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Techno-Economic Assessment of Wind Energy in Urban Environments: A Case Study in Pattaya, Thailand

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ABSTRACT

The goal of reducing carbon dioxide (CO_2) emissions is a global collective challenge for the clean energy group, and it is reflected in Thailand's Renewable Energy Development Plan (AEDP) in 2018, which includes wind power as one of the six clean energy sectors. This study analysed the wind energy potential in Pattaya City, Bang Lamung District, Chonburi Province, in the Eastern Economic Corridor (EEC) Development Zone Plan, by utilizing data from weather stations and the Meteorological Department during the period of 2019-2021 at a height of 10 meters above the ground, comparing the areas of Pattaya Station, Chonburi Station, and Kao Si Chang Station. For the possibility of wind turbines with default heights ranging from 60 to 90 meters, three models are available: Bonus 1.3 MW, SWT-1.3-62, and SWT-2.3-82, as per the research results. The wind resources were found to be of Wind Power Class 1, with poor resource potential, and the prevailing wind direction in the study area was identified as northeast and west in Ko Sichang, southeast in Pattaya, and southwest and west in Chonburi. The Pattaya Station area was deemed unsuitable for wind farm establishment due to its low-wind power potential, as indicated by an economic analysis (public sector). It is not recommended for private or business sectors as it may not generate attractive returns or may result in losses. Based on the observations, the wind turbine with the highest AEP may not be the best choice for investment returns. This was demonstrated through an analysis of the SWT-2.3-82 VS wind turbine on Kaya Sira Hill, Koh Sichang, which had a CO_2 Emission Reduction capacity of 2,154.24 tons CO_2/GWh and an AEP of 3.366 GWh. Despite this, the LOCE of this model was not the lowest among the three models, and the LCOE and NPV of the SWT-1.3-62 were higher than the SWT-2.3-82 VS at all discount rate values. Moreover, the IRR of the SWT-1.3-62 were lower than the others, indicating that higher investments do not always lead to better returns.

Keywords:
Levelized Cost of Electricity (LCOE); Net Present Value (NPV); Benefit Cost ratio (BCR or B/C ratio); Payback Period (PBP); Internal Rate of Return (IRR); carbon dioxide (CO_2) emissions; WAsP; Thailand

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1. Introduction

According to Thailand's Renewable Energy Development Plan (AEDP) 2018, the performance of renewable and alternative energy in terms of wind power has seen an expansion from 2016-2018, with sizes of 507.00, 627.80, and 1,102.82 MW, respectively [1]. The spatial base for this expansion covers more than 513,115 square kilometers (km^2) in over 23 provinces located near the sea [2,3]. As a result, Thailand has different topographies in each region, Previous research has surveyed the wind energy source area at an altitude of 120 meters above ground level (AGL) and found that the velocity ranged from 1.60-5.83 m/s, with the highest average annual power density of about 200 W/m^2 [4]. Simulation results from the Thongyai and Assawamartbunlue [5] showed that mountainous regions of the western, southern, and eastern regions of Thailand have higher wind energy resources than other regions, and the area located between 40-100 AGL in the east has the potential to generate electricity with an average wind speed of more than 6 m/s. Goudarzi *et al.,* [6] evaluated the technical and economic performance of more than 150 small wind turbines by Weibull probability density function and found that the average annual wind speed is about 3 m/s, which can produce electricity at 1990 kWh per year with a payback period of 13 years. Pawintanathon *et al.,* [7] analyzed wind energy potential in Roi Et, Buriram, Si Sa Ket, Surin, and Ubon Ratchathani at an altitude of 60 and 80 meters, using the Wind Atlas Analysis and Application Program (WAsP) [8]. The results showed that Roi Et had an annual energy production (AEP) of 18.932 GWh and 56.322 GWh at 60 and 80 meters, respectively, while the other provinces had AEPs ranging from 8.508 GWh to 45.737 GWh. Chand and Starcher [9] found that a 50 kW wind turbine system and a 42 kW PV system calculated PV WATTS, the annual energy production will be 228,531 kWh and 81,581 kWh, respectively, and the payback period of the wind is about 13 years. Bortolini *et al.,* [10] estimated the levelized energy cost (LCOE) of 10 MW and 25 MW wind farms at 4.01 c€/kWh and 5.76 c€/kWh, respectively, and assessed decision variables such as the number of wind turbines, distance to the main grid, and site perimeter conditions. Zakaria *et al.,* [11] found that the overall emission intensity for all power plants studied was approximately 0.54 tCO$_2$/MWh. Waewsak *et al.,* [12] conducted a high-resolution mapping of wind resources at 80, 100, 120, and 140 meters above ground level and found that wind potential at a wind speed of 120 m AGL above 8.0 m/s can produce electricity of 690 GWh/year and avoid greenhouse gas emissions of 1.2 million tones CO$_2$eq./year.

In this study, the scope was divided into the Eastern Economic Corridor (EEC) Development Zone Plan, which is a special local administrative organization area that includes Pattaya City, Bang Lamung District, Chonburi Province, as specified in the plan [13,14]. The research aimed to evaluate the feasibility of wind turbine farm construction in the area, specifically managing wind farm projects at heights between 60-90 meters above the ground using the WAsP tool. Wind speed data were collected from the Meteorological Department's weather station in Chonburi Province, Thailand, every 10 minutes at a height of 10 meters above the ground, during a 3-year period from January 1, 2019 to December 31, 2021, through supervision and a data collection system [15]. Wind data were compiled as periodic stratified data and analyzed using economic tools for a detailed joint analysis, including LCOE, NPV, PBP, IRR, BCR, and CO$_2$e reduction calculations, in order to evaluate the economic feasibility and potential environmental impact of a wind farm project [16]. Previous studies have used only some of these tools. Therefore, the results of this study can provide important insights into the feasibility of wind farm projects in urban areas and contribute to the development of sustainable energy policies in Thailand.

2. Methodology

2.1 Wind Data Collection

This research study focuses on evaluating the potential of wind energy resources in Thailand. The scope of the study was divided into regions according to the Meteorological Department and the area was selected from the weather station meteorology in Chonburi province, Thailand by collecting wind speed data [15]. This data was collected every 10 minutes at a height of 10 meters above the ground during the 3-year period from January 1, 2019, to December 31, 2021. The wind data was collected through supervision and the data collection system over a period of time as shown in Table 1 [16].

Table 1
Location of stations, including geographic positions and zones

Station area	Lat-Lon-Height		UTM/USNG		
	Latitude	Longitude	Northing (m) or Y co-ordinate	Easting (m) or X co-ordinate	Zone
Chonburi	N13° 21′ 20.00160″	E100° 58′ 55.89840″	1477313.912	714680.218	47
Ko Sichang	N13° 09′ 46.00080″	E100° 48′ 10.10160″	1455837.043	695399.636	47
Pattaya	N12° 55′ 23.00160″	E100° 51′ 56.19960″	1429363.948	702403.949	47

2.2 Wind Atlas Analysis and Application Program (WAsP)

The Wind Atlas Analysis and Application Program (WAsP) is a linear numerical model that is widely used in the wind energy industry as a standard for wind farm assessments [17]. It is based on actual data on turbine power generation and has been validated for both unresolved and user-defined changes in wind speeds at hub heights across all sites [16]. The uncorrected forecast produced the lowest deviation for annual net production (-1.2%) [17].

2.3 Data and Size of Wind Turbines

In order to analyze the opportunities and feasibility of the area, wind turbines with High-speed limit cut and Low speed limit cut were used, with a wide range to support high fluctuating wind power, and rotor diameters of 60-90 meters and default heights of 60-90 meters. From the collected wind data and spatial data, it was found that there are 3 models of wind turbines as shown in Table 2.

Table 2
Wind turbine model information

No.	Turbines	Rotor diameter (m)	Rated power (estimated) (MW)	Default height (m)	Low speed limit cut (m/s)	High speed limit cut (m/s)
1	Bonus 1.3 MW	62.00	1.3000	60.00	3.00	25.00
2	SWT-1.3-62	62.00	1.3000	60.00	3.00	25.00
3	SWT-2.3-82 VS	82.40	2.3000	80.00	3.00	25.00

2.4 Analysis of Meteorological Data

To assess the potential for wind energy production, data was analyzed using the WAsP software to estimate wind speed at heights of 60 and 90 meters above ground level, as well as the monthly average. The distribution of wind direction was also estimated to analyze the wind power production of each selected type of wind turbine and to create a wind map. To improve the accuracy of the predictions, the terrain effect was "removed" first. The results, including topography, roughness, and obstruction, were extracted from the estimated wind conditions using a linear flow model based on the topographical map of the surrounding area [8]. The Weibull distribution, wind direction or wind rose histogram, gust factor, wind power quantity, and potential energy production were calculated for each turbine size [18,19].

2.4.1 Frequency distribution

A feasibility assessment of setting up wind farms for energy production requires careful consideration of the highly volatile nature of wind, which can vary by time of day, day of the year, and year over year [20,21]. In this process, it is crucial to characterize the wind speed data, and describe wind speed frequency [20,22]. The most commonly used evaluation technique to estimate the distribution of wind energy density, is the Weibull distribution [23-25]. Eq. (1) and Eq. (2) demonstrate how the shape of the Weibull distribution can be expressed [26-30]

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} exp\left[-\left(\frac{V}{c}\right)^{k}\right], k > 0, v > 0, c > 1 \quad (1)$$

$$f(V) = 1 - exp\left[-\left(\frac{V}{c}\right)^{k}\right] \quad (2)$$

In these equations, f(V) is the probability of observing the wind speed, V is the wind speed (m/s), k is the contour parameter, and c is the level parameter (m/s).

2.4.2 Wind direction or wind rose histogram

Accurate characterization of average wind direction is critical in determining the feasibility of wind farms for energy production. This information helps determine the optimal placement of wind turbines within a wind farm as well as the direction in which they should face to maximize energy output. An analysis of average wind direction can be conducted using the frequency distribution method of wind direction data. The wind direction is expressed as the wind direction angle value, as shown in Eq. (3), which is calculated using the mean wind direction over time (degree angle), the total number of hours (N) (hour), the number of hours (n_i) (hour), and the mid-range value of the wind direction (d_i) (angle) [30]

$$WD_m = \frac{1}{N}\sum_{i=1}^{\infty} n_i d_i \quad (3)$$

2.5 Economic Analysis of Site Area and Decision-Making Criteria for Investment

The decision to establish a new electrical system powered by renewable energy sources is becoming increasingly necessary due to the non-polluting and renewable nature of these systems [31]. However, transitioning to these technologies presents several challenges, including (i) high initial costs, (ii) operating costs, and (iii) increased operational and investment risks. Moreover, political instability, existing innovation policy tools, and carbon policies can also impact the potential value of a project and the criteria used to evaluate it [32].

To measure the economic value of different investments, it is crucial to consider not only the initial investment but also the annual cash inflows and outflows associated with the 25-year project life. Additional economic issues that need to be considered include the index used to solve these problems, which consists of [33].

2.5.1 Levelized Cost of Energy (LCOE)

The LCOE is a metric proposed by the International Renewable Energy Agency (IRENA) [34] and is widely used in global government policies for evaluating the cost of new renewable energy technologies. It estimates the economic value of the average total cost of building and operating a power generation system over its lifetime, relative to the total power generated by the system over its lifetime [35]. This metric is considered significant for assessing the economic feasibility of renewable energy projects [31,32]. The LCOE is typically expressed in units of $/MWh and is calculated using Eq. (4) and Eq. (5), where I_t is the capital expenditure in year t, M_t is an operating expense, and maintenance in year t, F_t is the fuel cost in year t, E_t is the electrical energy generated in year t, r is the discount rate, and n is the expected service life of the system or power station [36]. The LCOE can also be used to examine the production cost ratio of wind power plants and to calculate the proportion of the Levelized cost of energy (LCOE). It assumes discount rates of 7%, 5.4%, and 5% to determine costs.

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ eletrical\ energy\ produced\ over\ lifetime} \tag{4}$$

$$LCOE = \frac{\sum_{t=1}^{n}\frac{I_t M_t F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \tag{5}$$

2.5.2 Net Present Value (NPV)

Net Present Value (NPV) is a widely used measure for determining the financial viability of a plan over the analysis period by calculating the difference between the present value of benefits (PVB) and the present value of costs (PVC) [37]. It is commonly used to evaluate the net value of all benefits. To calculate the NPV, data on the annual return from electricity sales (B_A), annual costs (C_A), initial investment cost (C_I), discount interest rate (I), duration or economic life of the project (n), and percentage of annual operation and maintenance costs (m) are required. Eq. (6) represents the NPV, which is calculated by using the assumption of discount rates of 7%, 5.4%, and 5% to determine the ratio.

$$NPV = B_A\left[\frac{(1+I)^n-1}{I(1+I)^n}\right] - \left\{C_I\left[1 + m\left(\frac{(1+I)^n-1}{I(1+I)^n}\right)\right]\right\} \tag{6}$$

2.5.3 Cost-benefit ratio or rate of return on expenses (BCR or B/C ratio)

The benefit-cost ratio (BCR) is a metric used to compare the present value of all benefits to the present value of all costs, including the initial investment, even if the investment has been made or only available in the first year of operation [33]. Using only the net present value (NPV) may not provide a complete picture when comparing two projects with different initial investment levels. Projects with high capital investments may have a higher chance of showing a positive NPV than projects with lower capital requirements. In such cases, the cost-benefit ratio (BCR) is a better tool for economic decision-making. The BCR can be calculated using Eq. (7), taking into account factors such as the annual return on electricity sales(B_A), annual operation and maintenance costs (C_A), total investment cost (C_I), discount interest rate (I), period or economic life of the project (n), and percentage of annual operation and maintenance costs (m). To ensure the accuracy of the calculation, the assumption of discount rates of 7%, 5.4%, and 5% can be used.

$$BCR = \frac{B_A\left[\frac{(1+I)^n-1}{I(1+I)^n}\right]}{C_I\left[1+m\left(\frac{(1+I)^n-1}{I(1+I)^n}\right)\right]} \tag{7}$$

2.5.4 Payback Period (PBP)

The payback period (PBP) is a widely used metric to evaluate the feasibility of investments, indicating the amount of time needed for the investment to be recouped [38]. A shorter PBP generally indicates a better investment. However, PBP has limitations, as it does not account for changes in operating costs over time or the time value of money [39]. Moreover, PBP does not require making assumptions about discounts or interest rates. The project's economic viability is compromised when the PBP is too long, indicating an unacceptably high payback period, and when the PBP value criterion for availability is higher than the capacity project profit [40]. The initial investment and annual operating cash flow income (annual savings) can be used to calculate project profit using Eq. (8).

$$PBP = \frac{Initial\ investment\ (USD)}{Annual\ saving\ (USD)/years} = \text{years} \tag{8}$$

2.5.5 Internal rate of return (IRR)

The internal rate of return (IRR) is a crucial criterion for evaluating the economic viability of a project. It represents the discount rate at which the accumulated present value of all costs is equal to the benefits, or the point at which the net present value (NPV) of the project is zero [33]. In other words, IRR is the discount rate at which the present value of total benefits (PVB) is equivalent to the present value of total costs (PVC) [41]. The IRR reflects the maximum interest rate that the investment can achieve, and the discounted NPV of the project at IRR is zero. The payback period (PBP) where IRR is the life span of the project, with variables such as the annual return on electricity sales (B_A), operation fee and annual maintenance (C_A), total investment cost (C_I), discount interest rate (IRR), duration or economic life of the project (n), and the percentage of annual operation and maintenance costs (m) being the determining factors.

$$B_A\left[\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right] = C_I\left[1+m\left(\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right)\right] \tag{9}$$

2.6 Impact of Wind Energy on Carbon Dioxide (CO_2) Emissions Reduction

Reducing carbon dioxide (CO_2) emissions is one of the best practices for achieving constrained use objectives on the environment, emphasizing the mitigation of global warming through energy policy [42]. Approximately 40% of global CO_2 emissions are emitted from electricity generation through the burning of fossil fuels to generate the heat used to power steam turbines [43]. There is therefore a global effort to mitigate climate change and its impacts through multidisciplinary research that raises global debate and awareness for national policies and planning on climate change in each country [44]. The process of evaluating and analysing the equivalent carbon emissions details has an average value of CO_2 emissions per unit of 640 g CO_2/kWh according to Eq. (10), where Activity Data is the amount of energy (e.g., kWh) and Emission Factor is the average unit emissions for a given period (g CO_2/kWh) [45-48].

$$Emission\ or\ CO_{2,emission} = ActivityData \times EmissionFactor \tag{10}$$

3. Results

This section describes in detail the wind resource assessment in a wind farm setup simulation. For elevations of 60 m and 90 m, the averages per plant indicate probabilities on a Levelized cost of electricity (LCOE), net present value (NPV), benefit-cost ratio (BCR), payback period (PBP), and internal rate of return (IRR) basis, as well as carbon dioxide equivalent (CO_2e) emissions.

3.1 Frequency Distribution

Based on simulations in WAsP and calculations obtained from the Weibull histogram (Figure 1 to 3) for the Chonburi station, the average velocity is 1.23 m/s with a power density of 6 W/m². For the Ko Sichang station, the average velocity is 1.09 m/s with a power density of 2 W/m², and for the third station, the average velocity is 1.42 m/s with a power density of 5 W/m².

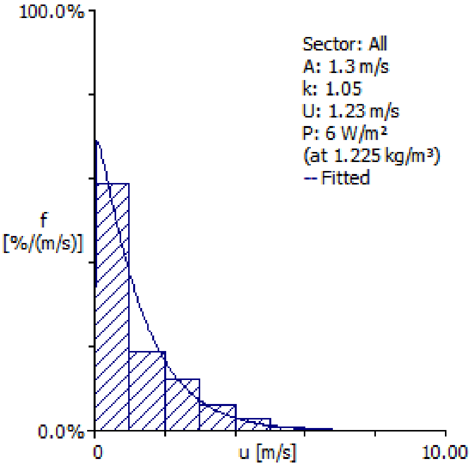

Fig. 1. Weibull histogram Chonburi station area

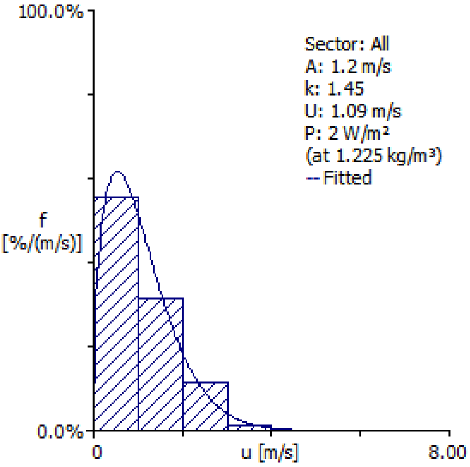

Fig. 2. Weibull histogram Ko Sichang station area

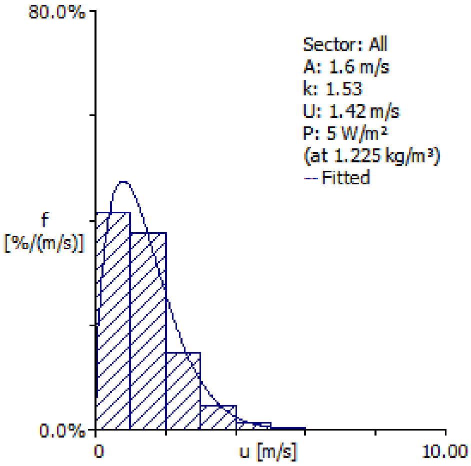

Fig. 3. Weibull histogram Pattaya station area

3.2 Wind Direction

The simulations in WAsP and the calculations in the wind rose diagram (Figure 4 to 6) show strong winds blowing from the northeast and west at the Chonburi station, strong winds blowing from the southeast at the Ko Sichang station, and strong winds blowing from the west and southwest at the Pattaya station.

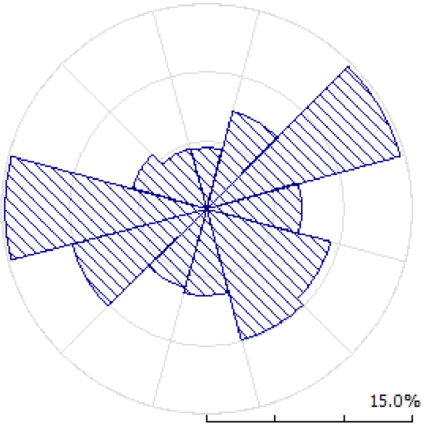

Fig. 4. Wind Direction and Wind rose histogram Chonburi station area

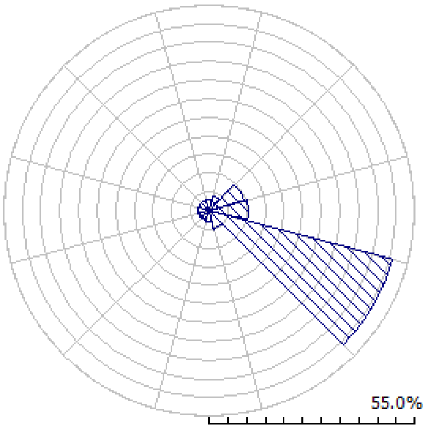

Fig. 5. Wind Direction and Wind rose histogram Ko Sichang station area

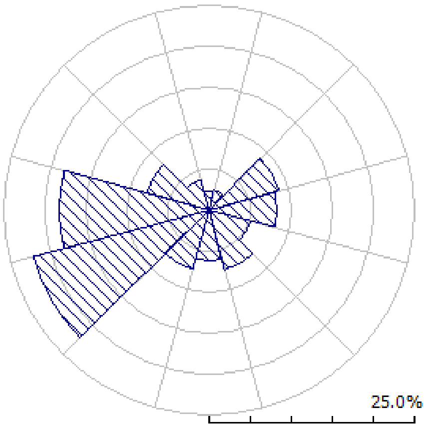

Fig. 6. Wind Direction and Wind rose histogram Pattaya station area

3.3 Economic Analysis of Site Area and Decision-Making Criteria for Investment

The data for this research were collected over a period of 3 years from January 1, 2019, to December 31, 2021, as previously mentioned. The focus of this study is on the economics of wind power in Thailand and the criteria used for investment decisions. In particular, we will examine the economic analysis from a public sector perspective, as presented in Table 3 [49].

Table 3
Cost elements in the calculation of the Levelized cost of energy

	Economic analysis (public sector)	Financial analysis (private sector)
Viewpoint	Overall society	Investor / Developer
Decision criteria	Positive net present value	Payback or internal rate of return
Timeframe	Life cycle (technical life)	Often shorter term
Discount rate	Reflects social preferences and other factors	Reflects costs of borrowing, desired returns (normally higher than the economic discount rate)
Energy prices (benefits)	Social values reflect willingness to pay; alternative uses	Prevailing market prices
Costs	Overall costs to society	Private, prevailing market prices
Taxes and subsidies	Ignored	Considered
Social infrastructure (e.g., roads)	Considered	Ignored, if not part of investment
External impacts	Analyzed as much as possible	Ignored

The data were collected additional decision criteria, such as the Payback Period and Internal Rate of Return, were included to support investment decisions. The results are presented as the average per wind turbine tower using the 6-pole model and based on calculation data. The base parameters used were Net AEP (GWh) and Capacity factor (%), derived from WAsP and shown in Table 4 and Table 5. The Discount rate was obtained and the average was found to be 5.40%, with the median at 5.00%, while the total average from IEA, 2022 is at 7.00% [49-51]. The lifetime of wind power plants was found to be 25 years from Danish Energy Agency [49], and Badouard *et al.,* [50]. Additionally, the Total Installed cost for 2021 was found to be 1,412 USD/kW and the O&M cost for onshore wind was 33 USD/kW, as per Renewable Power Generation Costs in 2021 [52].

This research focuses on wind energy and utilizes the Feed-In Tariff (FiT) structure for renewable energy projects in Thailand, as per Sinsadok [53]. The current exchange rate is 31.4395 THB/USD, and the FiT for wind farms is set at 0.0986 USD/kWh [54]. This tariff will be used to estimate income and address economic issues such as the Levelized Energy Cost (LCOE), Net Present Value (NPV), Cost-Benefit Ratio or Benefit-Cost Ratio (BCR or B/C ratio), Payback Period (PBP), and Internal Rate of Return (IRR).

Table 4
Unit information for reading in Table 5 to Table 7

Note: The calculation results are stored in the form

- Average Net AEP (Unit: MWh)
- LCOE (Unit: USD)
- NPV (Unit: USD)
- BCR (Unit: -)
- PBP (Unit: Year)
    - PBP^a is PBP without O&M
    - PBP^b is PBP with O&M
- IRR (Unit: %)

Table 5
Economic analysis of wind power area Chonburi

Area		Chonburi					
Wind farm		cluster Ban Bueng	cluster Nong Khang Khok	cluster Ban Bueng	cluster Nong Khang Khok	cluster Ban Bueng	cluster Nong Khang Khok
wind turbine models		Bonus 1.3 MW	Bonus 1.3 MW	SWT-1.3-62	SWT-1.3-62	SWT-2.3-82 VS	SWT-2.3-82 VS
Average Net AEP		1,010.00	1,111.00	1,044.00	1,160.00	1,791.00	2,055.00
LCOE (USD)	5.0%	162.42	147.65	157.13	141.41	162.05	141.23
	5.4%	166.79	151.63	161.36	145.23	166.42	145.04
	7.0%	184.82	168.02	178.80	160.92	184.40	160.71
NPV (USD)	5.0%	-1,036,007.21	-895,584.91	-988,736.34	-827,459.24	-1,827,267.61	-1,460,223.18
	5.4%	-1,067,103.25	-932,141.95	-1,021,670.73	-866,665.68	-1,882,504.11	-1,529,733.98
	7.0%	-1,174,456.41	-1,058,348.18	-1,135,370.48	-1,002,018.45	-2,073,197.65	-1,769,706.83
BCR	5.0%	-1.36	-1.72	-1.47	-1.95	-1.36	-1.96
	5.4%	-1.26	-1.59	-1.37	-1.79	-1.27	-1.80
	7.0%	-0.99	-1.21	-1.06	-1.33	-0.99	-1.33
PBP (Year)	PBP^a	18.42	16.75	17.82	16.04	18.38	16.02
	PBP^b	32.36	27.52	30.55	25.66	32.23	25.61
IRR (%)		2.50%	3.35%	2.79%	3.75%	2.52%	3.76%

Table 6
Economic analysis of wind power area Ko Sichang

Area		Ko Sichang					
Wind farm		cluster Khao Kaya Sira Hill	cluster Hat Tham Phang	cluster Khao Kaya Sira Hill	cluster Hat Tham Phang	cluster Khao Kaya Sira Hill	cluster Hat Tham Phang
wind turbine models		Bonus 1.3 MW	Bonus 1.3 MW	SWT-1.3-62	SWT-1.3-62	SWT-2.3-82 VS	SWT-2.3-82 VS
Average Net AEP		2,077.00	1,507.00	2,231.00	1,615.00	3,366.00	2,750.00
LCOE (USD)	5.0%	78.98	108.85	73.53	101.57	86.22	105.54
	5.4%	81.11	111.79	75.51	104.31	88.55	108.38
	7.0%	89.87	123.87	83.67	115.58	98.12	120.09
NPV (USD)	5.0%	447,464.02	-345,018.27	661,573.27	-194,863.73	362,486.09	-493,950.91
	5.4%	358,676.03	-402,986.75	564,458.60	-258,671.70	222,090.41	-601,039.89
	7.0%	52,152.32	-603,111.95	229,188.63	-478,956.62	-262,599.01	-970,744.25
BCR	5.0%	6.45	-6.07	4.69	-11.52	12.91	-7.74
	5.4%	7.74	-5.00	5.28	-8.34	20.25	-6.11
	7.0%	45.78	-2.87	11.19	-3.88	-14.74	-3.26
PBP (Year)	PBP^a	8.96	12.35	8.34	11.52	9.78	11.97
	PBP^b	11.33	17.36	10.36	15.77	12.68	16.62
IRR (%)		10.17%	6.37%	11.13%	7.13%	6.70%	9.05%

Table 7
Economic analysis of wind power area Pattaya

Area		Pattaya					
Wind farm		cluster Phra Tamnak Mountain	cluster Ko Lan	cluster Phra Tamnak Mountain	cluster Ko Lan	cluster Phra Tamnak Mountain	cluster Ko Lan
wind turbine models		Bonus 1.3 MW	Bonus 1.3 MW	SWT-1.3-62	SWT-1.3-62	SWT-2.3-82 VS	SWT-2.3-82 VS
Average Net AEP		34.52	151.05	42.09	184.37	66.67	260.12
LCOE	5.0%	4,752.56	1,085.99	3,897.26	889.71	4,353.27	1,115.73
(USD)	5.4%	4,880.72	1,115.28	4,002.35	913.70	4,470.66	1,145.81
	7.0%	5,408.18	1,235.81	4,434.88	1,012.45	4,953.80	1,269.64
NPV	5.0%	-2,392,241.94	-2,230,222.41	-2,381,710.27	-2,183,891.40	-4,224,640.55	-3,955,679.01
(USD)	5.4%	-2,370,594.23	-2,214,875.61	-2,360,472.13	-2,170,346.40	-4,186,643.60	-3,928,141.93
	7.0%	-2,295,859.59	-2,161,893.69	-2,287,151.48	-2,123,584.87	-4,055,466.33	-3,833,075.39
BCR	5.0%	-0.02	-0.09	-0.02	-0.12	-0.02	-0.09
	5.4%	-0.02	-0.09	-0.02	-0.11	-0.02	-0.09
	7.0%	-0.02	-0.08	-0.02	-0.10	-0.02	-0.08
PBP	PBP[a]	539.11	123.19	442.09	100.92	493.81	126.56
(Year)	PBP[b]	-46.48	-65.56	-47.37	-74.28	-46.85	-64.64
IRR (%)		-16.46%	-9.76%	-15.63%	-8.73%	-16.10%	-9.89%

The present study aimed to calculate the Levelized Cost of Energy (LCOE) for a 25-year project involving three wind turbines located in the Pattaya, Chonburi, and Ko Sichang station areas. The LCOE was computed to assess the feasibility of wind power generation in the region. At a 5% discount rate, the LCOE in the Pattaya station area was 889.71 USD/MWh, while the Chonburi station area and Ko Sichang station had an LCOE of 141.23 USD/MWh and 73.53 USD/MWh, respectively. When the discount rate was increased to 5.4%, the LCOE in the Pattaya, Chonburi, and Ko Sichang station areas decreased to 913.70, 145.04, and 75.51 USD/MWh, respectively. A further increase in the discount rate to 7% resulted in a decrease of the LCOE in the Pattaya, Chonburi, and Ko Sichang station areas to 1,012.45, 160.71, and 83.67 USD/MWh, respectively. Comparing the LCOE values obtained in this study with the averages reported by IRENA and Lazard's report revealed that the LCOE in the study area was significantly higher. According to International Energy Agency [52], the average LCOE for onshore wind in 2021 was 33 USD/MWh, while Lazard's [55] report indicated an average range of 26-50 USD/MWh. This result suggests that the LCOE in the study area is still far from the average for currently developed technology, indicating an inconsistency with the area's potential.

Net Present Value (NPV). The results indicated that only the Ko Sichang station area on the Khao Kaya Sira Hill cluster for the Bonus 1.3 MW and SWT-1.3-62 wind turbines had a positive NPV at discount rates of 5.0%, 5.4%, and 7.0%. The SWT-2.3-82 wind turbine model had a positive NPV only at discount rates of 5.0% and 5.4%. In contrast, the NPV was negative for all discount rates in the Chonburi and Pattaya station areas, with the Pattaya station area having the highest negative value of -4,224,640.55 (5%).

To further support the results, the Benefit Cost ratio (BCR) was also computed. The BCR values indicated both positive and negative values, with the negative values in the Pattaya station area being less negative than those in the Chonburi station area. Based on the BCR values, the economic viability of the areas was ranked as follows: Ko Sichang Station Area, Pattaya Station Area, and Chonburi Station Area.

In summary, the analysis of the NPV and BCR demonstrated that only the Khao Kaya Sira Hill cluster in the Ko Sichang station area showed positive potential for wind energy generation. However, the potential varied according to the discount rate, and the SWT-2.3-82 wind turbine generator had very negative NPV and BCR values at a discount rate of 7%. Furthermore, the Pattaya station area had a relatively high cost, and if the cost could be managed below the cost of education, the BCR could be positive.

The study investigated the payback period (PBP) in the study area and a comparable area, and found significant differences. The SWT-1.3-62 wind turbine generation in the Ko Sichang station (cluster Khao Kaya Sira Hill) area had the shortest PBP, at 8.34 years without O&M and 10.36 years with O&M. This was the only area with the potential to achieve payback within a project period of 25 years. On the other hand, the Pattaya station area had a PBP without O&M that could not be paid back within the specified period, and the value for PBP with O&M resulted in a negative value, indicating that payback cannot be achieved. Similarly, for the Chonburi station area, PBP without O&M could be achieved within the specified period, but PBP with O&M could not be achieved.

The internal rate of return (IRR) is a crucial metric for assessing project feasibility. To determine the IRR, this study used average discount rates of 5.0%, 5.4%, and 7.0% as simulations of possible IRR rates in the project. The results showed that only the Ko Sichang station area had positive values, with an average of 8.43%. Among all three stations, SWT-1.3-62 (cluster Hat Tham Phang, Ko Sichang), Bonus 1.3 MW wind turbines (cluster Khao Kaya Sira Hill, Ko Sichang), and SWT-1.3-62 (cluster Khao Kaya Sira Hill, Ko Sichang) had IRRs of 7.13%, 10.17%, and 8.35%, respectively, which were higher than the IEA Central case at 7% [51]. These results were based on the scenario of the purchase value of the system at the feed-in-tariff (FiT) equal to 3.1014 Baht/unit [56,57].

In contrast, the Pattaya Station area had negative IRRs for both cluster Ko Lan and cluster Phra Tamnak Mountain, with the highest negative value of -16.10% for the SWT-2.3-82 VS wind turbine (cluster Phra Tamnak Mountain) and the lowest negative value of -8.73% (cluster Ko Lan). These results indicate that investing in wind turbine projects in these areas may not be financially feasible. It is worth noting that the IRRs are affected by the cost of the project and the revenue generated from the energy sales, and any change in these factors can impact the IRR.

3.4 Impact of Wind Energy on Carbon Dioxide (CO_2) Emissions Reduction

In general, wind power is known to not produce direct air pollution, and the potential for reducing CO_2 emissions varies depending on the energy distribution of each region [58,59]. In this study, the average CO_2 emission per unit was assessed and analyzed, with a value of 640 g CO_2/kWh [45-48]. The findings indicated that all areas could contribute to reducing CO_2 emissions, depending on the amount of power produced in each area. Among the Pattaya Station area clusters, the SWT-2.3-82 VS wind turbine (cluster Ko Lan) had the highest potential for CO_2 emissions reduction at 166.48 tons CO_2/GWh. However, the Ko Sichang station area, specifically the SWT-2.3-82 VS (cluster Khao Kaya Sira Hill), showed the highest value for reduction among all three areas, with a CO_2 emissions reduction of 2,154.24 tons CO_2/GWh. Furthermore, this area is the only one with a positive NPV, BCR, and IRR.

4. Conclusions

The establishment of a wind farm involves considering both external and internal high-impact factors. External factors include wind resources, seasonality, and government policies, while internal factors comprise wind resource assessments, the potential of the area, cost management, and funding sources. This research assesses wind energy resources using WAsP software for the study site in Chonburi Province, Thailand, with data from three stations. The analysis reveals that wind direction prevails in the northeast and west in the Ko Sichang station area, southeast in the Pattaya station area, and southwest and west according to the WASP software analysis and yield maps of wind energy resources. However, wind resources in the study area have a low potential for setting up wind farms. Mountain peaks and ridges have slightly higher potential than the plains, which are in level 1 wind energy with poor resource potential. Additionally, the average wind speed decreases from May to October, but it increases from November to April due to the northeast monsoon bringing strong winds from the South China Sea to the Gulf of Thailand and the coastal areas of south-eastern Thailand.

Economic studies indicate that wind turbines with the maximum annual energy production (AEP) are not always the most economical choice. For example, the SWT-2.3-82 VS wind turbine (cluster Khao Kaya Sira Hill, Ko Sichang) had an AEP of 3.366 GWh, resulting in a potential reduction in CO_2 emissions of 2,154.24 metric tons CO_2/GWh. However, the scaled cost of electricity (LCOE) of this turbine was not the lowest of the three comparable areas, and the most economical LCOE was on the SWT-1.3-62 turbine. The net present value (NPV) of the SWT-1.3-62 turbine was also the highest of the three discount rates (5.0%, 5.4%, and 7.0%). Benefit ratios, cost-to-cost (BCR), and payback period (PBP) also supported the SWT-1.3-62 wind turbines. The internal rate of return (IRR) for SWT-2.3-82 VS wind turbines is lower than for SWT-1.3-62 wind turbines, although negative values were not shown, for example in the Chonburi and Pattaya station areas.

The results suggest that investment in wind farms with high-speed limit cuts and low-speed limit cuts has the widest range. The rotor diameter and initial height range between 60 and 90 meters is not recommended for businesses or the private sector in the Pattaya station area due to the low potential to generate sufficiently attractive returns or may suffer a loss. The economic feasibility of setting up wind farms in this area, and consequently lower potential CO_2 emission reductions compared to other areas, led to this conclusion.

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