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Article

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Research paper

Offshore wind power assessment on the western coast of Thailand

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ABSTRACT

This paper presents an offshore wind resource assessment and offshore wind power feasibility analysis on the western coast of Thailand using coupled mesoscale atmospheric and microscale Computational Fluid Dynamics wind flow modeling, along with a climatic database. Offshore wind maps at elevations of 80 m, 90 m and 120 m above mean sea level (amsl) are presented and validated with measured wind datasets gathered from nine met masts installed along the coast of the Andaman Sea and the Strait of Malacca on the western part of Thailand. Results show that, at an elevation of 120 m amsl, the northern region near Myanmar is characterized by wind speeds in the range of 5.5 to 6.0 m/s, while the area around Phuket Island has wind speeds in the range of 4.6 to 5.3 m/s. In line with the Thai energy policies for wind power plant development, the annual energy production, the capacity factors, the levelized cost of energy (LCOE), the CO_{2eq} emission avoidance, and the required Feed-in-Tariff (FiT) are analyzed for wind power plants integrating 3.3 MW, 8.0 MW and 9.5 MW offshore wind turbine generators. Results show that offshore wind power plants with 3.3 MW wind turbine generators could produce over 13 GWh of electricity per year under the Very Small Power Producer (VSPP) scenario for 10 MW wind power plants. For its part, 50 MW wind power plants under the Small Power Producer (SPP) scenario could produce 68 GWh/yr, and nearly 123 GWh/yr for SPP wind power plants with 90 MW of installed capacities. With capacity factors in the order of 16%, the lowest LCOE is 0.188 USD/kWh and the CO_{2eq} emission avoidances reach 774 tonnes CO_{2eq} per year. Finally, the required FiT to sustain the development of VSPP offshore wind power plants in the vicinity of Phuket Island is in the range of 0.314 to 0.688 USD/kWh.

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1. Introduction

Wind energy plays a significant role in the global transformation of energy systems towards renewable energy. Beyond the generation of power from a renewable source, in coherence with the United Nations Sustainable Development Goals (SDG), the development of wind energy provides socio-economic advantages to communities and jurisdictions (International Energy Agency, IEA, 2019).

The importance of environmental concerns in power generation has driven to a significant increase in the exploitation of various renewable energy resources, notably wind energy and solar energy (Argin et al., 2019). Amongst the various renewable energy deployments, the worldwide wind power installed capacity reached 597 GW at the end of 2018, with 50.1 GW added in 2018 (World Wind Energy Association, WWEA, 2019). In 2018, the Global Wind Energy Council (GWEC) reported that,

globally, the offshore wind power accumulated installed capacity reached 23 GW, with new added capacities of 4.5 GW in 2018 (Global Wind Energy Council, GWEC, 2019; International Renewable Energy Agency, IRENA, 2018). Most of the offshore wind power projects are installed in the North and Irish Seas, together with the Baltic Sea, hence, United Kingdom, Denmark, Germany, Belgium, Netherland, and Sweden (Arrambide et al., 2019). In 2010, the first offshore wind power plant in Asia was installed in China (Global Wind Energy Council, GWEC, 2012).

While offshore wind power is poised to play a significant role in future energy systems, this sector is characterized by important challenges. The primary inconveniences involve the additional costs due to the construction of the foundations; the integration to the electricity grid; transportation and installation of the offshore wind power plant; and operation and maintenance (Global Wind Energy Council, GWEC, 2019).

Offshore wind resource potential can initially be investigated based on offshore meteorological observations, mesoscale atmospheric modeling, and remote sensing techniques. Offshore meteorological masts have high costs of installation, which have been increasing (Henderson et al., 0000). Wind profiling lidars

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on platforms seem to be the most suitable alternative; however, it is often the case that a platform is not available where the observations are most needed for measurements. Satellite remote sensing observations of ocean surface vector winds is available operationally and in archives, but the limitations include the height of the observation, which is only 10 m above the sea surface, and the limited availability of observations.

On the other hand, wind resource mapping based on mesoscale atmospheric modeling offers a promising approach in performing offshore wind resource assessments, especially for large area applications, as well as in the early stages of wind power developments (Waewsak et al., 2015).

In this regards, Mattar and Borvaran (2016) presented the offshore wind power potential for the central coast of Chile. Using wind speed data from in-situ stations and climatic reanalysis data, the Weather Research and Forecasting (WRF) model was used to simulate wind fields at a regional level. Based on the simulated wind data, the wind power for the study area was estimated at approximately 1000 W/m² at an elevation of 140 m above mean sea level (amsl).

The offshore wind resource assessment and an offshore wind power plant optimization in the Gulf of Thailand (GoT) were assessed using the WRF atmospheric model, along with the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) R2 reanalysis climatic database. The wind resource maps at 80 m, 100 m, and 120 m amsl were presented in order to identify the potential surface areas for the development of offshore wind power plants (Waewsak et al., 2015; Chancham et al., 2017). The predicted wind speeds were validated using observed wind speeds obtained from 13 met masts installed along the coastline of the GoT. The results showed that the average annual mean wind speeds reach the range of 5.5–6.5 m/s in specific areas of the Bay of Bangkok, situated in the northern part of the GoT.

At another scale, using spatially explicit models and long-term satellite data, Elsner (2019) studied the technical offshore wind potential of the entire continent of Africa, both for near shore, shallow-water areas and for the deep-water areas with floating wind turbines. Considering the low resolution of the data, it was emphasized that the model results are subject to a number of uncertainties and therefore should be treated as first order estimates only. None-the-less, the results have shown a promising technical offshore wind energy potential for one third of the African coastal states, with Mozambique, South Africa, Somalia, Madagascar and Morocco exhibiting particularly good wind resources.

More recently, Costa et al. (2020) presented an offshore wind resource assessment for the United States of America. Using Regional Climate Models from the North America Coordinated Regional Climate Downscaling Experiment, the predicted results were validated with various field measurements. The offshore wind energy resource was classified following a Delphi approach which considered three factors: wind energy, environmental risks and costs. Under this classification, most of the areas under scope in both coasts were classified at least as a 4 (“good resource”), with higher wind energy resources on the west coast, where vast coastal areas are categorized as 5 (“excellent resource”).

According to the Power Development Plan 2018 (PDP2018) of Thailand, for 2018–37, the objective for offshore wind power installed capacity is targeted at 1485 MW (Energy Policy and Planning Office (EPPO), Thailand, 2018). While onshore wind power development in Thailand is constrained by the Energy Regulatory Commission (ERC) setback distances (Anon, 2019a) and conflict of land use, offshore wind power becomes an interesting alternative, notably in the Gulf of Thailand on the eastern coast; and in the Andaman Sea and the Strait of Malacca on the western coast of Thailand.

However, while wind resource assessments have been made in the Gulf of Thailand (Waewsak et al., 2015), the offshore wind resource potential in the Andaman Sea and the Strait of Malacca of Thailand has not yet been assessed for offshore wind power development. Consequently, the objective of this paper is to present an offshore wind resource assessment in the Andaman Sea and the Strait of Malacca of Thailand using a mesoscale atmospheric modeling, along with the NCEP/NCAR climatic database (1958–2000) for offshore wind power plant feasibility investigation under current offshore wind turbine generator technology.

For its part, Phuket Island has the largest load demand on the western coast of Thailand, while occupying a compact zone within the study area. Beyond its wind resource, Phuket Island has many attributes that supports the development of renewable energy sources, notably in regards to the concepts of sustainable tourism. Thus, considering the anticipated moderate wind resource for wind power development in the vicinity of Phuket Island, a financial incentive, in the form of a Feed-in-Tariff (FiT), is considered specifically for this region. Besides the greenhouse gas emission avoidances, a financial analysis is presented in order to analyze the FiT required to sustain the development of wind power plants in the vicinity of Phuket Island.

Besides contributing to the body of knowledge on wind resource assessment methodologies, this work provides guidance in the implementation and the development of offshore wind power in Thailand.

2. Methods and materials

2.1. Study area

The study area comprises the offshore area of the western coast of Thailand, namely the Andaman Sea and the Strait of Malacca. The area ranges between 6°N to 12°N in latitude, and 96°E to 101°E in longitude, as shown in Fig. 1. The locations of the nine met masts used to validate the wind maps are also presented on this figure, along with the computational domain, consisting of three partially overlapping mesoscale domains.

The Andaman Sea is a marginal sea of the eastern Indian Ocean, separated from the Bay of Bengal (to its west) by the Andaman Islands of India and Myanmar, and the Nicobar Islands of India, while touching Myanmar, Thailand and the Malay Peninsula. Its southernmost end is defined by Breueh Island, an island just north of Sumatra; while the Strait of Malacca is a narrow, 890 km stretch of water between the Malay Peninsula and the Indonesian island of Sumatra. The Strait of Malacca connects the Pacific Ocean to the East with the Indian Ocean to the West. The land part of the study area has a mountainous topography in the North–South orientation, along the Malaysia Peninsula, with elevations less than 1000 m. The mountainous areas split into two groups, the first group located in Ranong, Phangnga, Phuket and Krabri provinces, while the second group is located in Trang and Satun provinces.

2.2. Mesoscale atmospheric and microscale wind flow modeling

In this work, the mesoscale wind speeds over the Andaman Sea and the Strait of Malacca, on the western coast of Thailand, are obtained from a mesoscale atmospheric modeling. The input data for the Mesoscale Compressible Community (MC2) model (Benoit et al., 1997) include the NCEP/NCAR R1 (1958–2000) global reanalysis climatic database (Kalnay et al., 1996), digital topography (Digital Elevation Model, DEM) maps (NASA, 2019), and reclassified roughness heights from Land Use Land Cover (LULC) maps (Anon, 2019b). A detailed description of the

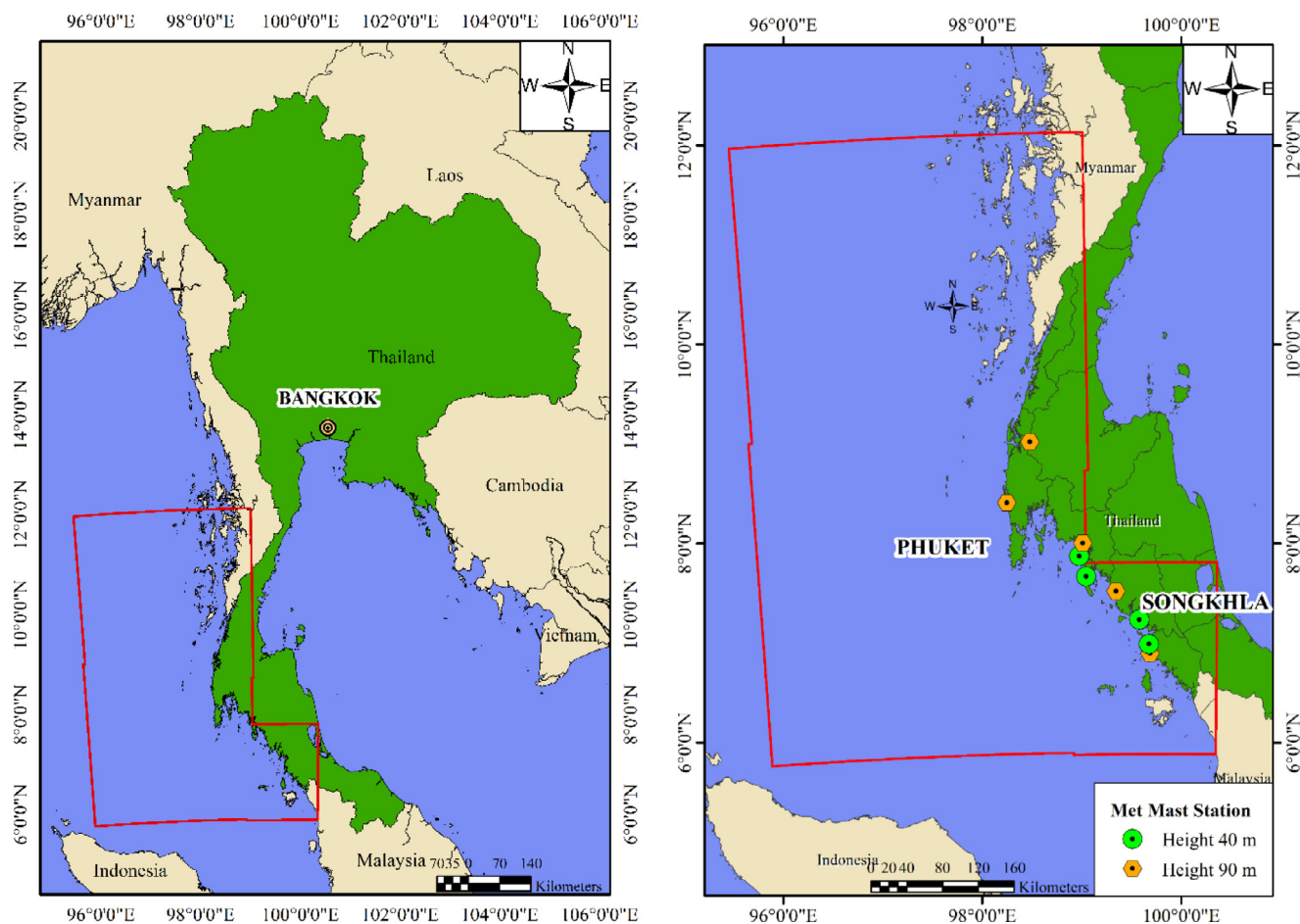


Fig. 1. The Andaman Sea and the Strait of Malacca in the study area (left), and locations of the nine met masts along the coastline (right). The red polygon represents the computational domain.

Source: ESRI (2019).

methodology can be found in Waewsak et al. (2015) and Gasset et al. (2012).

The NCEP/NCAR R1 global reanalysis climatic database provides the 3D representation of atmospheric states available every 6 h at 2.5° resolution (Kalnay et al., 1996). Using a statistical-dynamic downscaling method (Buness et al., 1995) and the concept of climate states, large scale and long-term atmospheric data, and their statistical properties, are used in the mesoscale model.

The topography digital database is interpolated to the model resolution from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) V2 database at 5 m resolution (NASA, 2019). Fig. 2 presents a 3D perspective view of the topography and the bathymetry of the study area, looking towards the north-east direction from way out at sea. The front part of the view (bottom part of the image, green and yellow colors) presents the bathymetry, with significant areas with less than 50 m of water depth along the coast. This is followed by the topography of the mountainous areas within the computational domain (brown color); and finally the rest of Thailand (outside of the computational domain, in purple color). The main cities are also presented to provide a notion of dimension in this plot.

The roughness field is determined entirely from the LULC data obtained from the Land Development Department (LDD) of Thailand (Anon, 2019b). The center of each domain is associated with the nearest grid point of the NCEP/NCAR global database. Fig. 3 presents the reclassified roughness heights map derived from the digital LULC database.

The WEstat mesoscale statistics module, a component of Environment Canada's Wind Energy Simulation Toolkit (WEST) (Yu et al., 2006), is used to generate the set of 2D data, at the model resolution, characterizing the wind potential of the domain. The statistics can be calculated for any elevations near the surface, where the modeling assumptions are satisfied. A logarithmic profile of the surface wind is assumed to interpolate the wind speeds from the model vertical levels to the elevations where the statistics are calculated.

For an area in the vicinity of Phuket Island, the microscale model MS-Micro (Walmsley et al., 1986), along with the mesoscale maps as input data, are used to generate a detailed description and quantification of the wind resource for the area in the vicinity of this island (Waewsak et al., 2015).

For both the mesoscale maps and the coupled mesoscale-microscale maps, the mean wind speed maps are prepared at elevations of 80 m, 100 m and 120 m amsl.

2.3. High resolution wind resource mapping and validation

The offshore wind maps are validated with land-based observed wind speeds at 40 m and 90 m above ground level (agl) obtained from nine met masts installed along the coastal areas of the Andaman Sea and the Strait of Malacca in Thailand. The details of each met masts are given in Table 1, while the geographical distribution of the met masts is shown in Fig. 1. The mean bias error (MBE) and the root mean square error (RMSE) are analyzed in order to validate the mesoscale offshore wind maps for the Andaman Sea and the Strait of Malacca of Thailand.

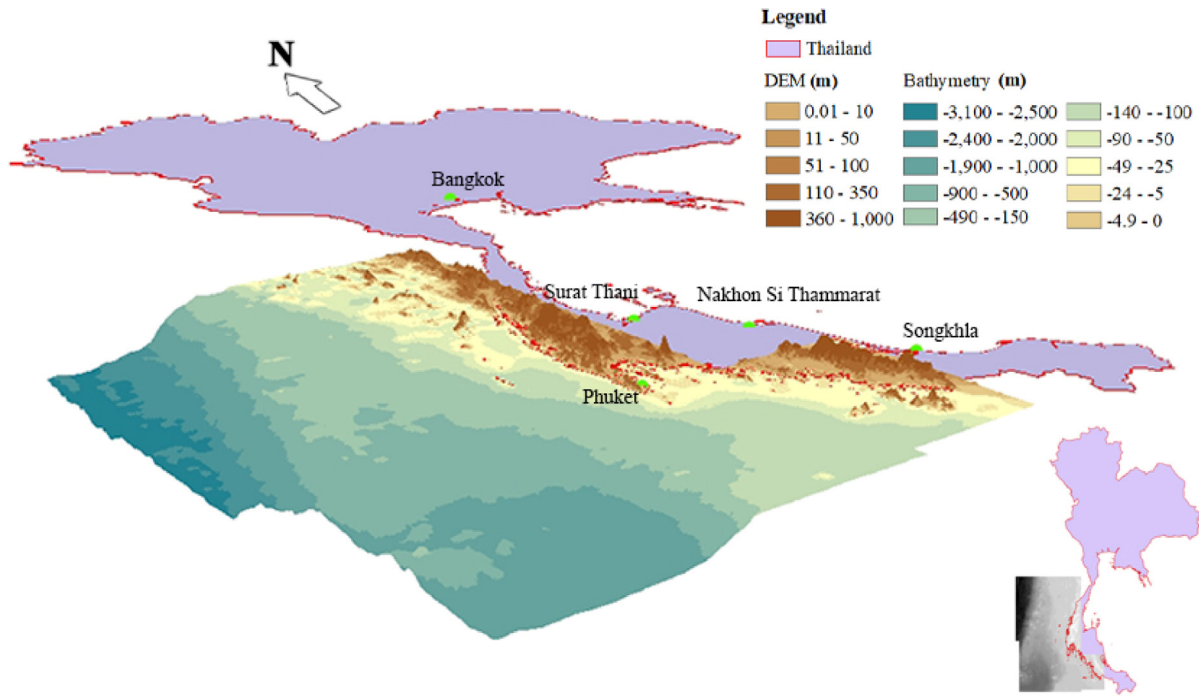


Fig. 2. The topography and bathymetry map of the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

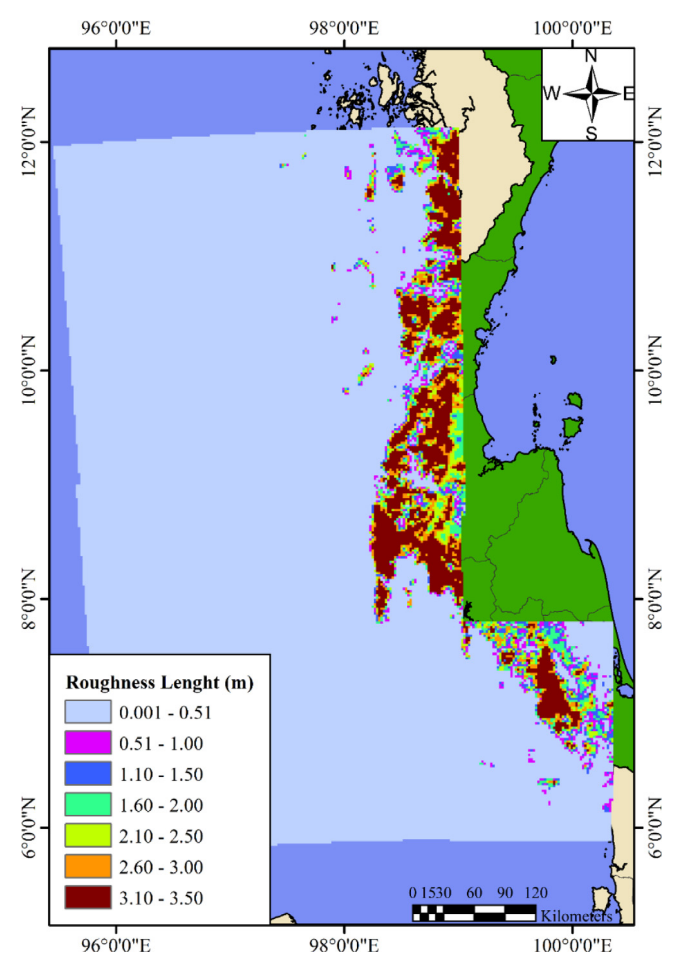


Fig. 3. The reclassified roughness height map from digital Land Use Land Cover (LULC) database.

Table 1

Geographical coordinates of the met masts for the mesoscale offshore wind map validation.

Name	Height (m)	Latitude (°N)	Longitude (°E)
Nuarklong	40	7.875797	98.97318
Ranong	90	9.018306	98.47686
Satun	90	6.895250	99.68440
Phangnga	90	8.407639	98.24578
Trang	90	7.520361	99.34206
Krabi	90	8.002389	99.00873
Lanta	40	7.671810	99.04286
Thungwa	40	6.992016	99.67361
Hat Samran	40	7.238258	99.57634

2.4. Estimation of the output parameters

The microscale offshore wind resource maps at elevations of 80 m, 100 m and 120 m amsl are used to simulate three scenarios of offshore wind power plants, according to the Thai energy policies, i.e., (1) Very Small Power Producer (VSPP) scenario with installed capacity less than 10 MW; (2) Small Power Producer (SPP) scenario with installed capacity less than 50 MW; and (3) SPP with installed capacity less than 90 MW. Three current offshore class wind turbine generators, i.e., 3.3 MW, 8.0 MW and 9.5 MW, with hub heights of 120 m, are chosen to analyze the annual energy production (AEP) of the individual wind power plants.

The AEP is analyzed using simple matching techniques between the offshore wind speeds and the power curves of three generic wind turbine generators, shown in Fig. 4. The capacity factors (CF) of the wind power plants are also analyzed to investigate their performances under the offshore wind climate in the Andaman Sea and the Strait of Malacca of Thailand.

The CF can be computed using Eq. (1) (Arrambide et al., 2019),

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

where 8760 is the number of hours in a year.

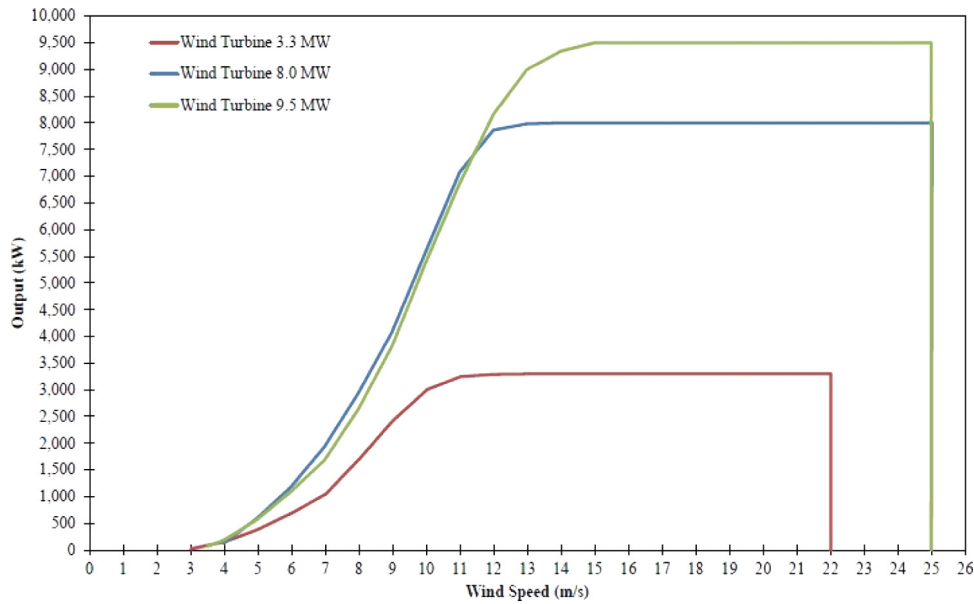


Fig. 4. The power curve of three generic offshore wind turbine generators.

Lowering the carbon levels in the atmosphere is one of the salient features of wind power (Pehl et al., 2017), and an objective of the Government of Thailand. Wind turbines, said to produce 96 times less carbon compared to gas fired power plants, emit only 6.3 g CO_{2eq}/kWh on average (Wang and Sun, 2012). The carbon 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, as per the Intergovernmental Panel on Climate Change 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006).

2.5. Feasibility of offshore wind power plants

The feasibility of offshore wind power plants near Phuket Island, the largest load demand center on the western coast of Thailand, is investigated using the following assumptions: Capital Expenditure (CAPEX) is 2400 USD/kW; Operation Expenditure (OPEX) is 75 USD/kW (Anon, 2019); currency exchange 1 USD = 31.55 THB (Bank of Thailand, 27 February 2019); interest rate is 6.5%; discount rate is 5%; debt ratio is 70:30; repayment loan is 10 years; tax holiday for 1st–8th year, 15% for 9th–14th year and 30% for 15th–20th year; project lifetime is 20 years; average Feed-in-Tariff (FIT) is 3.8681 THB without subsidy.

The four key financial indices (Saediman, 2014), 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 feasibility of offshore wind power projects in the vicinity of Phuket Island.

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. It can be computed using Eq. (2),

$$NPV = \sum_1^t \frac{B_t - C_t}{(1 - i)^t} \tag{2}$$

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 interest rate.

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

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

If the ratio is greater than one, the project is yielding more benefits than costs. An investment is financially acceptable if the BCR exceeds unity, and is not financially acceptable if it 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 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 offshore wind power around Phuket Island. 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 (Anon, 2020a). Thus,

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

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 (Anon, 2020b).

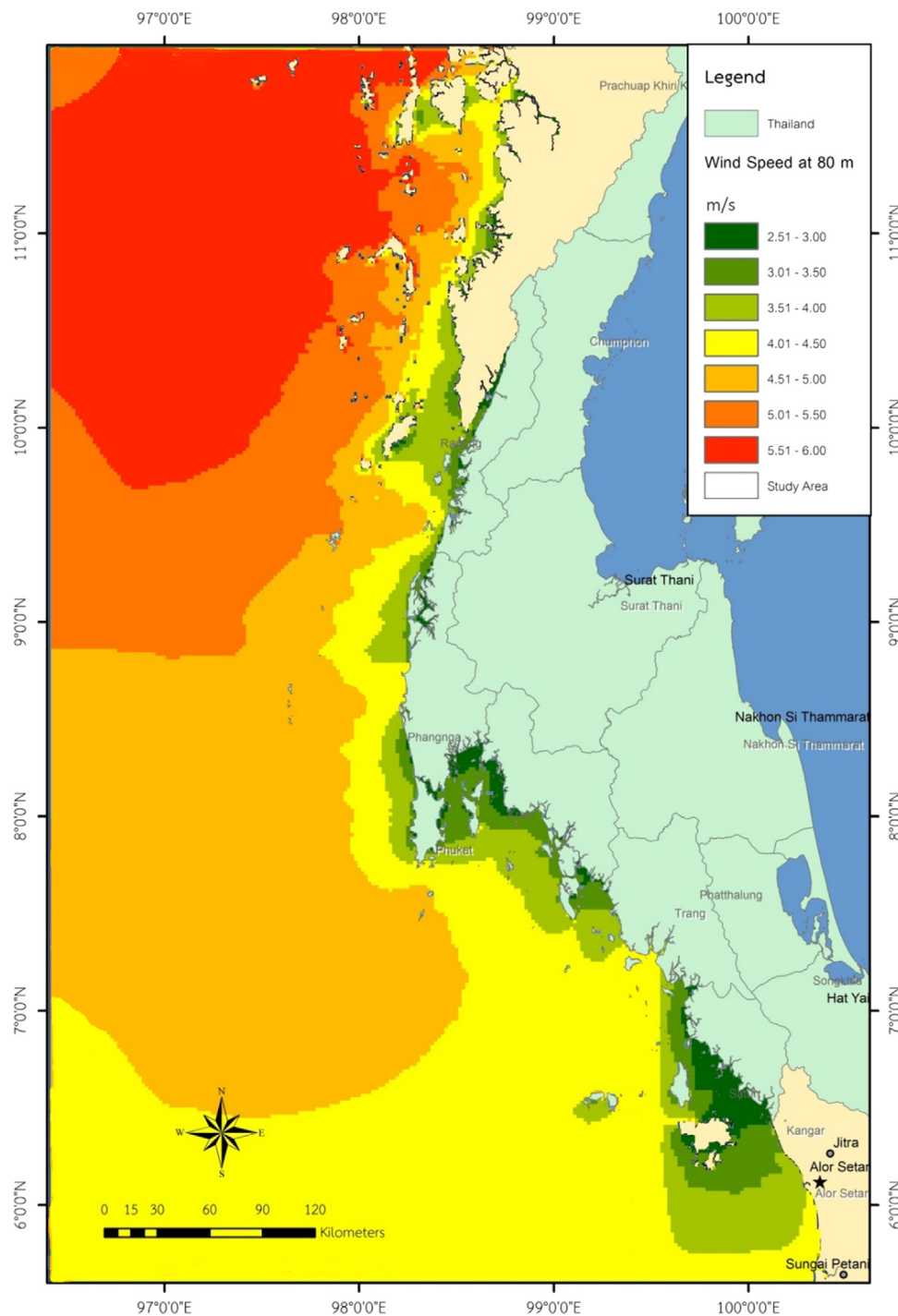


Fig. 5. Mesoscale wind map in the Andaman Sea and the Strait of Malacca at 80 m amsl.

Thailand's Ministry of Energy (MOE) has a FiT program of 5.6 THB/kWh for onshore wind power generation; this amount is not sufficient to compensate the additional costs incurred by offshore wind power development and operations in the region of Phuket Island. An objective of the Alternative Energy Development Plan (AEDP) (Anon, 2020c) of Thailand is to assure that promoters can secure the project financing for the long term viability of projects. Thus, various scenarios, under the condition of IRR of 10%, 15% and 20%, are analyzed to identify the most appropriate FiT, and its sensitivity, for bankable offshore wind power projects in the Andaman Sea and the Strait of Malacca of Thailand under present project costs.

3. Results and discussion

The mesoscale offshore wind resource maps, with 3 km resolution and at elevations of 80 m, 100 m and 120 m amsl, are shown in Figs. 5 to 7, respectively. Based on the results obtained from the mesoscale modeling, it can be observed that the highest mean wind speeds are in the range of 5.5–6.0 m/s in the northern part of the study area, west of Myanmar. However, most of the offshore wind resource, notably at 120 m amsl, near the western coast of Thailand is in the range of 5.0–5.5 m/s.

In order to validate the mesoscale wind maps, a scatter plot of the predicted wind speeds and the measured mean wind speeds

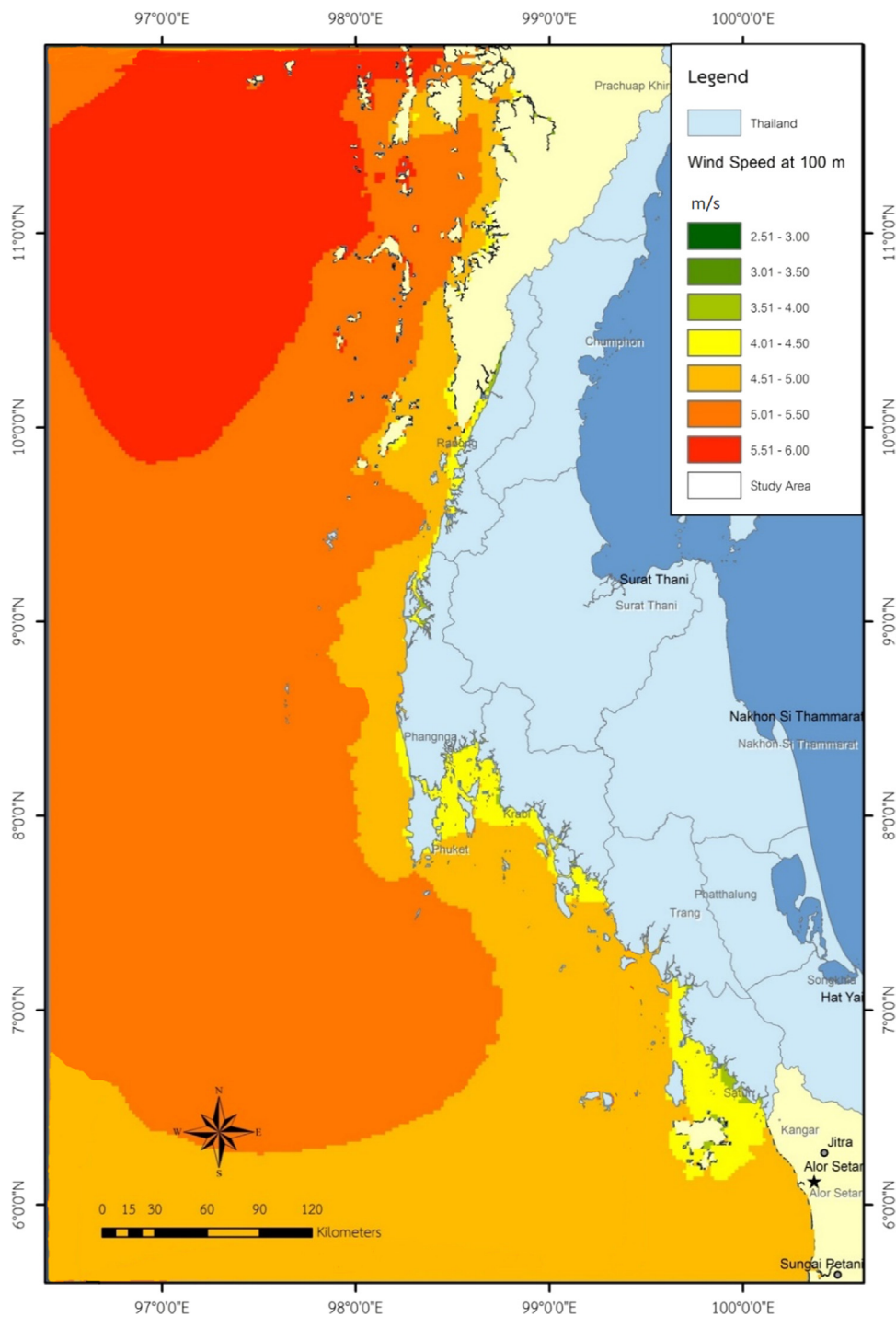


Fig. 6. Mesoscale wind map in the Andaman Sea and the Strait of Malacca at 100 m amsl.

at the met mast locations along the western coast of Thailand is presented in Fig. 8. The results show that the error between the predicted mean wind speeds and the measured mean wind speeds is mainly less than 15%, thus confirming that the wind speeds predicted are valid to assess the feasibility of wind power projects in the western coast of Thailand.

The area around Phuket Island was selected for further microscale Computational Fluid Dynamics (CFD) wind flow modeling and mapping. Results obtained from the MS-Micro wind resource modeling, with a 500 m resolution and at an elevation of 120 m amsl, are presented in Fig. 9. It can be seen from the microscale wind resource map that the highest mean wind speeds

are in the range of 4.6–5.3 m/s, with most of the near-coast offshore area around Phuket Island having mean wind speeds in this range. The wind power density around Phuket Island, at 120 m amsl, is in the range of 200 W/m².

Using the predicted wind resource at 120 m amsl, three scenarios of offshore wind power plants, i.e., Very Small Power Producer (VSPP) with nominal capacity less than 10 MW and Small Power Producer (SPP) with nominal capacities less than 50 MW and 90 MW, are chosen to investigate the feasibility of wind power projects around Phuket Island. The annual energy production (AEP) of generic wind power plants, using three generic offshore class wind turbine generators, i.e., 3.3 MW, 8.0

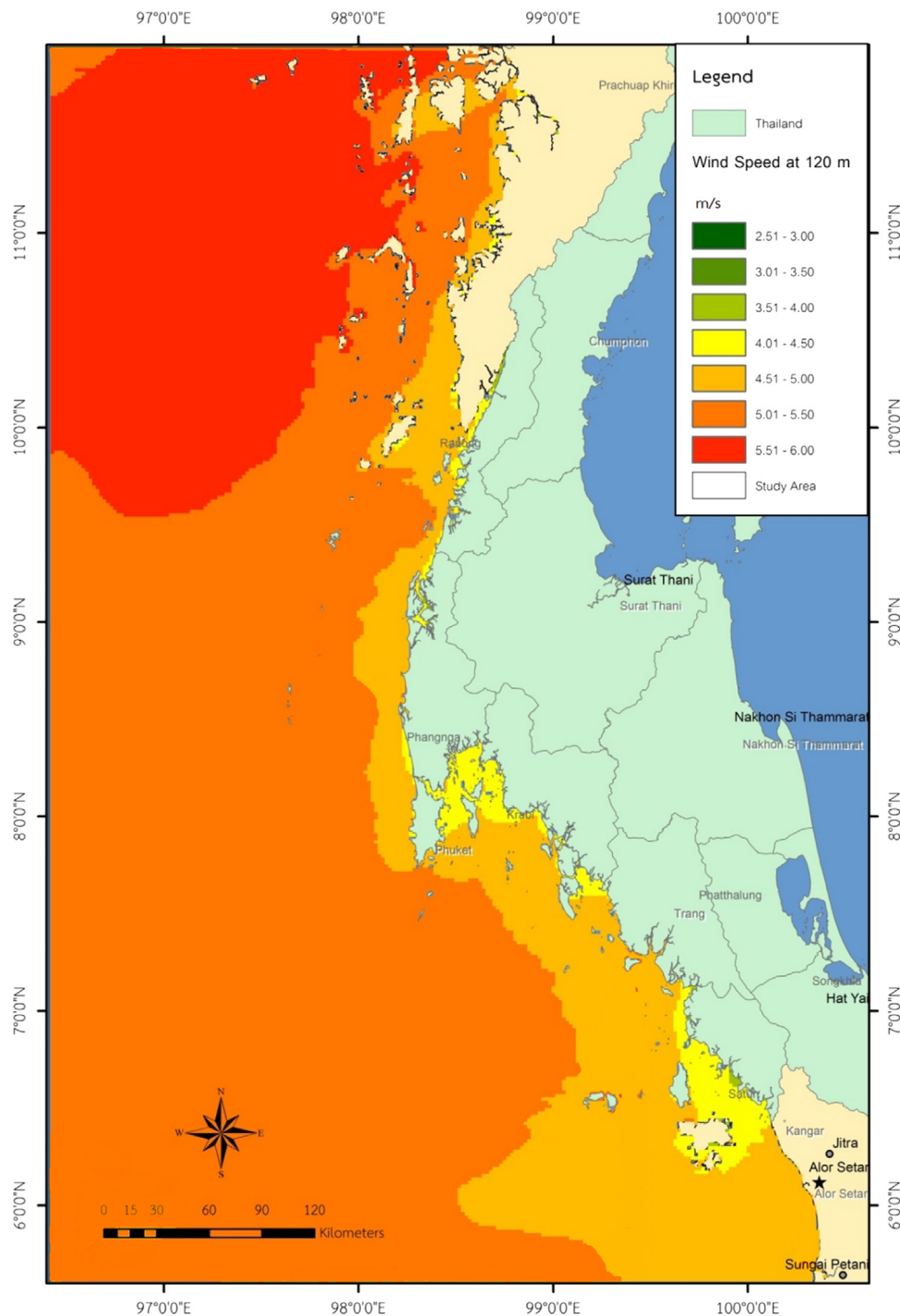


Fig. 7. Mesoscale wind map in the Andaman Sea and the Strait of Malacca at 120 m amsl.

MW and 9.5 MW, is estimated. Different configurations of wind turbine generators are studied for the generic wind power plants, as defined by the Thailand energy policies. Table 2 presents the various configurations of wind power plants studied in the work, along with their individual annual energy production and their respective $\text{CO}_{2\text{eq}}$ emission avoidances.

Results show that for the VSPP, the AEP is in the range of 7–13 GWh/yr; for the SPP less than 50 MW, the AEP is in the range of 35–68 GWh/yr; and for the SPP less than 90 MW, the AEP is in the range of 64–123 GWh/yr. For the various configurations studied, the capacity factors of the wind power plants are in the range of 9–16%. Fig. 10 provides a graphical summary of these results.

The $\text{CO}_{2\text{eq}}$ emission avoidances have been found to be in the range of 45–86 tonnes $\text{CO}_{2\text{eq}}$ per year for VSPP offshore wind power plants around Phuket Island. For the SPP less than 50 MW, the $\text{CO}_{2\text{eq}}$ emission avoidances are estimated in the range of 225–430 tonnes $\text{CO}_{2\text{eq}}$ per year, while the $\text{CO}_{2\text{eq}}$ emission avoidances for the SPP less than 90 MW is estimated in the range of 406–774 tonnes, as shown in Table 2.

The feasibility of offshore wind power plants around Phuket Island is investigated under the current average FiT and present CAPEX and OPEX costs in Thailand. The levelized cost of energy (LCOE) is also estimated in order to analyze the competitiveness of offshore wind power plants in terms of electricity generation

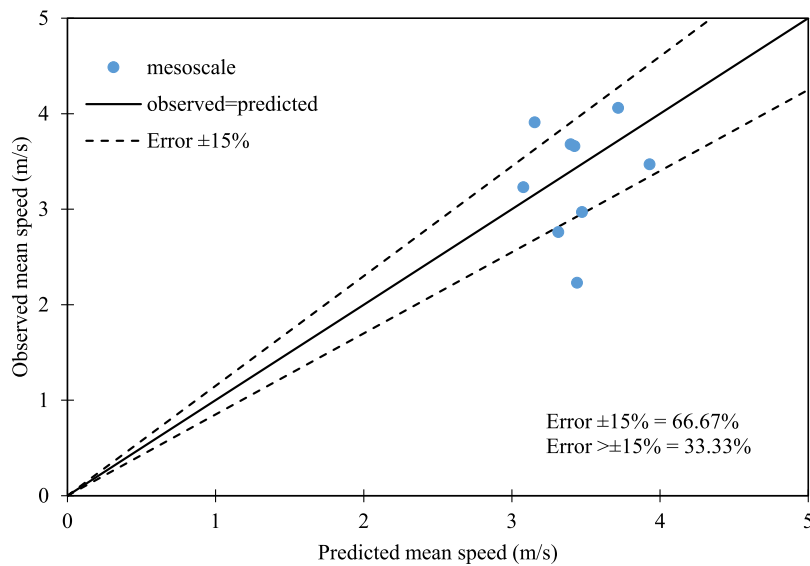


Fig. 8. Validation of the mesoscale wind predictions along the coast of the Andaman Sea and the Strait of Malacca of Thailand, at 40 m and 90 m above ground level.

Table 2

Annual energy production and capacity factors of the generic offshore wind power plants around Phuket Island.

Offshore wind power plant	Wind turbine generator capacity (MW)	No. of WTG/installed capacity (MW)	AEP (MWh/yr)	CF (%)	CO _{2eq} emission avoidance (tonnes CO _{2eq} /yr)
VSPP (<=10 MW)	3.3	3/9.9	13,655	16.3	86
	8.0	1/8.0	7600	11.3	48
	9.5	1/9.5	7159	8.9	45
SPP (<=50 MW)	3.3	15/49.5	68,275	16.3	430
	8.0	6/48.0	45,601	11.3	287
	9.5	5/47.5	35,795	8.9	225
SPP (<=90 MW)	3.3	27/89.1	122,895	16.3	774
	8.0	11/88.0	83,602	11.3	527
	9.5	9/85.5	64,430	8.9	406

costs. It was found that, within the current public policies of Thailand, all scenarios of offshore wind power projects around Phuket Island are not economically viable due to all financial indices not meeting the main bankable criteria, and with an LCOE in the range of 6.0–10.8 THB/kWh (0.188–0.343 USD/kWh). Table 3 presents a summary of these results, without the FiT incentive.

Based on the generation costs of offshore wind power reported by the International Renewable Energy Agency (IRENA) (Anon, 2019) in 2018, the global offshore wind power installations totaled 4.5 GW, almost exclusively in Europe and China. The global weighted average LCOE for offshore wind energy in 2018 was 0.127 USD/kWh (4.0 THB/kWh), which is 1% lower than in 2017, and 20% lower than in 2010. This lower, global LCOE is due to the fact that the wind resources of offshore wind power plants in Europe and China are better than the wind resource in the territory studied in this work. On the longer term, on a world basis, the offshore wind power LCOE is projected to go down to 0.09 Euro/kWh by 2030 (0.103 USD/kWh; 3.24 THB/kWh) (European Wind Energy Association, EWEA, 2015).

Since SPP offshore wind power plants require higher capital costs for project investments, the cost effectiveness, economy of scale and scalability of offshore wind power plants should be considered for large scale projects installed in areas with promising wind resources. However, since the offshore wind resource around Phuket Island is not high enough to justify large scale offshore wind power plant development, only the VSPP scenario is considered for project development in this region of Thailand.

For the area in the vicinity of Phuket Island, using an IRR ranging from 10% to 20% for VSPP offshore wind power plants, the results show that the FiT required to sustain the development of VSPP offshore wind power plants is in the range of 0.314–0.576 USD/kWh when using 3.3 MW offshore wind turbine generators; in the range of 0.346–0.638 USD/kWh when using 8.0 MW offshore wind turbine generators; and in the range of 0.376–0.688 USD/kWh when using 9.5 MW offshore wind turbine generator, as shown in Fig. 11.

Finally, it appears that a 3.3 MW offshore-class wind turbine generator is currently the most appropriate configuration for wind power plants in the vicinity of Phuket Island. These power plants offer the lowest LCOE, thus requiring the lowest FiT possible to sustain viable projects in the Andaman Sea of Thailand.

4. Conclusions

An offshore wind resource assessment and offshore wind power feasibility in the Andaman Sea and the Strait of Malacca of Thailand are presented in this work. The coupled mesoscale atmospheric and microscale CFD wind flow modeling along with an NCEP/NCAR climatic database were applied in order to develop offshore wind maps at elevations of 80 m, 90 m and 120 m above mean sea level (amsl). The mesoscale offshore wind resource maps, with 3 km resolution, and at elevations of 40 m and 90 m amsl, are validated with observed wind datasets measured from nine met masts installed along the coast of the Andaman Sea and the Strait of Malacca on the western part of Thailand.

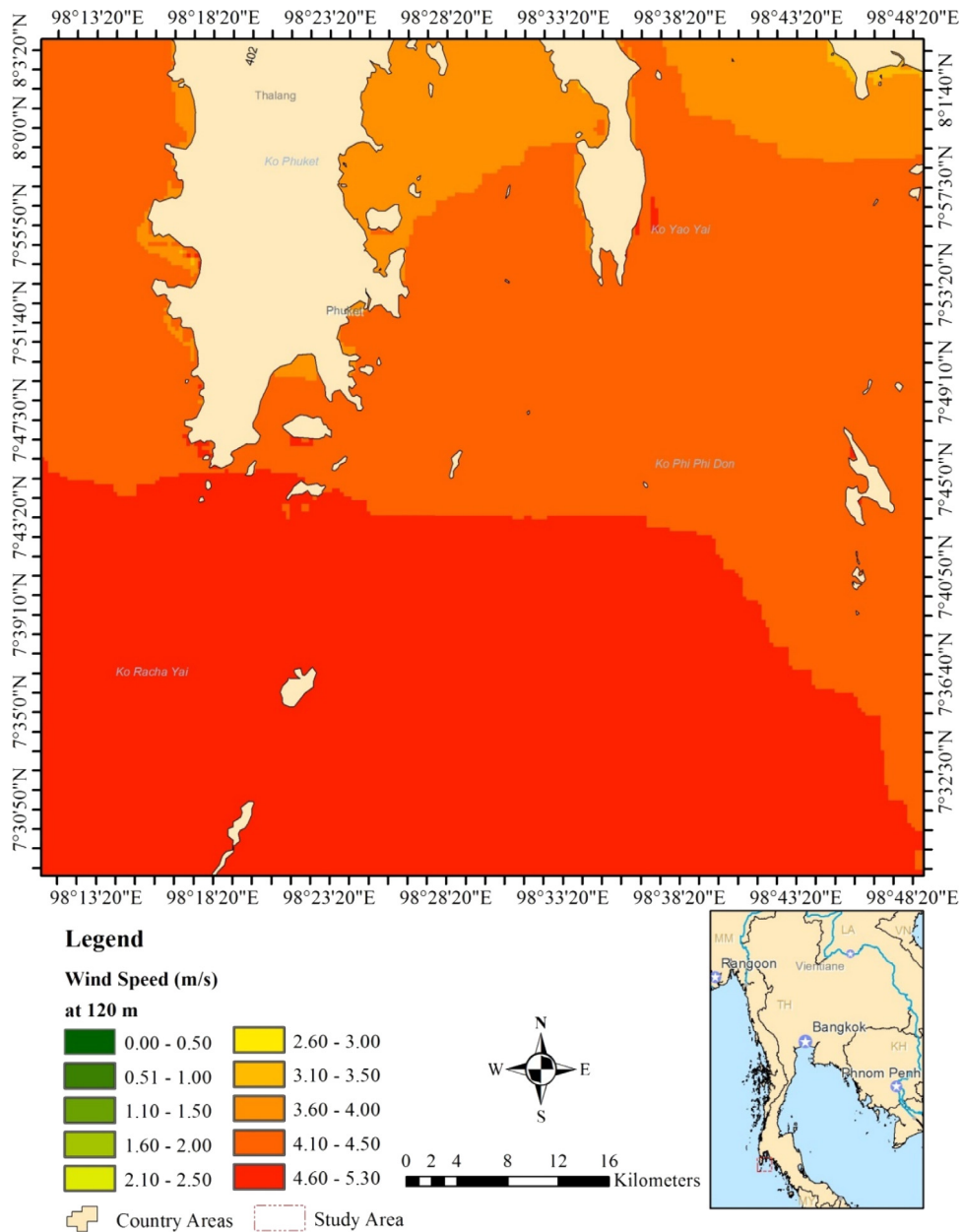


Fig. 9. Microscale offshore wind map around Phuket Island at 120 m amsl.

Table 3
Financial indices, without FiT, for the generic offshore wind power plants near Phuket Island.

Offshore wind power plant	BCR	NPV (MTHB)	IRR (%)	PBP (Year)	LCOE (USD/kWh)
VSPP @ 3.3 MW	0.54	-554	<0	>20	0.188
VSPP @ 8.0 MW	0.37	-613	<0	>20	0.272
VSPP @ 9.5 MW	0.30	-818	<0	>20	0.343

Using the wind resource map at 120 m amsl, the results show that the best area for wind power development is in the northern part of the study area, on the western coast of Myanmar, where the mean annual wind speeds are in the range of 5.5–6.0 m/s.

For its part, Phuket Island is considered a potential area to install near shore wind power plants, in line with sustainable tourism concepts promoted in Thailand. The results show that the region in the vicinity of Phuket Island is characterized by mean annual wind speeds in the range of 4.6–5.3 m/s.

Finally, the results show that offshore wind power plants using 3.3 MW wind turbine generators would offer the best performances for the wind conditions of the region. The best annual energy production for VSPP power plants is over 13 GWh/yr, while it is in the order of 68 GWh/yr for SPP less than 50 MW, and in the order of 123 GWh/yr for SPP less than 90 MW, corresponding to capacity factors of approximately 16%. The lowest levelized cost of energy is 0.188 USD/kWh, while the CO_{2eq} emission avoidances reach 774 tonnes CO_{2eq} per year. Finally, the required FiT to sustain the development of **VSPP offshore** wind

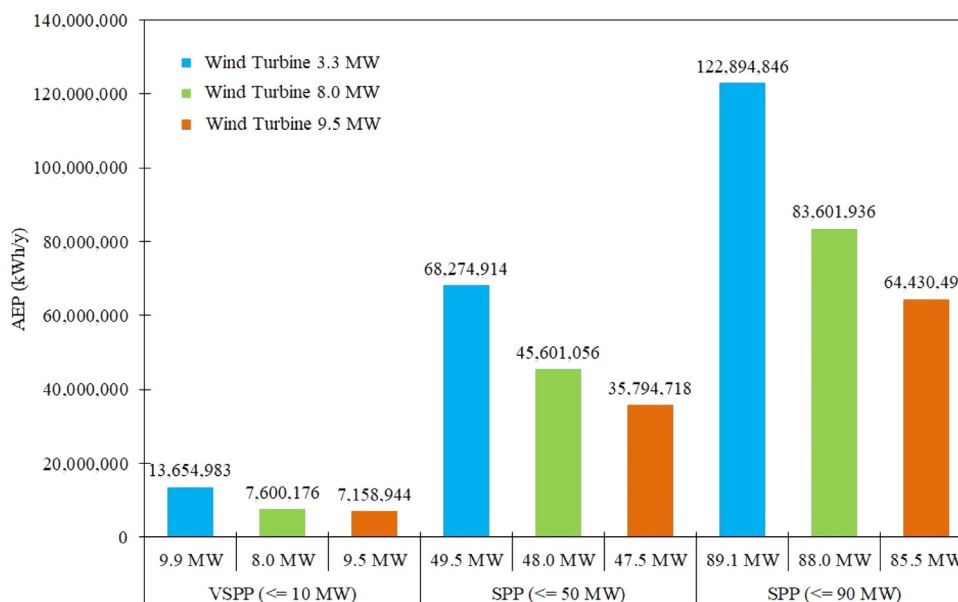


Fig. 10. Annual energy production (AEP) by VSPP and SPP offshore wind power plants around Phuket Island.

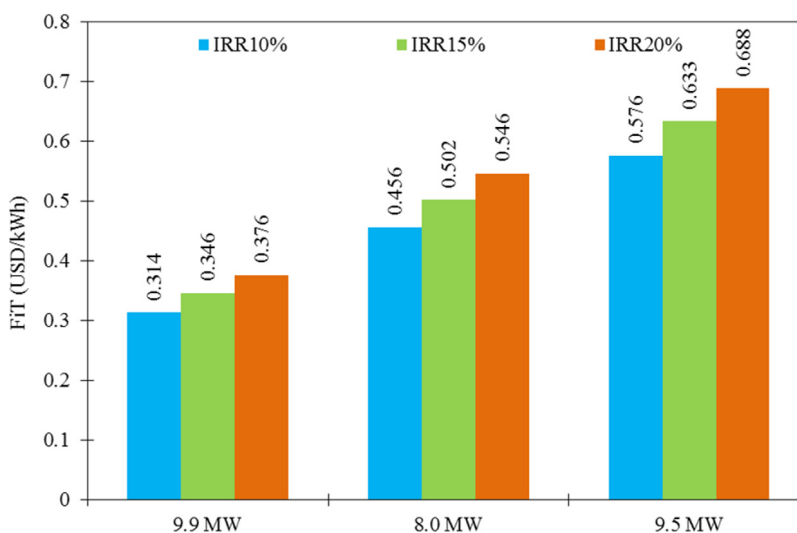


Fig. 11. Estimated Feed-in-Tariff (FiT) required for VSPP offshore wind power plants around Phuket Island.

power plants in the vicinity of Phuket Island is in the range of 0.314–0.688 USD/kWh.

In the future, when advanced offshore-class wind turbine generators for low to medium wind regime will be commercially available, the annual energy production and the economic feasibility of offshore wind power plants in the Andaman Sea and Malacca Strait of Thailand should be reanalyzed for cleaner power production towards sustainable development, and to contribute in achieving the energy plans for the country.

CRedit authorship contribution statement

Montree Ranthodsang: Software, Formal analysis, Visualization. **Jompob Waewsak:** Conceptualization, Methodology, Investigation, Validation, Supervision, Writing - original draft. **Chuleerat Kongruang:** Conceptualization. **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.

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