. This plan aims to increase the usage of renewable energy resources and to reduce the environmental impacts. Further, the notion of energy security was also included in to the plan.

The Global Wind Energy Outlook 2016 report shows that the current, global usage of wind power for electricity generation increased again in 2016. Throughout the world, wind turbine installed capacity reached 486,790 MW, while the annual installed wind turbine capacity has increased significantly [5]. In 2016, approximately 54,464 MW of wind turbine generator capacity was installed throughout the world. In the future, the usage of wind power is likely to continue to increase significantly.

The Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy of Thailand, proposed a renewable energy development strategy. Targeting the use of renewable energy to 20% of the nation's energy use by the year 2036, wind power could contribute 3,002 MW of wind power installed capacity across the country [4].

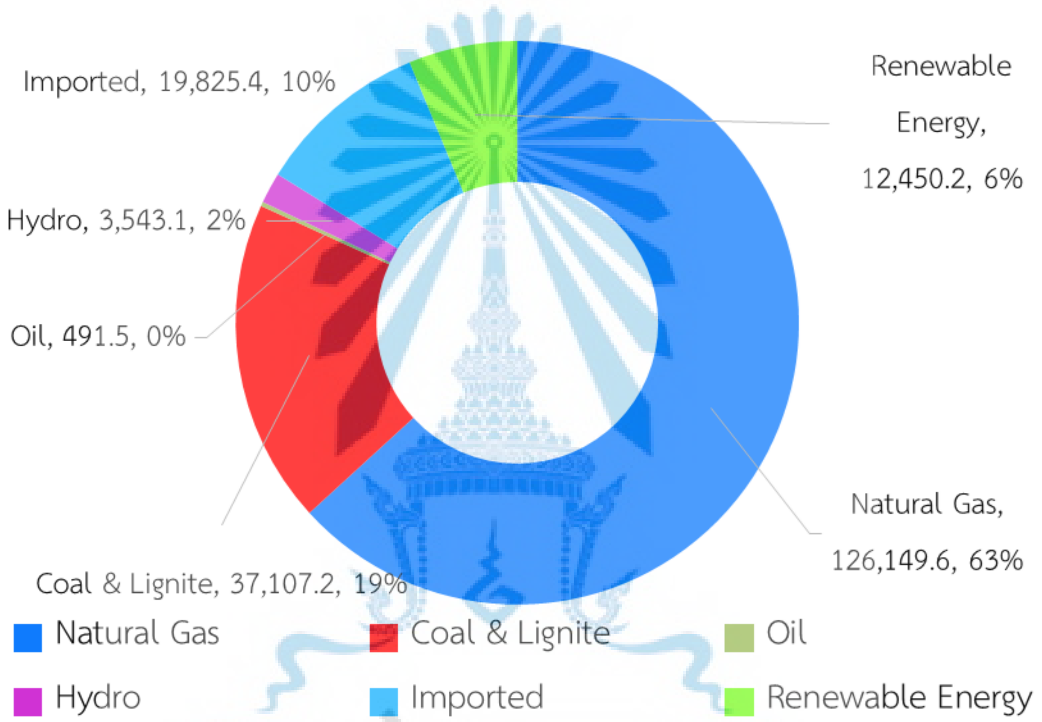

Figure 1.3 Thailand’s domestic power generation ratio attributed by fuel type in 2016 [3].

The country recently experienced a massive power blackout in southern Thailand after a transmission failure in Prachuap Khiri Khan province, in May 2013. According to the Power Development Plan in 2010 (PDP2010) [6], in order to reduce the risk of such blackouts occurring in the future, coal-fired power plants will be implemented, either as a 800 MW plant in Krabi or a 2,000 MW plant in Tepha district, Songkhla provinces (Energy Policy and Planning Office, Ministry of Energy, 2012). However, the people in these areas are concerned about the environmental impacts, the health impacts, and the impacts on the way of life in these regions. They have expressed their opposition to these projects, notably through the Environmental Impact Assessment (EIA) and the Environment Health Impact Assessment (EHIA).

At present, the energy consumption of the southern part of Thailand, under the authority of the Provincial Electricity Authority (PEA) and consisting of 18 provinces, requires 2,450 MW of electricity supply. While the local power plants can generate 3,171 MW, the Electricity Generating Authority of Thailand (EGAT) has declared that only 2,406 MW can operate as firm power plants. Further, since a reserve power of 15% (approximately 400 MW) of power consumption needs to be planned in the energy mix, 500 MW of power is supplied from the central region of Thailand. Thus, EGAT has to import power from the central part of the country in order to secure the power system in southern Thailand. The main power plants in southern Thailand consist of one 1,476 MW [7] and one 824 MW [8] natural gas combined cycle power plants in Songkhla and Nakhon Si Thammarat provinces; 240 MW [9] and 72 MW [10] hydropower plants in Suratthani and Yala provinces; and a 244 MW [11] diesel and a 315 MW [12] fuel oil thermal power plants in Suratthani and Krabi provinces. Moreover, the non-firm Very Small Power Producer (VSPP) from biogas, biomass, and municipal solid waste (MSW) energy sources, with generation capacity less than 10 MW, is approximately 843 MW [13] in total in southern Thailand.

Thailand continuously encounters energy risks due to the fact that it’s power generation relies mainly on natural gas consumption, accounting for over 63% of the power generation in the country. Once the natural gas reserves and supply have some problems, these have impacts on the national energy security. The maintenance of natural gas reserves in the Joint Development Area (JDA A18) during June-July 2014 affected the energy security in southern Thailand. Some parts of the combined cycle power plant in the Chana district had to shut down, with the loss of 710 MW from a total of power generation in southern Thailand, while the peak demand of the region is 2,450 MW. This required 700 to 950 MW of energy transferred from the central part of Thailand, along with importing energy from Malaysia. The other power plants had to fully operate, notably through the 824 MW of a combined cycle power plant at Khanom, 315 MW of crude oil thermal power plant at Krabi, 244 MW diesel thermal power plant at Suratthani, 240 MW hydropower plant at Suratthani, 72 MW hydropower plant at Yala and another 15 MW of renewable energy based power plants.

AEDP2015 has clearly projected an installed capacity totaling 3,002 MW of wind power in 2036, with Thailand currently having an wind power installed capacity of 585 MW. All of the existing wind power plants are installed onshore. Wind power in Thailand is constrained by the relatively limited wind potential and the land-use. Wind resource usually relies on region and climatology of the study area. Being located next to equatorial zones, the climate of Thailand is classified as tropical wet, which is characterized by low wind speed zones. Consequently, both of the onhore and the offshore wind resources need to be accurately identified in order to achieve the targets of the AEDP 2015.

Offshore wind energy is emerging as an interesting alternative renewable energy source for power generation as it has the potential to mitigate climate change, increase energy security and stimulate the global economy. The cumulative installed capacity of offshore wind power plants worldwide approached the 14,384 MW mark in 2016, with projections of the average rate equivalence increasing at 3.9% during the 2015 to 2020 period [14]. However, most of these existing offshore wind power plants are in specific locations, such as the North Sea, the Baltic Sea, the Irish Sea, the Atlantic Ocean, and China's East Coast. Globally, renewable energy installations accounted for more than 56% of the net additions to the global power capacity in 2013 [15]. At present, the important offshore wind power plants outside of Europe are located in China, while offshore wind power is in the early phase of development in Japan, South Korea, Taiwan, Vietnam and the United States.

The aim of this dissertation was to perform wind resource assessments for both onshore and offshore areas of Thailand. More specifically, the onshore wind energy potential in Thailand is assessed by using the Regional Atmospheric Modeling System (RAMS) at a 9 km resolution. Further, the offshore wind resource assessment of the Gulf of Thailand is studied. On the one hand, the wind resource in the northern part of the Gulf of Thailand (GoT) is assessed with the Mesoscale Compressible Community (MC2) atmospheric model, along with the Modern-Era Retrospective Analysis for Research and Applications (MERRA) climatic database. On the other hand, the wind resource for the entire Gulf of Thailand is studied, where the Weather Research and Forecasting (WRF) atmospheric model, along with the NCEP/NCAR R2 reanalysis climatic database, are applied to create wind resource maps at 80 m, 100 m, and 120 m above mean sea level (amsl) to identify the potential surface areas for the development of offshore wind power plants in the GoT. Ultimately, the thesis provides benefits for improving the wind power knowledge in Thailand in general, and in the Gulf of Thailand in particular. Suitable areas for the installation of wind power plants, notably in the Gulf of Thailand, are identified to facilitate the decision-making process in the implementation of energy policies in the country.

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CHAPTER 2

Assessment of Onshore Wind Energy Potential using Regional Atmospheric Modeling System (RAMS) for Thailand

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Foreword

Besides being involved in defining the general methodology of the research work, the main contributions of the candidate to this paper were in the preparation of the climatic data, the modeling operations, the interpretation of the results, and drafting the paper. In the preparation of the climatic data and the scientific and technical modeling operations of the wind resource, the candidate was responsible of all these activities, while the other activities were performed by the research team, with the candidate nonetheless playing a significant role. This research was published in Energy Procedia in 2014.

Energy Procedia, published by Elsevier, is an Open Access publication focussing on publishing high-quality conference proceedings across the energy field. According to the Elsevier website, this journal enables the fast dissemination of conference papers in dedicated online proceedings volumes made freely available on ScienceDirect, accessible to millions of researchers worldwide. The proceedings series is indexed in Scopus, the largest abstract and citation database of peer-reviewed literature (from the journal's website: https://www.journals.elsevier.com/energy-procedia). This paper was selected and peer-reviewed under the responsibility of the Organizing Committee of the 2013 International Conference on Alternative Energy in Developing Countries and Emerging Economies (AEDCEE), held in Bangkok, Thailand, in 2013.

Assessment of Onshore Wind Energy Potential using Regional Atmospheric Modeling System (RAMS) for Thailand

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Abstract

This paper presents an assessment of the onshore wind energy potential in Thailand using the Regional Atmospheric Modeling System (RAMS). A 9 km resolution, 1,150 km by 1,750 km, wind resource map at 120 m elevation above ground level (agl) is produced based on the NCEP reanalysis database for the three year period of 2009-2011. The onshore wind resource map is validated by comparing the modeling results to observed wind data at 100 m agl from the Pollution Control Department (PCD) of Thailand, and at 120 m agl from the National Research Council of Thailand (NRCT). The Mean Square Error (MSE) is computed and is used as the main criterion to evaluate the simulation results. Results showed that, for the study area, the annual mean wind speeds at 120 m agl are in the range of 1.60-5.83 m/s. For its part, the maximum annual mean power density at 120 m agl is approximately 200 W/m^2 which corresponds to a wind power density of Class 2. Results show that the region has a good wind regime in the mountain areas of western, southern and eastern Thailand. Further assessment is needed to determine if the onshore wind energy resource could be developed and exploited in order to achieve national renewable energy policy targets in Thailand.

Keywords: wind energy, wind resource assessment, onshore wind energy, power density, and Regional Atmospheric Modeling System (RAMS).

2.1 Introduction

Largely, because of its environmental benefits, wind energy is being developed worldwide as a reliable energy source. The Global Wind Energy Council (GWEC) reported that the global cumulative installed capacity in 2012 was 238,050 MW [1].

In the development of a wind energy project, high-quality wind data is required in order to achieve a proper wind resource assessment campaign. For its part, most of the scientific literature scrutinize the use of mesoscale modeling to assess wind energy resources, such as the fifth-generation of the mesoscale model (MM5), the Mesoscale Compressible Community (MC2) and the Karlsruhe Atmospheric Mesoscale Modeling (KAMM) [2-4].

On the other hand, the Regional Atmospheric Modeling System (RAMS) could also be applied to evaluate atmospheric parameters such as turbulence fluxes over the study area [5]. In one study, RAMS modeling was compared with aircraft, wind profiler, Lidar, tethered balloon and RASS data. It was shown that the RAMS model results were in good agreement with the validation data [6].

In this study, RAMS is used to assess the onshore wind energy resource potential of Thailand at 120 m above ground level with a 9 km resolution.

2.2 Methodology

2.2.1 Study Area

In this study, in order to cover the entire country of Thailand (Figure 2.1), a 1,150 km by 1,750 km mesoscale grid having a 9 km resolution is used.

2.2.2 Theoretical Considerations

Wind is a natural process, stimulated notably by differences in temperature, barometric pressure, and the Coriolis Effect.

In the Earth’s atmospheric boundary layer (ABL), the vertical distribution of wind speed above ground can be estimated by the logarithmic profile (log law), a semi-empirical relationship., which is usually limited to a maximum altitude of approximately 200 m agl [7].

For its part, in a free atmosphere, the wind speed, u_z (m/s), at a height z (m) above ground level can be estimated by the equation as shown in Eq. (2.1).

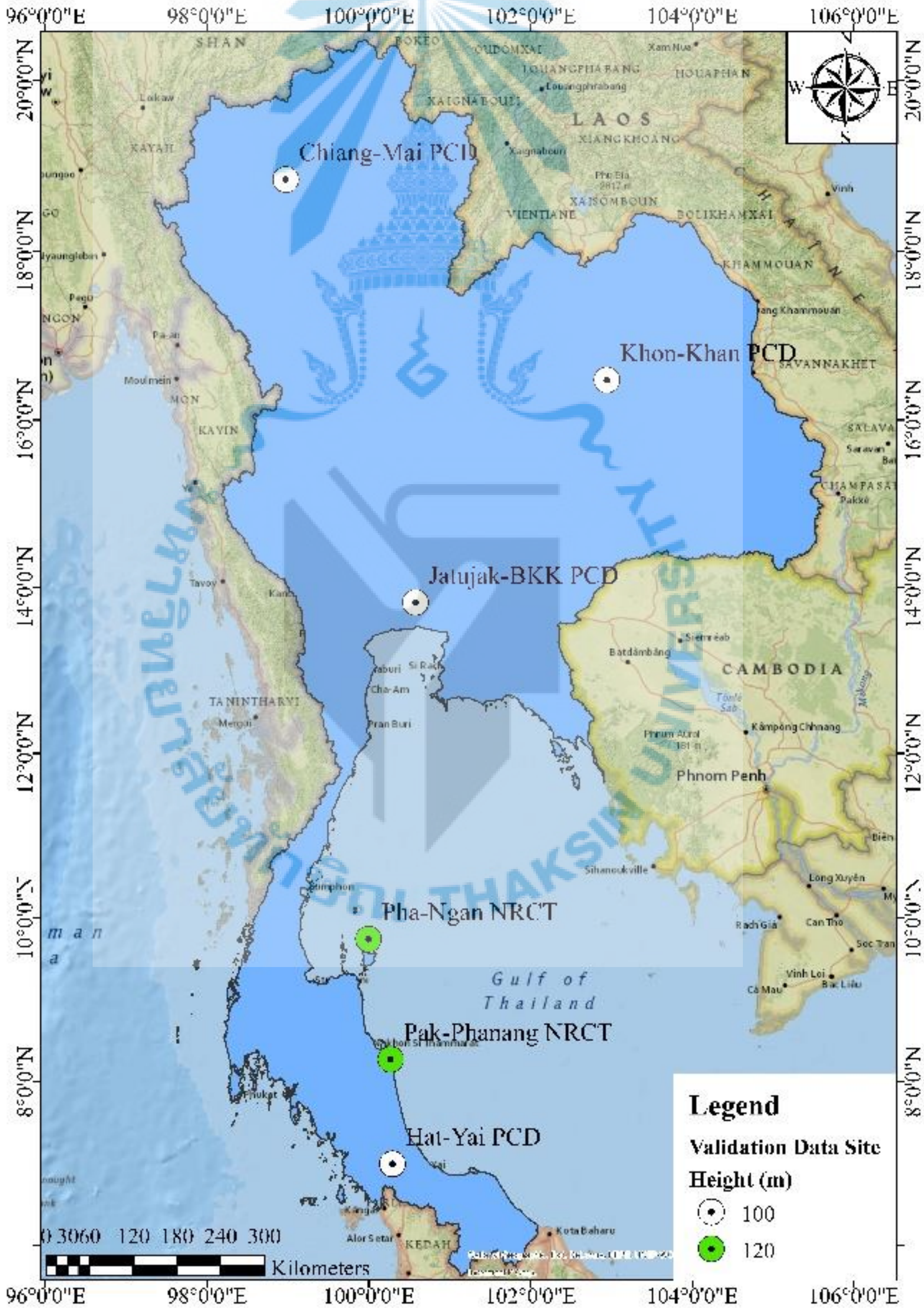


Figure 2.1 The study area and locations of met towers of the Pollution Control Department (PCD) and the National Research Council of Thailand (NRCT).

$$u_z = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) + \psi\left(z, z_0, L\right)\right] \tag{2.1}$$

where u_* is the friction velocity or shear velocity (m/s), k is the Von Karman constant (0.41), d is the zero plane displacement (m), z_0 is the surface roughness (m), ψ is a stability term, and L is the Monin-Obukhov stability parameter. Under neutral stability terms, $z/L = 0$ and ψ will have a value of zero. The resulting equation, called the logarithmic profile or log law, is given by:

$$u_z = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right)\right] \tag{2.2}$$

For its part, the wind power density can be computed by the following equation:

$$P_w = \frac{1}{2}\rho A V^3 \tag{2.3}$$

where P_W is the power from the wind (W), ρ is the air density (kg/m^3), A is the cross-sectional area of the rotor (m^2), and V is the wind velocity (m/s).

The air density at altitudes higher than sea level is a function of both the atmospheric pressure and temperature and can be estimated by:

$$\rho\left(z\right) = \frac{P_0}{\left(RT\right)\exp\left(\frac{-gz}{RT}\right)} \tag{2.4}$$

where ρ_0 is the atmospheric pressure at standard sea level (kg/m^3), R is the specific gas constant (J/mol Kelvin), T is the temperature (Kelvin), g is the gravity constant (m/s^2), and z is the height above sea level (m).

Energy from the wind can be converted into rotational mechanical energy by the turbine blades. In practice, all the energy from the wind cannot be transferred to mechanical energy. This would mean that the actual mass of air that hits the turbine blades would stop completely within the cross-sectional area of the turbine blades. As such, the output power from a wind turbine rotor can be computed using Eq. 2.5 [8].

$$P_{WT} = P_W C_P = \frac{1}{2}\rho A_R V^3 C_p \tag{2.5}$$

where P_W is the power of the wind (W), C_p is the power coefficient of the wind turbine A_R is the swept area of wind turbine rotor (m^2).

2.2.3 Regional Atmospheric Modeling System (RAMS)

The Regional Atmospheric Modeling System (RAMS), is a highly versatile numerical code developed by scientists at Colorado State University for simulating and forecasting meteorological phenomena, and for depicting the results [5]. The model has three major components:

I. An atmospheric model which performs the actual simulations.

II. A data analysis package which prepares initial data for the atmospheric model from observed meteorological data.

III. A post-processing model visualization and analysis package that interfaces the atmospheric model output with a variety of visualization software utilities.

In RAMS, the atmospheric model is constructed around the full set of primitive dynamical equations which govern atmospheric motions, and supplements these equations with optional parameterizations for turbulent diffusion, solar and terrestrial radiation, moist processes, sensible and latent heat exchange between the atmosphere, multiple soil layers, a vegetation canopy, surface water, the kinematic effects of terrain, and cumulus convection. Even though RAMS is fundamentally a limited-area model, the model can be configured to cover an area as large as a planetary hemisphere. This allows a user to simulate mesoscale and large-scale atmospheric systems. For its part, there is no lower limit to the domain size or to the mesh cell size of the model's finite difference grid. Microscale phenomena such as boundary layer eddies and tornadoes, as well as sub-microscale turbulent flow over buildings, have all been simulated with the RAMS model. In addition, compact atmospheric systems such as thunderstorms can be resolved in a local fine mesh grid while a coarser grid is used for the larger scale environment of the system in RAMS by the model’s two-way interactive grid nesting. Generally, RAMS is operated in a UNIX operating system. Finally, the model’s code is written almost exclusively in FORTRAN 77 using some common extensions. However, the model uses some C code to facilitate its I/O procedures and its dynamic memory allocation functions.

The general equations used by RAMS are the standard hydrostatic or non-hydrostatic Reynolds-averaged primitive equations. All variables, unless otherwise denoted, are grid-volume averaged quantities where the overbar has been omitted. The symbols are defined in Table 2.1. The non-hydrostatic equations are:

Equations of motion:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \theta\frac{\partial \pi'}{\partial x} + fv$$
$$+\frac{\partial}{\partial x}\left(K_m\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) \tag{2.6}$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \theta\frac{\partial \pi'}{\partial y} + fu$$
$$+\frac{\partial}{\partial x}\left(K_m\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) \tag{2.7}$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \theta\frac{\partial \pi'}{\partial z} - \frac{g\theta_v'}{\theta_0}A$$
$$+\frac{\partial}{\partial x}\left(K_m\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) \tag{2.8}$$

Thermodynamics equation:

$$\frac{\partial \theta_{il}}{\partial t} = -u\frac{\partial \theta_{il}}{\partial x} - v\frac{\partial \theta_{il}}{\partial y} - w\frac{\partial \theta_{il}}{\partial z} + \frac{\partial}{\partial x}\left(K_h\frac{\partial \theta_{il}}{\partial x}\right)$$
$$+\frac{\partial}{\partial y}\left(K_h\frac{\partial \theta_{il}}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial \theta_{il}}{\partial z}\right) + \left(\frac{\partial \theta_{il}}{\partial t}\right)_{rad} \tag{2.9}$$

Water species mixing ratio continuity equation:

$$\frac{\partial r_n}{\partial t} = -u\frac{\partial r_n}{\partial x} - v\frac{\partial r_n}{\partial y} - w\frac{\partial r_n}{\partial z} + \frac{\partial}{\partial x}\left(K_h\frac{\partial r_n}{\partial x}\right)$$
$$+\frac{\partial}{\partial y}\left(K_h\frac{\partial r_n}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial r_n}{\partial z}\right) \tag{2.10}$$

Mass continuity equation:

$$\frac{\partial \pi'}{\partial z} = -\frac{R\pi_0}{c_v\rho_0\theta_0}\left(\frac{\partial \rho_0\theta_0 u_0}{\partial x} + \frac{\partial \rho_0\theta_0 v}{\partial y} + \frac{\partial \rho_0\theta_0 w}{\partial z}\right) \tag{2.11}$$

For its part, the hydrostatic option in RAMS replaces the vertical equation of motion and the mass continuity equation with the hydrostatic equations:

$$\frac{\partial \pi}{\partial z} = -\frac{g}{\theta_v} + g\left(r_T - r_v\right) \tag{2.12}$$

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \tag{2.13}$$

Table 2.1 Parameterization for Regional Atmospheric Modeling System.

Symbol	Definition
u	East-west wind component
v	North-south wind component
w	Vertical wind component
f	Coriolis parameter
K_m	Eddy viscosity coefficient momentum
K_h	Eddy viscosity coefficient head and moisture
θ_{il}	Ice-liquid potential temperature
r_n	Water mixing ratio species of total water, rain, pristine crystals aggregates, and snow
ρ	Density
con	Subscript denoting tendency from convective parameterization
rad	Subscript denoting tendency from radiation parameterization
res	Subscript denoting tendency from resolvable scale microphysical parameterization
G	Gravity
r_t	Total water mixing ratio
r_v	Total vapor mixing ratio
π	Total Exner function
π'	Perturbation Exner function
θ_v	Virtual potential function
p	Pressure

2.2.4 Statistical Validation of Wind Resource Results

In this work, to validate the wind resource map, monthly mean speed at 100 m agl are extracted from the RAMS modeling's output to the location where the met towers of the Pollution Control Department of Thailand (PCD) and the National Research Council of Thailand (NRCT) are located, as illustrated in Figure 2.1. The simulation results are compared with observed monthly mean wind speeds from these met towers. In addition, for this study, the mean square error (MSE) is used to evaluate the difference between the simulation results and the observational data, as expressed by:

$$MSE = \frac{1}{N}\sum_{i=1}^{n}(P_i - O_i)^2 \tag{2.14}$$

where P_t is the predicted monthly mean wind speed by RAMS (m/s), O_t is the observed monthly mean wind speed at the met tower location (m/s), i is the time interval (in months), and N is the number of data.

2.3 Results and Discussion

Figure 2.2 presents the wind resource map at 120 m agl for Thailand for the three year period of 2009-2011. Results show that, for the study area, the annual mean wind speeds at 120 m agl are in the range of 1.60-5.83 m/s.

For its part, Figure 2.3 presents the monthly wind resource maps at 120 m agl for Thailand for the three year period of 2009-2011. Results show that, for the study area, the monthly mean wind speeds at 120 m agl are in the range of 0.97-9.67 m/s.

Results tend to show that the country has a good wind resource potential along the western part of Thailand and in a few regions of Meahongson province, Prachuab Kiri Khun province. In addition, the southern part of Chumporn province, Ranong province, and Surat Thani province, and the eastern parts of Nakhonnayok and Chanthaburi provinces, also have good wind regimes with annual mean wind speeds in the range of 6.01-7.00 m/s. The maximum annual mean power density in these regions is approximately 200 W/m^2 at 120 m agl, which corresponds to a wind power density class of 2 at 120 m agl, as is shown in Figure 2.4.

The mean square errors (MSE) between both the computed annual mean wind speeds and the observed annual mean wind speeds at the met tower locations are shown in Table 2.2. The power law profile using a 1/7 power coefficient was used to extrapolate the observed mean wind speeds to 120 m agl. Results show that the MSE is in the range of 0.50-4.38 m^2/s^2. The comparison of the computed wind speeds and the observed wind speeds at the met tower locations are reasonably good, which confirms the validity of the wind resource map. However, to mitigate these results, it is important to note that most of these met tower stations (4 of 6) were not installed for wind energy assessment purposes, but rather to gather data in regards to the dispersion of pollutants in the atmosphere by the Pollution Control Department (PCD) of Thailand. As a consequence, it was decided to be prudent with the comparison because of issues pertaining to the verification and quality of the met tower data. Nevertheless, the comparisons show a relatively good agreement between the computed wind speeds and the observed wind speeds at the met tower locations. The validation indicates that the computed wind resource map could be used for initial site surveying for potential wind energy project developments.

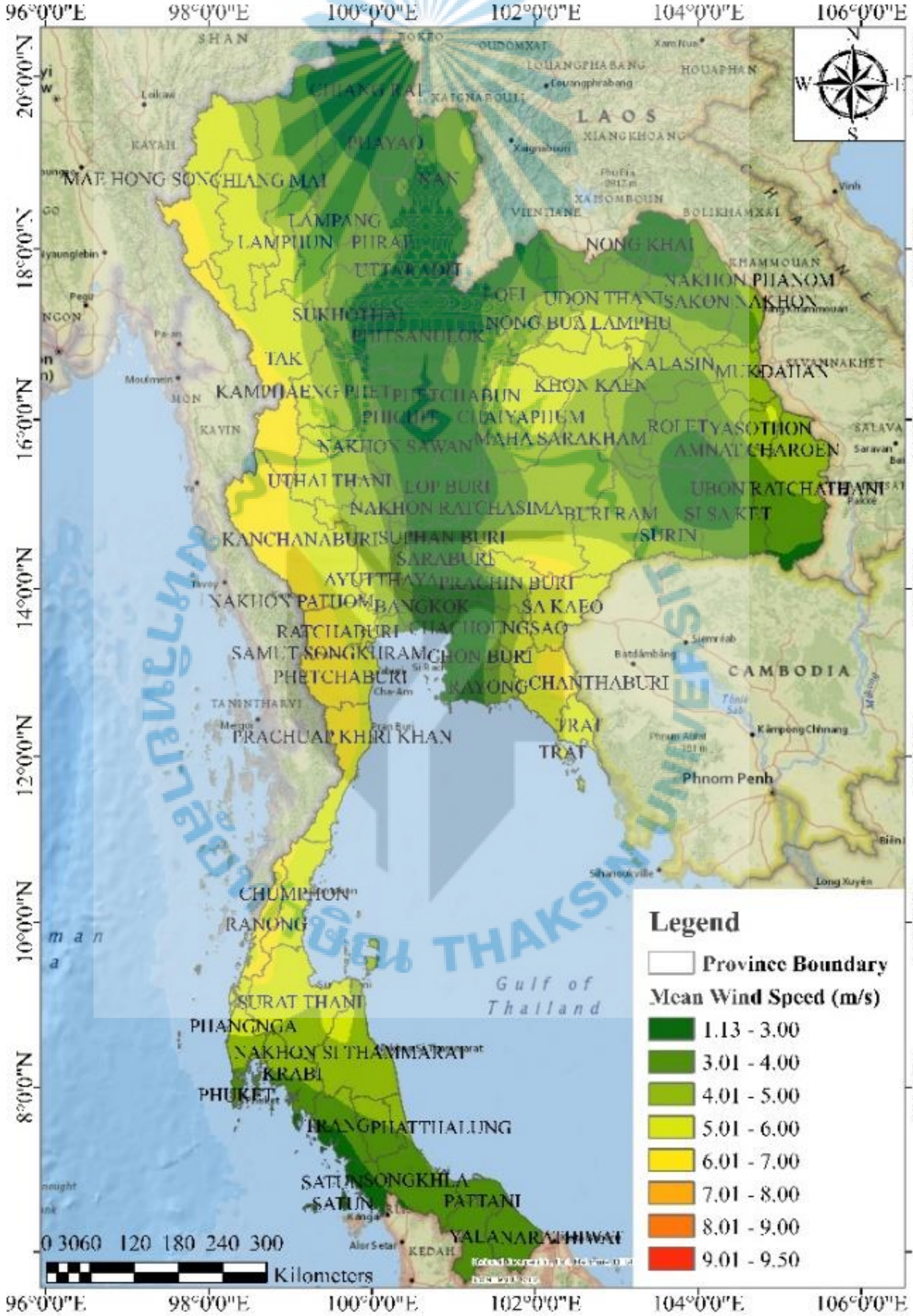
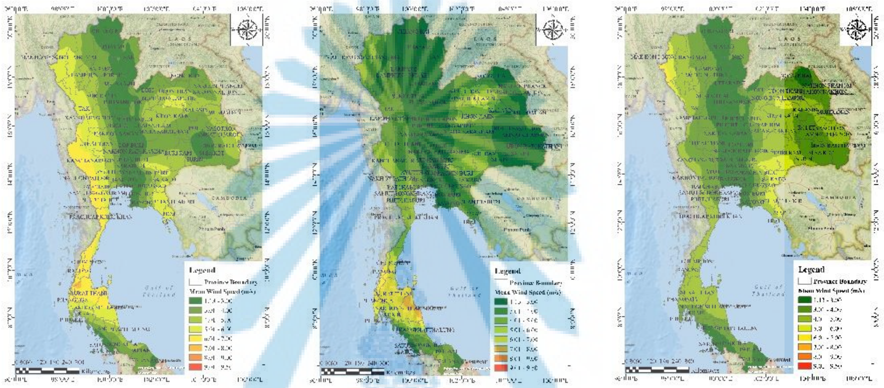


Figure 2.2 Annual mean wind speeds at 120 m agl over Thailand for the three year period of 2009-2011.



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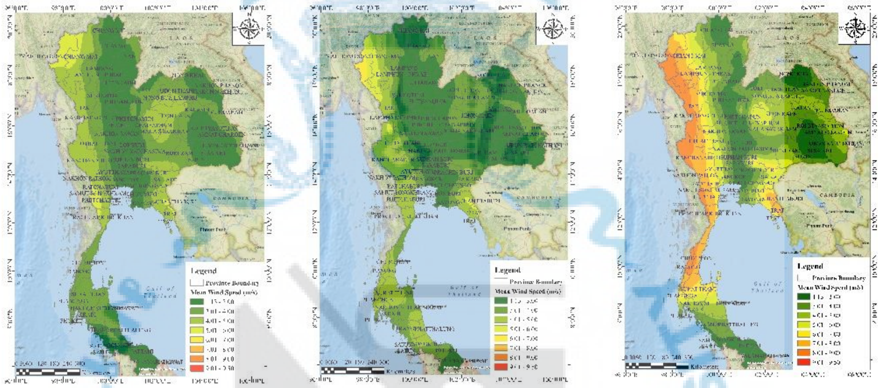

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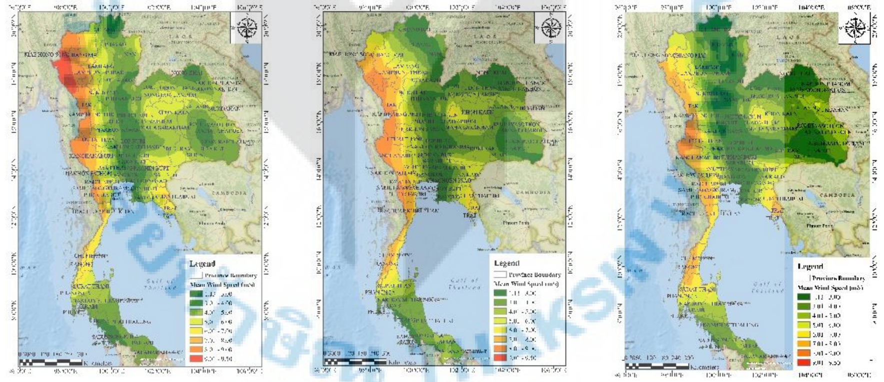

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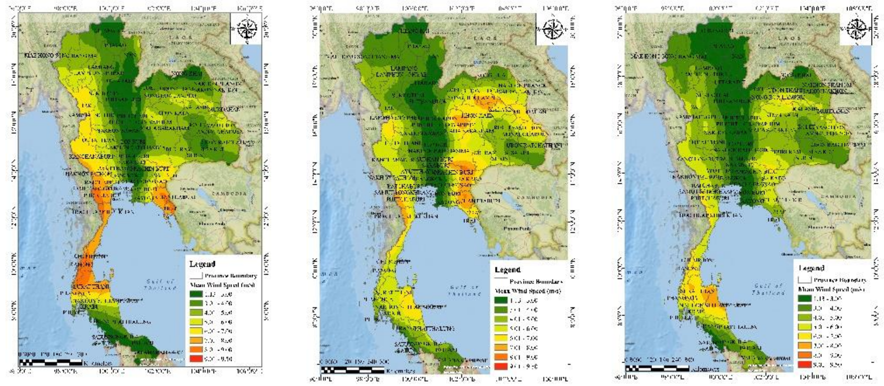

October November December

Figure 2.3 Monthly mean wind speeds at 120 m agl over Thailand for the three year period 2009-2011.

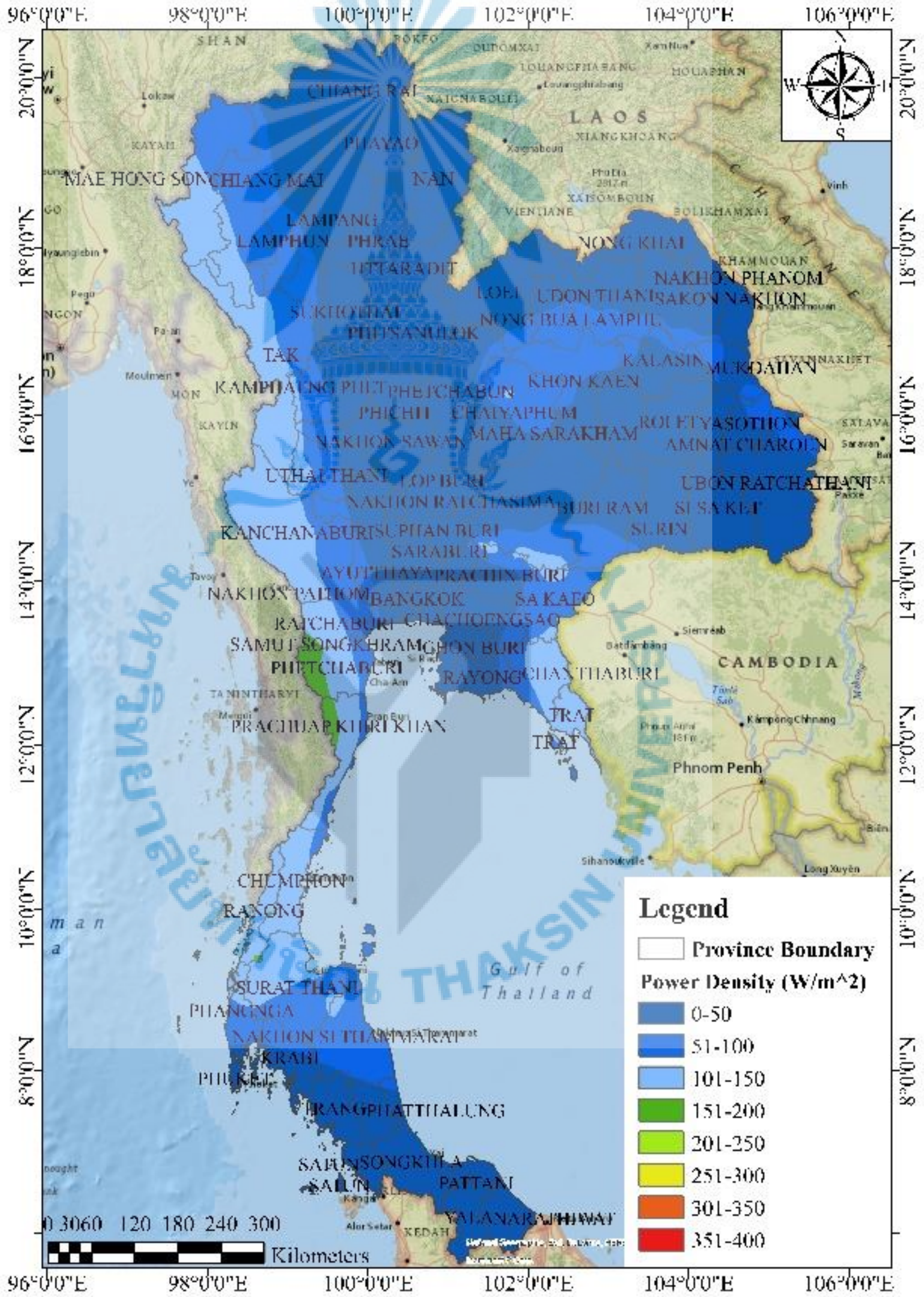

Figure 2.4 Mean wind power density at 120 m agl over Thailand for the three year period of 2009-2011.

Table 2.2 Validation results.

No.	Met Station	Observed Mean Speed (m/s)	Predicted Mean Speed (m/s)	Mean Square Error (m^2/s^2)
1	Chiang-Mai	3.41	4.19	2.87
2	Khon-Kan	4.42	4.77	0.50
3	Jatujak	3.95	2.63	1.95
4	Phangan	4.11	4.86	4.38
5	Pak-Phanang	4.97	4.65	3.76
6	Hat Yai	4.19	3.49	1.08

Furthermore, in this study, the technical power potential (TPP) of Thailand is calculated at 120 m agl and is classified into three zones. Zone I is defined as areas where the annual mean wind speed is in the range of 3.5-5 m/s; Zone II is for areas where the annual mean wind speed is in the range of 5-6 m/s; and Zone III is for areas where the annual mean wind speed is above 6 m/s (at 120 m agl). The classified TPP zones are presented in Figure 2.5.

In order to estimate the TPP at 120 m agl in each classified zone, GIS-based tools are used. The TPP is evaluated using a virtual wind turbine having a nominal power of 1 MW and a 120 m hub height. For its part, the area occupied by the virtual wind turbine is set at 0.42 km^2. In the TPP analysis, no provision is made with regards to landscape conservation, migratory corridors for birds, and other constraints such as access to roads, distance to electricity transmission lines, and land availability. Table 2.3 shows the results of the technical power potential for the three classified zones. Results show that Zone 1 has a total surface area of approximately 127,000 km^2 which corresponds to approximately 23% of the total surface area of Thailand. For its part, the TPP for Zone 1 is estimated at 53,080 MW. In regards to Zone 2, results show that it has a total surface area of approximately 115,000 km^2, which corresponds to approximately 21% of the total surface area of the country. The TPP for Zone 2 is estimated at 48,016 MW. Finally, results show that the total surface area of Zone 3, is approximately 45,000 km^2, which corresponds to approximately 8% of the total surface area of Thailand, while its TPP is estimated at 18,585 MW.

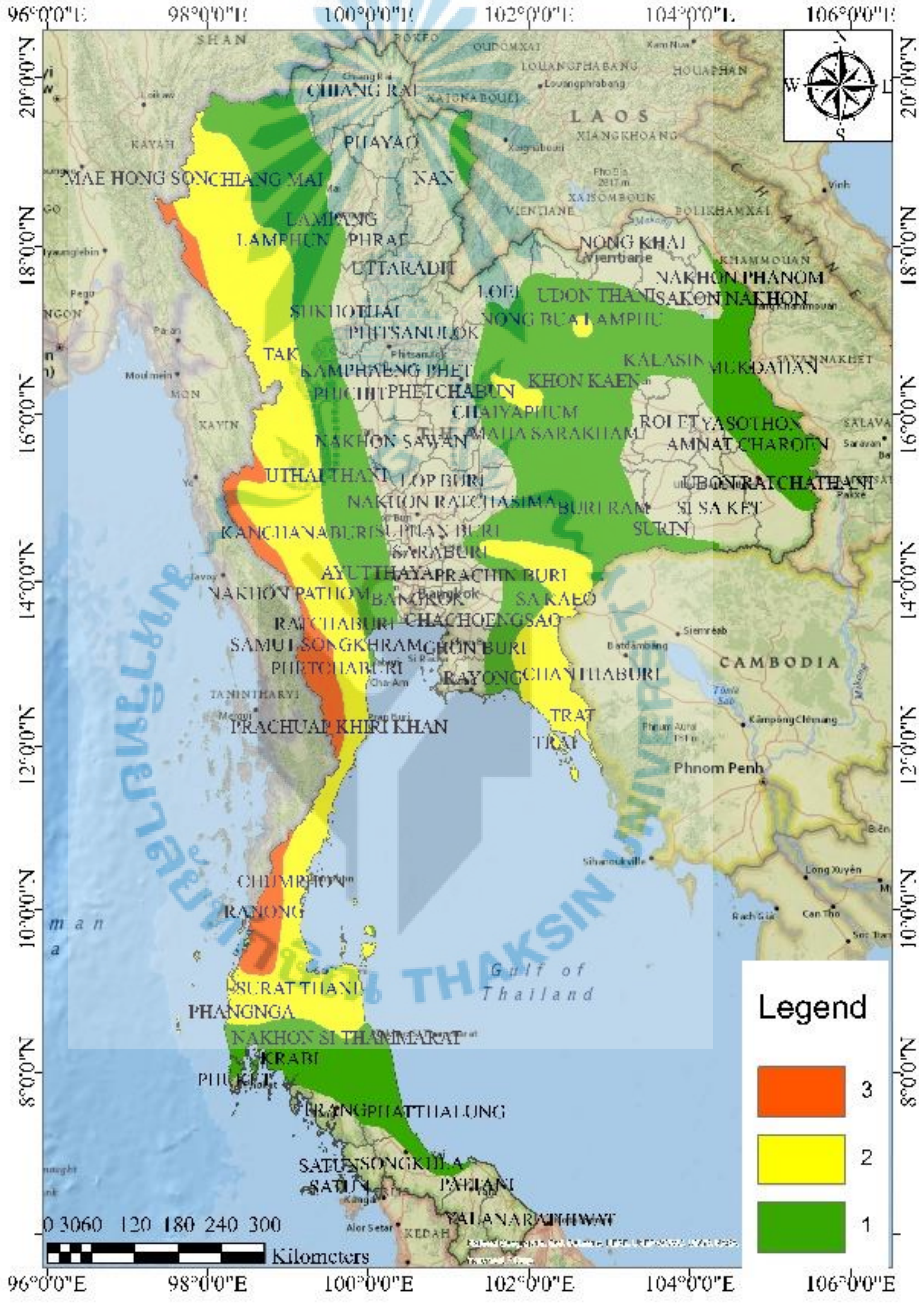

Figure 2.5 Classified technical power potential in Thailand for the three year period of 2009-2011.

Table 2.3 Technical potential and installed capacity.

Zone	Technical Power Potential Area (km^2)	Surface Area of Thailand Covered by Zone (%)	Technical Power Potential (MW)
I	127,352	22.8	53,080
II	115,220	20.6	48,016
III	44,590	8.0	18,585

2.4 Conclusion

This paper presents an assessment of the onshore wind energy potential in Thailand using the Regional Atmospheric Modeling System (RAMS). A 9 km resolution, 1,150 km by 1,750 km, wind resource map at 120 m elevation agl was produced based on the NCEP reanalysis database for the three year period of 2009-2011. The onshore wind resource map was validated by comparing the modeling results to observed wind data at 100 m agl from the Pollution Control Department (PCD) of Thailand, and at 120 m agl from the National Research Council of Thailand (NRCT). The Mean Square Error (MSE) was computed and was used as the main criterion to evaluate the simulation results. Results showed that, for the study area, the annual mean wind speeds at 120 m agl were in the range of 1.60-5.83 m/s. For its part, the maximum annual mean power density at 120 m agl was approximately 200 W/m^2 which corresponds to a wind power density of Class 2. Results showed that the region has a good wind regime in the mountain areas of western, southern and eastern Thailand. Further assessment is needed to determine if the onshore wind energy resource could be developed and exploited in order to achieve national renewable energy policy targets in Thailand.

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CHAPTER 3

Wind Resource Assessment in the Northern Gulf of Thailand using Atmospheric Modeling and Climatic Database

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Foreword

In Chapter 3, the assessment of the offshore wind resource in the northern part of the Gulf of Thailand is presented with a particular emphasis on the Bay of Bangkok. Besides being involved in defining the general methodology of the research work, the main contributions of the candidate to this paper were for the preparation of the MERRA climatic data, the modeling operations, the interpretation of the results, and drafting the paper. In the preparation of the climatic data and the scientific and technical modeling operations of the wind resource, the candidate was responsible of all these activities, while the other activities were performed by the research team, with the candidate nonetheless playing a significant role. This research was published in the Journal of International Renewable Energy Journal in 2016.

The purpose of the International Journal of Renewable Energy is to disseminate articles relating to renewable energy. According to its website, the Journal encourages and supports the exchange of renewable energy academic information, in order to develop renewable energy technology for the public reader. The Journal also carries reviews on important development areas and these may either be submitted in the normal way or invited by the editors.

Wind Resource Assessment in the Northern Gulf of Thailand using Atmospheric Modeling and Climatic Database

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Abstract

An assessment of the wind energy potential is an important process in the development of wind power projects. An accurate and precise assessment requires long term wind data recorded over at least one year by installing a standard met mast, which consumes most of the costs in the early stages of development. Therefore, this research aims to assess the wind resource in the northern part of the Gulf of Thailand, by using the Mesoscale Compressible Community (MC2) atmospheric model and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) climatic database, in order to investigate the mean wind speed and the technical power potential (TPP). Moreover, the comparison has been made using the Weather Research and Forecast (WRF) atmospheric modeling along with MERRA climatic database. Results show that the annual mean speed is in the range of 2.3 to 7.5 m/s and the technical power potential, over an area of 1,500 km^2, is in the range of 2,500 MW. The comparison of the results, in terms of the measured/predicted ratio (M/P) and the percent mean relative error (PMRE), is in the range of 0.70 to 0.96, and 4 to 42%, respectively. Regional outcomes from this study can be applied to develop offshore wind power projects in Thailand.

Keywords: MC2, offshore wind, MERRA, technical power potential

3.1 Introduction

Almost 70% of the fuel needed for power generation in Thailand is natural gas; this affects the energy security of the country. The Government of Thailand enacted the Power Development Plan (PDP 2015) in order to increase the share of renewable energy in power generation. By the end of the PDP2015, the aim of policymakers is to reduce natural gas to a share of 30-40% from the current 64%. The proportion of renewable energy will rise to 15-20% from the current 12%. The new plan foresees a rising share of coal and lignite, up from currently 20% to 20-25% in 2036. An unspecified amount of this capacity is supposed to be delivered as “clean coal” by carbon capture and storage technology. Hydropower should deliver 15-20%, while a share of 0-5% is expected from nuclear power. All shares mentioned referring to total electricity production by focusing on wind power of 3,002 MW in 2036 [1]. At present, the wind power capacity in Thailand is 222.7 MW [2]. All of the wind power generation in Thailand is onshore, which is complicated by land-use issues such as biological, agricultural and inhabited areas. Recently, 7.5 GW offshore wind power has been installed throughout the world. More than 87% of it is installed off Northern Europe, 14% off China east coast and the rest in Japan, Korea and the US. To develop any offshore wind power project, the developer needs to begin with an investigation on offshore wind resources [3]. The Gulf of Thailand (GOT) (Figure 3.1) is situated from 6º N to 13º30’ N latitude and 99ºE to 104º E longitudes. It is a shallow, semi-enclosed tropical marine embayment situated in the South China Sea, which is surrounded by the land mass of Malaysia, Thailand, Cambodia and Vietnam. The GOT is relatively shallow with a mean depth of 45 m and a maximum depth of 80 m [4]. Wind power over this area has been estimated using the Mesoscale Compressible Community (MC2) atmospheric model, along with the National Centers for Environmental Prediction (NCEP) climatic database [9]. The results show the potential areas of development in the Bay of Bangkok. Although, the latest climatic databases, such as the Modern-Era Retrospective Analysis for Research and Applications (MERRA) climatic database are more accurate in regards to the spatial grid. Therefore, the objective of this paper is to investigate the offshore wind energy potential in the Gulf of Thailand using the MC2 model, along with the MERRA climatic database.

3.2 Methodology

3.2.1 Study Area

The study area of this work is selected to investigate the offshore wind energy potential in the Gulf of Thailand, with an emphasis on the northern Gulf of Thailand, as shown as domain 2, the computational domain and globally located of Thailand as shown in Figure 3.1. The two main resolution domains for computational and geophysical are 3 km and 500 m, respectively.

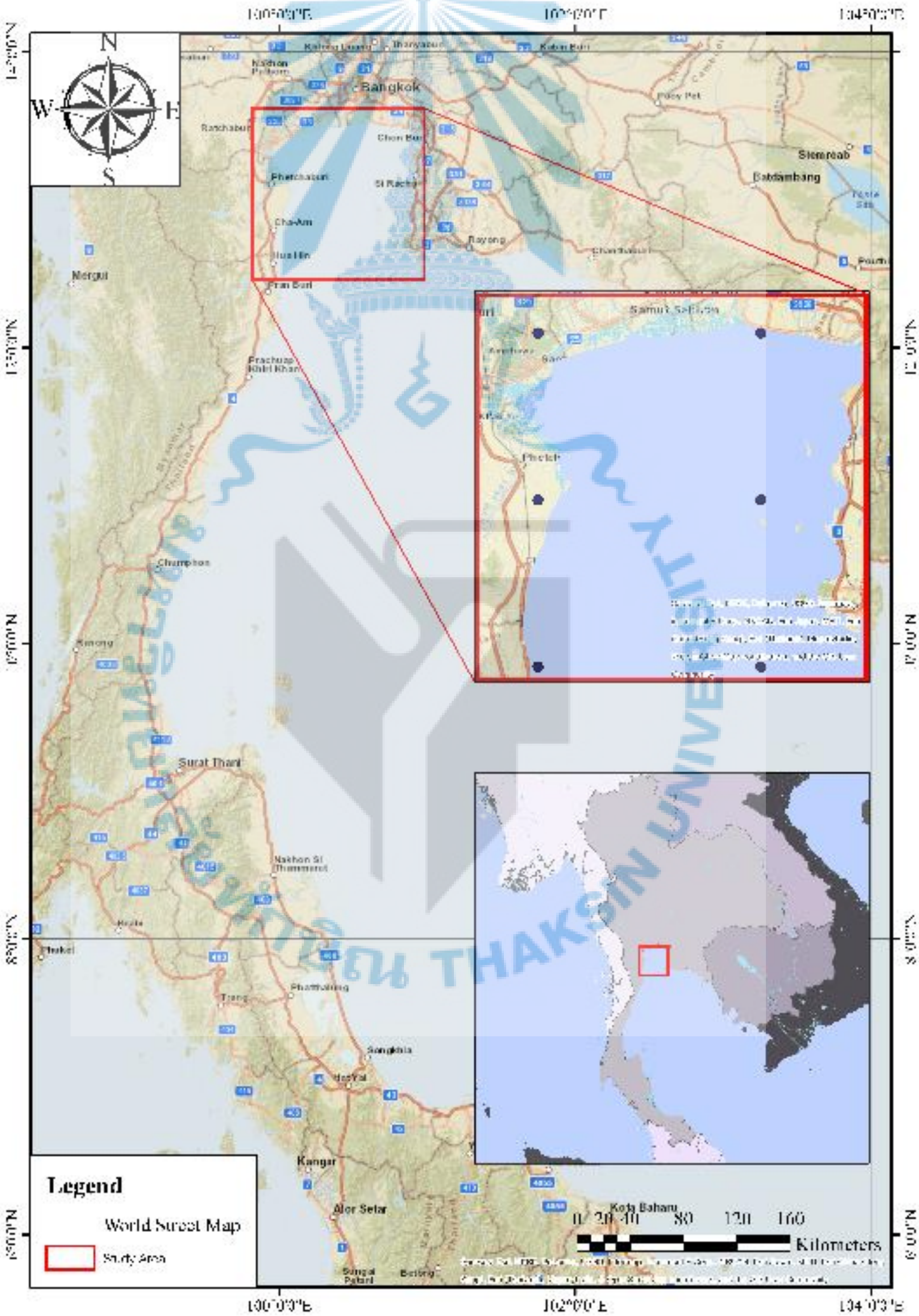


Figure 3.1 The atmospheric model boundary and domain of study area and a horizontal resolution of 2/3-degree longitude by 1/2-degree latitude over the Bay of Bangkok and the northern part of the Gulf of Thailand.

3.2.2 MERRA Database

The Modern-Era Retrospective Analysis for Research and Applications (MERRA) climatic database [5] is a NASA atmospheric reanalysis from satellite data, using the Goddard Earth Observing System Model, Version 5 (GEOS-5) with its Atmospheric Data Assimilation System (ADAS), version 5.2.0. MERRA focuses on historical analyses of the hydrological cycle on a broad range of weather and climate time scales and places the NASA EOS suite of observations in a climate context. MERRA covers the period 1979 to present, continuing as an ongoing climate analysis as resources allow. The GEOS-5 system actively assimilates roughly 2 × 106 observations for each analysis, including about 7.5 × 105 AIRS radiance data. The input stream is rough twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures designed to detect effects such as the presence of clouds. In order to minimize the spurious periodic perturbations of the analysis, MERRA uses the Incremental Analysis Update (IAU) technique. The analysis is performed at a horizontal resolution of 2/3-degree longitude by 1/2-degree latitude and at 72 levels, extending to 0.01 hPa. Some products, such as the instantaneous analysis fields, are available on the native three-dimensional grid. Hourly two-dimensional diagnostic fields are also available at the native horizontal resolution. Figure 3.1 presents the MERRA horizontal resolution of 2/3-degree longitude by 1/2-degree latitude over the Bay of Bangkok and the northern part of the Gulf of Thailand.

3.2.3 Mesoscale Compressible Community (MC2) Model

MC2 is a compressible non-hydrostatic limited area model used to develop wind maps (Benoit et al. [6]). The composition of three-dimensional meteorological data is shown in the form of momentum expression displayed in the spherical coordinate system.

$$RT\frac{\partial q}{\partial X} = fV - K\frac{\partial S}{\partial X} \tag{3.1}$$

$$RT\frac{\partial q}{\partial Y} = fU - K\frac{\partial S}{\partial Y} \tag{3.2}$$

$$RT\frac{\partial q}{\partial z} = -g \tag{3.3}$$

where R is the gas constant for dry air (287 J kg^{-1} K^{-1}), T is the air temperature, q is the natural logarithm of the air pressure, f is the Coriolis parameter $f = \Omega \sin\phi$ with Ω being the angular velocity of the Earth's rotation, and ϕ is the latitude, U and V are the component of horizontal wind along X and Y, $K = (U^2 + V^2)/2$ is the kinetic energy, S is the square of the map scale of a map factor m, and g is the effective gravitational acceleration.

In the MC2 model, thermodynamic variations are decomposed into a basic state and perturbation components, $T = T^* + T^{'}$ and $q = q^* + q^{'}$. When this basic state, representing a stationary isothermal atmosphere in hydrostatic equilibrium, $[\partial q^* / \partial z = -g / RT^*]$ is subtracted from equations (3.1-3.3):

$$R(T^* + T^{'}) \frac{\partial q}{\partial X} = fV - K \frac{\partial S}{\partial X} \tag{3.4}$$

$$R(T^* + T^{'}) \frac{\partial q}{\partial Y} = fU - K \frac{\partial S}{\partial Y} \tag{3.5}$$

$$R(T^* + T^{'}) \frac{\partial q}{\partial z} = g \frac{T^{'}}{T^*} \tag{3.6}$$

Finally, new variables are defined using the generalized pressure $P = RT^* q^{'}$ and a buoyancy $b = gT'/T^*$, with this change of variables, equations 4-6 become:

$$(1 + \frac{b}{g}) \frac{\partial P}{\partial X} = fV - K \frac{\partial S}{\partial X} \tag{3.7}$$

$$(1 + \frac{b}{g}) \frac{\partial P}{\partial Y} = fV - K \frac{\partial S}{\partial Y} \tag{3.8}$$

$$(1 + \frac{b}{g}) \frac{\partial q}{\partial z} = -b \tag{3.9}$$

3.2.4 Topographic data

The topographic data used to create the wind resource maps is taken from the Land Development Department, Ministry of Natural Resources and Environment, Royal Thai Government. The corresponding topographic data consists of the Digital Elevation Model (DEM) at a resolution of 30 m, where the ground elevations are recorded in meters relative to the Mean Sea Level (MSL), based on the World Geodetic System (WGS) 1984 reference datum. Before using the topographic data in the modeling, the database is merged into one large raster file with 90 m by 90 m pixels encompassing the entire region of study as shown in Figure 3.1. The details regarding the land cover and the roughness length [7].

3.2.5 The technical power potential (TPP)

The technical power potential (TPP) is estimated by identifying a current wind turbine generator (WTG), consisting of a Vestas V112-3.0 MW, with a hub height of 100 m, a rotor diameter of 112 m, a rated wind speed of 12.0 m/s and rated capacity of 3 MW. The area A occupied by a WTG is considered as a square having twelve times the rotor diameter (12D x 12D) and C.F. is a capacity factor of wind turbine generator and the power curve of wind turbine generator is shown in Figure 3.2. The technical power potential (TPP) is thus given in Chancham et al [8].

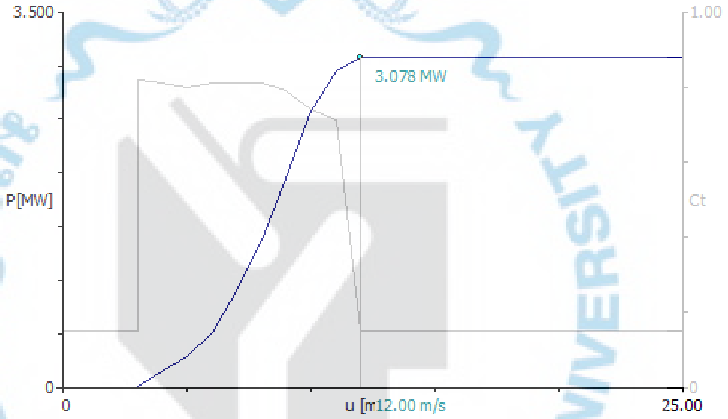


Figure 3.2 Wind turbine generator power curve that applies to calculate electric.

$$TPP = \frac{A}{12D^2} \times \text{Rated Capacity} \times \text{C.F.} \qquad (3.10)$$

3.3 Results and Discussion

The high resolution wind map, at an elevation of 100 m above sea level (asl), obtained from the modeling is shown in Figure 3.3. As a result, the mean wind speeds in the Bay of Bangkok vary from 2.3 to 7.5 m/s. It is observed that the computed results based on MC2 along with the MERRA climatic database are not significantly different from the MC2-NCEP presented by Waewsak et al. [4].

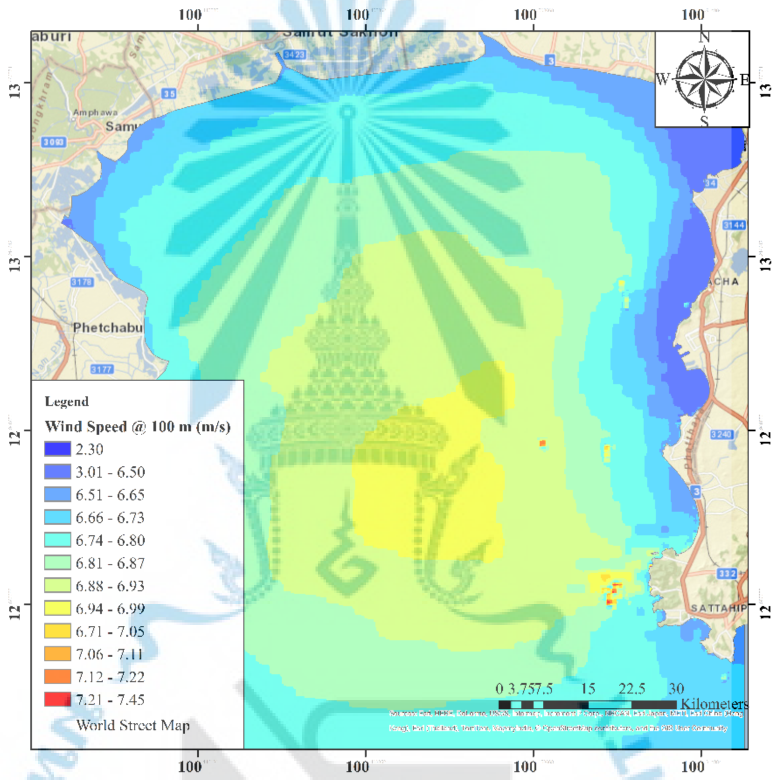


Figure 3.3 The mean wind speed at 100 m amsl in the Bay of Bangkok (resolution 500 m).

An optimal area of development is selected by taking into consideration the marine resources, the navy routes and the submarine cables, which is an area of approximately 20 km radius around the point of latitude 12.12 and longitude 100.89. The technical power potential is in the range of 2,500 MW, which could generate approximately 7 GWh /year.

The wind resource maps were validated using statistical models [8]. This investigation has applied a percent mean relative error and a mean bias to assess the differences between the Weather Research and Forecast based wind data source (WRF-MERRA) and the MC2-MERRAwind data at the same elevation and geological position. The technical power potential area is estimated to be approximately 1,500 km^2, with a potential installed capacity of approximately 2,500 MW in the areas with mean speeds over 7 m/s. The results of wind map validation, shown in terms of measured/predicted (M/P) ratio and the percent mean relative error (PMRE), are found to be in the range of 0.70 to 0.96, and 4 to 42%, respectively. Figure 3.4 shows a wind speed M/P ratio for the microscale (resolution 500 m) wind model, while Figure 3.5

shows the PMRE for the microscale (resolution 500 m) wind model. For its part, Figure 3.6 presents seasonal time series comparing the mean wind speed at 100 m asl between the WRF-MERRA and the MC2-MERRA databases.

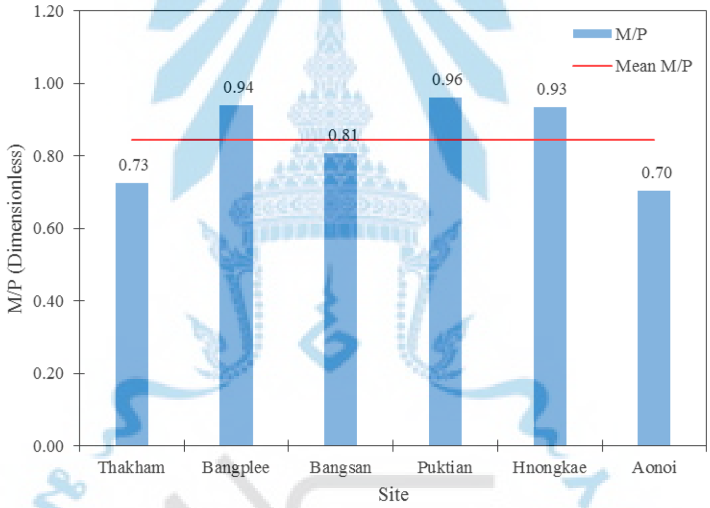


Figure 3.4 Wind speed M/P ratio for the microscale (resolution 500 m) wind model.

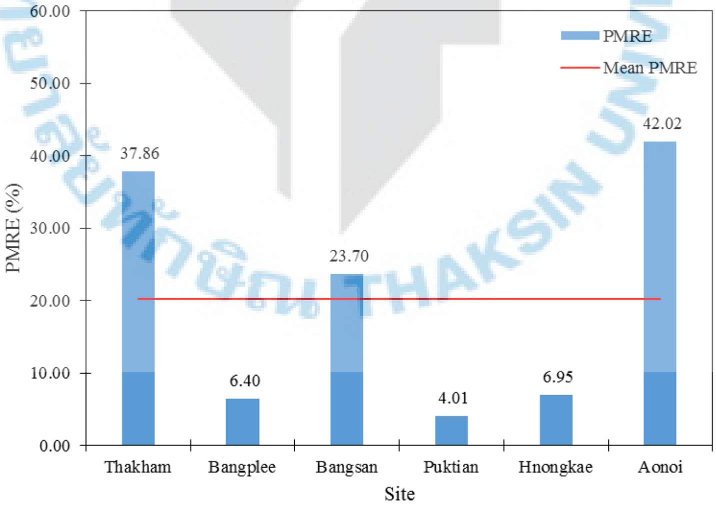
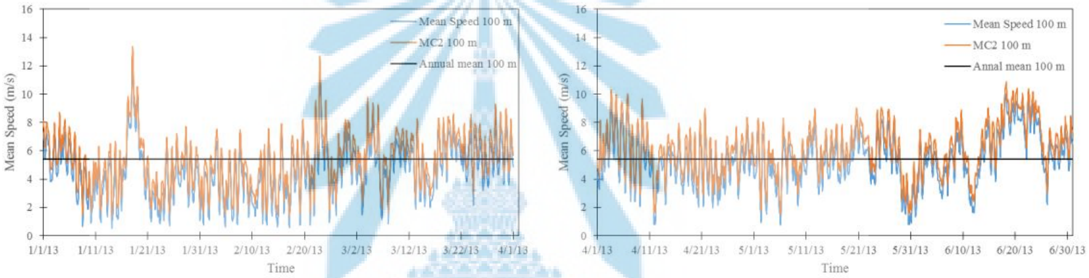


Figure 3.5 Percent mean relative error (PMRE) for the microscale (resolution 500 m) wind model.



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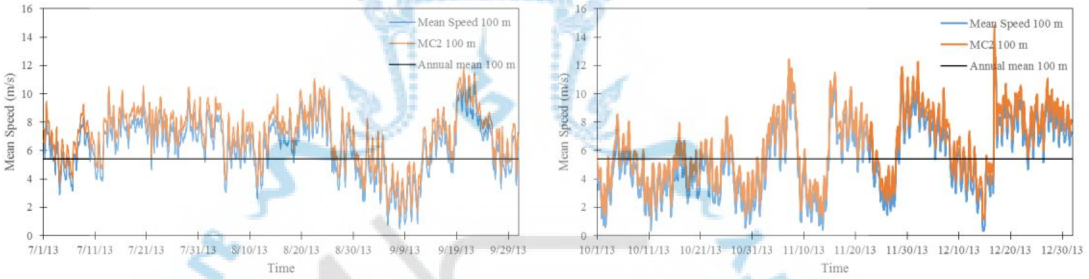

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Figure 3.6 The comparison between MC2-MERRA (orange) wind model and WRF-MERRA (blue) time series.

3.4 Conclusion

The mean wind speed in the Bay of Bangkok ranges from 2.3 to 7.5 m/s, predicted by applying the MC2 model, along with MERRA climatic database is not significantly different from other models. An optimal area of development is selected by taking into consideration the marine resources, the navy routes and the submarine cables, which is an area of approximately 20 km radius around the point of latitude 12.12 and longitude 100.89. In the validation technique, a percent mean relative error and a mean bias were applied to demonstrate the differences between the WRF-MERRA wind data source and the MC2-MERRA wind data at the same elevation and geological position. The technical power potential area is estimated to be approximately 1,500 km^2, with a potential installed capacity of approximately 2,500 MW in the areas with mean speeds over 7 m/s. The results of wind map validation, shown in terms of measured/predicted (M/P) ratio and the percent mean relative error (PMRE), are found to be in the range of 0.70 to 0.96, and 4 to 42%, respectively. On the basis of this work, wind developers should install offshore wind measurement equipment, over a period of not less than one year to confirm the precision and feasibility of offshore wind projects.

Acknowledgements

The author gratefully acknowledges the Thailand Research Fund (TRF) and the Electricity Generating Authority of Thailand (EGAT) for their financial support to this research work.

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CHAPTER 4

Offshore Wind Resource Assessment and Wind Power Plant Optimization in the Gulf of Thailand

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Foreword

In Chapter 4, a high resolution assessment of the offshore wind resource in the Gulf of Thailand, including the Bay of Bangkok, is presented. Besides being involved in defining the general methodology of the research work, the main contributions of the candidate to this paper were for the preparation of the NCEP/NCAR R2 climatic data, the modeling operations, the interpretation of the results, and drafting the paper. In the preparation of the climatic data and the scientific and technical modeling operations of the wind resource, for both the mesoscale and the microscale CFD-based models, the candidate was responsible of all these activities, while the other activities were performed by the research team, with the candidate nonetheless playing a significant role.

Energy is an international, multi-disciplinary journal in energy engineering and research. According to the Elsevier website, the journal aims to be a leading peer-reviewed platform and an authoritative source of information for analyses, reviews and evaluations related to energy. The journal covers research in mechanical engineering and thermal sciences, with a strong focus on energy analysis, energy modeling and prediction, integrated energy systems, energy planning and energy management. The journal also welcomes papers on related topics such as energy conservation, energy efficiency, biomass and bioenergy, renewable energy, electricity supply and demand, energy storage, energy in buildings, and on economic and policy issues, provided such topics are within the context of the broader multi-disciplinary scope of Energy.

Offshore Wind Resource Assessment and Wind Power Plant Optimization in the Gulf of Thailand

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Abstract

This paper presents the offshore wind resource assessment and an offshore wind power plant optimization in the Gulf of Thailand (GoT). The Weather Research and Forecasting (WRF) atmospheric model, along with the NCEP/NCAR R2 reanalysis climatic database, are applied to create wind resource maps at 80 m, 100 m, and 120 m above mean sea level (amsl) in order to identify the potential surface areas for the development of offshore wind power plants. The predicted wind speeds are validated using observed wind speeds obtained from 13 met masts installed along the coastline of the GoT. Results show that the average annual mean wind speeds reach the range of 5.5 to 6.5 m/s in specific areas of the Bay of Bangkok, situated in the northern part of the GoT. Based on the results of the wind resource assessment and using computational fluid dynamics microscale wind flow modelings, a wind power plant optimization is performed. The technical power potential and a priority zoning for offshore wind power development are performed using wind turbine generators of 3.3 to 8.0 MW capacity. Depending on the wind turbine generator selected, it is found that 642 to 924 MW of capacity could be installed in the short-term planning; 2,658 to 3,825 MW of additional capacity could be added in the medium-term planning, and 2,864 to 4,120 MW of additional capacity in the long-term planning. These wind power plants would have an annual energy production in the order of 5.6 to 8 PWh in the short-term, an additional 23 to 33 PWh in the medium-term, and an additional 25 to 36 PWh in the long-term, thus avoiding CO_{2eq} emissions in the order of 3 to 4.5 million tons CO_{2eq} per year in the short-term, 13 to 18 million tonnes in the medium-term, and 14 to 20 million tonnes in the long-term. In total, depending on the wind turbine generator selected, wind power plants in the GoT could have a total installed capacity of 6,000 to over 8,000 MW,

would generate between 50 and 75 PWh of energy per year, while avoiding emissions of 30 to 40 million tonnes CO_{2eq} per year.

Keywords: offshore wind power, wind resource map, Weather Research and Forecasting atmospheric model, offshore wind turbine generator

4.1 Introduction

Offshore wind power is emerging as an interesting renewable energy source for power generation, with the potential to mitigate climate change, increase energy security and stimulate the global economy. The cumulative installed capacity of offshore wind power projects worldwide approached the 11 GW mark in 2015 [1], with most of these projects situated in specific locations, such as the North Sea, the Baltic Sea, the Irish Sea and China's East Coast [2].

While being a country with an emerging economy, Thailand is highly dependent on fossil fuel-based energy consumption. The country has the 20th highest energy intensity worldwide, along with the 34th highest carbon intensity worldwide [3]. In regards to its electricity sector, natural gas-fired generation represents approximately 68% of the total electricity supply in the country, while coal and lignite-based generation consist of approximately 18% of the total electricity supply [4].

In the context of climate change, renewable energy can play a significant role in reducing anthropogenic greenhouse gas emissions. To this end, the Government of Thailand has revised the Alternative Energy Development Plan (AEDP 2015) to increase the share of installed capacity of renewable energy-based power plants in the energy portfolio of the country. The target of renewable energy-based power plants on the horizon of 2036 is 30% of the electricity consumed in the country, with wind power being targeted at 3,002 MW [5].

Based on the experiences from around the world, four key factors can positively influence the development of offshore wind power plants, i.e., government policies [6], technological advancements, the reliability of the equipment and infrastructure, and cost reductions [7]. However, offshore wind resource assessment is the first, and necessary, key step in the development phase of offshore wind power plants.

Because of the costs to engage in a full one-year in-situ measurement campaign of offshore wind resource assessment, wind resource maps can play an important role in the initial site identification and the selection for offshore wind power projects [8, 9].

Once potential areas of development have been properly identified, offshore wind power developers can focus on the most promising areas using several measurement technologies, such as met stations and LiDAR, to obtain in-situ wind resource measurements [10].

Considering that onshore wind power is still the main option for the development of the wind power industry, onshore wind resource assessment is highly present in the scientific literature. Early stage wind resource assessments using meteorological models concentrated on low resolution, country-wide maps (see e.g. the United States [11], Canada [12], Australia [13], Turkey [14], Europe [15], etc.). More recent work concentrate on high resolution wind modeling, covering smaller territories, both for the objective of developing mesoscale and microscale modeling, and to assess the wind resource for eventual wind power development. In this regards, Rehman et al. [16] presented the wind resource assessment, along with the design and the economic feasibility of a 20 MW wind power plant, using 2 MW turbines, located in the Eastern region of oil-rich Saudi Arabia. Once the wind resource is properly assessed for a site, several models of wind turbines, including of various nominal capacities, can be integrated into the study to identify the most promising turbine model to maximize the energy production on the site [17]. In this regards, intuitively, the annual energy production constitutes the basis of analysis for the viability of a wind power plant. However, Himri et al. [18], using long-term data, extended the analysis of a 30 MW wind power plant in the Southwest region of Algeria to include an assessment of the avoidance of CO_2 emissions, and its impacts on the local environment. Finally, Hernandez Escobedo [19], influenced by the rapid wind power development in neighboring US States, have assessed the wind resource of Mexico, with an emphasis on wind patterns.

Specifically to onshore wind resource assessment in Thailand, a few studies have developed wind resource maps in Thailand; however, these studies have generally only focused on the evaluation of the onshore wind resource [20, 21]. In Thailand, due to the relatively low onshore wind resource and to both the public perceptions and the visual impacts of onshore wind power projects, offshore wind power is an interesting alternative for the development of wind power.

Regarding offshore wind energy, the Energy Interactive Agency Model of the US Energy Information Administration can be applied to investigate the global feasibilities for offshore wind power [3]. Specifically to offshore wind power assessments, Oh et al. [22] assessed the wind resource around the Korean peninsula by extrapolating wind speeds using marine buoy data at 4 m above mean sea level (amsl) to a height of 80 m amsl in order to study the feasibility of a 100 MW offshore wind power project. For their part, Kota et al. [23] presented a comparative analysis of the offshore wind potential in the UK, in the USA and in India. Finally, the offshore wind resource mapping in the northern European Sea was investigated by comparison of the predicted wind speeds and the extrapolated wind speeds via QuickSCAT satellite image processing [24]. At another scale, Bagiorgas et al. [25] presented an assessment of the viability of offshore wind energy in the Aegean and Ionian Seas. Using a 5 MW wind turbine model, they showed the variability of the wind resource in a relatively large area, and thus the importance of doing thorough wind resource assessments in the early phase of a project development. Thus, once the wind resource is assessed, other constraints can be added to assess the overall viability of a project, notably in regards to detailed economic feasibility studies [26]. For their part, Nagababu et al. [27] provided a summary of offshore wind potential available in the Exclusive Economic Zone (EEZ) of India, where reanalysis climatic data, along with corresponding bathymetry and cumulative human impact on marine ecosystems.

The climate of Thailand is influenced by a rainy, southwest monsoon period (mid-May to mid-October), a wintery, northeast monsoon period (mid-October to mid-February), and summer period during the rest of the year [28]. Surface wind directions are influenced by the monsoon systems, with prevailing winds from the south, southwest and west during the southwest monsoon period; north and northeast during the northeast monsoon period; and south during the summer period. Thailand is also affected by tropical storms, where winds can be well over 30 m/s.

In a specific application to the GoT, Waewsak et al. [29] identified a significant wind power potential for the GoT, with a particular emphasis on the potential within the Bay of Bangkok. The study, based on the MC2/MS-Micro atmospheric modeling, at a resolution of 200 m, and the NCEP/NCAR R1 reanalysis climatic database, showed that average annual wind speeds reached 3 to 8 m/s at 40 m, 80 m, 100 m and 120 m amsl, while the technical power potential of the exploitable surface area was estimated to be in the vicinity of 7,000 MW.

As a contribution to assess wind resource assessment models, and considering the potential of offshore wind power in Thailand, the objective of this paper is to present the wind resource assessment of the Gulf of Thailand using the Weather Research and

Forecasting (WRF) atmospheric model, along with the NCEP/NCAR R2 reanalysis climatic database and computational fluid dynamics microscale wind flow modeling. The methodology, presented in Section 2, describes the mesoscale and the microscale modeling to obtain estimated annual energy production, which is used to quantify the technical power potential of the territory, along with an estimation of the CO_{2eq} emission avoidance if wind power plants are developed. The results are analyzed in Section 3, while the last section provides overall conclusions for the work.

4.2 Methodology

Wind resource mapping is an efficient tool in wind power project development, both at the large scale and to identify sites where micro-siting wind resource assessments should be performed in the early stages of projects. In this work, wind resource maps, at 9 km resolution, for the GoT are developed using the Weather Research and Forecasting (WRF) atmospheric model, along with NCEP/NCAR R2 reanalysis climatic database for the period 2008-12. Microscale computational fluid dynamics wind flow modeling is then used, along with a time series wind dataset obtained from a virtual met mast within the area of interest, to investigate the performance of wind power plants in the GoT.

The WRF model, considered a next-generation atmospheric model, is a numerical weather prediction and atmospheric simulation system that was designed for research and operational applications [30]. Developed through a collaboration of various institutes in the United States, the WRF model has been applied in international research, e.g. the wind power production estimation in the Iberian Peninsula [31], the offshore wind power simulation in Chile [32], and the investigation of the turbulent kinetic energy in wind power projects [33].

In this work, the WRF atmospheric model is applied under nesting grids on two domains, i.e. a large domain with a resolution of 27 km and a smaller domain with a resolution of 9 km, along with the NCEP/NCAR R2 reanalysis climatic database [34] to predict the wind speeds and directions over the GoT. The large computational domain covers most of Southeast Asia, while the smaller domain covers the whole territory of Thailand, as shown in Figure 4.1.

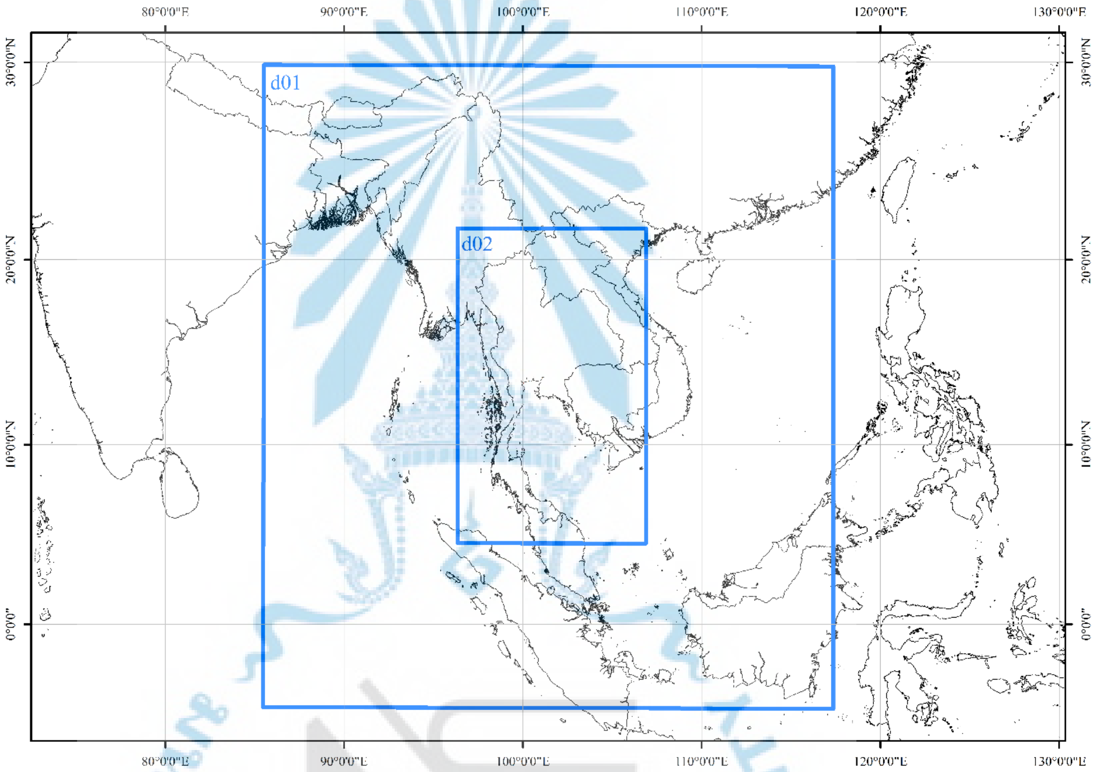


Figure 4.1 Computational domains for the Weather Research and Forecasting (WRF) atmospheric modeling of the Gulf of Thailand.

4.2.1 Mesoscale Modeling: Weather Research and Forecasting

4.2.1.1 Vertical coordinate and variables

The modeling equations of the Advanced Research Weather Research and Forecasting (ARW) are formulated using a terrain-following hydrostatic-pressure vertical coordinate. The coordinate definition, proposed by Laprise [35]. This vertical coordinate is also called a mass vertical coordinate [30]. The ARW solver employs a numerical method to solve the differential equations, applying a C grid staggering strategy. With this strategy, the normal velocities are staggered one-half grid length from the thermodynamic variables.

4.2.1.2 Climatic database

The long-term National Center for Environmental Prediction - Final Analysis (NCEP-FNL) Operational Global Analysis data, between 2008 and 2012, are used as WRF’s climatic input parameters. These data are on a 1-degree grid resolution prepared operationally every six hours. This database is obtained from the Global Data Assimilation System (GDAS), which continuously collects observational data from the

Global Telecommunications System (GTS), and other sources, for many analyses. The FNLs are prepared approximately an hour or so after the Global Forecasting System (GFS) is initialized. The analyses are available on the surface, at 26 mandatory (and other pressure) levels from 1,000 mb to 10 mb, in the surface boundary layer and at some sigma layers, the tropopause and a few others. Parameters include surface pressure, sea level pressure, geopotential height, temperature, sea surface temperature, soil values, ice cover, relative humidity, (u, v, w) winds, and vertical motion [34].

4.2.1.3 Validation of the wind resource maps

In order to validate the numerical data obtained from the WRF atmospheric modeling, the predicted wind speeds are compared to the measured wind speeds obtained from 13 met masts installed along the coastline of the GoT (six 90 m height and seven 120 m height above ground level (agl). The details of these met masts are given in Table 4.1, while their geographical locations are shown in Figure 4.2.

Table 4.1 Location and height of installed met masts along the coastline of the Gulf of Thailand and position of a virtual met mast in the Gulf of Thailand.

No.	Site Name	Province	Latitude (^{o}N)	Longitude (^{o}E)	Height (m agl)
1	Aonoi	Prachub Kirikhun	11.91258	99.82369	90
2	BangPlee	Samutprakarn	13.51754	100.74973	90
3	Rumpan	Chanthaburi	12.63860	101.90984	90
4	Pakklong	Chumphon	10.95024	99.48784	90
5	Thungsai	Nakhon Si Thammarat	9.01923	99.91565	90
6	Koyai	Songkhla	7.52854	100.27769	90
7	Chumko	Chumphon	10.77630	99.37376	120
8	Hnongkae	Prachuabkirikhun	12.47944	99.96975	120
9	Puktian	Petchburi	12.95797	99.99715	120
10	Thakham	Bangkok	13.57619	100.44303	120
11	Bangsaen	Chuntaburi	13.29502	100.90143	120
12	Pangan	Suratthani	9.73771	99.99473	120
13	Tha Phaya	Nakhon Si Thammarat	8.27619	100.26914	120
14	Virtual Met Mast	Gulf of Thailand	12.66495	100.60037	100

The Measured/Predicted ratio (M/P), Eq. (4.1), and the Percent Mean Relative

Error (PMRE) of the predicted wind speeds, Eq. (4.2), are analyzed to display the performance of the WRF atmospheric modeling. Thus,

$$\text{M/P} = \text{Observed wind speed} / \text{Predicted wind speed} \tag{4.1}$$

$$\text{PMRE} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{o_i - p_i}{o_i}\right)\times 100\% \tag{4.2}$$

where o_i is the observed wind speed (m/s), p_i is the predicted wind speed (m/s) and n is the number of data in the period of the sample.

4.2.2 Microscale Modeling: Wind Resource and Wakes

The output of the WRF modeling, i.e. wind speeds and directions at 100 m amsl, is used to create a virtual met mast at the most promising anticipated zone for offshore wind power development in the GoT [29], Figure 4.2. The wind characteristics of the WRF modeling at the position of the virtual met mast are considered to represent the wind resource at that location in the reference year 2011 (1 January to 31 December). The Weibull distribution and the wind rose of the wind dataset obtained from the virtual met mast in the GoT, used for the microscale wind resource mapping, are shown in Figure 4.3. The results of the microscale modeling are then used as the wind resource to estimates the energy production of wind power plants in the Gulf of Thailand.

In this work, both linearized wind flow modeling in WAsP and in a CFD model are used to create 10x10 km^2 microscale wind resource maps for the offshore wind power yield assessment. A Small Power Producer (SPP) offshore wind power plant, with a 90 MW capacity, is selected as the basic wind power plant in the simulations with WAsP and WindSim.

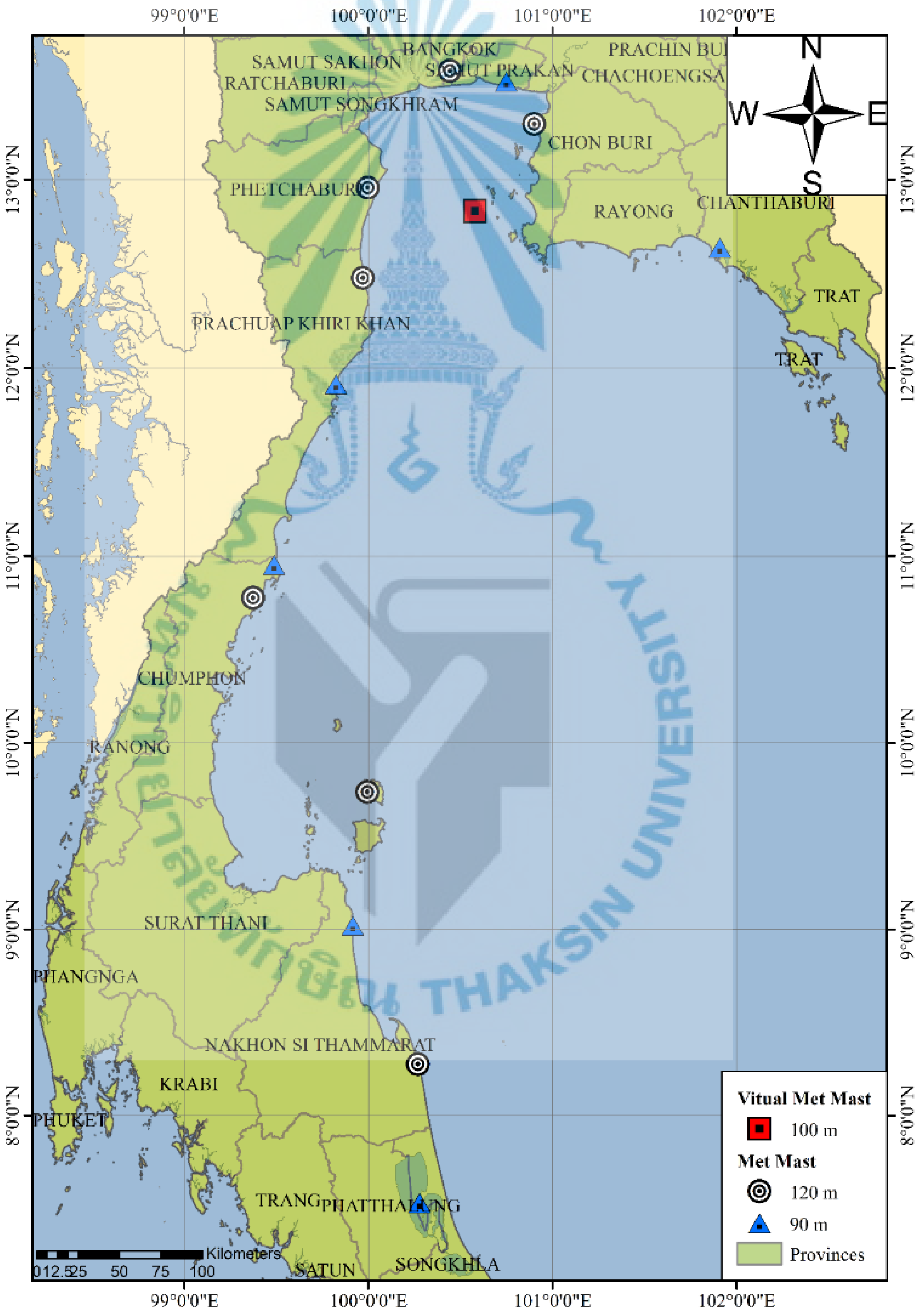


Figure 4.2 Geographical distribution of the 13 met masts and the virtual met mast in the Gulf of Thailand.

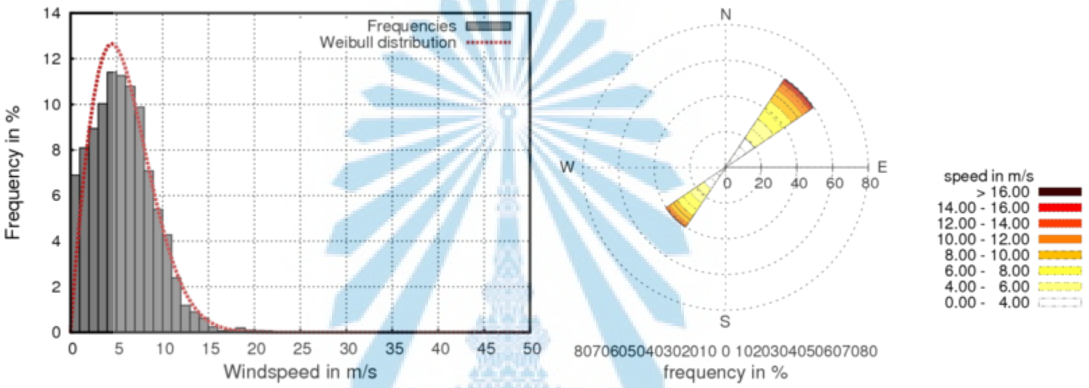


Figure 4.3 The wind climate at 100 m amsl obtained from the WRF modeling, considered as the wind dataset of a virtual met mast in the Gulf of Thailand.

Wind flow modeling using computational fluid dynamics (CFD) modeling is preferably used in complex terrain for microscale wind resource mapping and energy estimation [36]. However, for offshore areas, where the effect of terrain is negligible, linearized wind flow models should perform quite accurately in comparison to CFD models. By using two different wind flow modelings, i.e. linearized wind flow model under the WAsP methodology [37] and the CFD wind flow model in WindSim [38], microscale wind resource maps at 100 m amsl, with a 50 m resolution, over the target potential area in the GoT are created under neutral condition and air density of 1.225 kg/m^3. The basic Jensen Wake Model [39], used in WAsP (wake model no. 1) and in WindSim (wake model no. 2), along with two other wake models developed in WindSim by Larsen [40] (wake model no. 3) and Ishihara [41] (wake model no. 4), are applied in the energy yield assessment for the offshore wind power simulation in order to investigate the uncertainty in the wake loss analysis and the estimation of the annual energy production (AEP) of the wind power plants.

4.2.3 Estimated Energy Production

Prior to investigating the energy-based feasibility of an offshore wind power plant in the Gulf of Thailand, a zoning of offshore wind power development is recommended for the short, medium, and long-term planning. Building on a multi-criteria decision making analysis for the site selection for offshore wind power plants [29], the load demand of electricity consumption is also considered as one of the major criteria for the siting of offshore wind power plants. In this approach, the energy generated by an offshore wind power plant is assumed to be transferred to the closest load in order to minimize losses. The criteria for the selection of the potential sites, along with their respective weight, consist of: mean annual wind speed (50%), water depth (15%), distance from shore (15%), and distance from load (20%). The values for three of these criteria are presented in Figure 4.4. Since the area is composed of several load centers, the graphical representation is not presented.

The energy generated by the offshore wind power plants is estimated by applying a generic power curve of three offshore-class wind turbine generators (WTG) available on the market, i.e., 3.3 MW, 5 MW, and 8 MW. The specifications and the characteristics of these three typical offshore class WTGs are given in Table 4.2, while the generic power curves of these three WTGs are shown in Figure 4.5.

Wake effect plays an important role in reducing the energy production of a wind power plant. Along with the wind direction, this effect is directly related to the positions of each WTG with respect to the other WTGs, the dimensions of the WTGs, and the geophysical characteristics of the site.

Table 4.2 Characteristics of the three offshore class wind turbine generators used in the optimization of the wind power plants and the estimation of the annual energy production (AEP).

Installed Capacity (MW)	Hub Height (m)	Rotor Diameter (m)	Cut-in Speed (m/s)	Rated Speed (m/s)	Cut-out Speed (m/s)
3.3 [42]	137	126	3.0	12.0	22.5
5 [43]	90	126	3.0	11.5	25.0
8 [42]	100	164	4.0	13.0	25.0

Consequently, the optimum spacing between the WTGs is investigated by varying the distance between each WTG for 3, 5, 7, 9, and 11 rotor diameters. The optimum distance is selected based on the AEP-wake loss aspect only. The Response Surface Methodology (RSM) in the Design-Expert model [44] is applied to investigate the optimum distance between the WTGs.

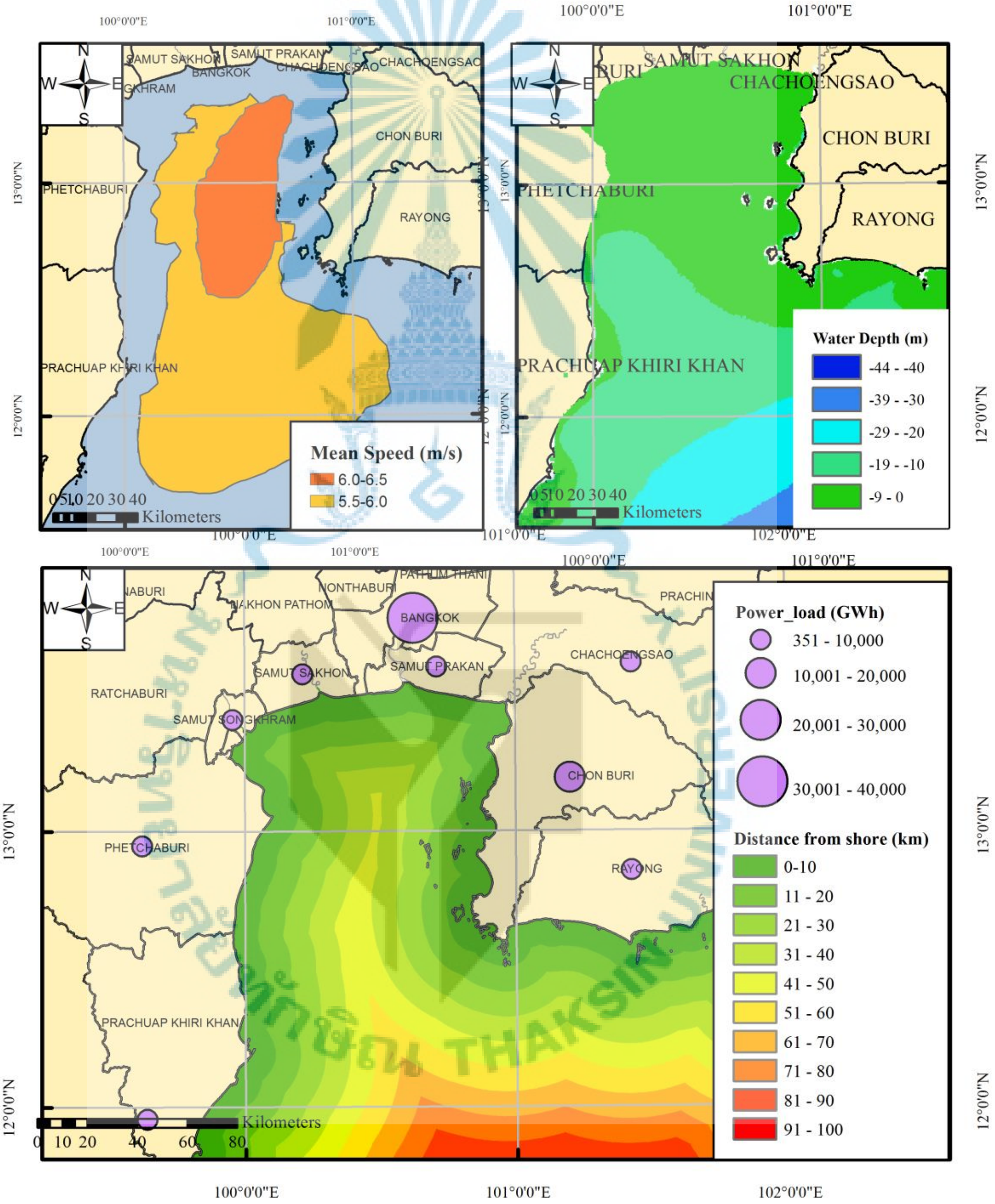


Figure 4.4 Multi-criteria decision making analysis for the site selection of offshore wind power plants in the Gulf of Thailand. Top left: mean annual wind speed; top right: water depth; bottom: distance from shore.

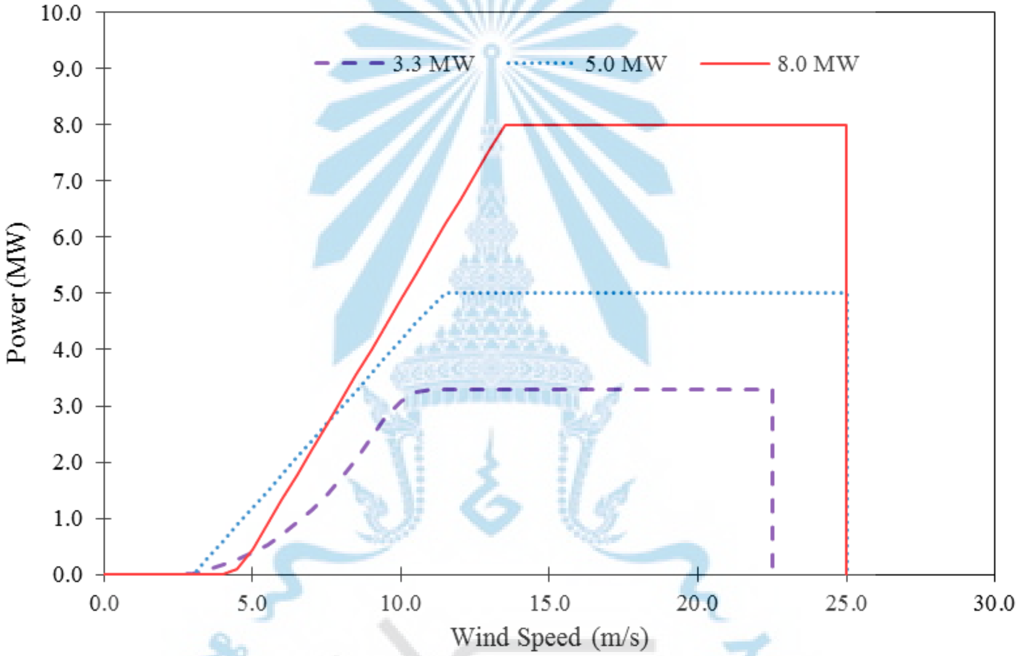


Figure 4.5 The generic power curves of the wind turbine generator models, at their rated capacities (3.3, 5.0 and 8.0 MW).

Finally, several losses in the energy production by an offshore wind power plant are taken into consideration, i.e. wind turbine availability effect is equal to 3% losses, scheduled maintenance allowable downtime effect is equal to 0.7%, balance of plant availability effect is equal to 0.3%, grid availability effect is equal to 1.1%, electrical transmission efficiency effect is equal to 0.5%, power curve performance effect is equal to 0.5% and performance degradation is equal to 0.5% [45,46]. Considering these losses, the net AEP is calculated, and the capacity factor (CF) can be computed using Eq. (4.3):

$$\mathrm{CF} = \frac{\mathrm{AEP}}{8{,}760 \times \mathrm{N} \times \text{Rated Capacity}} \times 100\% \tag{4.3}$$

where AEP is the net annual energy production, 8,760 is the number of hours in a year, and N is the number of wind turbines.

4.2.4 Technical Power Potential (TPP)

For the purpose of this study, the layout of the WTGs in the offshore wind power plant is designed by using the optimum distance found from the investigation. The Technical Power Potential (TPP) can thus be estimated from Eq. (4.4):

$$\mathrm{TPP} = \left(\sum_{i=1}^{n} \frac{\mathrm{A}}{\mathrm{XD}^2} \times \mathrm{CF} \right) \times \mathrm{NomCap} \tag{4.4}$$

where A is the potential area (km^2) of development, X is the distance layout factor (multiple of rotor diameter) of a WTG, D is the rotor diameter of the WTG (m), CF is the capacity factor (%), NomCap is the nominal capacity of the WTG (MW), while *n* is the number of wind speed bins and *i* is the initial count of wind speed bins.

4.2.5 CO_{2eq} Emission Avoidance

The energy production from offshore wind power plants could reduce the CO_{2eq} emission into the atmosphere. The CO_{2eq} emission avoidance is estimated using the conversion factor 0.56 kg CO_{2eq}/kWh for wind power project development in Thailand [34]. The CO_{2eq} emission avoidance from a renewable energy-based power plant project, once registered as Certified Emission Reductions (CERs), could be traded and would be an important externality of the project.

4.3 Results and Discussion

Results from the WRF atmospheric modeling, along with the NCEP/NCAR R2 reanalysis climatic database, are post-processed to generate the monthly mean wind speeds at 80 m, 100 m and 120 m amsl in the GoT, as shown in Figure 4.6-4.8. It can be seen that the wind resource in the GoT is strongly influenced by the Northeast monsoon from November to February, and also affected by the Southwest monsoon from May to September. During this period, the monthly mean wind speed is in the range of 5 to 9 m/s.

The annual mean wind speed maps at 80 m, 100 m and 120 m amsl in the GoT are shown in Figure 4.9. Results show that the annual mean wind speeds at 120 m amsl are in the range of 3 to 6.5 m/s across the area studied. Generally, the results show that the wind speeds increase from the southern regions towards the northern regions of the GoT. The highest wind speeds are located in the Bay of Bangkok (Figure 4.10), where results show that the annual mean wind speeds are in the range of 5.5 to 6.5 m/s at 120 m amsl.

The spatial distribution of the wind resource obtained with the WRF model is similar to the spatial distribution obtained with the MC2/MS-Micro wind flow modeling investigated in Waewsak et al. [29]. However, the results obtained from the MC2/MS-Micro tend to cover more potential areas, especially for wind speeds in the range of 5.0 to 6.0 m/s, in comparison to what is shown in Figure 4.10. The zones presenting a good wind resource in both methods of assessments are thus considered in the technical feasibility assessment of offshore wind power development in the GoT.

The current study, for the same general area, but with a completely different methodology and a different climatic database, has confirmed that the Gulf of Thailand in general, and the Bay of Bangkok in particular, have a promising wind resource potential for wind power generation. Thus, the results presented in the current study, while comparing the effectiveness of the WRF model combined with micro-scale modeling, validates the overall wind resource in this territory.

Figure 4.11 shows the Measured/Predicted ratio (M/P) and the Percent Mean Relative Error (PMRE) obtained in the validation of the mesoscale wind maps around the GoT. It can be noticed that the M/P ratio ranges from 0.6 to 1.8, while the PMRE ranges from 7 to 44%. The mean M/P ratio is 1.3, while the mean PMRE is 33%. However, when eliminating outlying data (Sichon, Krasaesin, Patiew, and Pak Phanang), the mean M/P ratio drops to 1.15, indicating that the measured and predicted data are in relatively good agreement for most of the coastal met towers. Coastal effects could explain some differences between the winds predicted offshore and the winds measured along the coast. Indeed, while the met towers have been installed at positions that border the coastline, some are impacted by high ground roughness due to vegetation or infrastructures, and by the specific topography of the specific areas.

In order to better assess the accuracy of the wind resource maps, a correlation between daily observed mean wind speeds and daily predicted mean wind speeds are applied to the results. Figure 4.12 shows the comparison between daily observed wind speeds and daily predicted wind speeds at 90 m amsl, while Figure 4.13 presents the same at 120 m amsl. On these figures, the line of Observed-Predicted data should follow the solid line of the unit slope, thus indicating that the predicted wind speeds are the same as the observed wind speeds. Error margins between 15 and 45 % have been added. It can be observed that the predicted wind speeds tend to systematically over-estimate the wind resource at 90 m, while being evenly distributed around the unit slope at 120 m. This difference could possibly explained by the ground (roughness and topography) of the areas around each met towers, which would have a stronger effect at lower elevations. Further, the distribution of the error, as indicated by the pie charts, are relatively evenly distributed within each of the error margins.

The comparison of measured wind directions at a height of 120 m agl, and the WRF-predicted wind directions at 100 m amsl are shown in Figure 4.14. It can be observed that the wind directions measured in the coastal areas have similar patterns than the WRF-predicted wind directions obtained offshore, the differences being attributed to local geophysical effects.

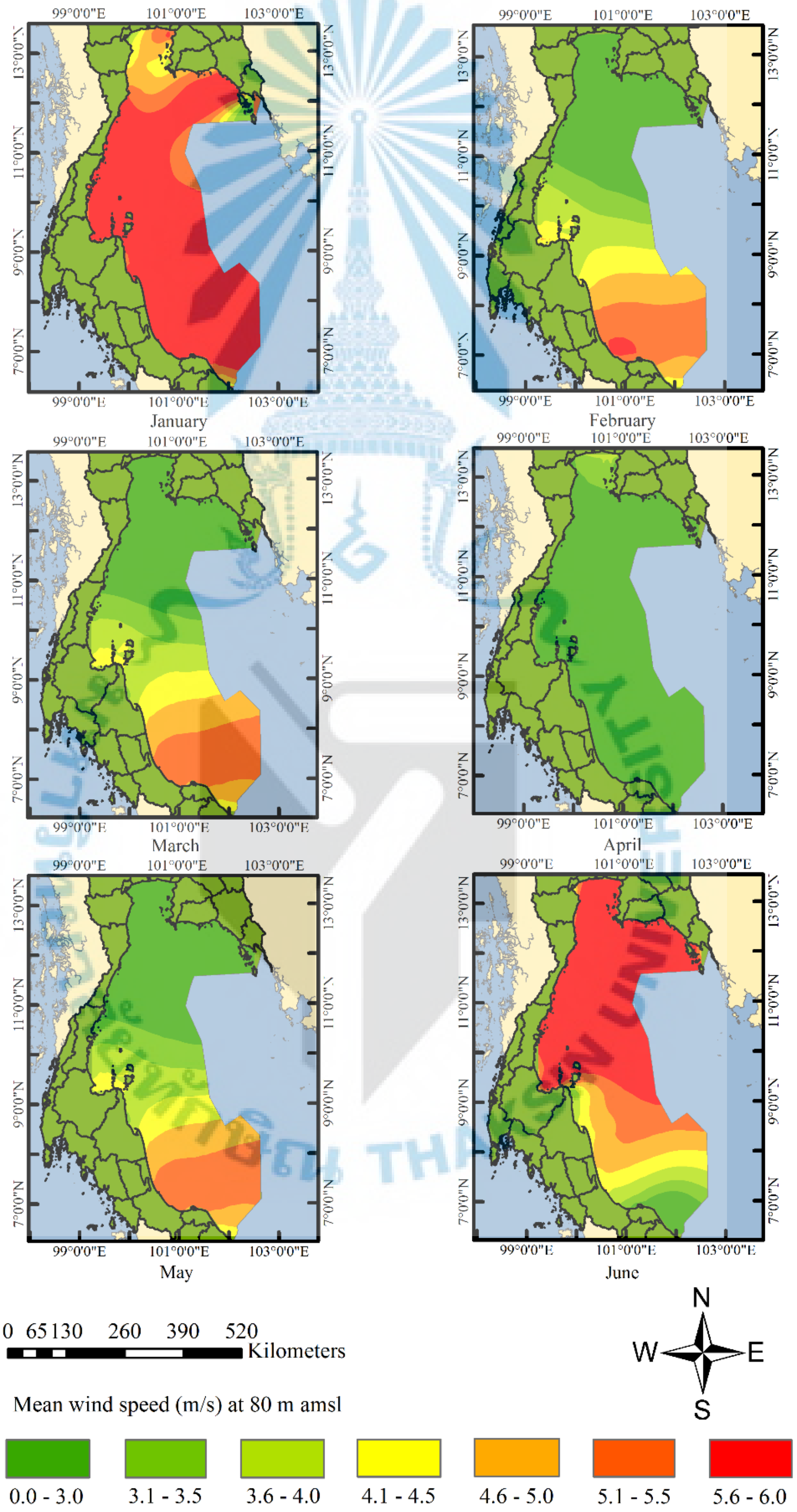
In order to identify the optimum spacing between the WTGs in the modeled wind power plant, the spacing or distance between the WTGs, in terms of a multiple of rotor diameter, and the wake losses for each WTGs modeled are used as input to the Response Surface Method (RSM) [44]. In order to identify the most significant parameters, a desirability function of 0.995 is selected, with the objective that the optimum solution will provide the maximum annual energy production, while minimizing the wake losses.

For the 3.3 MW WTG, the RSM analysis indicates that a spacing of 7 rotor diameters between the WTGs provides the optimum solution for the grid matrix of the WTG of power plants in the GoT. Figure 4.15 shows the results of the RSM analysis. The optimum solution is also confirmed by the results of Figure 4.16, where the AEP remains relatively constant and the wake losses do not reduce significantly beyond this spacing of the WTGs.

For the 5 MW and 8 MW WTGs, the optimum spacing between the WTGs corresponds to a spacing of 5D, as shown in Figures 4.17 and 4.18, respectively. The surface area occupied by a single WTG thus corresponds to 7Dx7D for the 3.3 MW WTG (0.78 km^2), and 5Dx5D for the 5 MW WTG (0.40 km^2) and the 8 MW WTG (0.67 km^2).

Figure 4.19 shows the results of the multi-criteria decision making analysis applied to the surface area where the mean annual wind speeds are in the range of 6 to 6.5 m/s. Further, the potential surface areas of development are selected and classified into six different zones, with a priority zoning from short-term to long-term planning for offshore wind power development in the GoT.

Table 4.3 summarizes the potential surface areas, as well as the TPP for short-term to long-term planning of wind power plants in the GoT, based on the WTGs selected. For short-term planning, Zone I is the top priority, with a total surface area of 280 km^2 available for development.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January
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March
April
May
June
0 65 130 260 390 520
Kilometers
N
W
E
S
Mean wind speed (m/s) at 80 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
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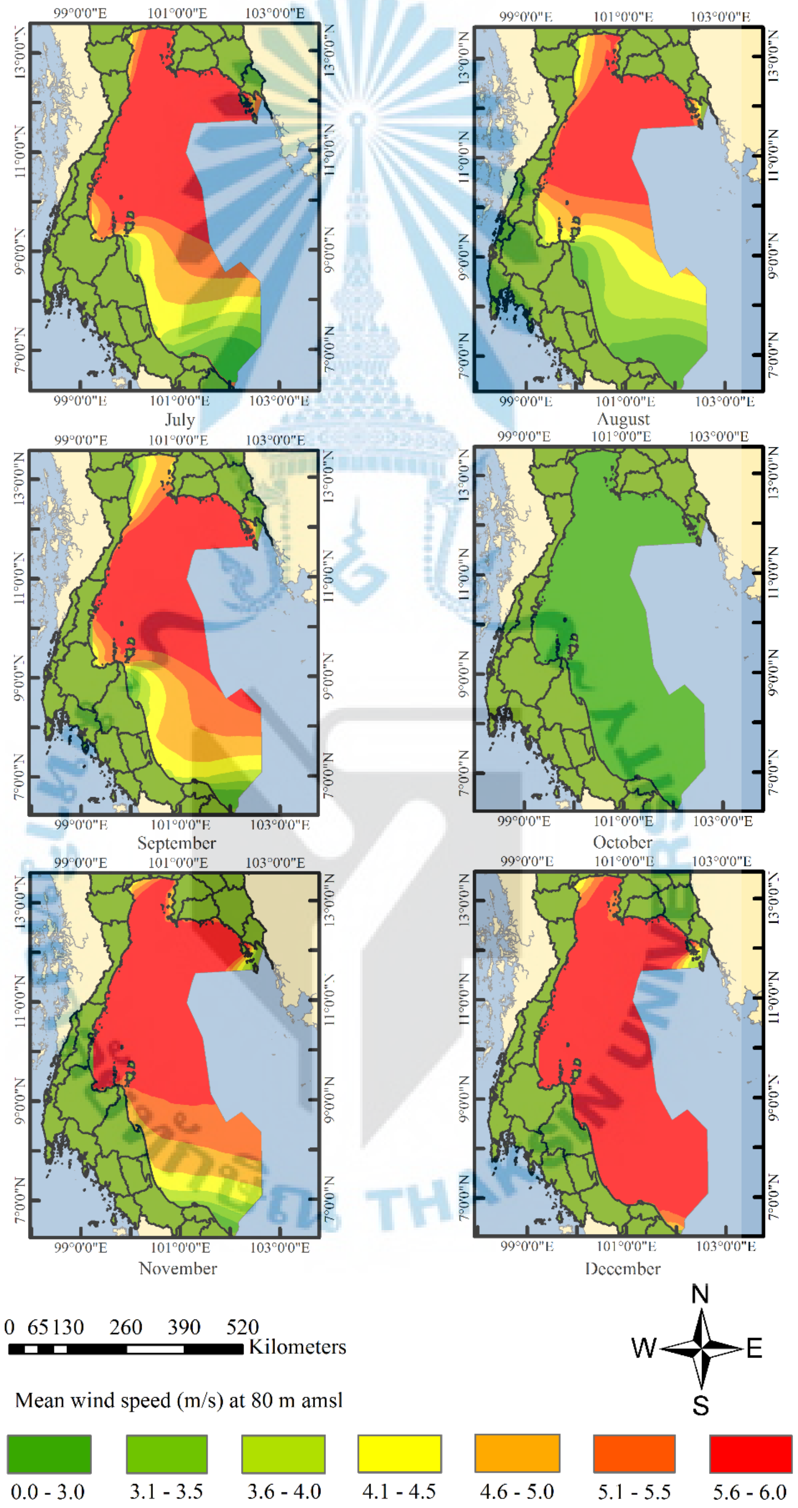
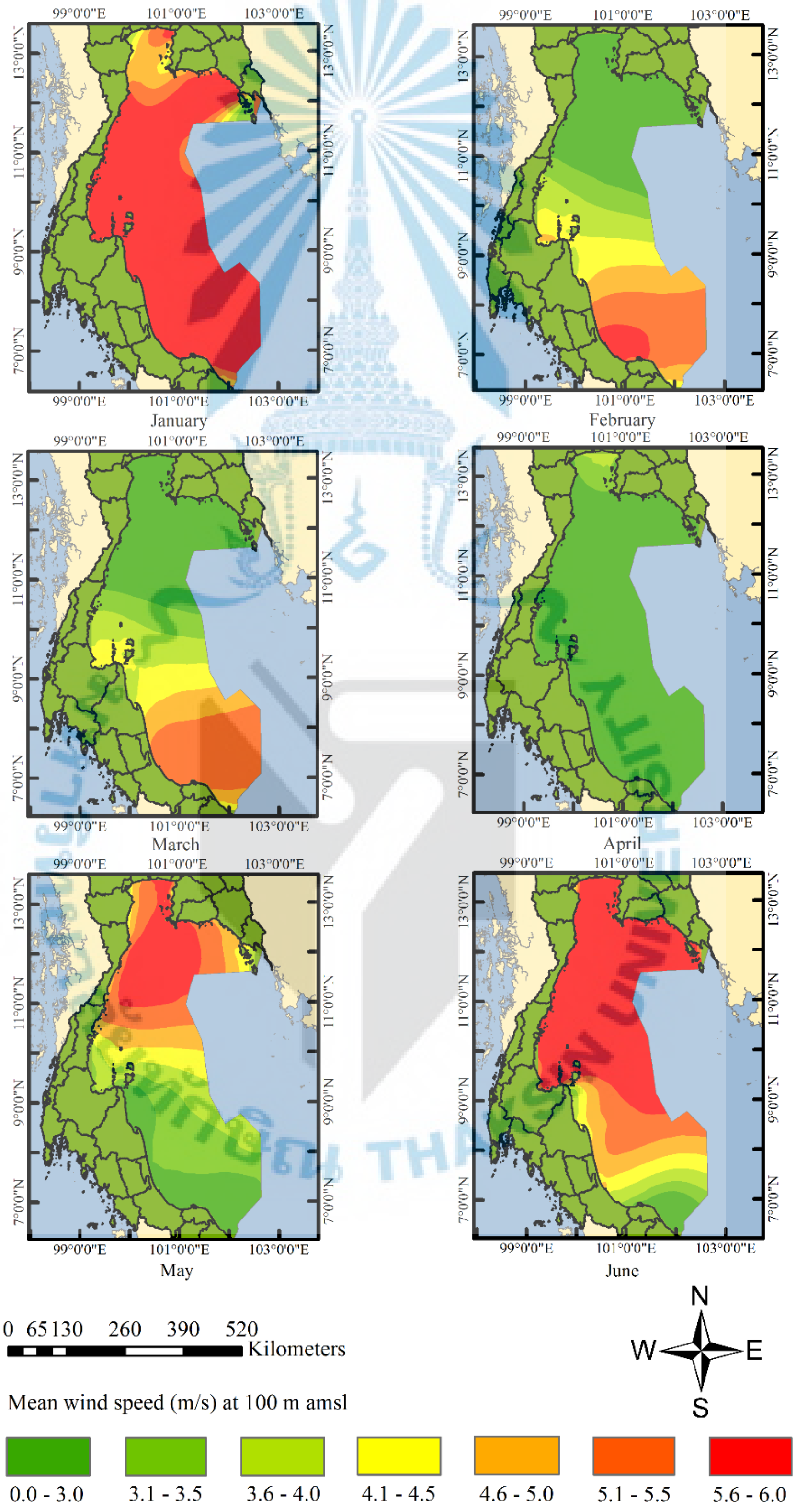
(a)



(b)

Figure 4.6 Monthly mean wind speeds at 80 m amsl in the Gulf of Thailand, predicted by the WRF atmospheric modeling, with the NCEP/NCAR R2 climatic database (2008-12) at 9 km resolution: a) January-June, b) July-December.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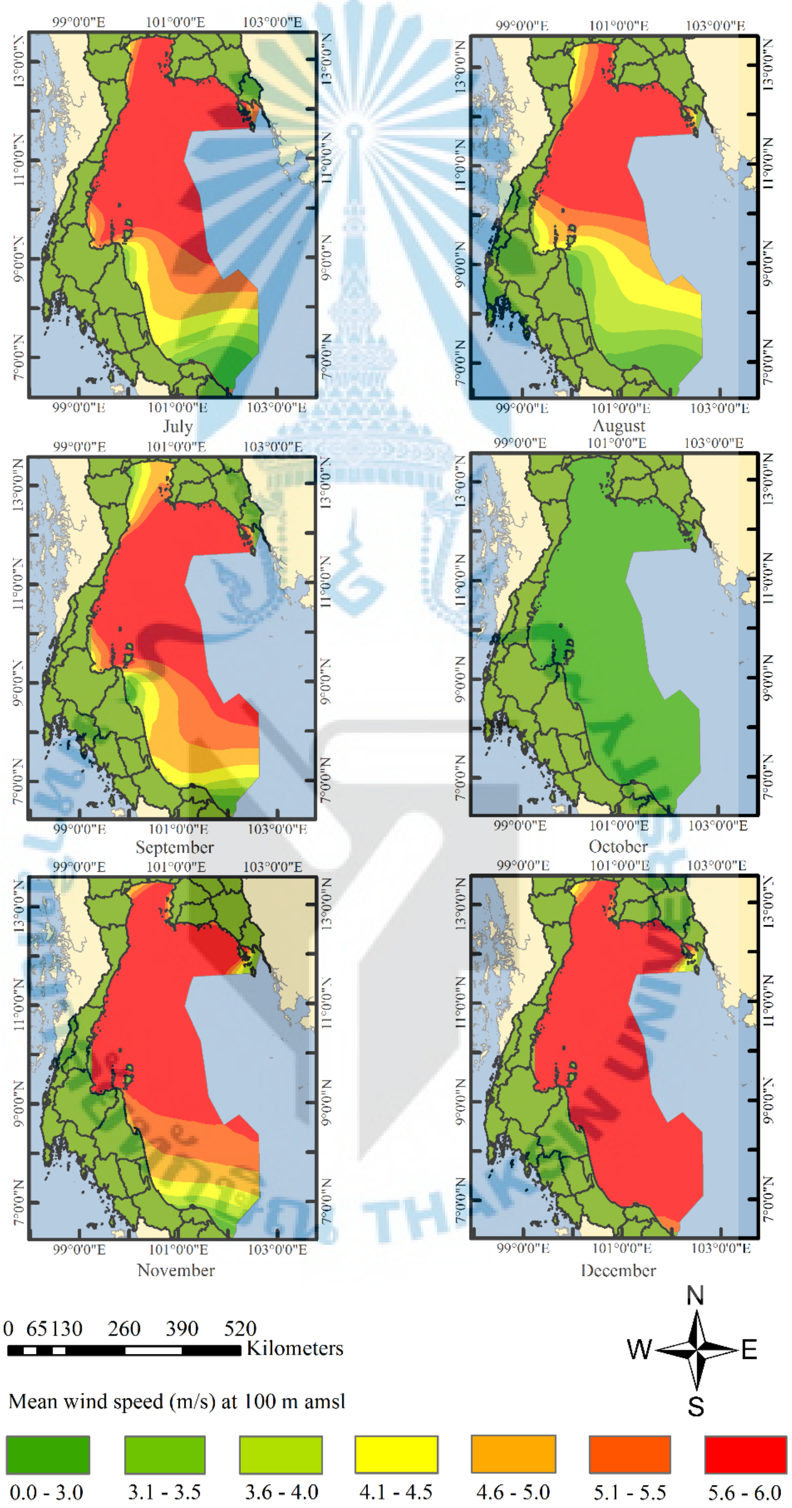
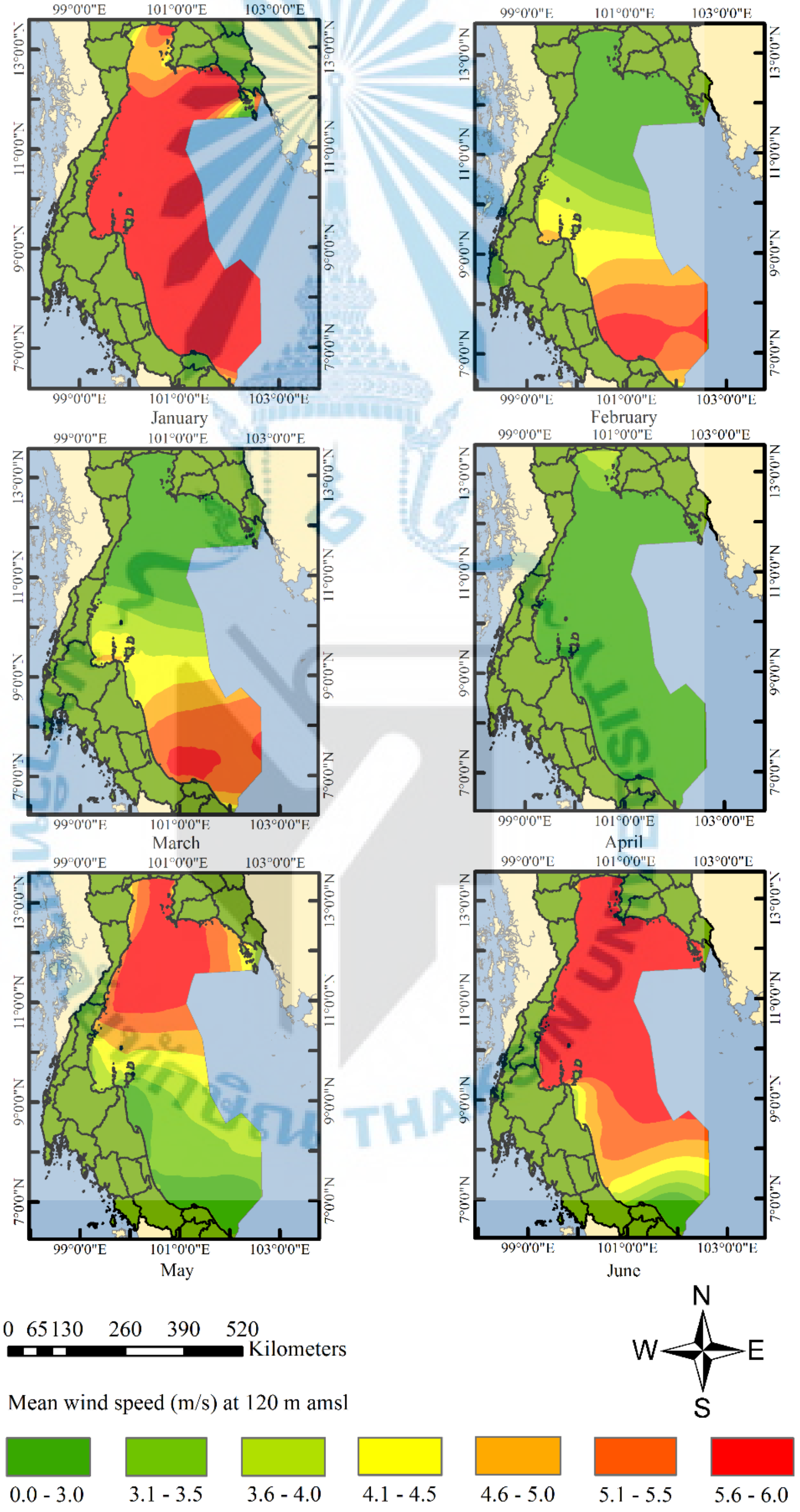
0 65 130 260 390 520
Kilometers
N
W
E
S
Mean wind speed (m/s) at 100 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
4.1 - 4.5
4.6 - 5.0
5.1 - 5.5
5.6 - 6.0

(a)



(b)

Figure 4.7 Monthly mean wind speeds at 100 m amsl in the Gulf of Thailand, predicted by the WRF atmospheric modeling, with the NCEP/NCAR R2 climatic database (2008-12) at 9 km resolution: a) January-June, b) July-December.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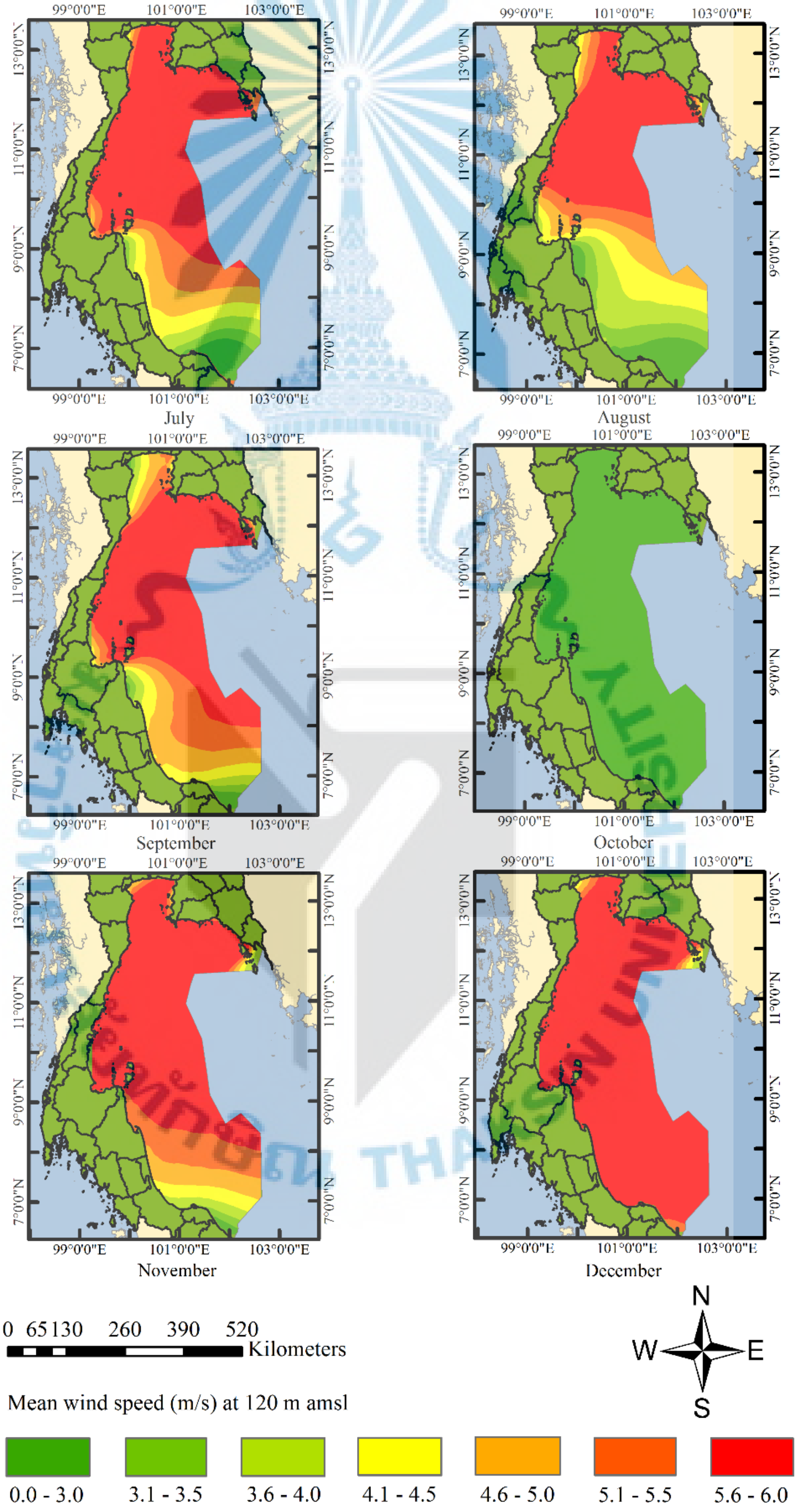
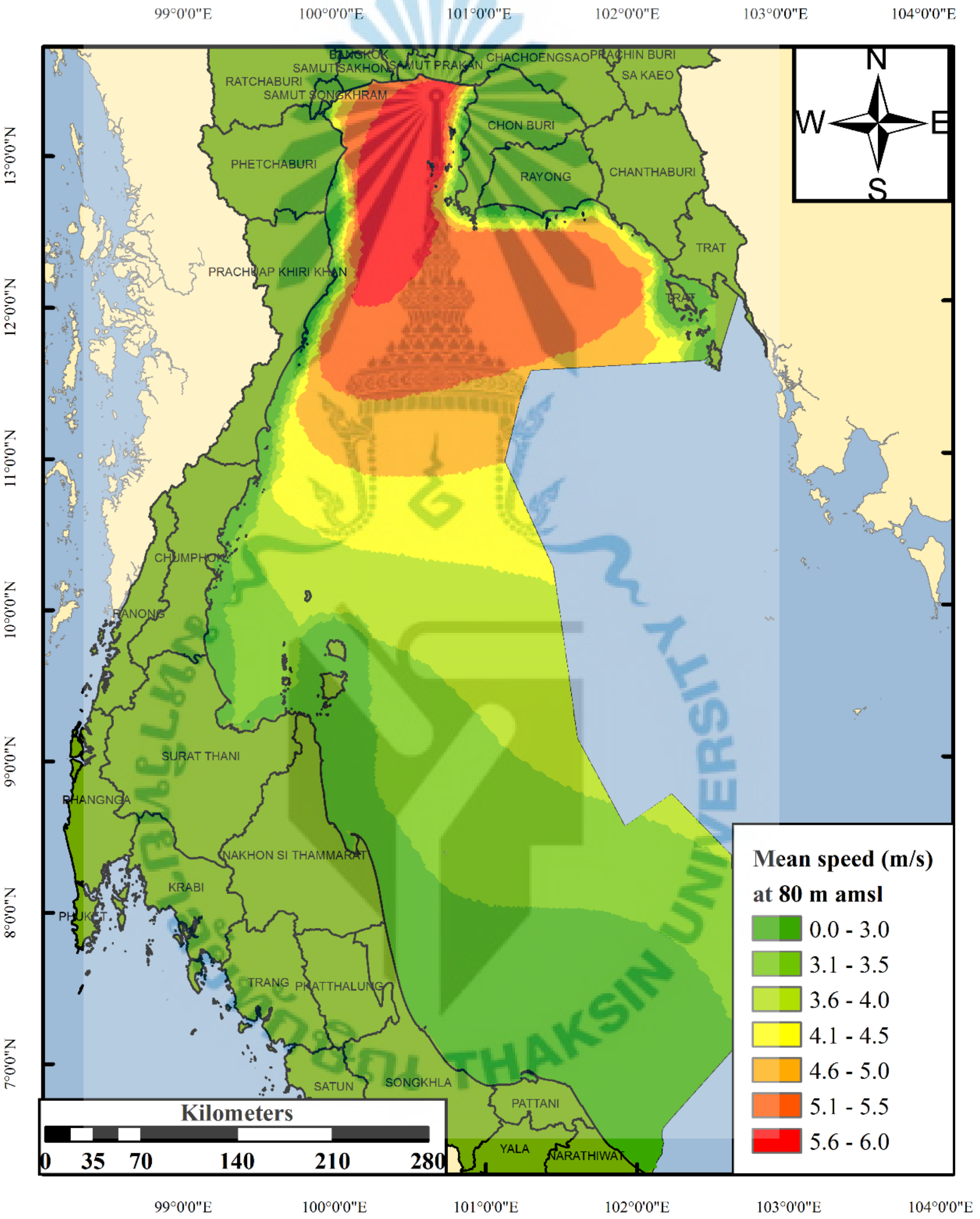
7°0'0"N
January
February
March
April
May
June
0 65 130 260 390 520
Kilometers
N
W
E
S
Mean wind speed (m/s) at 120 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
4.1 - 4.5
4.6 - 5.0
5.1 - 5.5
5.6 - 6.0

(a)



(b)

Figure 4.8 Monthly mean wind speeds at 120 m amsl in the Gulf of Thailand, predicted by the WRF atmospheric modeling, with the NCEP/NCAR R2 climatic database (2008-12) at 9 km resolution: a) January-June, b) July-December.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SAMUT SONGKHRAM
CHON BURI
PHETCHABURI
RAYONG
CHANTHABURI
TRAT
PRACHUAP KHIRI KHAN
CHUMPHON
RANONG
SURAT THANI
PHANGNGA
NAKHON SI THAMMARAT
KRABI
PHUKET
TRANG
PHATTHALUNG
SATUN
SONGKHLA
PATTANI
YALA
NARATHIWAT
Mean speed (m/s)
at 80 m amsl
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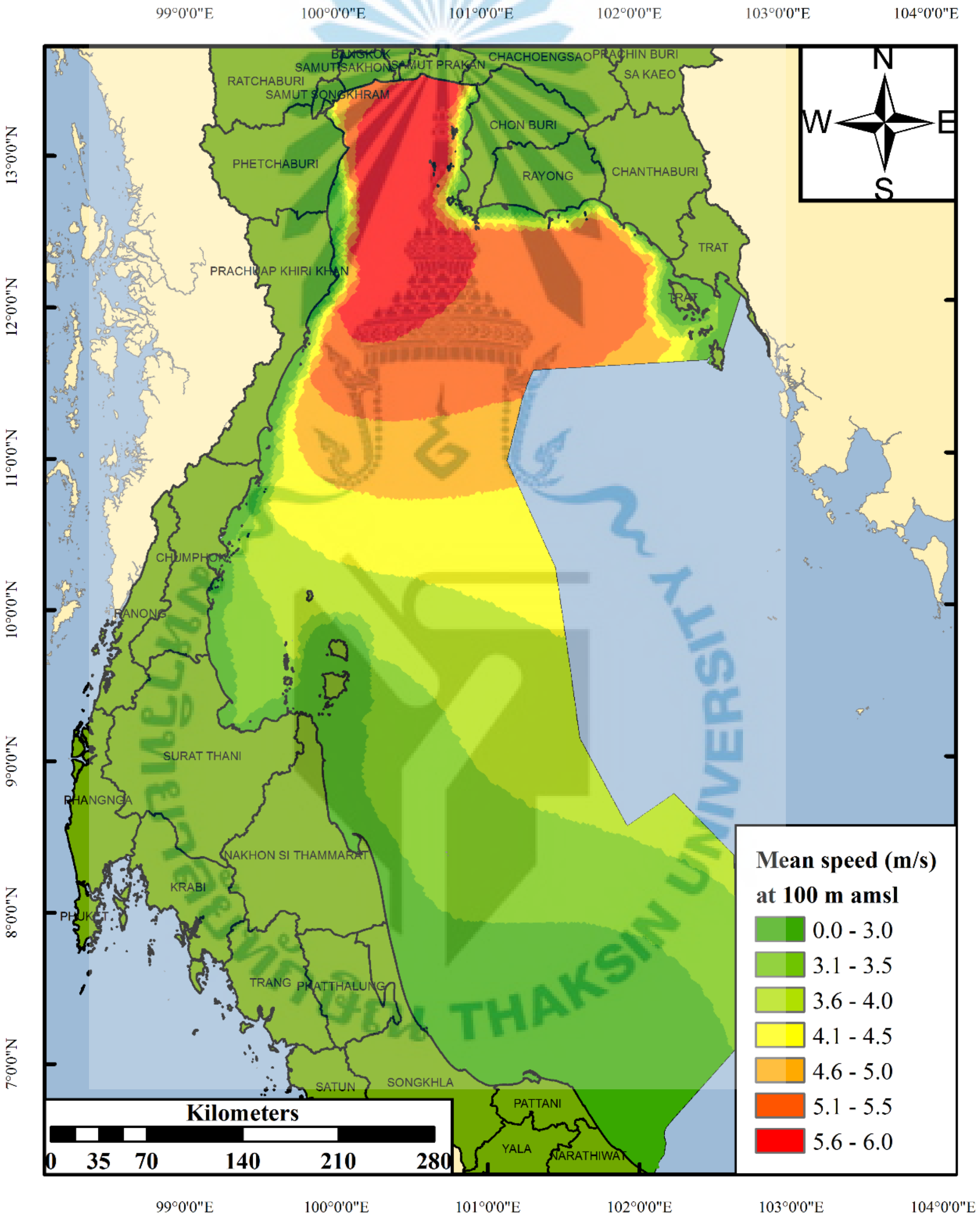
🟩 3.1 - 3.5
🟩 3.6 - 4.0
🟨 4.1 - 4.5
🟧 4.6 - 5.0
🟧 5.1 - 5.5
🟥 5.6 - 6.0
Kilometers
0 35 70 140 210 280

(a)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NARATHIWAT
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Kilometers
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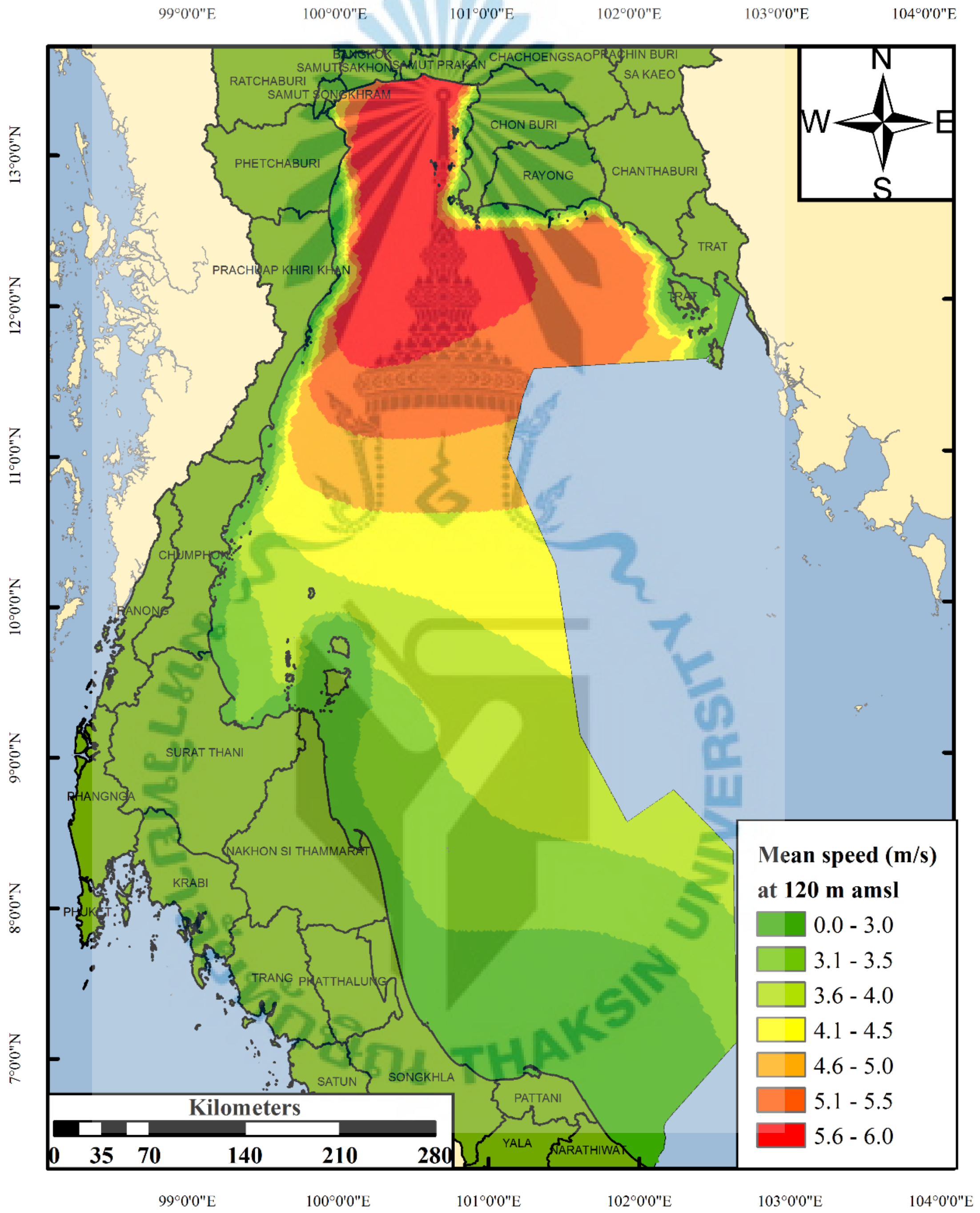
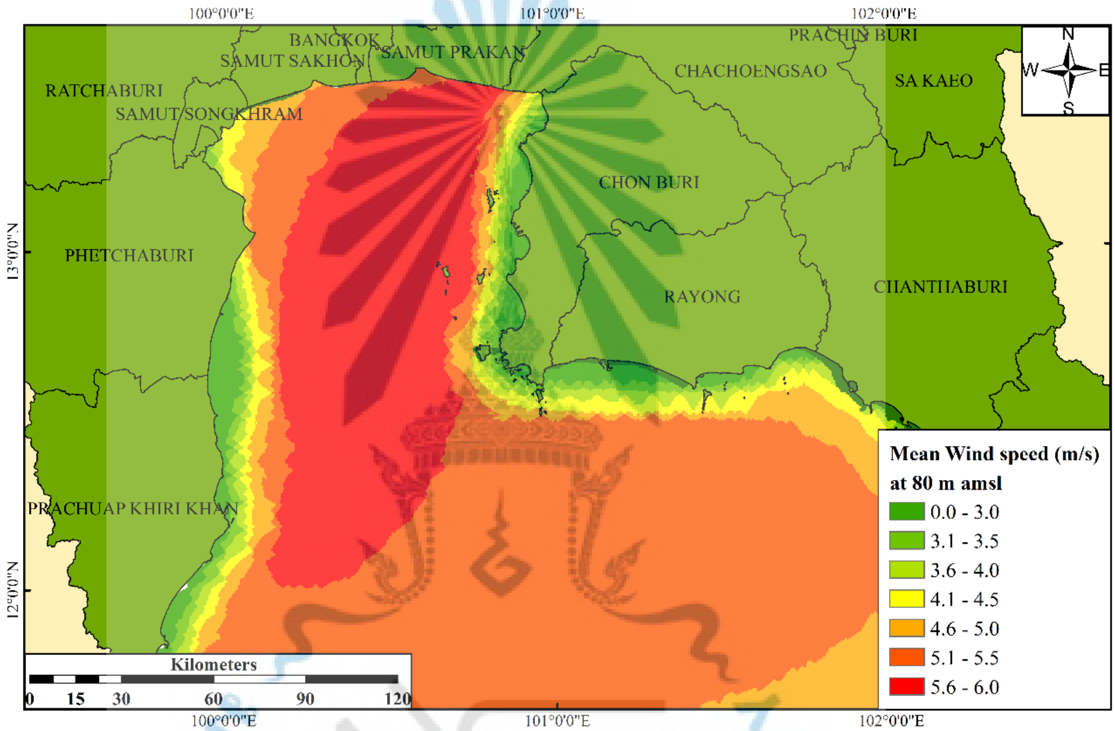
Mean speed (m/s) at 100 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
4.1 - 4.5
4.6 - 5.0
5.1 - 5.5
5.6 - 6.0

(b)



(c)

Figure 4.9 Annual mean wind speeds at a) 80 m, b) 100 m and c) 120 m amsl in the Gulf of Thailand.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SAMUT SONGKHRAM
CHON BURI
PHETCHABURI
RAYONG
CHANTHABURI
PRACHUAP KHIRI KHAN
N
W
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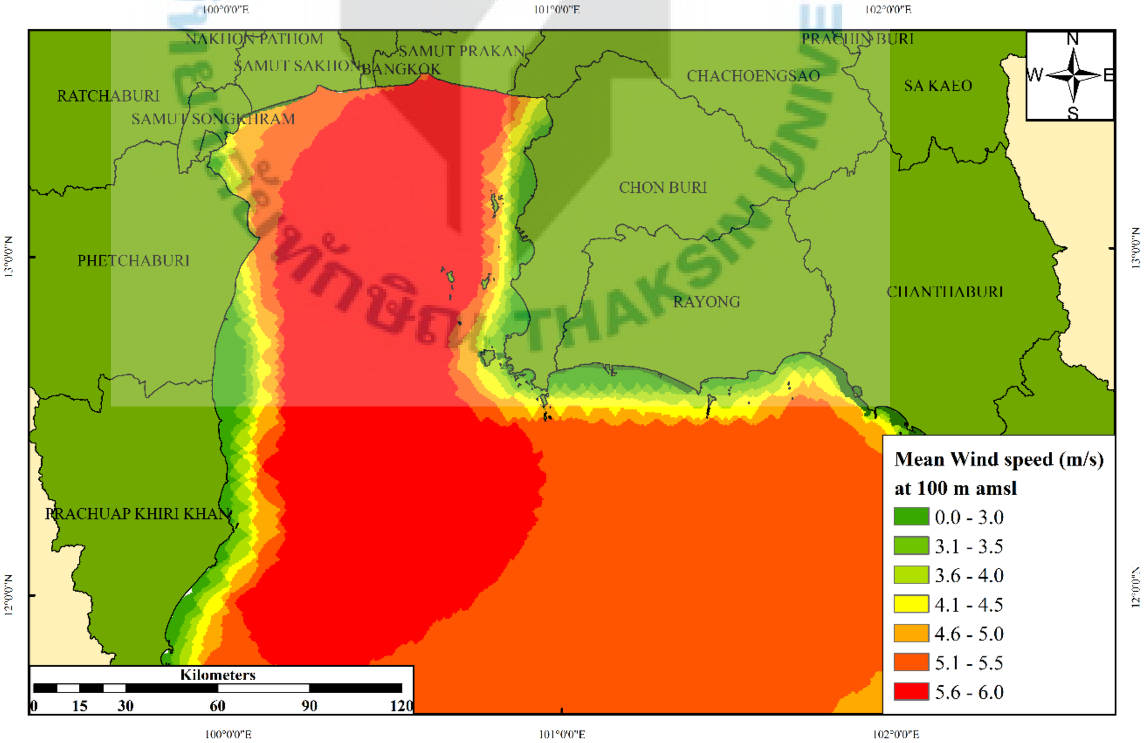
S
Mean Wind speed (m/s) at 80 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
4.1 - 4.5
4.6 - 5.0
5.1 - 5.5
5.6 - 6.0
Kilometers
0 15 30 60 90 120

(a)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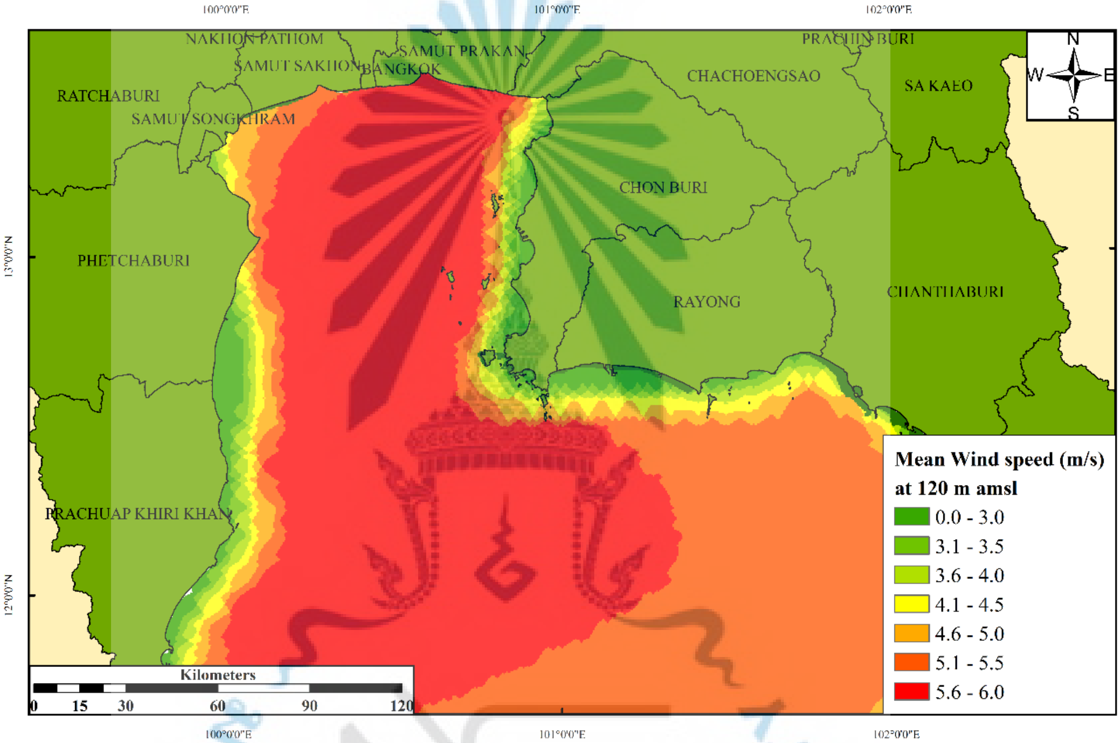
Mean Wind speed (m/s) at 100 m amsl
0.0 - 3.0
3.1 - 3.5
3.6 - 4.0
4.1 - 4.5
4.6 - 5.0
5.1 - 5.5
5.6 - 6.0
Kilometers
0 15 30 60 90 120

(b)



(c)

Figure 4.10 Annual mean wind speeds at a) 80 m, b) 100 m and c) 120 m amsl in the Bay of Bangkok.

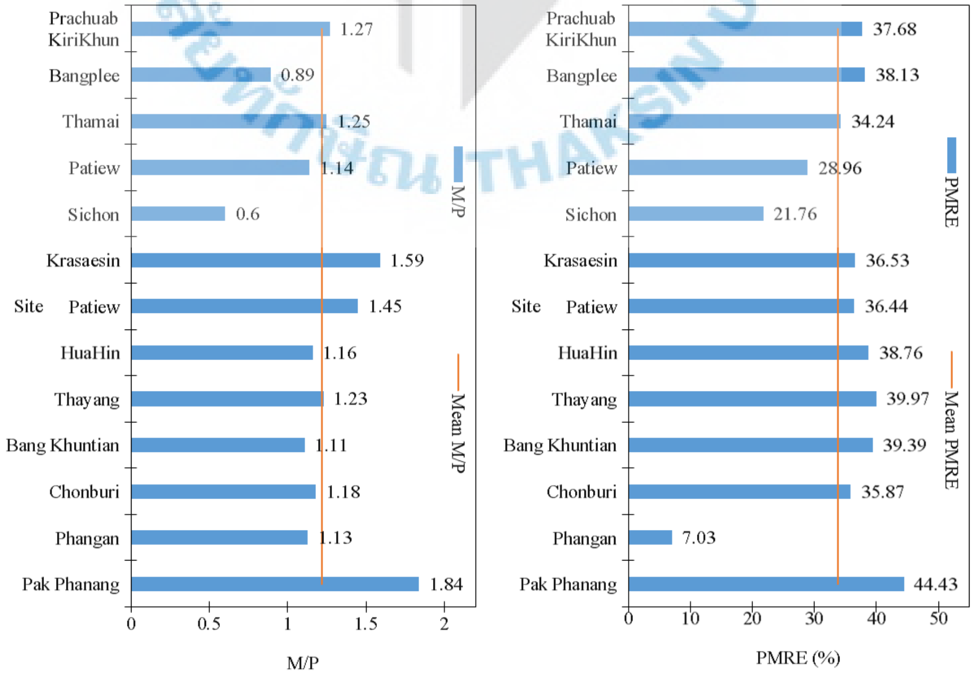


Figure 4.11 Validation of the wind resource maps using the 13 met masts on the coastline of the Gulf of Thailand: M/P ratio (left) and PMRE (right).

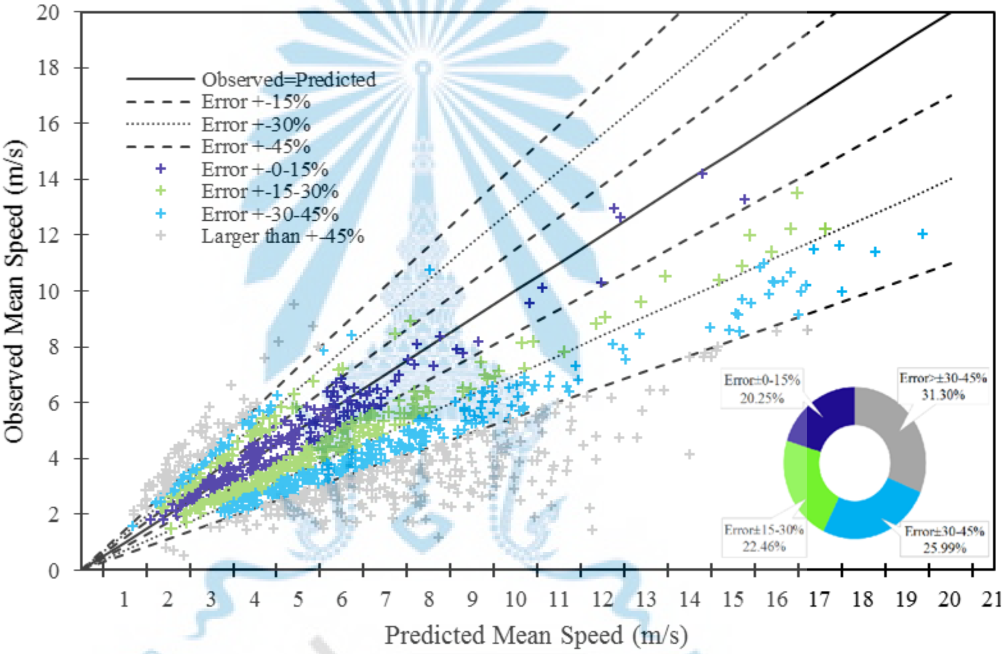


Figure 4.12 Comparisons between daily observed wind speeds and daily predicted wind speeds at 90 m agl.

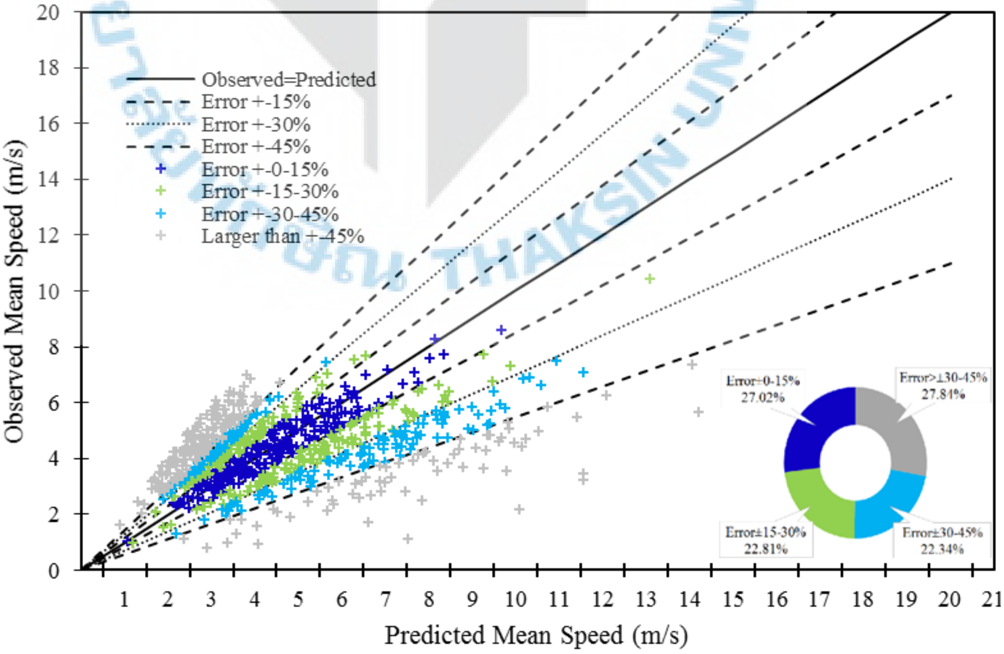
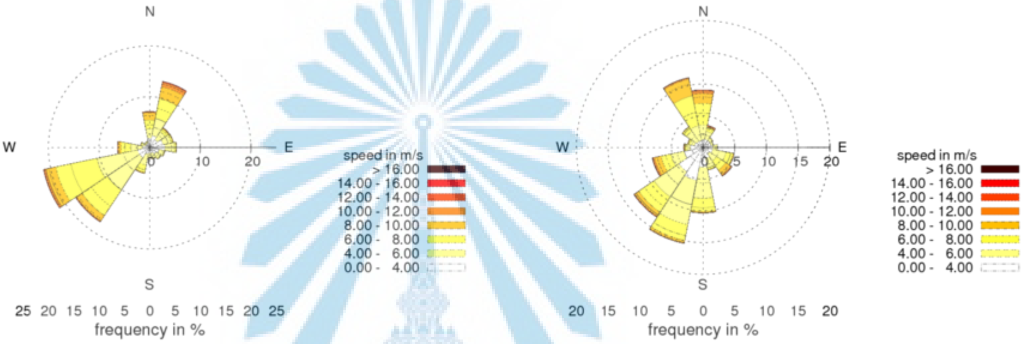
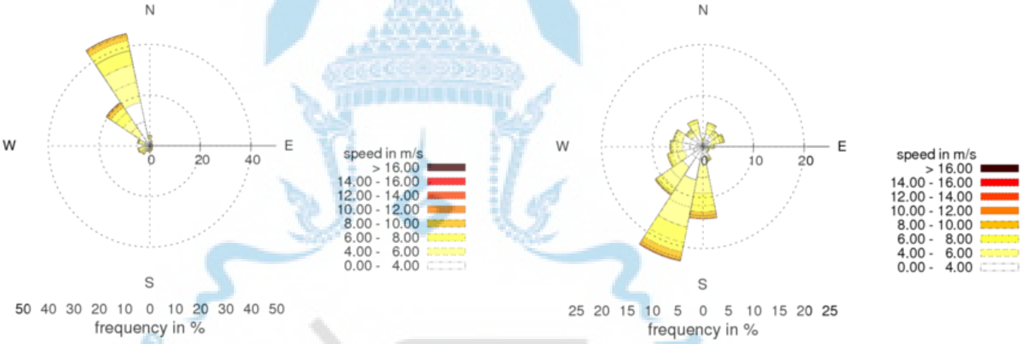


Figure 4.13 Comparisons between daily observed wind speeds and daily predicted wind speeds at 120 m agl.



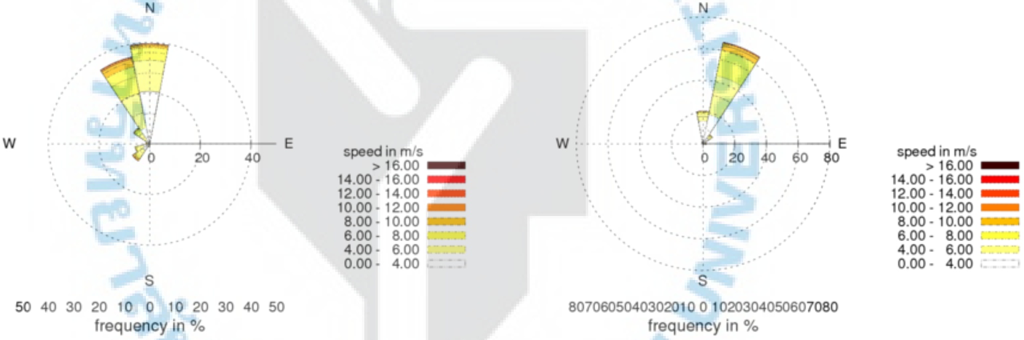
Patiew 120 m AGL

Hua Hin 120 m AGL



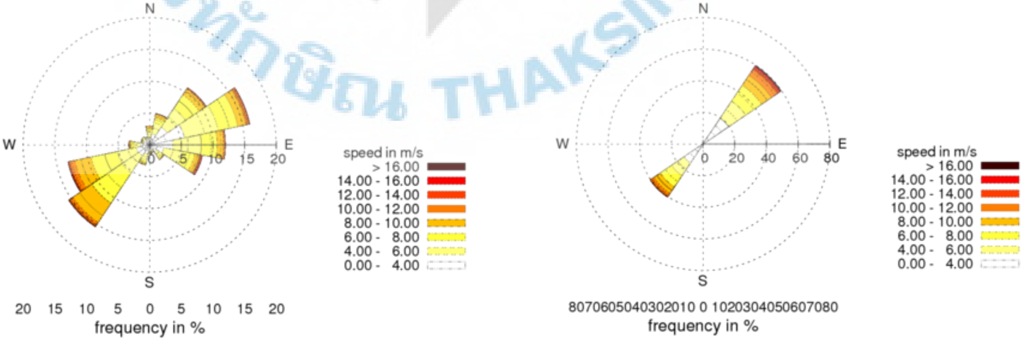
Thayang 120 m AGL

Bank Khuantian 120 m AGL



Chonburi 120 m AGL

Phangan 120 m AGL



Pak Phanang 120 m AGL

WRF Predicted 100 MASL

Figure 4.14 The comparison of measured (120 m agl) and predicted (100 m amsl) wind directions along the coastal area of the Gulf of Thailand.

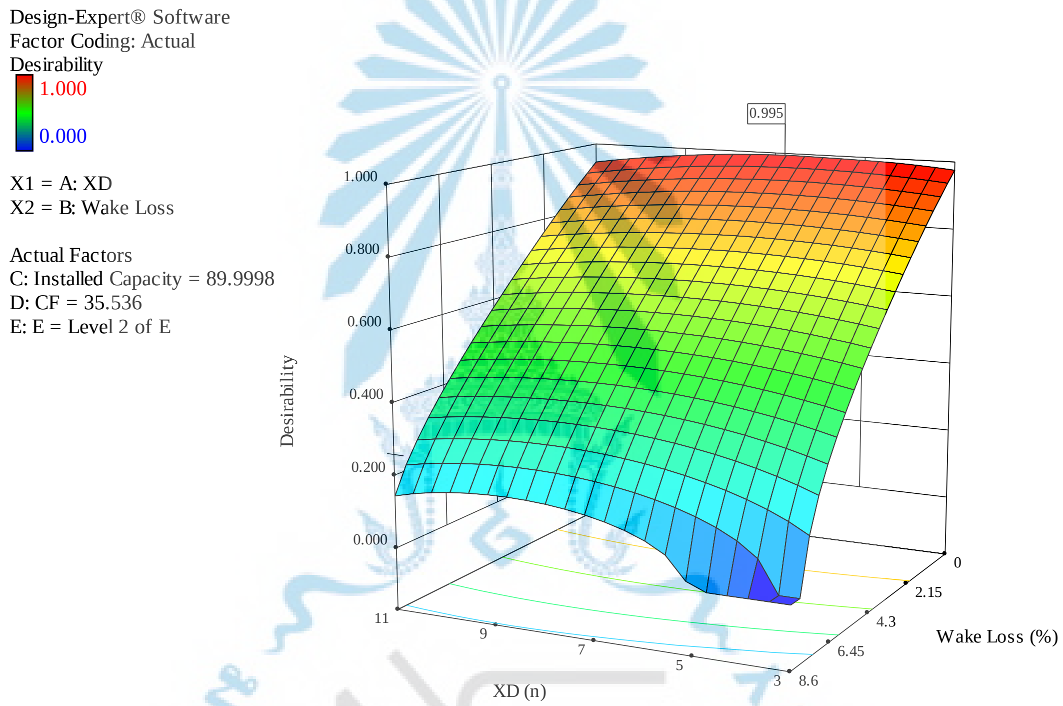


Figure 4.15 The RSM of desirability for the number of rotor diameter and wake losses, for the 3.3 MW wind turbine generator.

More specifically, the installed capacity of offshore wind power plants in Zone I is in the range of 642 to 924 MW, depending on the WTG selected. For medium-term planning, Zones II, III and IV, with a combined total surface area of 1,158 km^2, could integrate an additional installed capacity in the range of 2,658 to 3,825 MW. Finally, for long-term planning, Zones V and VI, with a combined total surface area of 1,248 km^2, could integrate an additional installed capacity in the range of 2,864 to 4,120 MW.

The zoning approach provides a pathway of development of the offshore wind resource in the GoT. Once the different zones are fully developed, 6,000 to over 8,000 MW of offshore wind power plants could produce the following AEP: short-term planning (Zone I), between 5 and 8 PWh per annum; medium-term planning (Zones II, III and IV), an additional 23 to 33 PWh per year; long-term planning (Zones V and VI), an additional 25 to 36 PWh per year. Once all zones would be fully occupied by offshore wind power plants, they could generate approximately between 30% (3.3 MW WTG)and 45% (8 MW WTG) of the current domestic electricity load (173 PWh in 2014 [48]).

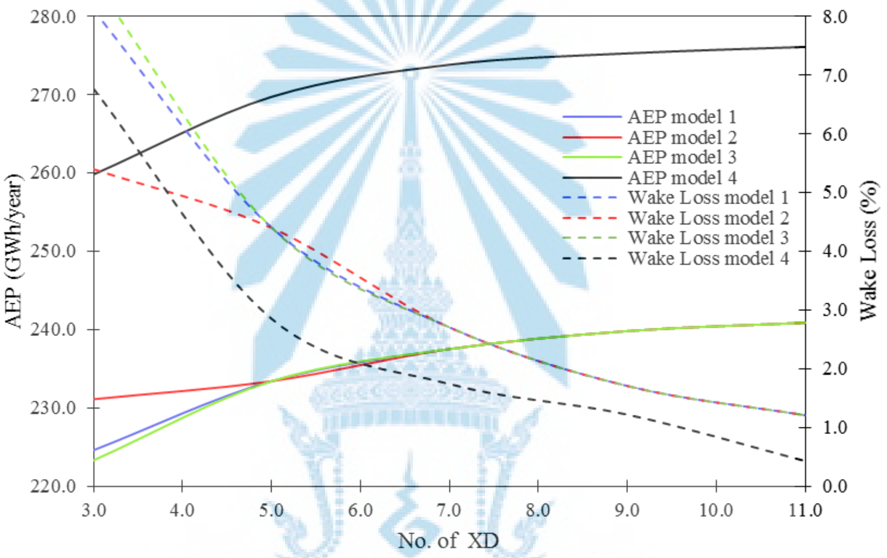


Figure 4.16 The annual energy production and the wake losses for the 3.3 MW wind turbine generator and multiple wake models.

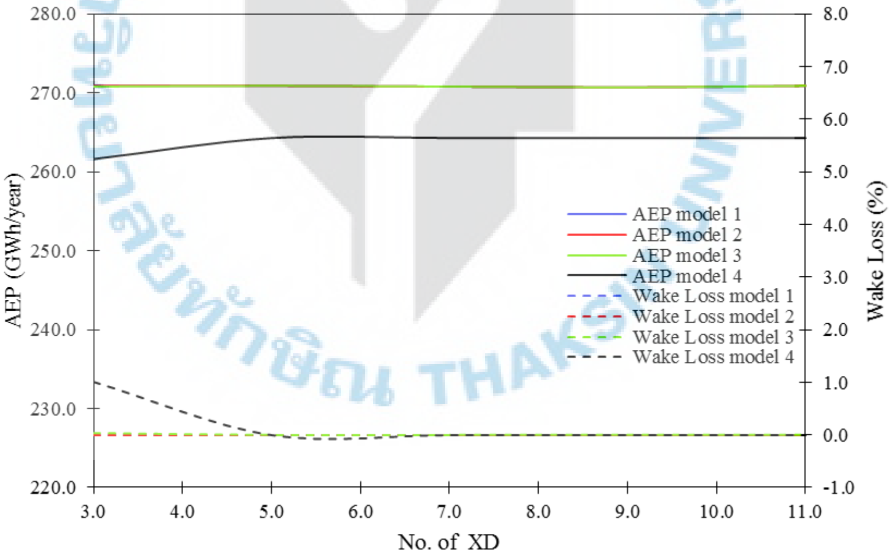


Figure 4.17 The annual energy production and the wake losses for the 5 MW wind turbine generator and multiple wake models.

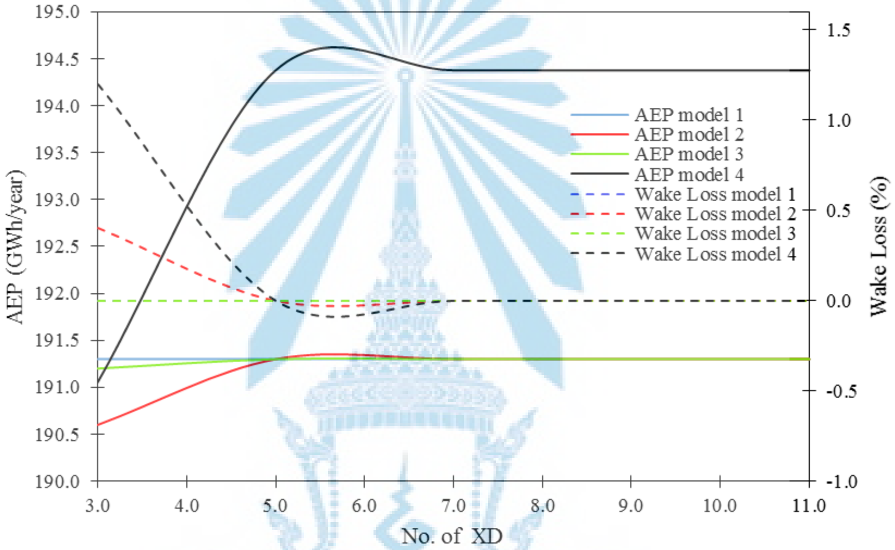


Figure 4.18 The annual energy production and the wake losses for the 8 MW wind turbine generator and multiple wake models.

The offshore wind power plants could also significantly avoid CO_{2eq} emissions, thus mitigating global climate change while enhancing the sustainable development of the country. Indeed, the proposed offshore wind power plants could avoid CO_{2eq} emissions in the order of 3 to 4.5 million tonnes CO_{2eq} per year in the short-term planning, an additional 13 to 18 million tonnes CO_{2eq} per year in the medium-term planning, and an additional 14 to 20 million tonnes CO_{2eq} per year in the long-term planning of wind power developments. Table 4.4 summarizes the AEP and the CO_{2eq} emission avoidance by the proposed wind power plants in each zone.

Table 4.3 Technical power potential (TPP) of potential offshore wind power plants in the Gulf of Thailand.

Planning	Zone	Surface Area (km^2)	TPP (MW)		
			3 MW	5 MW	8 MW
Short-Term	I	280	642	881	924
Medium-Term	II	460	1,056	1,449	1,519
	III	348	799	1,097	1,150
	IV	350	803	1,103	1,156
Total Medium-Term		1,158	2,658	3,639	3,825
Long-Term	V	591	1,356	1,861	1,951
	VI	657	1,508	2,069	2,169
Total Long-Term		1,248	2,864	3,930	4,120
All		2,686	6,164	8,450	8,869

Table 4.4 Annual energy production and CO_{2eq} emission avoidance by the potential offshore wind power plants in the Gulf of Thailand.

Planning	Zone	Surface Area (km^2)	Energy (GWh/year)			CO_{2eq} Emission Avoidance (million tons CO_{2eq})		
			3 MW	5 MW	8 MW	3 MW	5 MW	8 MW
Short-Term	I	280	5,638	7,719	8,092	3.1	4.2	4.5
Medium-Term	II	460	9,273	12,695	13,309	5.1	7.0	7.2
	III	348	7,016	9,606	10,070	3.8	5.3	5.5
	IV	350	7,055	9,660	10,126	3.9	5.3	5.6
Total Medium-Term		1,158	23,344	31,961	33,505	12.8	17.6	18.3
Long-Term	V	591	11,905	16,299	17,087	6.5	9.0	9.4
	VI	657	13,240	18,127	19,003	7.3	10.0	10.4
Total Long-Term		1,248	25,145	34,426	36,090	13.8	19.0	19.8
All		2,686	54,127	74,106	77,687	29.7	40.8	42.6

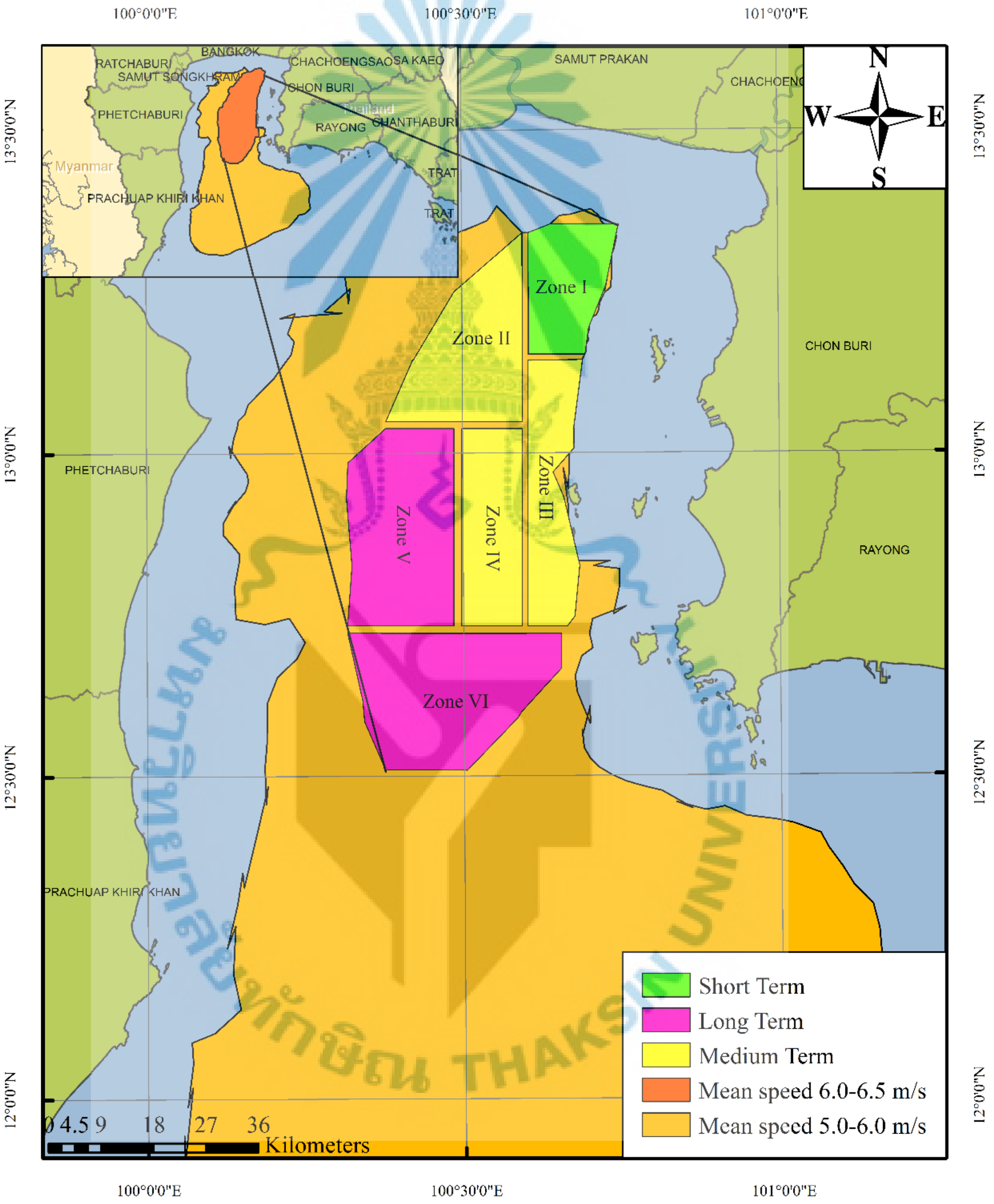


Figure 4.19 Priority zoning for the development of offshore wind power plants in the Gulf of Thailand.

4.4 Conclusion

The investigation of the offshore wind power potential in the GoT show that, in the most promising locations for wind power development, the average annual mean wind speeds are in the range of 5.5 to 6.5 m/s at 120 m amsl. The wind regime in the Gulf of Thailand is strongly affected by the Northeast (November to February) and Southwest (May to September) monsoons, when high wind speeds occur.

The current study, for the same general area, but with a completely different methodology and a different climatic database than a previous study [29], has confirmed that the Gulf of Thailand in general, and the Bay of Bangkok in particular, have a promising wind resource potential for wind power generation. Thus, the results presented in the current study, while comparing the effectiveness of the WRF model combined with micro-scale modeling, validates the overall wind resource in this territory.

The spatial distribution of the mean wind speeds shows that the northern part of the GoT, particularly in the Bay of Bangkok, is characterized by the most interesting wind resource for electricity generation.

Depending on the wind turbine generator selected, it is found that 642 to 924 MW of capacity could be installed in the short-term planning; 2,658 to 3,825 MW of additional capacity could be added in the medium-term planning, and 2,864 to 4,120 MW of additional capacity in the long-term planning. These wind power plants would have an annual energy production in the order of 5.6 to 8 PWh in the short-term, an additional 23 to 33 PWh in the medium-term, and an additional 25 to 36 PWh in the long-term, respectively.

With growing concerns about climate change, electricity generation facilities are increasingly assessed in regards in regards to CO_{2eq} emissions, or their avoidances. By developing wind power plants in the GoT, the country would avoid CO_{2eq} emissions in the order of 3 to 4.5 million tonnes CO_{2eq} per year in the short-term, 13 to 18 million tonnes in the medium-term, and 14 to 20 million tons in the long-term. Depending on future CO_{2eq} emission tariffs, these avoidance cold have an interesting economic value, thus enhancing the economic viability of the wind power projects.

In total, depending on the wind turbine generator selected, wind power plants in the GoT could have a total installed capacity of 6,000 to 8,000 MW, would generate between 50 and 75 PWh of energy per year, while avoiding emissions of 30 to 40 million tonnes CO_{2eq} per year. More detailed economic analyses would be needed to estimate the specific capital expenditures needed to build the specific projects; however, this work has shown that the economic viability of projects is possible without the additional revenues from eventual CO_{2eq} emission taxations or trading.

The wind resource in the Gulf of Thailand predicted in this work should be validated with an offshore met mast, appropriately located within the area of the most promising wind resource. Further, work should be engaged to assess the environmental impacts of developing offshore wind power in the Gulf of Thailand. Finally, building on the experiences of other jurisdictions who have developed an offshore wind power industry, an assessment of the social acceptance of such development should be performed to ensure the sustainability of this promising energy sector for Thailand.

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CHAPTER 5

Conclusion and Recommendations

5.1 Conclusion

Thailand has developed at least two development plans for its alternative energy sector, namely the Alternative Energy Development Plan of 2015 (AEDP2015) and the Power Development Plan of 2015 (PDP2015). The main objective of these plans is to develop renewable energy sources to supply power in Thailand. In regards to wind power, the target is to have an installed capacity of up to 3002 MW by the end of 2036. At present, the wind power installed capacity is 585 MW, or 20% of the AEDP2015 target, entirely consisting of onshore wind power plants. Because of the limited onshore wind resource in Thailand, and since many of the most windy sites are in forests or difficult mountainous regions or conservation areas, the need to further investigate the possibilities offered by offshore wind power appears to be an important enabler to achieve the AEDP2015 targets. While a low resolution wind resource map is presented for the entire country, this work ultimately presents a high resolution offshore wind resource assessment for the Gulf of Thailand by using different atmospheric and computational fluid dynamics models.

The three main components of the work consist of 1) the assessment of the onshore wind power potential of Thailand using the Regional Atmospheric Modeling System (RAMS), 2) the offshore wind resource assessment in the northern Gulf of Thailand, and the Bay of Bangkok, using atmospheric modeling and a climatic database and 3) the offshore wind resource assessment and wind power plant optimization in the Gulf of Thailand in general, and the Bay of Bangkok in particular.

The first component of the work presents an assessment of the onshore wind power potential in Thailand using the Regional Atmospheric Modeling System (RAMS). A 9 km resolution, 1,150 km by 1,750 km, wind resource map at 120 m elevation agl was produced based on the NCEP reanalysis database for the three year period of 2009-11. The onshore wind resource map was validated by comparing the modeling results to observed wind data at 100 m agl from the Pollution Control Department (PCD) of Thailand, and at 120 m agl from the National Research Council of Thailand (NRCT). The mean square error (MSE) was computed and was used as the main criterion to evaluate the simulation results. Results showed that, for the study area, the annual mean wind speeds at 120 m agl were in the range of 1.60 to 5.83 m/s.

For its part, the maximum annual mean power density at 120 m agl was approximately 200 W/m^2, which corresponds to a wind power density of Class 2. Results show that the region has a good wind regime in the mountain areas of western, southern and eastern Thailand. However, because of the limited resources and the constrained imposed by the territory, further assessments would be needed to determine how best to integrate and develop the onshore wind energy resource to achieve the national renewable energy policy targets in Thailand.

The second component of the work assesses the wind resource in the northern part of the Gulf of Thailand, where the mean wind speeds in the Bay of Bangkok ranges from 2.3 to 7.5 m/s. These predictions, obtained by applying the MC2 model, along with the MERRA climatic database, is not significantly different from other models. An optimal area of development is selected by taking into consideration the marine resources, the navy routes and the submarine cables, which is an area of approximately 20 km radius around the point of latitude 12.12 N and longitude 100.89 N. In the validation process, a percent mean relative error and a mean bias were applied to demonstrate the differences between the WRF-MERRA wind data source and the MC2-MERRA wind data at the same elevation and geological position. The technical power potential area is estimated to be approximately 1,500 km^2, with a technical potential installed capacity of approximately 2,500 MW in the areas with mean speeds over 7 m/s. The results of the wind map validation, shown in terms of measured/predicted (M/P) ratio and the percent mean relative error (PMRE), are found in the range of 0.70 to 0.96, and 4 to 42%, respectively. On the basis of this work, wind developers should install offshore wind measurement equipment, over a period of not less than one year, to confirm the wind resource and to determine the feasibility of offshore wind power projects.

In the last component of the work, the investigation of the offshore wind power potential in the GoT show that, in the most promising locations for wind power development, the average annual mean wind speeds are in the range of 5.5 to 6.5 m/s at 120 m amsl. The wind regime in the Gulf of Thailand is strongly affected by the Northeast (November to February) and Southwest (May to September) monsoons, when high wind speeds occur. The current study, for the same general area, but with a completely different methodology and a different climatic database than a previous study, has confirmed that the Gulf of Thailand in general, and the Bay of Bangkok in particular, have promising wind resource potentials for wind power generation. Thus, the results presented in the current study, while comparing the effectiveness of the WRF model combined with micro-scale modeling, validates the overall wind resource in this territory. The spatial distribution of the mean wind speeds shows that the northern part of the GoT, particularly in the Bay of Bangkok, is characterized by the most promising wind resource for electricity generation. Depending on the wind turbine generator selected, it is found that 642 to 924 MW of capacity could be installed in the short-term planning; 2,658 to 3,825 MW of additional capacity could be added in the medium-term planning, and 2,864 to 4,120 MW of additional capacity in the long-term planning. These wind power plants would have an annual energy production in the order of 5.6 to 8 PWh in the short-term, an additional 23 to 33 PWh in the medium-term, and an additional 25 to 36 PWh in the long-term, respectively. With growing concerns about climate change, electricity generation facilities are increasingly assessed in regards to CO_{2eq} emissions, or their avoidances. By developing wind power plants in the GoT, the country would avoid CO_{2eq} emissions in the order of 3 to 4.5 million tonnes CO_{2eq} per year in the short-term, 13 to 18 million tonnes in the medium-term, and 14 to 20 million tonnes in the long-term. Depending on future CO_{2eq} emission tariffs, these avoidance could have an interesting economic value, thus enhancing the economic viability of the wind power projects.

5.2 Recommendations

For the future assessments, the offshore wind energy resource in the Gulf of Thailand should be evaluated by using other meteorological models and climatic data in order to reduce the uncertainties in the estimation of the annual energy production of wind power plants that could be installed in this territory.

Furthermore, the wind resource in the Gulf of Thailand predicted in this work should be validated with an offshore met mast, appropriately located within the area of the most promising wind resource. The future work should also be engaged to assess the environmental impacts of developing offshore wind power in the Gulf of Thailand. Finally, building on the experiences of other jurisdictions who have developed an offshore wind power industry, an assessment of the social acceptance of such development should be performed to ensure the sustainability of this promising energy sector of Thailand.

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