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Article *in* Energy Reports · November 2022

DOI: 10.1016/j.egyr.2022.04.068

Energy Reports 8 (2022) 6220–6233

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Wind power generation and appropriate feed-in-tariff under limited wind resource in central Thailand

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ARTICLE INFO

Article history:
Received 20 June 2021
Received in revised form 9 March 2022
Accepted 25 April 2022
Available online xxxx

Keywords:
Computational Fluid Dynamics (CFD) wind flow modeling
Economic analysis
Feed-in-tariff (FIT)
Wind turbine generator technology
Wind power

ABSTRACT

The objective of this paper is to assess the wind energy resource in the central region of Thailand for wind power generation, along with analyzing the economic feasibility and appropriate feed-in-tariff (FIT) of a proposed 15 MW wind power plant. A microscale wind resource map was created using measured wind data, a computational fluid dynamics wind flow modeling and high-resolution topography databases. Five utility-scale wind turbine generators (WTG), with hub heights ranging from 80 to 120 m above ground level (agl), were used to estimate the annual energy production (AEP). Considering the available wind resource, the most appropriate WTG was identified, and a wind power plant layout was achieved to maximize the AEP as well as minimizing the wake losses. The maximum net AEP, capacity factor (CF), %AEP improvement, %wake loss reduction, and CO_{2eq} emission avoidance were also analyzed. Several financial indices and the levelized cost of energy (LCOE) were analyzed on the basis of a cost–benefit analysis. The economic sensitivity of the costs was used to determine the most appropriate FIT for the project. Results reveal that the mean annual wind speed at 120 m agl in the central region of Thailand reaches 5.8 m/s. The net AEP, CF, %AEP improvement, %wake loss, and CO_{2eq} emission avoidance for a 15 MW wind power plant are estimated at 41 GWh/year, 30%, 6%, 10% and 231 ktonnes CO_{2eq}/year, respectively. The LCOE for a base case scenario is estimated at 0.093 US$/kWh, with a FIT of 0.195 US$/kWh. Finally, the results of this work can be used as guidelines for wind power project development in the central region of Thailand and in other regions of the world where the wind resource is low to moderate under current existing WTG technology.

1. Introduction

On the basis of the 5th assessment report provided by the Intergovernmental Panel on Climate Change (IPCC) on the anthropogenic emissions of greenhouse gases (GHG) (Anon, 2021a), and in consideration of the benchmarks established at the Conference of Parties (COP21) held in Paris in 2015 (Anon, 2021b), Thailand intends to reduce its GHG emission by 20% from the projected business-as-usual (BAU) level by 2030 (Anon, 2021b).

Based on facts provided by the United Nations Development Programme (UNDP), energy is a main contributor to climate change worldwide, accounting for 60% of the anthropogenic GHG emissions. Goal 7 of the UN Sustainable Development Goals (SDG) aims to correct important imbalances by ensuring everyone has access to affordable, reliable, and modern energy services by the year 2030. To expand energy access, it is necessary to enhance energy efficiency and to invest in renewable energy (Anon, 2021c).

Renewable energy is useful energy that is collected from renewable resources, which are naturally replenished on a human timescale. Amongst the renewable energy power generation sources, wind power is expected to increase the most in absolute generation terms (Anon, 2021d). Despite the constraints imposed by the new coronavirus pandemic, which has led to construction activities slowing down due to supply chain disruptions and logistical challenge in many countries, the net wind capacity additions have continued to increase (Anon, 2021e).

Focusing on Thailand, studies have shown that the wind resource is in general low to moderate (5–7 m/s); however, there are some potential specific areas where the wind speeds are above 8 m/s (Waewsak et al., 2013). However, these potential

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https://doi.org/10.1016/j.egyr.2022.04.068

areas are mostly in the mountainous region, while some areas are prohibited for the development of wind power plants due to constraints on land usage and legislation. Even so, the existing wind power capacity in Thailand is currently close to 1500 MW across the country (Anon, 2021f). The success of the wind power development in Thailand is based on three key factors, i.e., (1) wind power plants are developed in suitable areas, (2) the commercial utility-scale WTG are currently well developed to exploit moderate wind regimes and (3) suitable financial supporting schemes for investments are provided by governmental policies.

In 2015, the Thai Ministry of Energy has set clear policy and target goals through the Alternative Energy Development Plan (AEDP 2015) (Anon, 2021g), with a goal of 30% share of renewable energy in the form of electricity, heat and biofuel. Under this plan, wind power is expected to reach a capacity of 3002 MW beyond 2030. In order to achieve the AEDP 2015, several main supportive schemes and campaigns are also included and promoted, e.g. power purchase agreements (PPA) under one stop service, adder tariff (0.116 US$/kWh), feed-in-tariff (FIT) (0.201 US$/kWh), tax holidays and exemption by the Board of Investment (BOI), initial environmental examination (IEE) for wind power plant development rather than environmental impact assessment (EIA), and carbon credit trading under Thailand voluntary emission reduction (T-VER) program (Anon, 2021h).

Recently, in 2018, a revised AEDP (AEDP 2018) was launched, with a revised wind power capacity of 2989 MW beyond 2036 (Anon, 2021i). While a FIT program was implemented in 2013 by the National Energy Board (Pita et al., 2015), the selection process for wind power plant developments are now through competitive bidding processes (Anon, 2021j).

The development of wind power plants with lower initial investment costs and lower levelized cost of energy (LCOE) is quite challenging for competitive bidding process. The cost effectiveness in wind power plant development can be controlled by seeking the suitable wind resource sites where the logistic and transportation of WTG and construction phase are possible and easy. Not only that, suitable sites near electricity grids for interconnection is another key factor to be taken into consideration.

Preliminary wind resource assessment (WRA) can be accomplished by simply identifying suitable sites using wind resource maps provided by either a national database or available in the public domain. In Thailand, a national wind resource map at 90 m agl was developed and is provided by the Department of Alternative Energy Development and Efficiency (DEDE) (Anon, 2021k). For a global perspective, wind resource maps are also provided by Vaisala (Anon, 2021l), Vortex (Anon, 2021m) and the Technical University of Denmark (DTU) (Anon, 2021n). Nonetheless, the critical issues in using these maps are related to their low resolutions, while needing interpolations to assess the wind resource at specific elevations corresponding to the hub heights of a current WTG technologies.

At present, several research works are being done on WRA, thus providing critical information for wind power development in various regions of the globe. Further, these studies provide data points on the wind resource throughout the globe, thus contributing to better understanding of the wind resource in a global perspective.

In this context, the wind power potential was recently assessed in the coastal region of Tamil Nadu, India by analyzing ground-based meteorological masts measurement data from seven selected sites with wind power density of more than 200 W/m^2 (Boopathi et al., 2021), while a multi-criteria analysis method, combining the analytical hierarchy process (AHP) and geographical information systems (GIS), is applied to identify the most suitable locations for the installation of wind turbine generators, with case studies in Serbia (Potic et al., 2021) and in Thailand (Ali et al., 2019).

The wind energy potential of China was assessed, with an emphasis on its variability/intermittency. The study took the first attempt to quantify the cost of the variability/intermittency of wind energy coupled with energy storage system, with the aim of comprehensively assessing the spatial distribution of the exploitability of wind energy in China. This work has concluded that in the near future, wind power plants with advanced energy storage technology in 2030 or 2050 could provide stable wind energy, with comparable market prices, which are lower than the price of current coal-fired electricity (Gao et al., 2020).

The Weibull distribution model was also extensively used to estimate wind energy potential for coastal locations in India. A novel method has been developed for estimating the actual wind power available to the WTG. The main finding concluded that the parent two-parameter Weibull model can be used to determine the availability factor, whereas when determining the available wind energy between cut-in and rated wind speeds, wind speed data should be refitted in the range defined by the cut-in and rated speed using a three-parameter Weibull model (Deep et al., 2020).

An assessment of wind power potential along the coast of Tamaulipas, northeastern Mexico was also presented. A gridded reanalysis BMW-CERSAT wind data from 2004–09 is used as input to analyze the mean wind power density by using the Wind Atlas Analysis and Application Program (WAsP). Results showed that the wind power potential of the southern half of the Tamaulipas State is classified as poor (200–300 W/m^2), becoming marginal in some areas near the coast. Only the northern half of the State is classified with moderate potential (400–500 W/m^2), while the lagoon zone has good potential (Carrasco-Diaz et al., 2015).

The potential of onshore wind power was assessed for European countries based on the wind atlas methodology. An assessment depicted via maps under national and regional socio-technical restrictions and regulations for wind power project development using spatial analysis tool (GIS). Results revealed that 52.5 TW of untapped onshore wind power potential in Europe was discovered (Enevoldsen et al., 2019).

Once the wind resource potential is assessed, the appropriate WTG technology that suit to the wind regime is further studied. Technical and economic aspects of wind power plants are analyzed in this stage of development. They include an analysis of the annual energy production (AEP), the capacity factor (CF), and the levelized cost of energy (LCOE). The environmental impacts and the social acceptance are also key factors needed for consideration in wind power plant developments (Waewsak et al., 2017).

The wind parameters based on the Weibull distribution have been used to calculate the wind power density, annual energy yield, capacity factor and cost of energy of Hawke's Bay in China. The site-specific wind shear coefficient is found to be 0.18. The annual wind speeds were 5.04, 5.84 and 6.05 m/s at 30 m, 60 m and 80 m agl. The mean power densities were 184.0, 231.5 and 307.5 W/m^2. Based on 2.3 MW WTG, the lowest price of cost of energy was 0.056 US$/kWh (Hulio et al., 2019).

Therefore, the development of wind power plant directly relates to not only wind resource assessment but also techno-economic evaluation, while environmental and social acceptance are also two key factors for wind power project implementation phase. Some exercises related to techno-economic assessment of wind power plant have been presented in the scientific literature, with applications in Pakistan (Jameel et al., 2021) and in Jordan (Ali and Dalabeeh, 2017).

Historical background knowledge, further confirmed by recent publications in the scientific literature, show that wind resource assessments, as well as techno-economic analysis, are crucial in the early stage of wind power plant developments, notably in regions with limited wind resources. Consequently, the main objectives of this paper are to assess the wind energy resource in the central region of Thailand, coupled with a techno-economic analysis of appropriate feed-in-tariffs (FIT) policies to meet the bankable financial criteria for wind power plant installation. The originality of this work is to develop a microscale wind resource map using in-situ measurements and CFD wind flow modeling with resolution of 50 m, along with the optimization of the wind turbine generator locations to maximize the AEP while minimizing wake losses for maximum benefit in the economic analysis. Besides documenting a high-resolution wind resource and the economic viability of wind energy in an emerging country (Thailand), the present work differs from previous work in the scientific literature, which usually applies either mesoscale atmospheric modeling or coupled mesoscale atmospheric and microscale wind flow modeling to predict wind speeds with resolution in the range of 1 to 3 km. While the methodology presented is applied to a region with limited wind resources in Thailand, the methodology can be applied in any region to assess the viability of wind power plant development.

2. Methodology

2.1. Study area

The study area, with a square boundary of 20 × 20 km^2, is located in the Pamok district, Ang Thong province, in central Thailand as shown in Fig. 1. Based on the ASTER GDEM v2 Worldwide Elevation Data with a resolution of 1 arc-second (NASA, 2021), the terrain of the study area is quite flat where the maximum elevation is less than 28 m above mean sea level, as illustrated in the upper part of Fig. 2. By using the land cover land use (LCLU) database of 2003, which is the commercial product of the Land Development Department (LDD), along with Arc GIS V 10.4 software package for spatial data analysis, it is found that 70.3% of the territory studied is agricultural land, 15.8% is urban and built-up land while 8.7% is miscellaneous and 5.2% is water bodies. The spatial distribution of the land cover land use in the study area is also shown in the lower part of Fig. 2. The roughness length, another key parameter input in wind resource assessment, is analyzed using the LCLU database (Anon, 2021o). The spatial distribution of roughness length of the study area is given in Fig. 3.

2.2. The characteristics of the wind resource

Wind speeds and directions at 100 m, 80 m and 65 m agl are measured using NRG three-cup anemometer and wind vane, along with a Nomad II Wind data logger. A thirteen month observation campaign between February 2014–February 2015 was accomplished. The data recovery rate was 83%. Annual mean speeds and variations of the monthly mean wind speeds are analyzed and presented. The Weibull distribution, with 1.0 m/s interval and wind rose with 16 sectors, are investigated in order to analyze the shape and scale parameters and the incoming dominant wind direction.

2.3. Computational Fluid Dynamics (CFD) wind flow modeling

Micro-scale wind resource assessment based on Computational Fluid Dynamics (CFD) wind flow modeling is commonly applied to reproduce the flow field caused by the local terrain characteristics and topography. CFD simulations are particularly useful in the development of wind energy in regions with complex terrains, along with being used in the micro-sitting of wind turbine generators within wind power plants (Murthy and Rahi, 2017).

CFD simulations also offer high resolution 3D wind fields without the need for costly meteorological equipment. In the past, linear wind flow models, such as the one implemented in the Wind Atlas Analysis and Application Program (WAsP), were applied due to their efficiency and sufficient accuracy, notably over simple terrain (Palma et al., 2008).

However, the increase in computational capacity, along with a need for higher accuracy wind flow predictions over complex terrain, have led to the development of more advanced CFD models. Thus, most CFD simulations solve the steady Reynolds-Averaged Navier–Stokes (RANS) equations, which are time independent and which provide the statistics for wind speeds at any grid point (Dhunny et al., 2017).

Other CFD simulation techniques that provide higher accuracy, but also higher computational cost, are being developed to analyze wind flow patterns. These time-dependent turbulence-resolving methods consist of Large-Eddy Simulation (LES) and Direct Numerical Simulation (DNS). LES applies a low-pass spatial filter to average out turbulence at smaller length scales. In this method, the computationally expensive calculations of small turbulent structures is replaced by sub-grid-scale modeling. DNS involves solving the full non-linear Navier–Stokes equations, but is too computationally expensive to be used in large area applications (Tabas et al., 2019).

WindSim, a CFD software package for micro-scale WRA has been used and evaluated in both the wind industry and in academia. It is designed to execute and accomplish the spatial variability reproduction of wind speed distributions, as well as the dynamic wind speed estimation of any specific positions within the considered region. CFD simulations are carried out to provide detailed wind fields, which implicitly carry the correlations of physical properties with the concerned space (Tang et al., 2019; Yan and Li, 2016).

Several works compared the results of WindSim to WAsP, especially over complex terrains, and found better accuracy (Llombart et al., 2006; Gasset et al., 2012). Further, WindSim was applied to a WRA study in Thailand and good agreements were obtained between simulation results and met mast measurements (Waewsak et al., 2017, 2019). Using error estimations, the model was also validated against wind atlas data and WAsP simulations (Yang et al., 2020).

In this work, the WindSim CFD model is used to simulate and provide the microscale wind field over the territory studied. WindSim's CFD model is developed based on RANS equations for momentum, turbulence and temperature, assuming steady-state and incompressible flows (Gravdahl, 1998; Meissner et al., 2009). The standard k–ε model (Launder and Spalding, 1974) is used as a turbulence closure. Even though other turbulence models exist (Bechmann et al., 2011; Cabezón et al., 2011), the standard k–ε model is by far the most popular in the wind energy industry (Bechmann et al., 2011).

In order to execute the WindSim model, the following conditions were set: fixed pressure for the boundary condition at the top of the domain; 1.225 kg/m^3 for air density and no temperature correction; standard k- ε turbulence model; segregated solver; and spatial resolution of 50 m. The time series wind speeds and directions with 10-min interval data, DEM, roughness lengths of the land cover of the territory studied, and power and thrust curves of five selected wind turbine generators are used as inputs in the WindSim model.

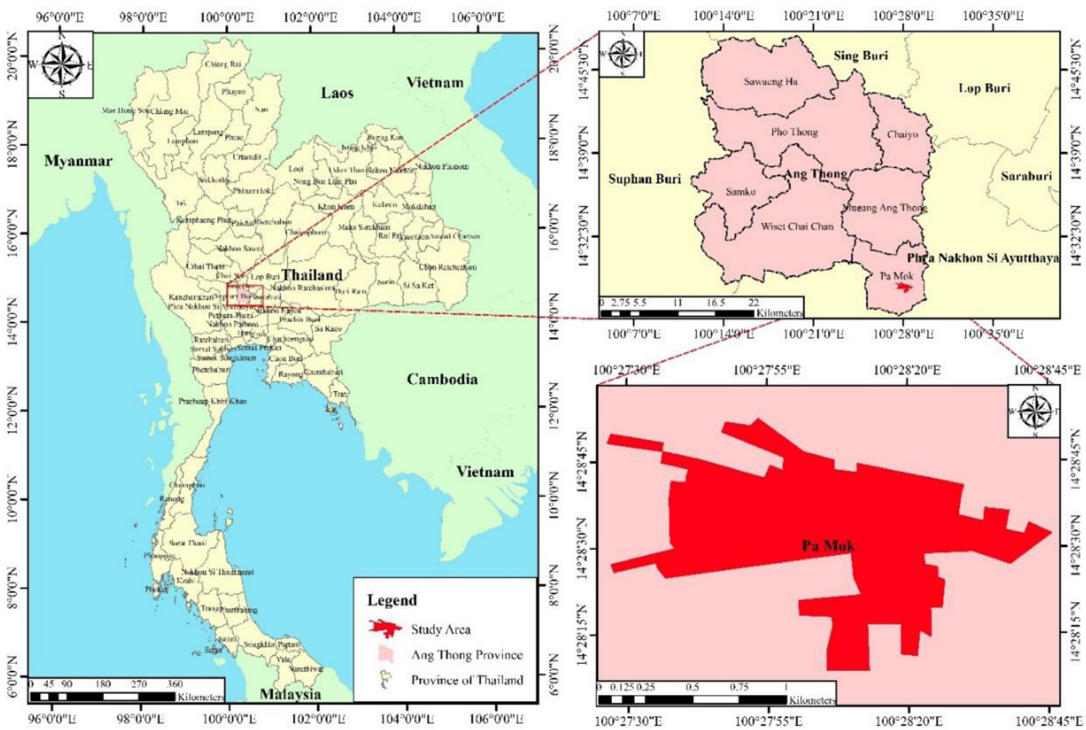

Fig. 1. The study area in this work (square domain of 20 × 20 km^2).

Table 1
The characteristics of the wind turbine generators used in this study.

WTG model	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)	Hub height (m)	Rotor diameter (m^2)	Swept area (m^2)	Capacity (MW)
I	3.0	12.0	21.0	120	120	11,310	2.5
II	3.0	15.0	23.0	80	100	7854	2.6
III	3.0	16.0	25.0	80	93	6793	2.3
IV	3.0	14.0	25.0	93	114	10,207	2.5
V	3.5	11.0	22.0	120	121	11,595	2.5

2.4. Annual Energy Production (AEP) and Capacity Factor (CF)

The microscale wind resource maps, based on CFD wind flow modeling, at hub height elevations of current WTG technology (93–120 m agl) are used to estimate the annual energy production (AEP) by using five selected utility-scale WTG. The details and characteristics of these five selected utility-scale WTG are given in Table 1.

The AEP is analyzed using the WindSim model with the Jensen wake loss modeling. The power curves (left scale) and the thrust curve (right scale) of the five WTG are shown in Fig. 4.

The capacity factors (CF) of the wind power plants are also analyzed to investigate their performances. The CF can be computed using Eq. (1) (Arrambide et al., 2019),

$$CF\ (\%) = \frac{AEP\ (\text{kWh})}{Installed\ Capacity\ (\text{kW}) \times 8760\ (\text{h})} \times 100\% \qquad (1)$$

where 8760 is the number of hours in a year.

In classical approaches, it is assumed that the uncertainty in the power production of a wind power plant is normally distributed. In accordance to the IEC 61 400 family of standards, the uncertainty in the production of wind power plants is expressed in terms of the probability of exceedance values P50, P75 and P90 (Yue et al., 2019). In this terminology, P50 means that there is a probability of 50% that the energy yield will be more than P50. In this study, P75 and P90 are also calculated for further financial evaluation due to the fact that accurate predictions of the wind resource are critical to a realistic internal rate of return (IRR).

2.5. Greenhouse gas emission avoidance

Wind power plants contribute in reducing the greenhouse gas (GHG) emissions into the atmosphere (Pehl et al., 2017). Wind power plant emits approximately 6.3 g CO_{2eq}/kWh on average (Wang and Sun, 2012). The CO_{2eq} emission avoidance from generating power from a non-carbon emitting source is estimated by relying on the specific national emission factors of the energy generation source. In this work, a grid emission factor of Thailand for a wind power plant of 5.692 g CO_{2eq}/kWh is used in the estimation of the CO_{2eq} emission avoidances (Anon, 2021p).

2.6. Economic analysis

Based on a cost–benefit analysis (CBA), four key financial indices (Ranthodsang et al., 2020), i.e., benefit cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and payback period (PBP), are analyzed in order to investigate the financial feasibility of a wind power plant in the study area.

The NPV is the algebraic sum of the discounted costs and revenues at a specified interest rate. An investment is financially acceptable if the NPV is positive and is not acceptable if it is negative. The NPV can be computed using Eq. (2),

$$\text{NPV} = \sum_{1}^{t} \frac{B_t - C_t}{(1-i)^t} \qquad (2)$$

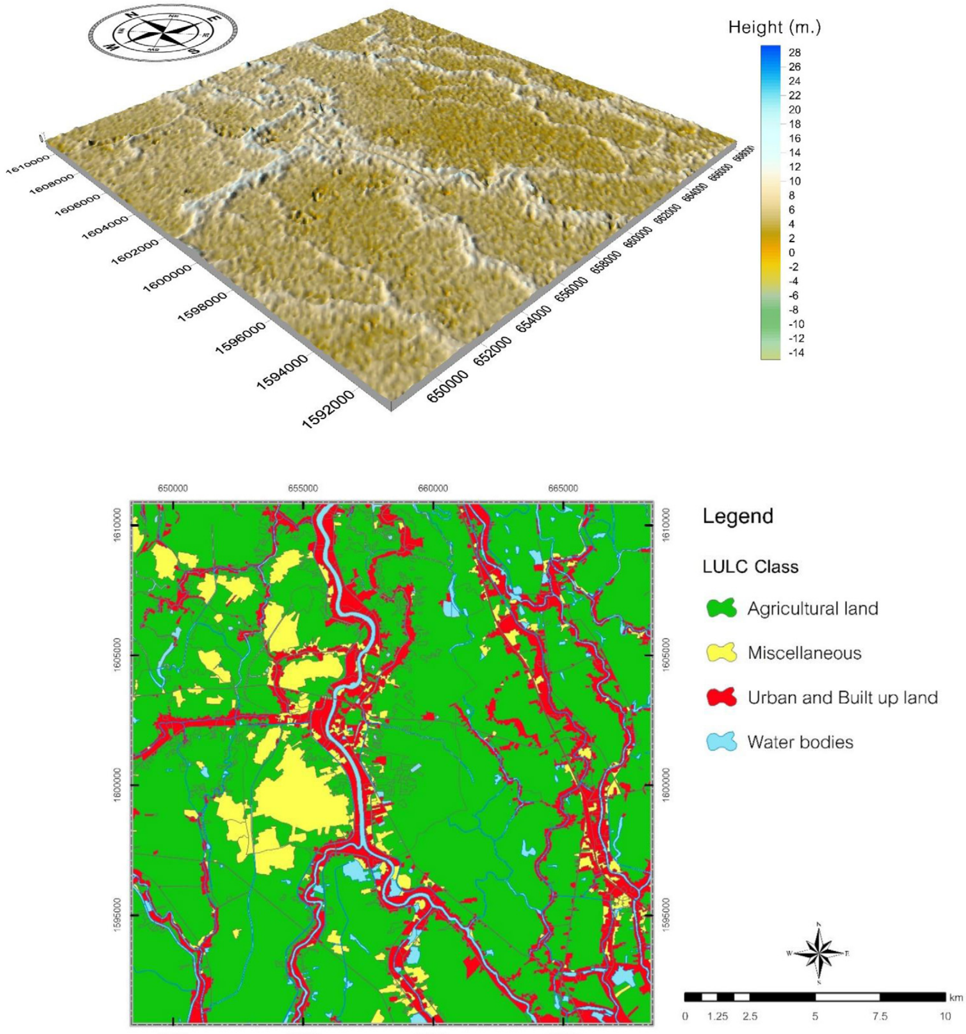

Fig. 2. Digital elevation model (DEM) (upper) and land cover land use (LCLU) (lower) of the study area.

where B_t is the revenue or positive cash flow in year t, C_t is the cost or negative cash flow in year t, t is the year in which the cash flow occurs, and i is the discount rate.

The BCR is computed as the present value of benefits divided by the present value of costs, as given in Eq. (3),

$$\mathrm{BCR} = \frac{\sum_1^t B_t\,(1+i)^t}{\sum_1^t C_t\,(1+i)^t} \tag{3}$$

If the BCR ratio is greater than one, the project is yielding more benefits than costs. An investment is financially acceptable if the BCR exceeds unity, while it is not financially acceptable if the BCR is less than unity.

The IRR is the discount rate that makes the net present value equals to zero. Thus, the financial benefits of the investment increases with the IRR. The IRR can be computed using Eq. (4),

$$IRR = i_1 + (i_2 - i_1) \times \left(\frac{NPV_1}{NPV_2 - NPV_1}\right) \tag{4}$$

where i_1 is the discount rate 1, i_2 is the discount rate 2, NPV_1 is the net present value at discount rate 1, and NPV_2 is the net present value at discount rate 2. The IRR is acceptable if it is greater than the discount rate.

The PBP, given in Eq. (5), is used to estimate the time needed to yield return that would cover the investment and the capital spent. The project is financially feasible if the PBP is less than the economic life of the project.

$$PBP = \frac{Investment}{Net\ annual\ cash\ flow} \tag{5}$$

Finally, the levelized cost of energy (LCOE) is computed to investigate the generation costs of a wind power plant. The LCOE, as given in Eq. (6)., compares the combination of capital costs, O&M, performance and fuel costs that does not include financing issues, discount issues, future replacement or degradation costs, which would need to be included for a more complex analysis (National Renewable Energy Laboratory, 2021). Thus,

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{6}$$

where I_t is the investment expenditures in year t (including financing), M_t is the operations and maintenance expenditures in year t, F_t is the fuel expenditures in year t, E_t is electricity generation in year t, r is the discount rate, and n is the life of the system (Ranthodsang et al., 2020).

By using the weighted average costing of onshore wind power plants, IRENA reported that, in 2019, the project costs per MW of installed capacity was 2658 US$/kW (IRENA, 2019). In the base case scenario presented in this paper, the capital expenditure (CAPEX) of a wind power plant project is thus estimated at 2658

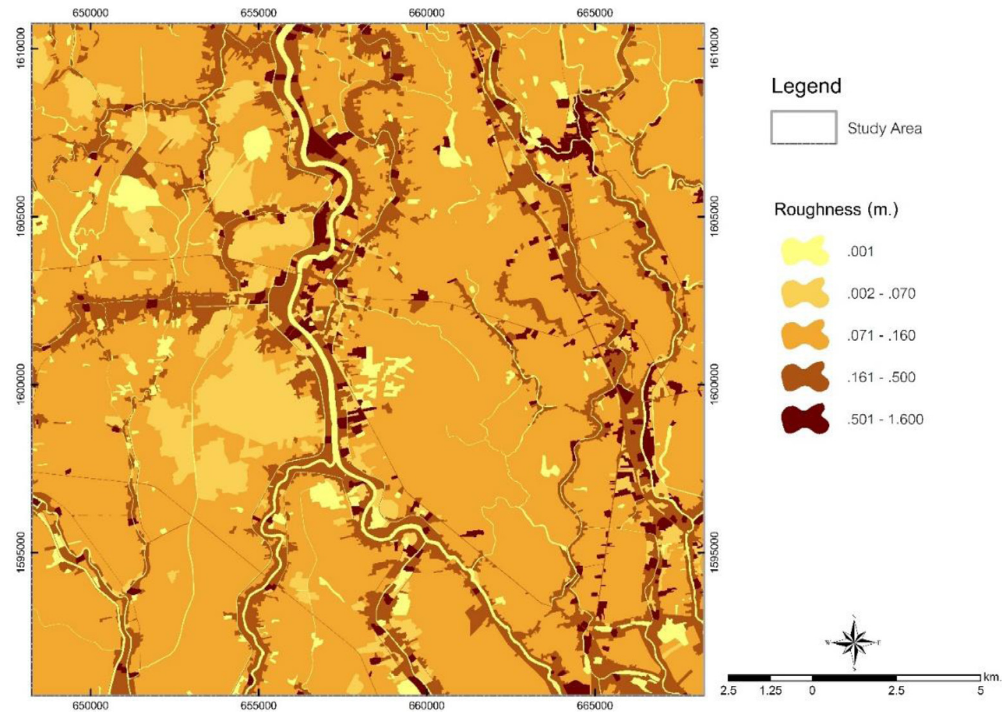

Fig. 3. Roughness length of the study area.

US$/kW. The operation, maintenance and replacement expenditure (OPEX) costs per MW of installed capacity are assumed to be 1.5% of CAPEX.

As per the policy regulations of Thailand, the Very Small Power Producer (VSPP) policy of Thailand (Anon, 2021q) caps the installed capacity of a renewable energy-based power plant integration at 10 MW for one feeder of a 33 kV distribution and at 8 MW for one feeder of 22 kV distribution system. Considering the grid connection capabilities in the study area, the proposed installed capacity of the wind power plant studied in the present work is 15 MW.

In order to accomplish the economic analysis, some assumptions are required as follows: currency exchange rate 1 USD = 30.0987 THB (Anon, 2021r); interest rate is minimum loan rate (MLR)+1% (7.301%); discount rate is 5%; debt ratio is 70:30; repayment loan term is 10 years; tax holiday approved by the Board of Investment of Thailand (tax payment 0% for 1st–8th year, 15% for 9th–14th year and 30% for 15th–20th year); project lifetime is 20 years; depreciation relies on a linear model; and salvage is 10%.

Wind power project investments require economic feasibility investigations for decision making during the development phase. Most utility-scale wind power projects need important initial investments and capital for the purchase of the WTG, along with the costs for the balance of plant (BOP) (IRENA, 2014). The economic viability of a wind power project relies on a rigorous analysis of the costs and benefits, which can be enhanced through government policies.

Recent experiences from around the globe suggests that Feed-In-Tariffs (FITs), a premium added to the AEP, are the most effective policies to encourage the rapid and sustained deployment of wind energy (Couture and Gagnon, 2010). In Thailand, an enhanced FIT policy, replacing the previous policy of Adder plus on-peak and off-peak tariffs, was adopted with a premium rate of 0.201 US$/kWh.

While the benefit of wind power project mostly stems from the electricity purchase, the carbon trading can also be a financial incentive. Both parameters, energy produced and GHG emission avoidances, rely on the net AEP produced by a wind power plant. In Thailand, the carbon credits can traded through the Thailand Voluntary Emission Reduction (T-VER) project, which is verified by the Thailand Greenhouse Gases Organization (TGO), with a price of 6.64 US$/tonne CO_{2eq} (200 THB/tonne CO_{2eq}) (Anon, 2021s). In this analysis, the benefits of a wind power plant project are calculated based on two scenarios, i.e., with and without carbon credit trading.

Finally, the sensitivity of the costs is also analyzed using ±5% and ±10% scenarios to investigate the financial viability for investment. Due to the bidding process of a wind power plant subsidy, hence the possible lowest FIT is also investigated by decreasing the FIT with 0.03 US$/kWh (0.10 THB/kWh) interval, until the IRR reaches 15%. This value for the IRR is used as the guideline in the decision-making process to justify bidding on wind power projects.

3. Results and discussion

Based on a 13 months measurement campaign between February 2014 to February 2015, with a data recovery rate of 83%, it was found that the mean annual wind speed at 100 m agl was 5.01 m/s, while the maximum wind speeds were observed in December 2014, during the strong effects of the Southwest monsoon. The months with above average mean wind speeds included January, February, March, April, June, July, and December, as presented in Fig. 5.

The time series wind speed data is illustrated in Fig. 6. It is found that the percentage of wind speed in the range of the cut-in and cut-out speeds of a utility-scale wind turbine generator (3.0–25.0 m/s) is 81%.

Based on a Weibull distribution curve fitting and analysis, it is found that the Weibull shape parameter (k) (dimensionless) is 2.7, while the Weibull scale parameter (A) is 5.9 m/s, corresponding to an effective mean speed of 5.28 m/s, as presented in Fig. 7. Results from the Weibull distribution also show that the maximum occurrence of wind speeds is between 5.0 and 6.0 m/s,

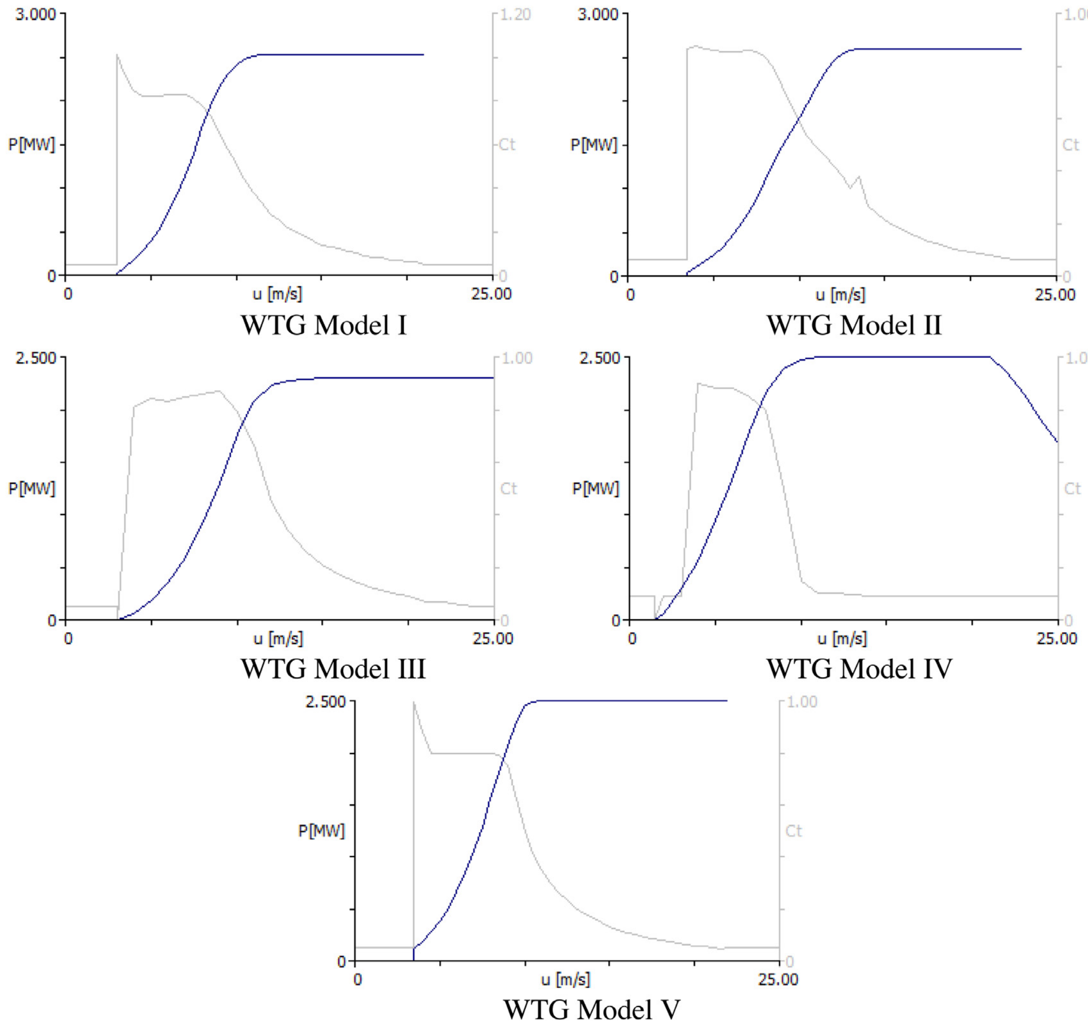

Fig. 4. Power curves (left scale) and thrust curve (right scale) of the five wind turbine generators studied.

while the occurrence of wind speeds beyond 10.0 m/s has a very low probability.

In a general sense, the wind resource over the area studied is relatively low for wind power generation, when compared to well recognized areas with exceptional wind regimes around the globe. However, as turbine technology evolves towards low wind regime power production, areas with limited wind resource can still offer interesting possibilities, notably when financial incentives are offered. Thus, rigorous economic and financial analyses are necessary to assess the viability of wind power plant projects in areas with limited wind resources. The following addresses these issues in the study area.

The wind rose of the area studied, at 100 m agl, is presented in Fig. 8. It can be seen that the dominant wind directions stem from the N to NE direction and from the S to SW direction, mainly due to the strong effects of the regional macro wind regime, i.e., the monsoon periods. The Northeast monsoon plays an important role for wind energy resource in the central region of Thailand during the months of December and January, while the Southwest monsoon has its effects during the months of June and July.

The microscale wind resource map, with a resolution of 50 m and at a utility-scale WTG hub height of 120 m agl, is presented in Fig. 9 (similar maps at 80 and 93 m agl show similar characteristics). It is found that the maximum mean speeds at 80 m, 93 m, and 120 m agl are 5.28 m/s, 5.32 m/s and 5.40 m/s, respectively. In consideration of NREL's assessment that suitable wind class for wind energy production should be in the range of 5.0–7.0 m/s (National Renewable Energy Laboratory, 2021), the studied area can be considered for wind power production.

The net AEP of a wind power plant with installed capacity of 15 MW (6 WTG with a nominal capacity of 2.5 MW) is analyzed using P50, P75 and P90, for the five wind turbine models considered, as shown in Fig. 10. Amongst the five WTG considered, the WTG model 1 would produce the most energy, in comparison to the other models studied. Based on P50 net AEP, the WTG model 1 could produce 41 GWh/year of electricity fed to the distribution system of the Provincial Electricity Authority (PEA). Therefore, the WTG model 1 is identified as the best and most suitable WTG under the moderate wind resource of the study area.

The net AEP and CF and wake losses, based on a P50 analysis of a 15 MW wind power plant integrating the five selected WTG technologies, are presented in Fig. 11. It is found that the maximum CF of the WTG model 1 is in the vicinity of 30%, while the CF of the other WTG models are less than 20%. The relatively large differences in the CF of the WTG can be linked to the characteristics of the model 1, notably in regards to the rated speed in the power curve, which is relatively low (12 m/s) compared to the other models; the hub height, which is at 120 m agl; as well as the large rotor diameter and swept area, at 120 m and 11,310 m^2, respectively.

The WTG model 1 was further analyzed for maximizing the AEP by searching the optimum location for the micro-sitting of

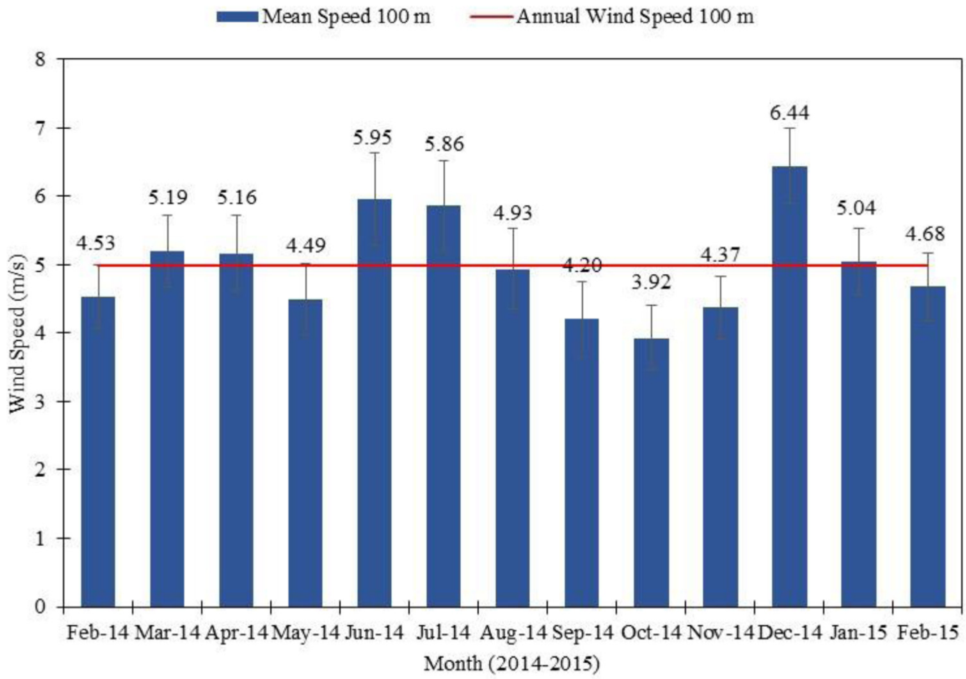

Fig. 5. Annual mean speed and variation of monthly mean speed at 100 m agl.

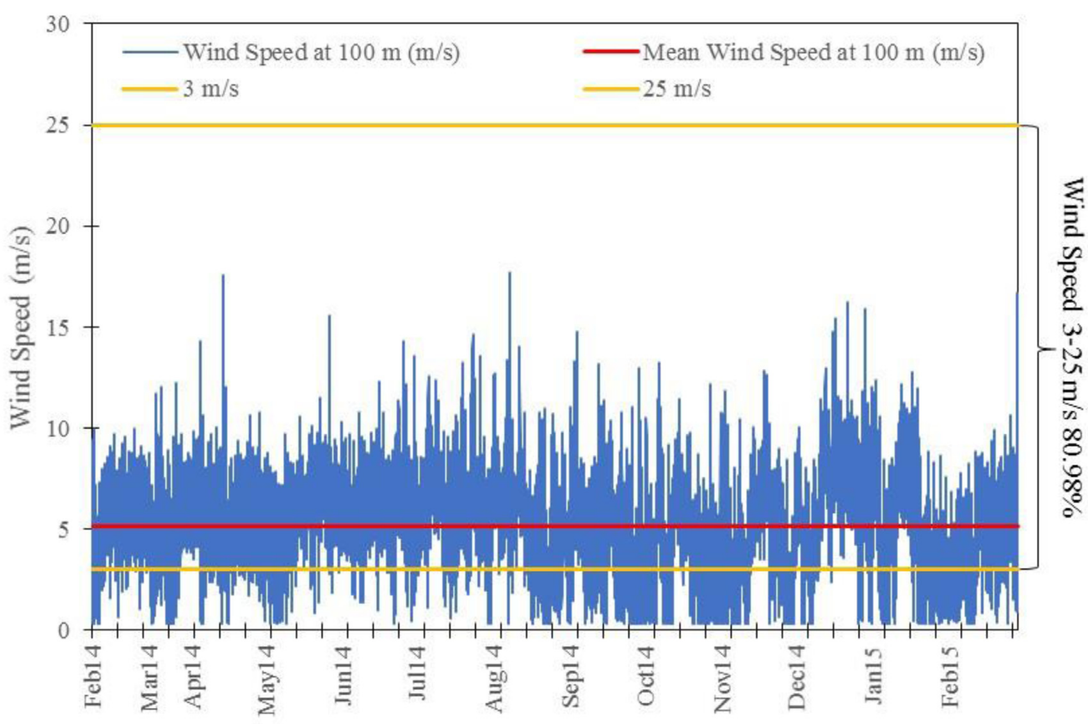

Fig. 6. Time series of the wind speed at 100 m agl.

the WTG to minimize the wake losses in a wind power plant. By using the WindFarmer software package, the optimum locations for the location of the 6 turbine units of the WTG model 1 are presented in Fig. 12. The optimization reveals that the %AEP increased 6.1% (initial net AEP was 38.1 GWh/year and final net AEP is 40.6 GWh/year) and the wake losses were in the range of 0.6 to 17.8%, with an average of 9.8%. The optimum proposed 15 MW wind power plant could avoid CO_{2eq} emissions into the atmosphere of 231 ktonnes CO_{2eq}/year. The key results of a proposed 15 MW wind power plant are summarized in Table 2.

The financial analysis for the wind power plant project is projected over a 25-year period. Figs. 13 and 14 present the key financial indices, without and with T-VER, respectively. Fig. 13, without T-VER, shows that four financial indices meet the requirement for investment as the BCR is 1.34, the NPV is 22.88 million US$, the IRR is 20% and the PBP is 4 years for the base case scenario. Even without the T-VER support, the economic analysis indicates that wind power projects in areas with limited wind resource in Thailand can be feasible. Furthermore, even if the costs of a wind power project would increase by 10%, the

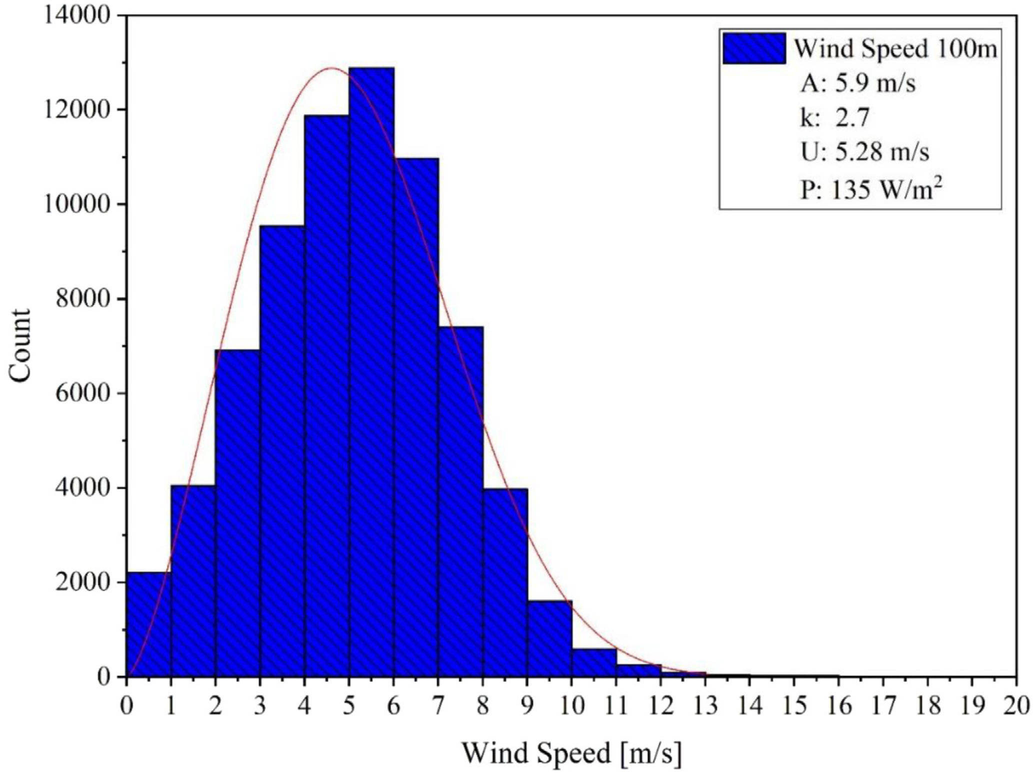

Fig. 7. Weibull distribution of the wind speed at 100 m agl.

Table 2
Key results of a proposed 15 MW wind power plant using WTG model 1.

Turbine ID	Mean speed at hub height (m/s)	Gross AEP (MWh/year)	Net AEP (MWh/year)	CF (%)	Wake losses (%)	CO_{2eq} emission avoidance (ktonnes/year)
1	5.80	7486	7092	31.98	5.3	40.36
2	5.62	7028	6582	29.68	6.4	37.46
3	5.86	7620	6385	28.79	16.2	36.34
4	5.75	7394	6079	27.41	17.8	34.60
5	5.73	7356	6434	29.01	12.5	36.62
6	6.04	8079	8031	36.13	0.6	45.71
Average/Total	5.80	44,964	40,603	30.50	9.8	231.09

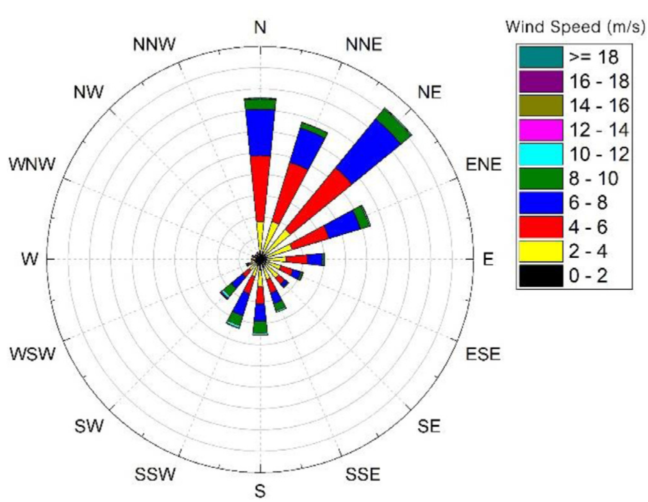

Fig. 8. Wind rose at 100 m agl.

economic analysis show that a wind power investment would still be beneficial.

For its part, Fig. 14 shows the same indices, but with the provisions for the carbon trading under the T-VER program. Obviously, including provisions for carbon trading, and thus additional revenues to the project, renders the projects even more favorable.

The results of the economic analysis show that the LCOE for the base case scenario wind power project is estimated at 0.093 US$/kWh. Since the benefit of wind power project mostly relies on the amount of AEP, the sensitivity of the AEP based on P50, P75, and P90, along with and without T-VER support, are also analyzed in order to investigate the effects on the financial indices. Fig. 15 shows that for P75, the four financial indices still meet the criteria of favorability, but the values are not high enough to justify investments. For P90 and the base case scenario, the benefit of a wind power project in the study area seems to be infeasible, as the IRR is less than the MLR for project financing. In this case, two approaches for improving the potential of project financing could include costs reductions and access to soft loans for project financing with interest rates less than 5%.

Finally, the current PPA award process for onshore wind power project development in Thailand applies the bidding selection with the minimum FIT requirements. Fig. 16 shows the variations of the FIT against the financial indices, with and without T-VER, and for IRR above 10%. The results show that the minimum FIT

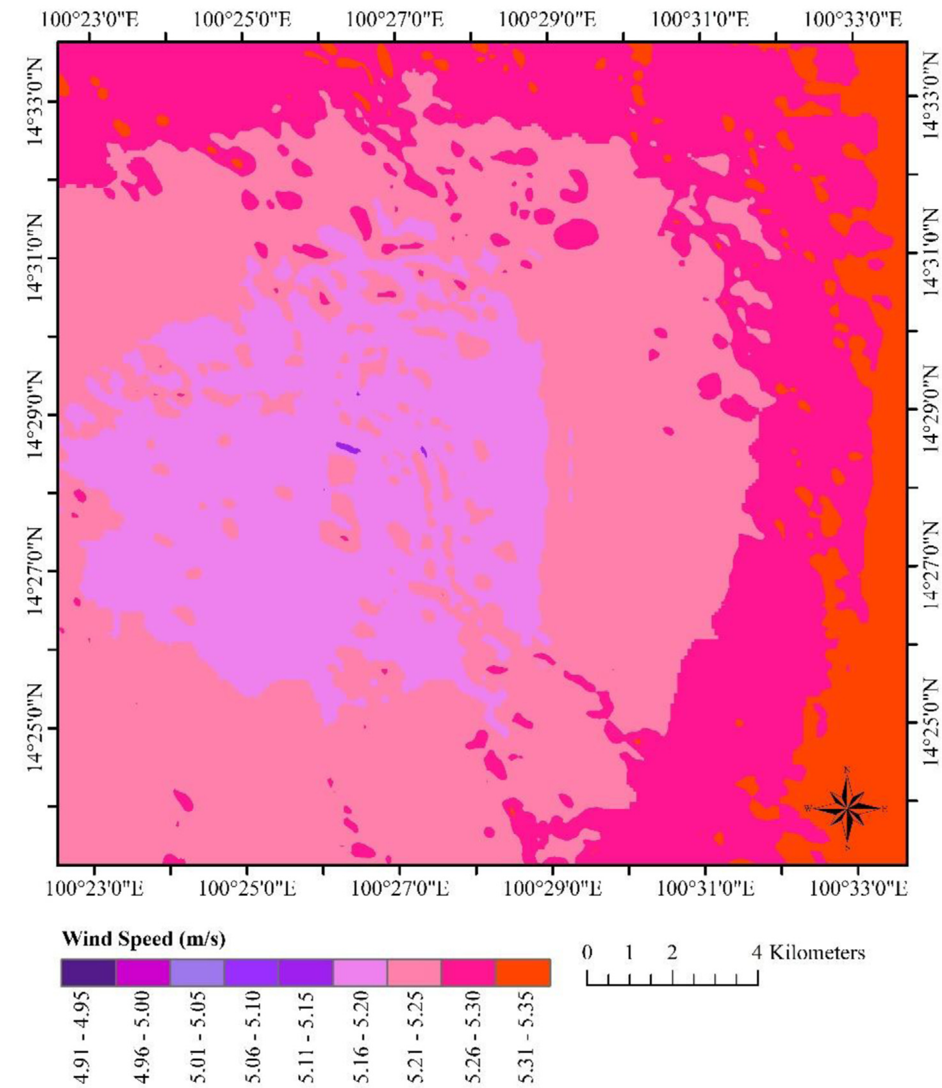

Fig. 9. Microscale wind resource map (domain of 20 × 20 km^2), with a 50 m resolution, at an elevation of 120 m agl, over the study area.

for offering sustainable financial indices for a 15 MW wind power project is 0.195 US$/kWh.

4. Conclusions

In this work, a wind resource assessment is investigated using the data from a thirteen-month measuring campaign. Using a CFD-based wind flow modeling, the microscale wind resource mapping, with resolution of 50 m and a 20 × 20 km^2 domain, is presented using in-situ measured wind speeds and directions along with high-resolution DEM and LCLU. An appropriate wind turbine generator (WTG) is selected amongst five utility-scale current WTG technology. The best WTG for the site studied is further optimized for the micro-sitting of the WTG in order to maximize the annual energy production (AEP) and minimizing the wake losses.

The maximum net AEP, capacity factor (CF) and CO_{2eq} emission avoidance of a proposed 15 MW wind power plant are analyzed. Various economic indices and the levelized-cost of energy (LCOE) are also analyzed using a cost-benefit approach for wind power investments in a region of Thailand with limited wind resources. The economic sensitivity of key parameters, i.e, costs, AEP estimation uncertainty and lowest FIT in the bidding selection process, are also analyzed and presented.

The main findings of this work show that the wind resource in the study area is moderate, with a mean annual wind speed of 5.8 m/s at 120 m agl. A 15 MW wind power plant, incorporating the most appropriate utility-scale WTG identified for the site situated in the central region of Thailand, could produce an AEP of 41 GWh/year, corresponding to a CF of 31%. The CO_{2eq} emission avoidances to the atmosphere could reach 231 ktonnes CO_{2eq}/year. The optimization of the micro-sitting of the WTG provided a 6.1% increase in the AEP, while reducing wake losses by 10%.

For the base case scenario and a P50 AEP estimation, four main financial indices meet the criteria for a bankable project and financing, thus assuring the feasibility of wind power plant projects under current FIT policies in Thailand. The LCOE of a proposed 15 MW wind power plant is 0.093 US$/kWh. The lowest offering FIT for a bidding selection process of a wind power plant project in the central region of Thailand would need to be fixed at 0.195 US$/kWh.

Finally, the results of this work could be applied as guidelines for the deployment of onshore wind power generation, especially in regions with limited wind regimes. Indeed, the work presented in this paper shows that wind power projects can be developed in regions of limited wind resource, if a careful wind resource assessment is performed, coupled with a rigorous micro-siting

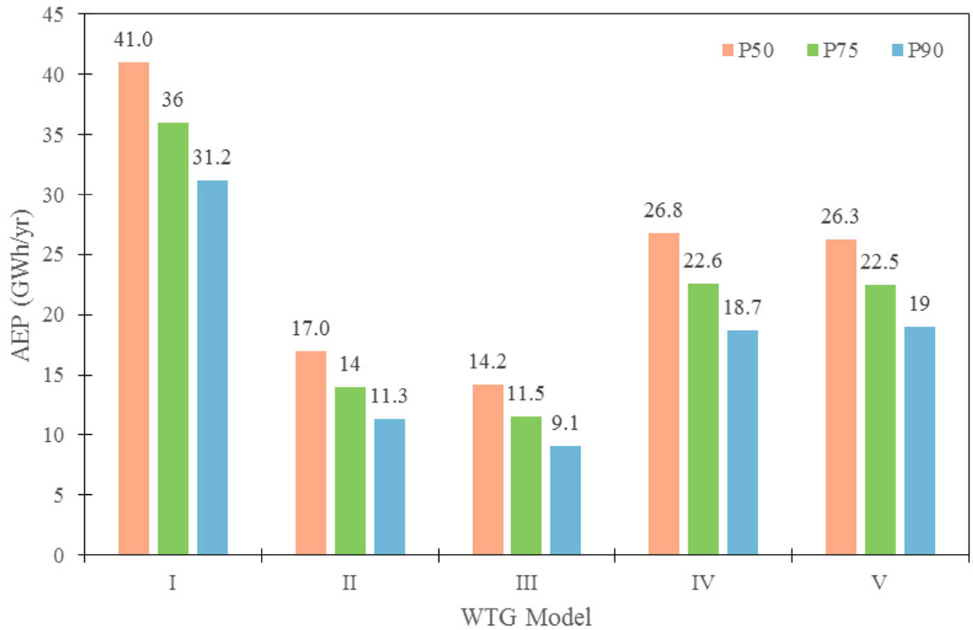

Fig. 10. The net AEP of a 15 MW wind power plant based on P50, P75 and P90, for the five wind turbine generators studied.

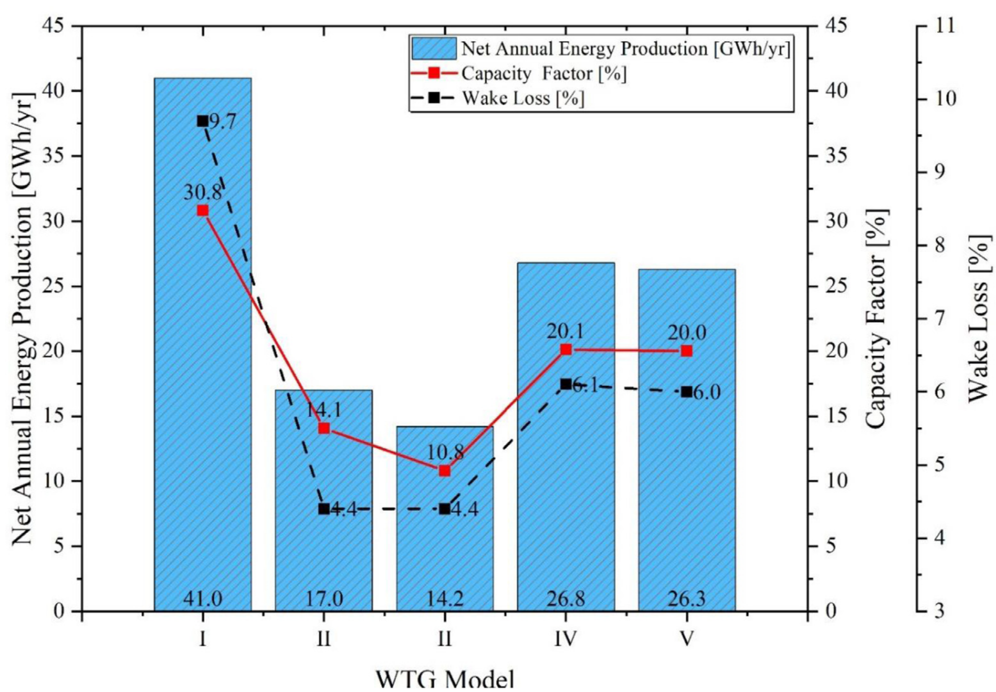

Fig. 11. The annual energy production (AEP), capacity factor (CF) and wake losses of a 15 MW wind power plant, for the five wind turbine generators studied.

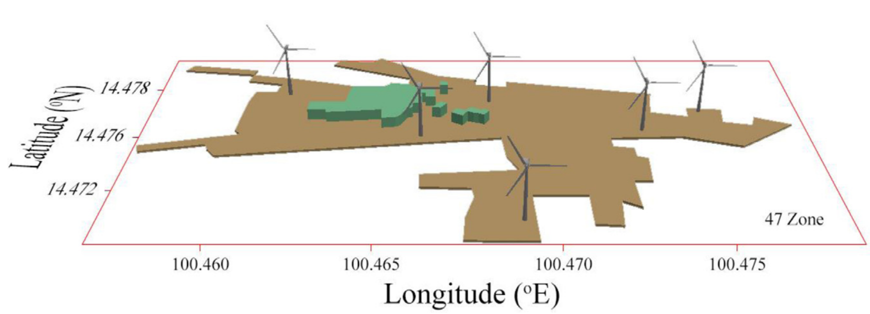

Fig. 12. The optimum locations for the WTG of a proposed 15 MW wind power plant.

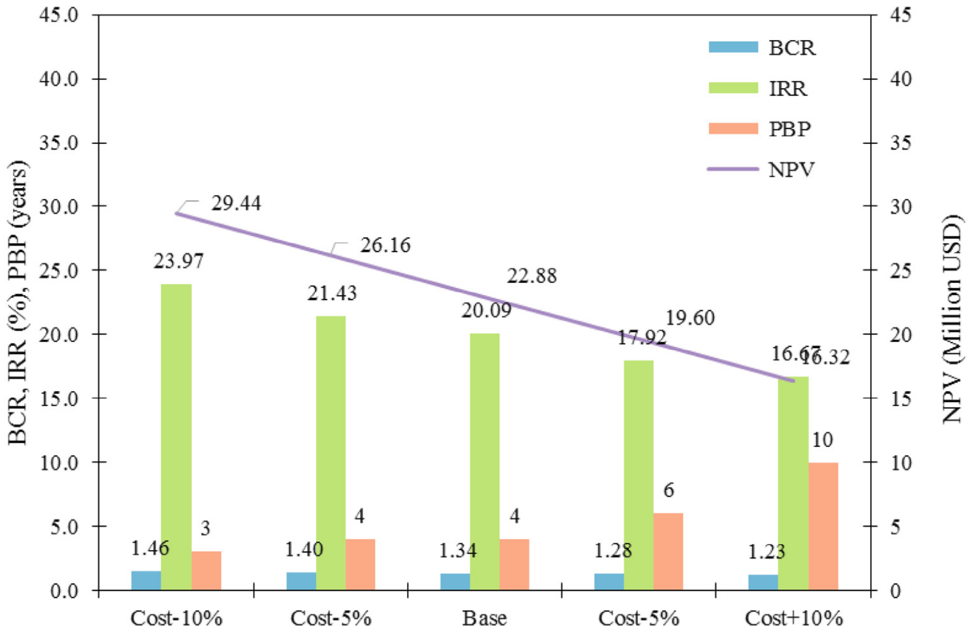

Fig. 13. Financial indices for sensitivity analysis of a project cost without T-VER.

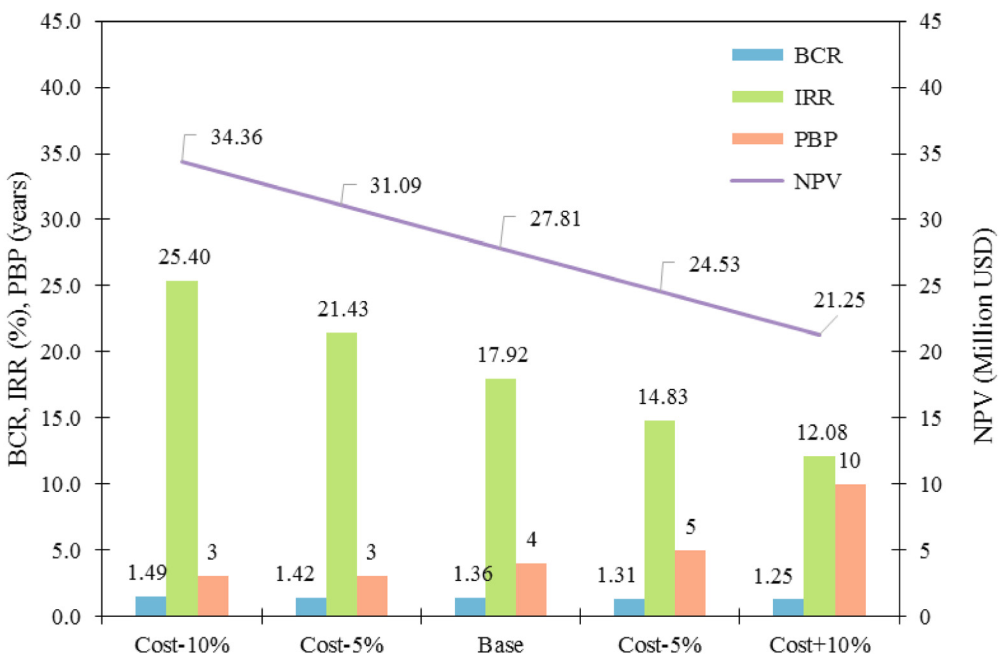

Fig. 14. Financial indices for sensitivity analysis of a project cost with T-VER.

exercise to optimize the economic indices, notably the LCOE. Besides performing wind measurements over a longer period, further work on this topic could extend to analyzing the social acceptability of such projects in small communities.

CRediT authorship contribution statement

Lattawan Niyomtham: Conceptualization, Investigation, Data curation, Writing – original draft. **Jompob Waewsak:** Project administration, Funding acquisition, Methodology, Resources. **Chuleerat Kongruang:** Formal analysis, Investigation, Validation. **Somphol Chiwamongkhonkarn:** Software. **Chana Chancham:** Visualization. **Yves Gagnon:** Writing – review & editing.

Declaration of competing interest

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

Acknowledgments

The authors would like to thank the Energy Conservation and Promotion Fund, Energy Policy and Planning Office (EPPO) for supporting the graduate research fund, sincere gratitude to the International College, Thaksin University (Songkhla Campus) for the Ph.D. scholarships and also thanks to the Research Center in Energy and Environment, Thaksin University (Phatthalung Campus) for its financial and research facilities supports.

Fig. 15. Financial indices for P50, P75 and P90 AEP with and without T-VER.

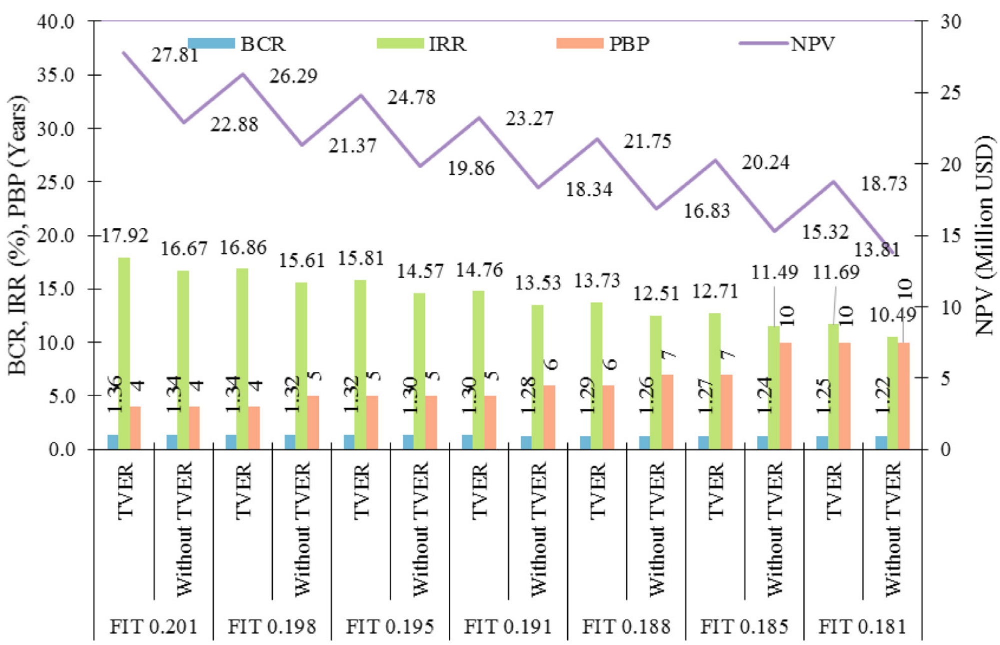

Fig. 16. Variation FIT against the financial indices, with and without T-VER, and for IRR above 10%.

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