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Research article

Techno-Economic Assessment of Utility-Scale Dual-Rotor Wind Power Generation: A Case Study of Siam Eastern Industrial Park, Rayong Province, Thailand

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Abstract: The energy transition to renewables is considered one of the primary ways to limit the emissions of greenhouse gases (GHG), as the electricity sector is among the major users of fossil fuels. Solar and wind power are leading the way and becoming more cost-effective than coal and other fossil fuels. As renewable energy is becoming more economical, industries worldwide are adopting it to reduce their carbon footprints. This study is aimed at the techno-economic assessment of a 20 MW utility-scale dual-rotor wind power plant installed at Siam Eastern Industrial Park in the Rayong province of Thailand. Using the MERRA-2 wind database, Digital Elevation Model (DEM), and the rough digital data of the study area, computational fluid dynamics (CFD) wind flow modeling was used to create a microscale wind resource map of the study area. The modeling yielded an average windspeed of 5.4 m/s at the hub height of 90 m above ground level (agl). Using four 5 MW dual-rotor wind turbine generators, the wind power plant would have an annual energy production (AEP) of 75.7 GWh/yr with a capacity factor (CF) of 43%. The economic assessment of the power plant was performed using various economic indicators, notably the benefit-cost ratio (BCR), the net present value (NPV), the internal rate of return (IRR), and the payback period (PBP) at different benefit scenarios defined by the Provincial Electricity Authority of Thailand (PEA) and private power purchase agreements. The financial parameters were all positive for each of the PEA's benefits scenarios, even without the carbon trading benefits, thus making this wind power plant economically viable. Studies like these are essential to build the confidence of investors and developers by providing them with well-informed information on the feasibility of wind power plant projects and their benefits, thus contributing to the development of wind energy in various jurisdictions.

Keywords: Computational Fluid Dynamics; Wind Flow Modeling; Feed-in-Tariff; Levelized Cost of Energy; Wind Energy

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1. Introduction

The energy sector is among the major contributors to global warming due to its heavy reliance on fossil fuels. With a 35.8% share, coal is still the biggest source of global electricity production, followed by natural gas with a 22.2% share, while wind energy and solar energy have shares of 7.5% and 4.5%, respectively, with the remainder being hydropower [1]. Concerns over global warming and its devastating effects have brought together countries to pledge to decrease carbon emissions [2]. Countries worldwide have fast-tracked their energy transitions to renewables not only because of their pledge but because renewable energy has surpassed fossil fuels as the cheapest source of electricity [3].

Like the rest of the world, Thailand depends heavily on fossil fuels to meet its growing energy demands, with natural gas and coal accounting for most of the fuel mix share [4]. Currently, renewables make up 13% of the electricity generation in Thailand [5]. However, based on ambitious plans, Thailand is committed to diversifying its energy mix and increasing its renewable energy share significantly over the coming years. The Power Development Plan PDP 2015-36 aims to reduce the share of fossil fuels to 30-40% by 2036 and increase renewable energy to 20% [6]. Besides having significant solar and bioenergy potentials, Thailand has good wind potentials in various localized regions, which can be developed to achieve the country’s renewable energy targets.

Thailand has installed 754 MW of wind power [7] so far, but it has the potential to develop significant onshore and offshore wind power projects if given proper policy and regulatory attention. Many studies have been carried out in Thailand to assess the potential of wind energy. Using CFD microscale wind flow modeling, the offshore wind power resource in the Gulf of Thailand has average wind speeds of 5.5 to 6.5 m/s, resulting in promising offshore wind power potential [8]. Using CFD wind flow modeling at multiple elevations, the wind power potential of the southernmost region of Thailand was assessed, resulting in a wind power potential of 300 MW, which can generate 690 GWh/year of electricity [7]. Employing CFD wind flow mapping at 120 to 125 m above ground level (agl), the annual energy production (AEP) of wind power plants on the Andaman Coast of Thailand could reach 135 GWh/year [9]. Finally, a techno-economic assessment of a 15 MW wind power plant in central Thailand, using measured windspeed data and CFD wind flow modeling for multiple hub height wind turbine generators, estimates an AEP of 41 GWh/year. The CFD wind flow modeling provides a high degree of accuracy for modeling wind speeds, particularly in complex terrains, which explains why it is used frequently for wind power assessments [9].

The study presented in this paper also uses CFD wind flow modeling for the techno-economic assessment of a 20 MW wind power plant installed in the Siam Eastern industrial park to study the technical and economic feasibility of a wind power plant using four units of a 5 MW dual-rotor wind turbine generator. Studies like these are vital to promoting the development of small wind power in Thailand by providing techno-economic data for investors.

2. Materials and Methods

2.1 Study area

The Siam Eastern Industrial Park (SEP) is located in Map Yang Phon, Pluak Daeng District of Rayong Province, approximately 110 km from Bangkok International Airport, 30 km from Leam Chabang deep seaport, and near Highway No. 311 on the eastern coast of Thailand, as shown in Figure 1. The SEP covers an area of 805.8 acres and provides industrial and commercial services such as warehousing, manufacturing plants, and conference facilities, among others. The SEP has a central location connecting major industrial zones/estates, making it ideal for developing wind farms, which can be used to provide clean power to industrial and commercial facilities.

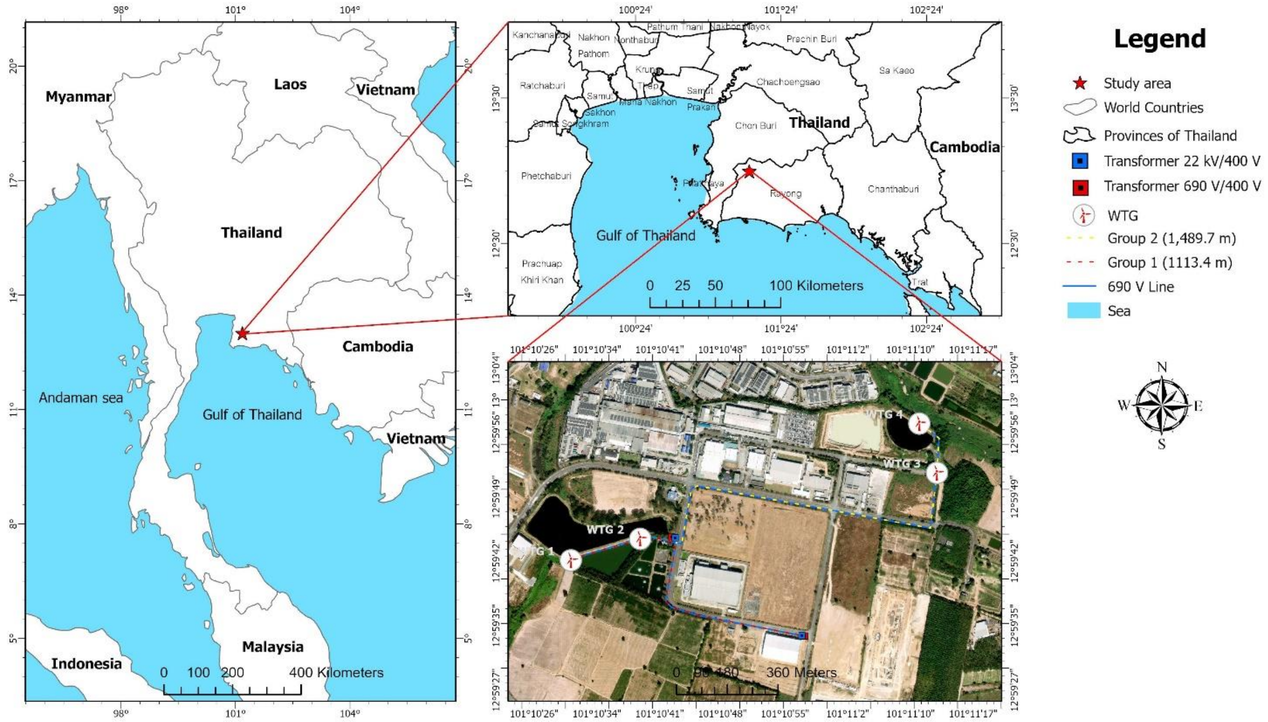

Figure 1. Study area and geographical location of the Siam Eastern Industrial Park in Thailand.

2.2 Wind Resource Mapping of the Study Area

The microscale wind resource mapping of the study area was done using CFD wind flow modeling. CFD-based microscale wind resource mapping is commonly used for wind flow modeling in complex terrains. It is frequently used in micro-sitting wind turbine generators within wind power plants [10]. The CFD modeling is done by solving the Reynolds-averaged Navier–Stokes (RANS) equations using the k-epsilon and k-omega turbulence models [11,12]. The CFD wind flow model developed by WindSim AS [13, 14] was used in this study with the MERRA-2 wind dataset as the climatic wind input. MERRA-2 is a satellite-based wind observation dataset provided by NASA using the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) [15]. The 5 km spatial resolution data was created with a 5-year (2018-2022) numerical weather prediction model. In addition, the digital elevation model (DEM), shown in Figure 2, was obtained from NASA [16], while the roughness data of the study area, shown in Figure 3, was obtained from the Land Development Department (LDD) of Thailand [17]

The Weibull distribution and the wind rose of the study based on MERRA-2 database analysis, presented in Figure 4, shows an annual mean wind speed of 5.4 m/s at 50 m agl, with a k-shape parameter of 2.812 and an A-scale parameter of 5.12 m/s, making it a good area for setting up a small-scale wind power plant. The resulting high-resolution wind resource map of the study area, at a standard elevation of wind turbine generators of 90 m agl and based on CFD wind flow modeling, is shown in Figure 5. Finally, a dual-rotor 5 MW wind turbine generator was used to simulate the techno-economic assessment of the wind power plant to assess its feasibility and economic viability.

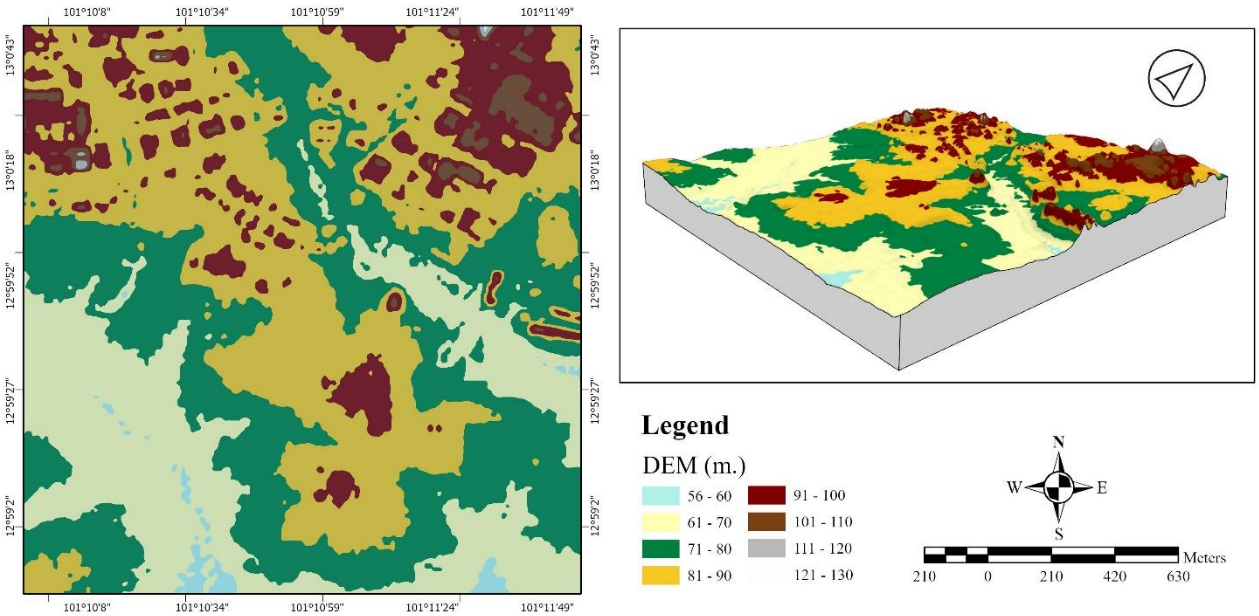

Figure 2. Digital Elevation Model (DEM) of the study area.

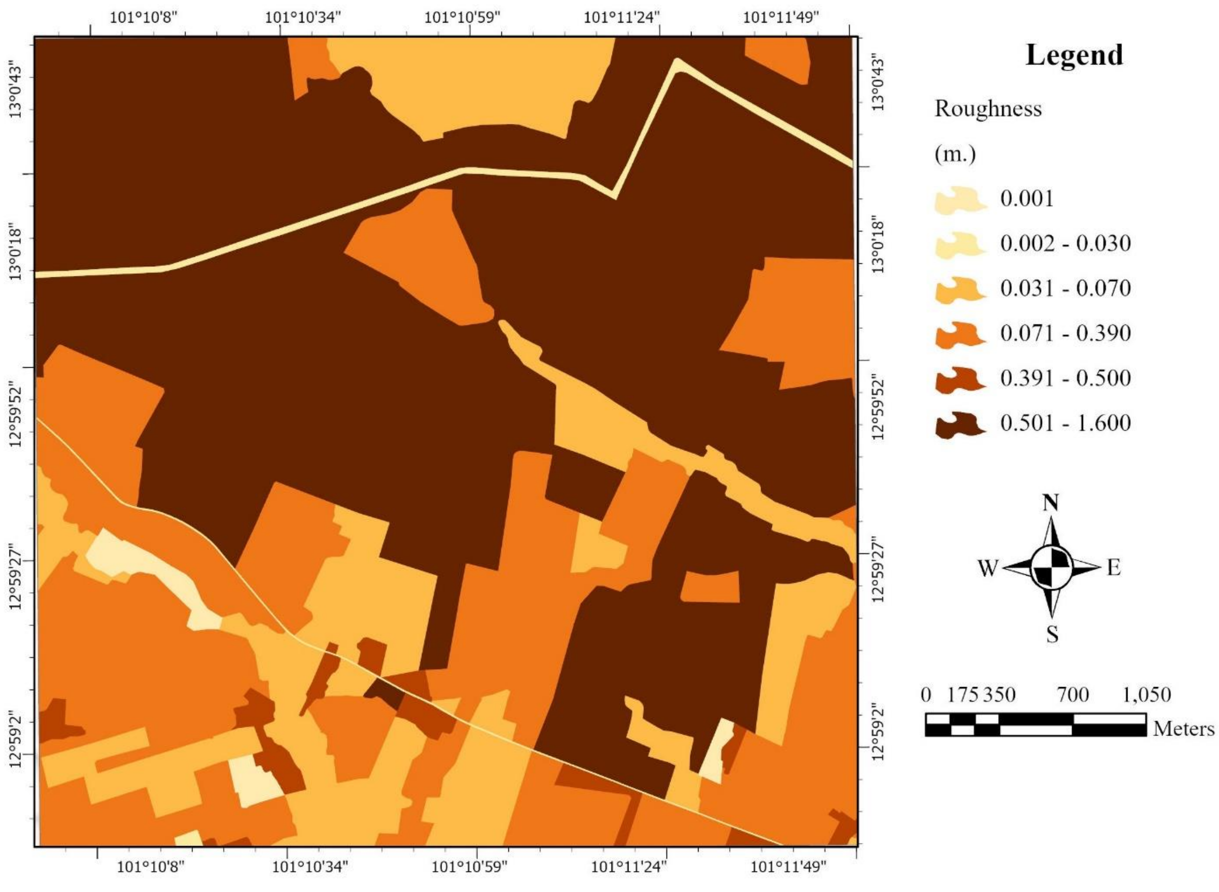

Figure 3. Roughness height of the study area.

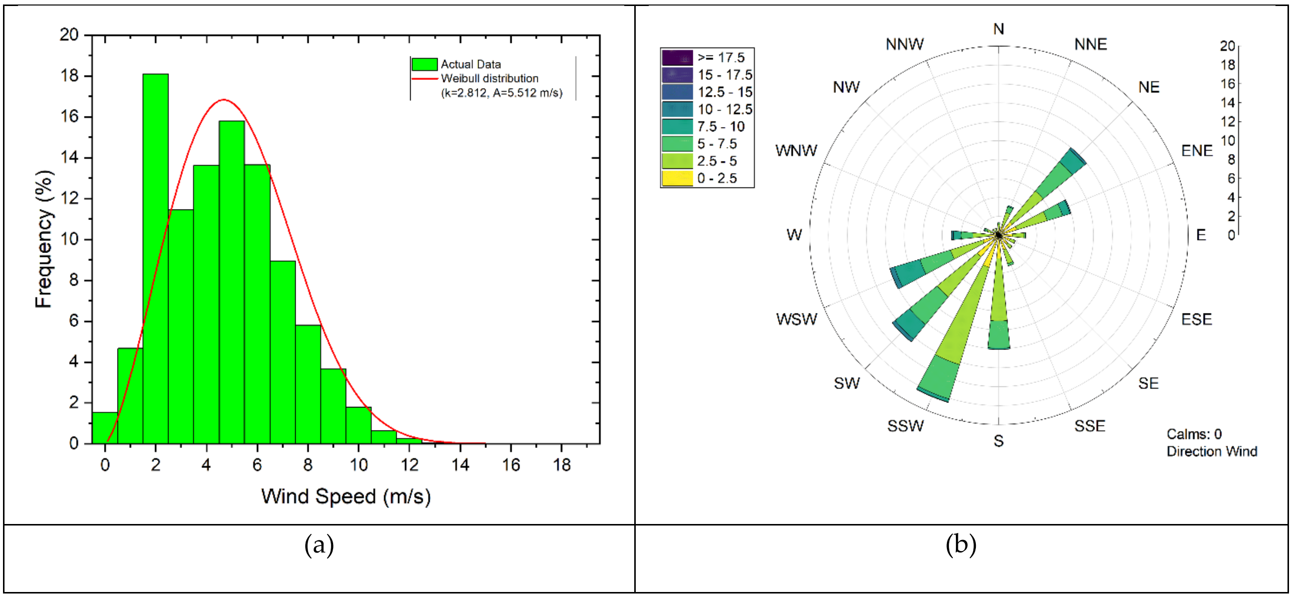

Figure 4. Weibull distribution (a) and wind rose (b) of the wind resource at 50 m agl. (MERRA-2).

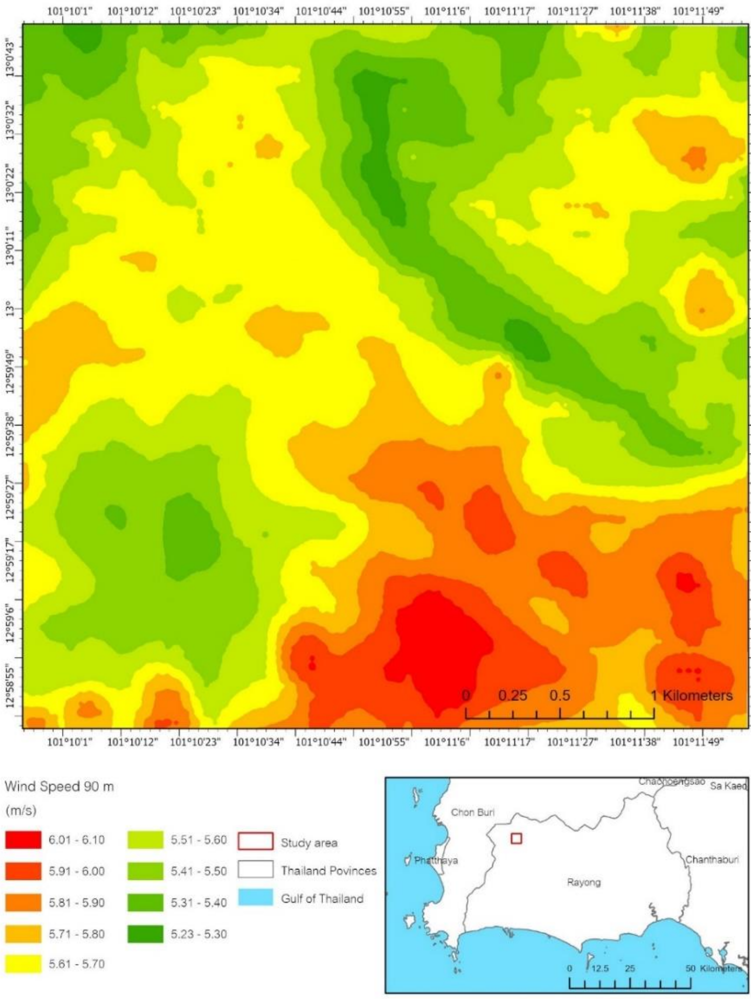

Figure 5. High-resolution wind resource map at 90 m agl over the study area.

2.3 Dual-rotor Wind Turbine Generator

A dual-rotor wind turbine generator, shown in Figure 6, was used in this study for the techno-economic assessment of the 20 MW wind power plant. Many studies have validated the superior energy-capturing capability of double-rotor wind turbine generators over single-rotor models [18]. Adding a rear rotor can compensate for the wake deficits, resulting in increased energy output from the wind turbine generator [19]. The characteristics of the dual-rotor wind turbine generator used in this study are presented in Table 1, while the power curve and the thrust coefficient are presented in Figure 7. The 20 MW wind power plant would be installed at the Siam Eastern industrial park, consisting of four 5 MW dual-rotor wind turbine generators connected to the Provincial Electricity Authority (PEA) 22 kV distribution system, as shown by the single line diagram in Figure 8. The wind power plant would provide electric power to the industrial park's facilities through the PEA distribution system.

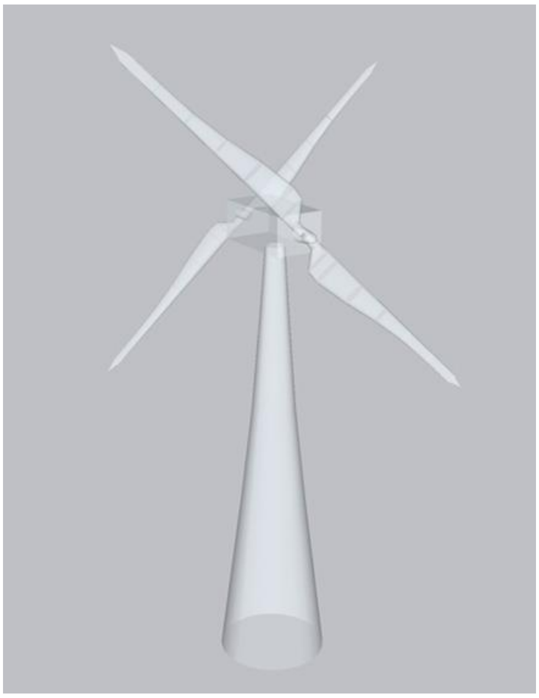

Figure 6. 5 MW dual-rotor WTG used in this study.

Table 1. Characteristics of the dual-rotor wind turbine generator used in this study.

Parameter	Value	Unit
Rotor Diameter	126	m
Swept Area	12,474	m^2
Hub Height	90	m
Nominal Capacity	5	MW
Cut-in Speed	2.0	m/s
Rated Speed	10.0	m/s
Cut-out Speed	21.0	m/s
Generator Technology	Asynchronous Generator	-
Transmission	Gearbox	-

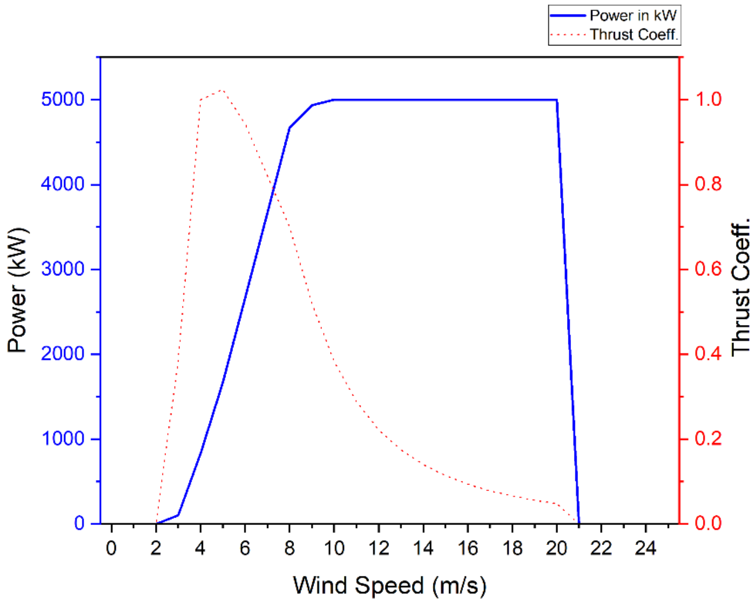

Figure 7. Power curve and thrust coefficient of the 5 MW dual-rotor wind turbine generator used in the study.

2.4 Annual Energy Production and Capacity Factor

The annual energy production (AEP) of the WTGs is calculated using the power curve of the WTG shown in Figure 7. For its part, the capacity factor (CF) is calculated using equation (1).

$$CF = \left(\frac{AEP\,(kWh)}{Rated\,Capacity\ (kW) \times 8{,}760\ (hr)} \right) \times 100\% \tag{1}$$

The net AEP is then calculated based on the gross AEP, while the wake losses are computed with the Jensen model available in WindSim [14].

2.5 Economic analysis

Several economic indicators were used to assess the economic viability of the project, including the benefit-cost ratio (BCR), the net present value (NPV), the internal rate of return (IRR), and the payback period (PBB) to analyze the financial benefits of the wind power plant based on the benefits scenarios defined by the PEA, as summarized in Table 2.

2.5.1 Benefit-Cost Ratio (BCR)

The BCR is computed as the present value of benefits divided by the present value of costs, as given in equation (2).

$$BCR = \frac{\sum_1^t B_t (1+t)^t}{\sum_1^t C_t (1+t)^t} \tag{2}$$

B_t is the revenue or positive cash flow in year t, and C_t is the cost or negative cash flow in year t. A BCR value of greater than one indicates that the project yields more benefits than cost, while a negative BCR value indicates a loss.

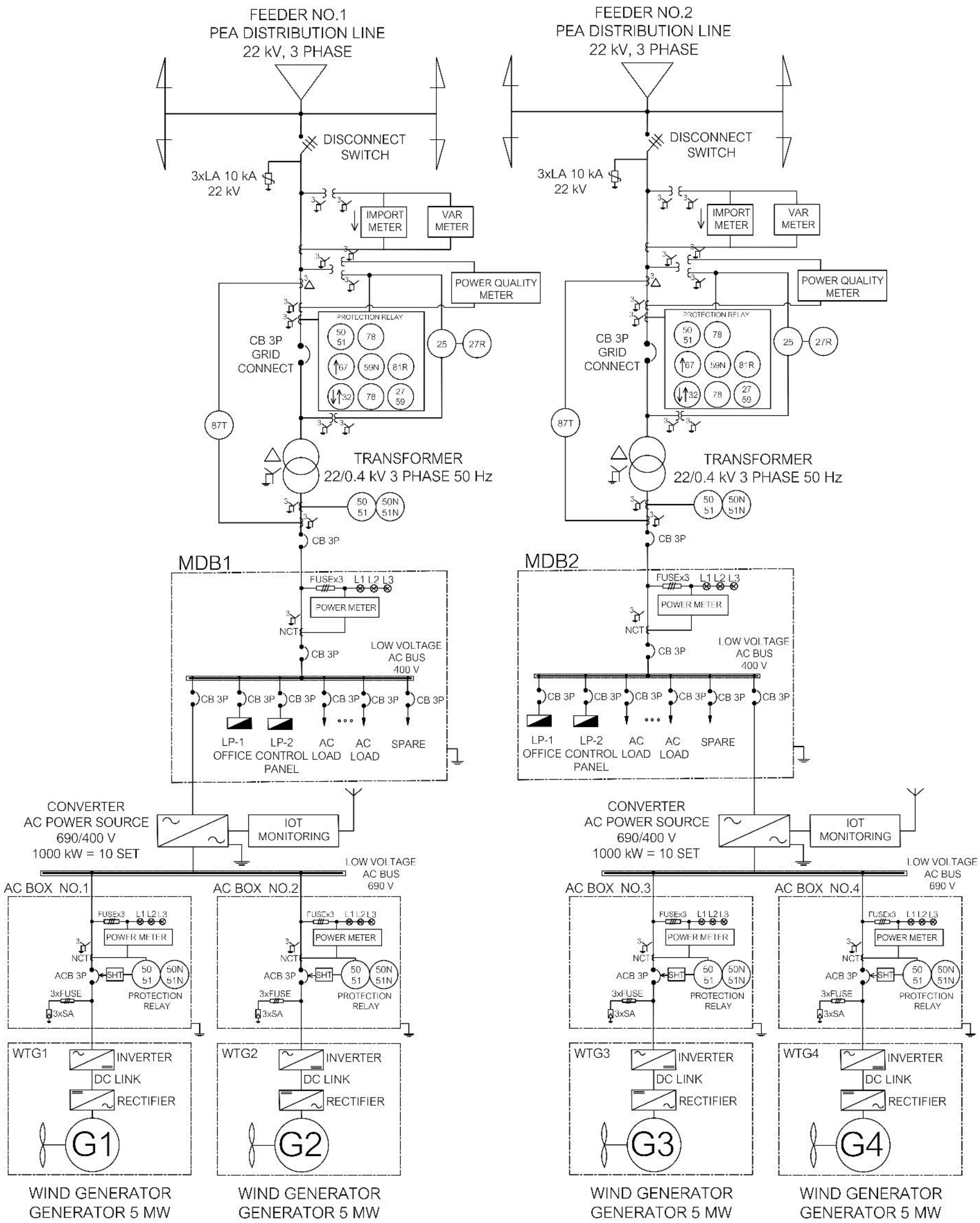

Figure 8. Single line diagram of two 10 MW wind power plant interconnection to the distribution system of Thailand's Provincial Electricity Authority (PEA).

Table 2. Assumptions in the economics analysis.

Parameter	Value
CAPEX (MTHB/kW)	60
OPEX (% of CAPEX)	1.50
Installation Capacity (MW)	20
Capacity Factor (%)	43
Annual Energy Production (kWh/yr)	75,756,480
Exchange Rate (THB/USD)	35.3674
Debt Ratio	70:30
Discount Rate (%)	5
MLR+1 rate (%)	7.30
PEA On-Peak Tariff (THB)	4.5180
PEA Off-Peak Tariff (THB)	2.6115
Benefit Scenarios	**Value (THB/kWh)**
1. Feed-in Tariff	3.1014
2. PEA Tariff (On-Peak 70% / Off-Peak 30%)	3.9460
3. Private PPA (PEA Tariff (On-Peak 70% / Off-Peak 30%) + Discount 10%)	3.5514
4. Private PPA (PEA Tariff (On-Peak 70% / Off-Peak 30%) + Discount 12.5%)	3.1075
5. Private PPA (PEA Tariff (On-Peak 70% / Off-Peak 30%) + Discount 15%)	2.6414

2.5.2 Net present value (NPV)

The net present value (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 not if it is negative. The NPV can be computed using equation (3).

$$NPV = \sum_{1}^{t} \frac{B_t + C_t}{(1-i)^t} \tag{3}$$

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 the cash flow occurs, and i is the interest rate.

2.5.3 Internal rate of return (IRR)

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

$$IRR = i_1 + (i_2 + i_3) \times \left(\frac{NPV_1}{NPV_2 + NPV_3}\right) \tag{4}$$

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, NPV_2 is the net present value at discount rate 2, and NPV_3 is the net present value at discount rate 3. The IRR is acceptable if it is greater than the discount rate.

2.5.4 Payback period (PBP)

The payback period (PBP) estimates the time needed to make a return covering the investment and the capital spent. The project is financially feasible if the PBP is less than the project's economic life. The PBP is given by equation (5).

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

2.6 Greenhouse gas emission avoidance

This study uses the grid emission factor of 5.692 g CO2/kWh in Thailand to estimate CO_2 emission avoidance by generating electricity with a wind power plant [20].

3. Results and Discussion

The CFD wind flow modeling-based wind resource map using the MERRA-2 database from 2018-2022, the DEM and roughness map of the study area are shown in Figure 4. At 90 m agl, the wind speed of 2 m/s has the highest frequency addition; an average wind speed of 5 m/s also has some good frequency, while wind speeds above 6 m/s decrease steadily. Based on the Weibull distribution, the k-shape parameter is 2.812. The A-scale parameter is 5.12 m/s, and the mean annual wind speed is 5.4 m/s, as shown in Figures 5 (a) and (b). According to Niyomtham et al. [9], the National Renewable Energy Laboratory (NREL) considers annual wind speeds between 5 and 7 m/s suitable for commercial wind power production.

Overall, the study area has low wind speeds compared to other high-speed potential areas. However, selecting a suitable wind turbine generator model and rigorous economic and financial analyses are essential to make the area viable for utility-scale wind power production. This study used a dual-rotor wind turbine generator, which has the advantage of increasing energy output from the same wind speeds as conventional single-rotor models.

The results show that a 20 MW power plant with four 5 MW dual-rotor wind turbine generators would have an AEP of 75.7 GWh/year, with a CF of 43%. The 20 MW wind power plant would avoid the emission of 37.3 ktonnes of CO_{2eq}/year of GHG emissions, with the grid emission factor of 5.692 g CO_{2eq}/kWh.

For the economic and financial assessment of the wind power plant, the NPV, BCR, IRR, and PBP were assessed based on the PEA feed-in-tariff guidelines. PEA purchases power from independent power producers at different tariff rates for on-peak and off-peak demand, as summarized in Table 2. Figure 9 shows the results for the economic and financial indicators. The indicators are assessed over 20 years with two different scenarios: the Thailand Voluntary Emission Trading (T-VER) program for CO2 trading, which offers more incentives to projects with low carbon emissions, and the other without the T-VER program.

Even without the T-VER incentives, the economic and financial indicators indicate a highly feasible wind power project. The financial indicators of the base feed-in-tariff (FiT) scenario, even without the T-VER, show the feasibility of the project with a BCR of 1.81, an NPV of 1,306 MTHB, a 22.39% IRR, and a PBP of 5 years, all of which are positive indicators of a financially feasible wind power project. With the addition of the T-VER incentives, the project becomes even more feasible. Similarly, other scenarios are equally financially feasible with T-VER and without T-VER incentives, as shown in Figure 9.

The basic on-off peak scenario offers the best financial feasibility among the PEA-defined scenarios, with a 2.24 BCR, a 2,063 MTHB NPV, a 38.01% IRR, and a PBP of just 3 years. In extreme conditions, the on-off peak with a 15% discount scenario has the least financial feasibility with a 1.56 BCR, an 893 MTHB NPV, a 14.64% IRR, and a PBP of 8 years. However, even this scenario is still financially feasible with the positive indicators. Hence, the 20 MW Siam Eastern industrial park location is feasible for operating a utility-scale wind power plant.

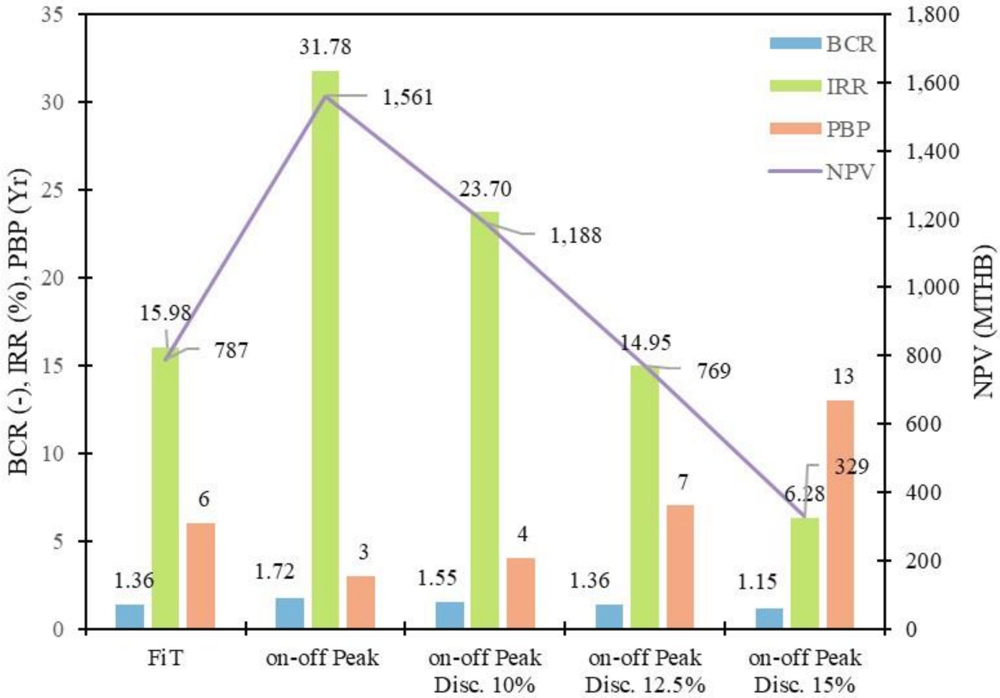

Figure 9. Five financial indices under several scenarios of a 20 MW wind power project at the Siam Eastern industrial park.

4. Conclusions

Wind power is a major renewable energy source worldwide, including in Thailand, for the transition to non-GHG-emitting electricity systems. Hence, this study presents a techno-economic assessment of a 20 MW utility-scale wind power plant at the Siam Eastern industrial park near the Gulf of Thailand. The wind resources mapping of the study area was performed using the CFD wind flow modeling, along with the MERRA-2 wind database for 5 years from 2018-2022, DEM, and roughness maps. The micro-scale wind resource mapping yielded an average annual wind speed of 5.4 m/s, making the area suitable for wind power production. The technical assessment of the wind power plant was done using four units of a 5 MW dual-rotor wind turbine generator, which has improved electricity output compared to conventional single-rotor models of the same dimensions. The 20 MW wind turbines produced an AEP of 75.7 GWh/yr, with a CF of 43%. The financial feasibility of the wind power plant was performed using the BCR, the IRR, the NPV, and the PBP indicators and considering multiple feed-in-tariff benefits offered by PEA. All the financial parameters indicated that the wind power plant is economically feasible for all the PEA tariff scenarios. The financial parameters of the basic on-off peak scenario with T-VER carbon trading benefits performed the best with a 2.24 BCR, a 2,063 MTHB NPV, a 38.01% IRR, and a PBP of just 3 years. On the other hand, the on-off peak with a 15% discount scenario has the least financial feasibility among the scenarios with a 1.56 BCR, an 893 MTHB NPV, a 14.64% IRR, and a PBP of 8 years. The financial parameters were positive even without the T-VER carbon trading benefit, making this 20 MW wind power plant an economically viable option. Studies like this are important for analyzing the techno-economic feasibility of utility-scale wind power plants in Thailand so that investors can get well-informed information encouraging them to invest in this renewable energy source and help expedite and achieve the energy transition targets of Thailand.

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Author Contributions: Conceptualization, W.J. and K.C.; methodology, K.S.; software, C.S.; validation, G.Y.; formal analysis, W.J. and M.P.; investigation, K.S.; resources, J.W.; data curation, A.F.; writing—original draft preparation, K.S.; writing—review and editing, W.J. and G.Y.; visualization, K.S., supervision, W.J. and K.C.; project administration, K.S.; funding acquisition, K.S.

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References

[1] Statista. *World Electricity Generation Shares by Source 2022*, **2022**. https://www.statista.com/statistics/269811/world-electricity-production-by-energy-source/. (accessed July 15, 2023).

[2] UNFCCC. *Adoption of the Paris Agreement - Paris Agreement text English*, **2015**. https://unfccc.int/sites/default/files/english_paris_agreement.pdf. (accessed July 10, 2023).

[3] In International Renewable Energy Agency (IRNEA). *Renewable Power Generation Costs in 2021*, **2021**. https://www.irena.org//media/Files/ IRENA/ Agency/ Publication/ 2018/Jan/ IRENA_2017_ Power_Costs_2018.pdf. (accessed July 21, 2023).

[4] Electricity Generating Authority of Thailand (EGAT). *Annual Report 2021 Electricity Generating Authority of Thailand*, **2021**. https://www. egat.co. th/ home/en/annual-report/. (accessed July 20, 2023).

[5] Energy Regulatory Commission of Thailand (ERC). *Annual Report 2021*, 2021. https://www.erc.or.th/en /annual-report. (accessed May 26, 2023).

[6] Ministry of Energy. *Thailand Power Development Plan (2015-2036)*, **2016**. https://www.egat.co.th /en/images/about-egat/PDP2015_Eng.pdf. (accessed June 26, 2023).

[7] Waewsak, J.; Chancham, C.; Chiwamongkhonkarn, S.; Gagnon, Y. Wind Resource Assessment of the Southernmost Region of Thailand Using Atmospheric and Computational Fluid Dynamics Wind Flow Modeling. *Energies*, **2019**; *12(10)*, pp. 1899. https://doi.org/10.3390/en12101899.

[8] Chancham, C.; Waewsak, J.; Gagnon, Y. Offshore Wind Resource Assessment and Wind Power Plant Optimization in the Gulf of Thailand. *Energy*, **2017**; *139*, pp. 706–731. https://doi.org/10.1016/j.energy.2017.08.026.

[9] Niyomtham, L.; Lertsathittanakorn, C.; Waewsak, J.; Gagnon, Y. Mesoscale/Microscale and CFD Modeling for Wind Resource Assessment: Application to the Andaman Coast of Southern Thailand. *Energies*, **2022**; *15(9)*, pp. 3025. https://doi.org/10.3390/en15093025.

[10] Murthy, K. S. R.; and Rahi, O. P. A Comprehensive Review of Wind Resource Assessment. *Renewable and Sustainable Energy Reviews*, **2017**; *72*, pp. 1320–1342. https://doi.org/10.1016/j.rser.2016.10.038.

[11] Dhunny, A. Z.; Lollchund, M. R.; Rughooputh, S. D. D. V. Wind Energy Evaluation for a Highly Complex Terrain using Computational Fluid Dynamics (CFD). *Renewable Energy*, **2017**; *101*, pp. 1–9. https://doi.org/10.1016/j.renene.2016.08.032.

[12] Gravdahl, A. R.; Vargvei, N. Meso Scale Modeling with a Reynolds Averaged Navier - Stokes Solver Assessment of wind resources along the Norwegian coast. 31st IEA Experts Meeting State of the Art on Wind Resource Estimation, B. Maribo Pedersen, Risø, Denmark, October 29-30 1998, pp. 31 – 45.

[13] Durán, P.; Meiβner, C.; Casso, P. A New Meso-Microscale Coupled Modelling Framework for Wind Resource Assessment: A Validation Study. *Renewable Energy*, **2020**; *160*, pp. 538–554, Nov. 2020, https://doi.org/10.1016/j.renene.2020.06.074.

[14] WindSim. *WindSim 11.0*, n.d. https://windsim.com/software/windsim-11-0/. (accessed July 18, 2023).

[15] Rienecker, M. M.; Suarez, Max. J.; Gelaro, R.; Todling, R.; Bacmeister, J.; Liu, E.; Bosilovich, M. G.; Schubert, S. D.; Takacs, L.; Kim, G-K.; Bloom, S.; Chen, J.; Collins, D.; Conaty, A.; Silva, A. da.; Gu, W.; Joiner, J.; Koster, R. D.; Lucchesi, R.; Molod, A.; Owens, T.; Pawson, S.; Pegion, P.; Redder, C. R.; Reichle, R.; Robertson, F. R.; Ruddick, A. G.; Sienkiewicz, M.; Woollen, J. MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, **2011**; *24*(14), 3624-3648. https://doi.org/10.1175/JCLI-D-11-00015.1.

[16] Jet Propulsion Laboratory. *ASTER Global Digital Elevation Map*, **2012**. https://asterweb.jpl.nasa.gov/gdem.asp. (accessed May 23, 2023).

[17] Land Development Department. *Land Use*, **2013**. http://www1.ldd.go.th/ldd/. (accessed July 21, 2023).

[18] Rosenberg, A.; Selvaraj, S.; Sharma. A. A Novel Dual-Rotor Turbine for Increased Wind Energy Capture, The Science of Making Torque from Wind 2014 (TORQUE 2014). IOP Publishing Ltd., Copenhagen, Denmark June 18 - 20 2014, pp. 012078.

[19] Wang, Y.; Sun, T. Life Cycle Assessment of CO2, Emissions from Wind Power Plants: Methodology and Case Studies. *Renewable Energy*, **2012**; *43*, pp. 30–36. https://doi.org/10.1016/j.renene.2011.12.017.

[20] Office of Analysis and Evaluation. *Thailand Grid Emission Factor for GHG Reduction Project/Activity*, **2017**. http://ghgreduction.tgo.or.th/images/Grid_Emission_Factor_2559_-_Finalised.pdf. (accessed July 21, 2023).