Comprehensive Analysis and Comparison of the Life Cycle Cost and the Levelized Cost of Energy of Commercial Onshore Wind Energy Farms in Thailand

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Abstract

This study presents a comprehensive analysis and comparison of the life cycle cost analysis (LCCA) and the Levelized cost of energy (LCOE) of commercial onshore wind energy farms in Thailand. This study presents data related to installed capacities; the twenty-nine commercial companies of wind turbines; models of wind turbines; scheduled commercial operation dates (SCODs); and commercial operation dates (CODs) of commercial onshore wind energy farms operated in Thailand. The total LCC of the 29 wind energy farms over the whole lifetime of the plant is around 2,718 million USD, whereas the capacity-weighted average of LCC is around 1.803 million USD/MWp. The result of the study shows that the capacity-weighted average of LCOE of all commercial wind energy farms in Thailand over the whole and deducted lifetimes of the plants are 0.0453 USD/kWh and 0.0459 USD/kWh, respectively. The study's results also show that if all 29 wind energy farms delay starting the operation for 12 months, the average LCOE of wind energy farms increases by just 3.07%. These findings show that delay in starting operation would not cause the LCOE of wind energy farms to be significantly higher. However, if all wind energy farms delay starting the operation for 23 months, the LCOE of utility-scale PV plants is lower.

Keywords:

Levelized Cost of Electricity; Life Cycle Cost Assessment; Onshore Wind Energy Farm; Wind Power

1. Introduction

The use of wind turbine generators for electricity generation in Thailand began in 1990 by the Electricity Generating Authority of Thailand (EGAT). Currently, 610 wind turbine generators install in 29 commercial onshore wind energy farms in Thailand. Three-bladed horizontal-axis wind turbines have been used for commercial electricity generation [1]. The main components of this type of wind turbine are shown in Fig. 1. Also, a sample system diagram of wind turbine generators is shown in Fig. 2. The model of wind turbine generators installed in the first commercial onshore wind energy farm in Thailand in 2012 is Siemens SWT-2.3-101 whereas Gamesa G145- 4.0 is the model of wind turbine generators installed in the latest commercial onshore wind energy farm in 2021. These two models are shown in Fig. 3 and Fig. 4.

Because of the continued development of wind turbine generator technology, demand for wind energy farms in Thailand has been very high over the past decade. The wind energy farm industry has been encouraged to lower the overall cost of energy production to provide wind energy farms. The incentive used to encourage the wind energy farm industry is the "Adder" program which provides an additional amount of the selling price of electricity that EGAT/Provincial Electricity Authority (PEA) purchased from wind energy farm investors [2]. It can be a competitive renewable energy source without government incentives in future trends [3]. In this regard, developing a framework that may lead to the use of life cycle cost analysis (LCCA) management of wind energy farms is essential. The costs related to the life cycle cost phases are categorized into three groups: Capital expenditure (CAPEX), operational expenditure (OPEX), and decommissioning expenditure (DECEX). The multi-dimensional design problem is addressed under two primary considerations: Minimizing the Levelized cost of energy (LCOE) and minimizing the LCCA, such as operation and maintenance cost or inspection cost in action.

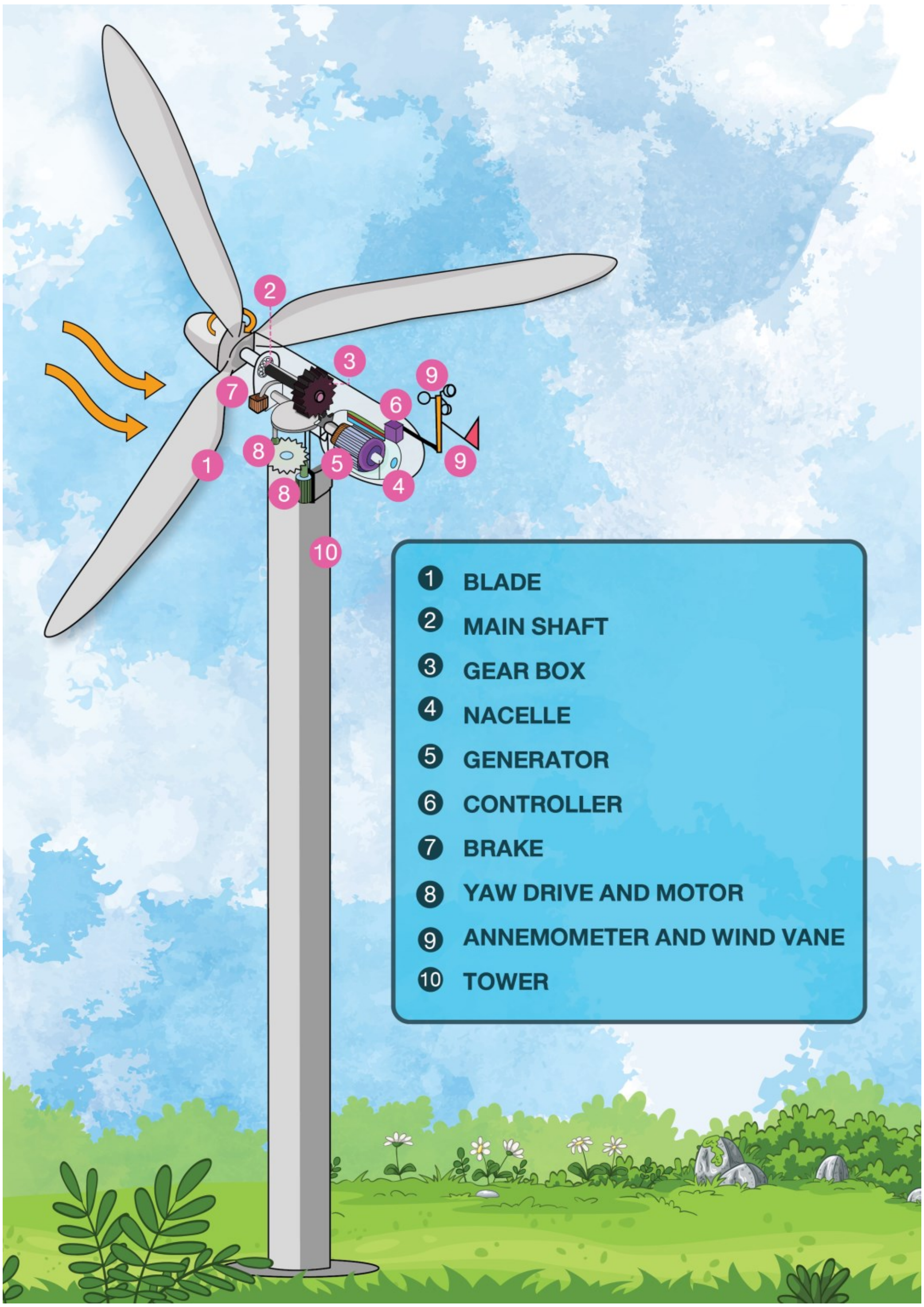

Fig. 1 Components of a wind turbine generator.

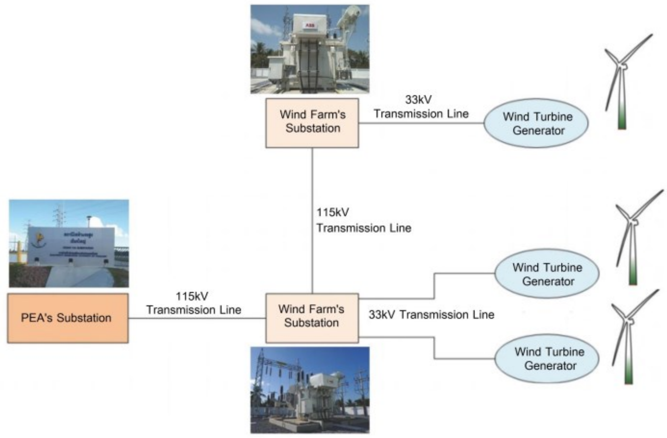

Fig.2 A system diagram of wind turbine generators installed in a wind energy farm [4].

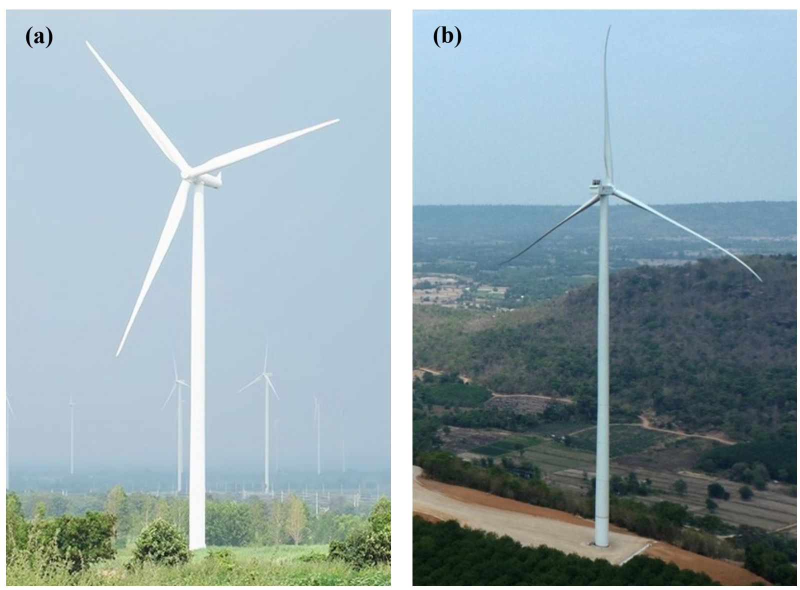

Fig. 3 (a) A 2.3 MW wind turbine generator of the first commercial wind energy farm [5] and (b) A 4.0 MW wind turbine generator of the latest commercial wind energy farm [6].

Fig. 4 The latest commercial onshore wind energy farm in Thailand [7].

2. Experimental detail

2.1. Life cycle cost analysis

Life cycle cost analysis (LCCA) evaluates the economic performance of the onshore wind turbine farm over its entire life. Sometimes known as "total cost of ownership," this is a methodology for calculating the entire cost of a system from inception to disposal [8]. It estimates the costs of all kinds of products and some construction facility projects. The LCCA of the wind power was used to analyze the cost of the wind power system over its entire life span. The system boundary of LCCA has been used to examine the economic benefits between wind power and other energy resources.

2.2. Levelized cost of energy

Levelized cost of energy (LCOE, also called Levelized Cost of Electricity) represents the cost per kilowatt-hour (kWh) of electricity generated by energy technology throughout the entire life cycle of the power plant considering the construction and operation cost of the power plant. According to [9], It is "the cost per unit of energy that, if held constant through the analysis period, would provide the same net present revenue value as the net present value cost of the system". The LCOE can be calculated by taking the net present value of the total cost of building and operating power plants [10]. The LCOE is the indicator used for evaluating the cost-effectiveness of different energy generation technologies [11]. The global weighted average LCOE of new onshore wind energy farms added in 2021 is 0.033 USD/kWh whereas that of utility-scale PV plants is 0.0480 kWh [12].

2.3. System boundary

The whole life cycle of wind energy farms was divided into the following five phases: Phase 1- materials & manufacture, including the production and manufacture of wind turbines and other materials; Phase 2- transport, including the transport of wind turbines and other materials except for wind turbines; Phase 3- construction and installation, including the construction and installation of wind turbines and other materials; Phase 4- operation, including the operation and maintenance of wind energy farms, and; Phase 5- end of life stage, including equipment disassembly, material recycling, and final disposal (landfilling and incineration) of wind energy farm equipment.

2.4. Deducted lifetimes of the plants

The start of wind energy farms must stick to scheduled commercial operation dates (SCODs) declared in Power Purchasing Agreements (PPAs) between EGAT/PEA and wind power producers. A SCOD is the date declared in the PPA that a power producer will transmit electricity generated from a power plant to PEA's grids. In contrast, a COD is an actual date a power producer starts to generate electricity, and PEA allows the power producer to transmit the electricity generated to the grids. If a COD is behind a SCOD, the plant's lifetime is deducted accordingly.

3. Data collection and research methods

3.1. Data collection

This study presents data related to installed capacities; the number of wind turbines; models of wind turbines; SCODs; and CODs of commercial onshore wind energy farms operated in Thailand, as presented in Tables 1 and 2. These data were collected from the Energy Regulatory Commission of Thailand (ERC). The annual electricity production (AEP) of wind energy farms no. 1 to 22, presented in Table 2, was collected from EGAT. However, those of wind energy farm no. 23 to 29 could not be collected.

Table 1 Data of commercial onshore wind turbines installed in Thailand.

Wind energy farm no.	Wind power producer	Model of wind turbine generators	Number of wind turbines installed	Installed capacity (MWp)
1	First Korat Wind Co., Ltd.	Siemens SWT-2.3-101	45	103.50
2	K.R. Two Co., Ltd.	Siemens SWT-2.3-101	45	103.50
3	Khao Kor Wind Power Co., Ltd.	GE2.5-120	24	60.72
4	Chaiyaphum Wind Farm Co., Ltd.	Goldwind GW121/2500	32	80.00
5	Watabak Wind Co., Ltd.	GE120-2.1	30	60.00
6	Wind Energy Development Co., Ltd.	Gamesa 114-2.0	25	50.00
7	EA Wind Hadkanghan 3 Co., Ltd	Vestas V110-1.8	20	36.00
8	EA Wind Hadkanghan 3 Co., Ltd	Vestas V110-1.8	25	45.00
9	EA Wind Hadkanghan 3 Co., Ltd	Vestas V110-1.8	25	45.00
10	Greenovation Power Co., Ltd.	Gamesa G114-2.0/2.1	33	67.50
11	Korat Wind Energy Co., Ltd.	Gamesa G126-2.5	20	50.00
12	Tropical Wind Co., Ltd.	Vestas V1360-3.0	30	90.00
13	K.R.S. Three Co., Ltd.	Vestas V1360-3.0	30	90.00
14	Theparak Wind Co., Ltd.	GE137-3.0	30	90.00
15	Krissana Wind Power Co., Ltd.	GE137-3.0	30	90.00
16	Nayangklak Wind Power Co., Ltd.	Gamesa G126-2.5	18	45.00
17	Nayangklak Wind Power Co., Ltd.	Gamesa G126-2.5	18	45.00
18	Pongnok Development Co., Ltd.	Gamesa G126-2.5	19	47.50
19	Benjarat Development Co., Ltd.	Gamesa G126-2.5	16	40.00
20	Winchai Co., Ltd.	Vestas V136-3.45	13	44.85
21	Banchuan Development Co., Ltd.	Gamesa G126-2.5	32	80.00
22	K.R. One Co., Ltd.	GE137-3.0	30	90.00
23	Theppana Wind Farm Co., Ltd.	Goldwind GW109/2500	3	7.50
24	Inter Far East Wind International Co., Ltd.	Goldwind GW121/2500	4	10.00
25	Wind Energy Development Co., Ltd.	Gamesa G114-2.0	4	8.00

Table 1 (continue).

Wind energy farm no.	Wind power producer	Model of wind turbine generators	Number of wind turbines installed	Installed capacity (MWp)
26	Wind Energy Development Co., Ltd.	Gamesa G114-2.0	1	2.00
27	Lomlikor Co., Ltd.	Goldwind GW121/2500	4	10.00
28	Bo Thong Wind Farm Co., Ltd.	Gamesa G145-4.0	2	8.00
29	Bo Thong Wind Farm Co., Ltd.	Gamesa G145-4.0	2	8.00

Table 2 Data of operation of the 29 commercial onshore wind energy farms in Thailand.

Wind energy farm no.	SCOD	COD	Deducted lifetime of the plant	Annual electricity production (kWh)
1	29th August 2012	14th November 2012	24 years 288 days	171,193,345
2	26th November 2012	8th Feb 2013	24 years 291 days	142,872,432
3	16th November 2015	5th August 2016	24 years 102 days	85,863,240
4	1st December 2016	16th December 2016	24 years 350 days	124,483,950
5	1st May 2016	24th December 2016	24 years 128 days	141,908,861
6	1st September 2016	29th December 2016	24 years 215 days	81,006,170
7	14th June 2016	3rd March 2017	24 years 103 days	72,274,286
8	29th September 2016	10th June 2017	24 years 111 days	93,720,713
9	14th September 2016	23rd June 2017	24 years 83 days	90,738,013
10	1st November 2017	27th March 2018	24 years 219 days	126,780,715
11	8th December 2017	20th June 2018	24 years 141 days	112,461,076
12	15th November 2017	28th September 2018	24 years 48 days	242,443,022
13	15th November 2017	28th September 2018	24 years 48 days	237,125,630
14	30th March 2018	21st November 2018	24 years 129 days	246,910,242
15	30th March 2018	28th December 2018	24 years 92 days	216,596,324
16	29th October 2018	25th January 2019	24 years 277 days	76,779,245
17	29th October 2018	25th January 2019	24 years 277 days	76,232,040
18	29th November 2018	22nd March 2019	24 years 252 days	108,138,868

Table 2 (Continue).

Wind energy farm no.	SCOD	COD	Deducted lifetime of the plant	Annual electricity production (kWh)
19	29th November 2018	30th March 2019	24 years 244 days	76,329,005
20	1st April 2019	1st April 2019	25 years	67,261,616
21	28th December 2018	13th April 2019	24 years 259 days	146,030,422
22	15th July 2018	16th March 2019	24 years 121 days	207,758,650
23	18th June 2013	18th July 2013	24 years 325 days	N/A
24	1st November 2015	6th November 2015	24 years 360 days	N/A
25	1st May 2016	17th March 2016	25 years	N/A
26	1st May 2016	17th March 2016	25 years	N/A
27	28th May 2019	11th April 2019	25 years	N/A
28	30th July 2021	16th August 2021	24 years 348 days	N/A
29	30th July 2021	2nd August 2021	24 years 362 days	N/A

3.2. Calculation method for the AEPs

Because the AEPs of wind energy farms no. 22 to 29 could not be collected, equation 1 was used in this study to calculate these AEPs instead. The AEP is given by

$$\mathrm{AEP} = \mathrm{A} \times \mathrm{CF} \times 8760 \tag{1}$$

The definitions of symbols used in the above equations are given below:

A	is	the total installed capacity of a wind energy farm
CF	is	capacity factor

Referred to [13], the CF of wind energy farms in Thailand is 28%.

3.3. Average costs of onshore wind energy farms

The study could not collect actual costs of wind energy farms from the wind power producers because these costs are commercial in confidence. Therefore, this study used the average costs of onshore wind energy farms to estimate the LCC and LCOE of onshore wind energy farms in Thailand. The capital expenditure consists of wind turbine purchase, development cost, engineering management cost, civil work and construction costs, finance cost, and contingency. The yearly operation and maintenance costs consist of service and spare parts costs, administration costs, cost of electricity used from the grid, land rent, and insurance. The sources of each type of cost are presented in Table 3.

Table 3 Data of commercial onshore wind turbines installed in Thailand.

Cost breakdown	Average costs	Source
Capital expenditure	1,325,000 USD/MWp	[12]
Operation and maintenance costs	44,000 USD/MWp/year	[14]
Decommissioning costs	66,250 USD/MWp	[15]

3.4. Calculation method for the LCC

In this study, the LCC of wind energy farms has three significant components shown in Table 3. The total life cycle cost is given by [16]

$$LCC = CAPEX + \sum_{t=1}^{NL} \frac{OPEX_t}{(1+r)^t} + \frac{DECEX}{(1+r)^{NL}} \quad (2)$$

The definitions of symbols used in the above equations are given below:

LCC	is	Life cycle cost of a wind energy farm (USD)
CAPEX	is	Capital expenditure in initial year (USD)
OPEX	is	Operation expenditure (operating and maintenance costs during the service life) (USD)
DECEX	is	Decommissioning expenditure (USD)
NL	is	Lifetime of a wind energy farm (year)
r	is	Discount rate (per cent) [17, 18, 19]
t	is	Current in time

The lifetime of the wind energy farms and discount rate considered in this study is 25 years and 8%, respectively.

3.5. Calculation method for the LCOE

In this study, LCOE is defined as the ratio between the LCC of the wind energy sfarm to the whole electricity generation over the plant's lifetime. Referred to [20], the LOCE is given by

$$LCOE = \frac{LCC}{LCE} \quad (3)$$

The equation adapted from [21]; the Life Cycle Energy produced (LCE) can be calculated on an annual base discounted with an r discount rate as shown in Eq. (3).

$$LCE = \sum_{t=1}^{NL} \frac{AEP_t}{(1+df)^t} \quad (4)$$

The definitions of symbols used in the above equations are given below:

AEP	is	Annual electricity production (kWh)
NL	is	Lifetime of a wind energy farm (25 years)
df	is	degraded factor
t	is	Current in time

The degraded factor of wind turbines is 1.6±0.2% of their output per year [22].

4. Results and discussion

Firstly, the LCC and LCOE of each wind energy farm estimated in this study are presented in Table 3. The total LCC of the 29 wind energy farms over the whole lifetime of the plant is around 2,718 million USD, whereas the capacity-weighted average of LCC is around 1.803 million USD/MWp. The result of the study shows that the capacity-weighted average of LCOE of all commercial wind energy farms in Thailand over the whole and deducted lifetimes of the plants are 0.0453 USD/kWh and 0.0459 USD/kWh, respectively. The sensitivity of LCOE to changes in the delay in starting operation is presented in Fig. 5.

Table 4 The LCC and LCOE of the 29 onshore wind energy farms in Thailand.

Wind energy farm no.	Duration of O&M reduced in year 25 (day)	LCC (USD)		LCE (kWh)		LCOE (USD/kWh)	
		Over the full lifetime of the plant	Over the deducted lifetime of the plant	Over the full lifetime of the plant	Over the deducted lifetime of the plant	Over the full lifetime of the plant	Over the deducted lifetime of the plant
1	60	186,677,492.36	186,640,829.69	3,504,693,434.29	3,480,408,214.41	0.0533	0.0536
2	60	186,677,492.36	186,640,829.69	2,924,903,863.08	2,905,425,852.58	0.0638	0.0642
3	240	109,517,462.18	109,300,896.86	1,757,803,913.01	1,716,200,644.18	0.0623	0.0637
4	0	144,291,781.53	144,092,115.57	2,548,452,349.24	2,545,012,265.17	0.0566	0.0566
5	210	108,218,836.15	108,036,962.74	2,905,177,506.56	2,843,215,952.94	0.0373	0.0380
6	150	90,182,363.46	90,084,342.18	1,658,369,325.84	1,635,983,465.24	0.0544	0.0551
7	240	64,931,301.69	64,802,903.28	1,479,609,009.40	1,444,723,141.01	0.0439	0.0449
8	240	81,164,127.11	81,003,629.10	1,918,663,178.80	1,874,806,702.25	0.0423	0.0432
9	270	81,164,127.11	80,979,536.14	1,857,600,938.88	1,810,459,502.63	0.0437	0.0447
10	120	121,746,190.67	121,650,001.37	2,595,472,034.59	2,561,370,769.61	0.0469	0.0475
11	210	90,182,363.46	90,030,802.28	2,302,318,427.84	2,255,908,094.51	0.0392	0.0399
12	300	162,328,254.22	161,910,886.38	4,963,326,519.17	4,821,736,256.08	0.0327	0.0336
13	300	162,328,254.22	161,910,886.38	4,854,468,136.96	4,715,983,308.69	0.0334	0.0343
14	210	162,328,254.22	162,055,444.10	5,054,780,054.38	4,947,426,718.09	0.0321	0.0328
15	270	162,328,254.22	161,959,072.29	4,434,189,403.60	4,325,251,712.44	0.0366	0.0374
16	90	81,164,127.11	81,124,093.87	1,571,835,142.55	1,559,387,390.00	0.0516	0.0520
17	90	81,164,127.11	81,124,093.87	1,560,632,687.39	1,548,273,649.86	0.0520	0.0524
18	90	85,673,245.28	85,630,987.97	2,213,833,598.02	2,191,321,047.66	0.0387	0.0391
19	120	72,145,890.77	72,088,889.70	1,562,617,768.05	1,545,602,475.98	0.0462	0.0466
20	0	80,893,580.02	80,781,642.29	1,376,988,947.64	1,376,988,947.64	0.0587	0.0587
21	90	144,291,781.53	144,220,611.32	2,989,554,663.72	2,961,037,019.67	0.0483	0.0487
22	240	162,328,254.22	162,007,258.20	4,253,263,329.67	4,159,870,533.61	0.0382	0.0389

Table 4 (Continue).

Wind energy farm no.	Duration of O&M reduced in year 25 (day)	LCC (USD)		LCE (kWh)		LCOE (USD/kWh)	
		Over the full lifetime of the plant	Over the deducted lifetime of the plant	Over the full lifetime of the plant	Over the deducted lifetime of the plant	Over the full lifetime of the plant	Over the deducted lifetime of the plant
23	30	13,527,354.52	13,528,713.30	376,605,413.12	375,588,675.03	0.0356	0.0360
24	0	18,036,472.69	18,011,514.45	502,140,550.83	501,914,609.03	0.0359	0.0359
25	0	14,429,178.15	14,409,211.56	401,712,440.66	401,712,440.66	0.0101	0.0359
26	0	3,607,294.54	3,602,302.89	100,428,110.17	100,428,110.17	0.0101	0.0359
27	0	18,036,472.69	18,011,514.45	502,140,550.83	502,140,550.83	0.0520	0.0359
28	0	14,429,178.15	14,409,211.56	401,712,440.66	401,097,878.97	0.0085	0.0359
29	0	14,429,178.15	14,409,211.56	401,712,440.66	401,603,988.60	0.0085	0.0359
Total		2,718,222,689.92	2,714,458,395.03	62,975,006,179.58	61,910,879,917.54		
Capacity-weighted average						0.0453	0.0459

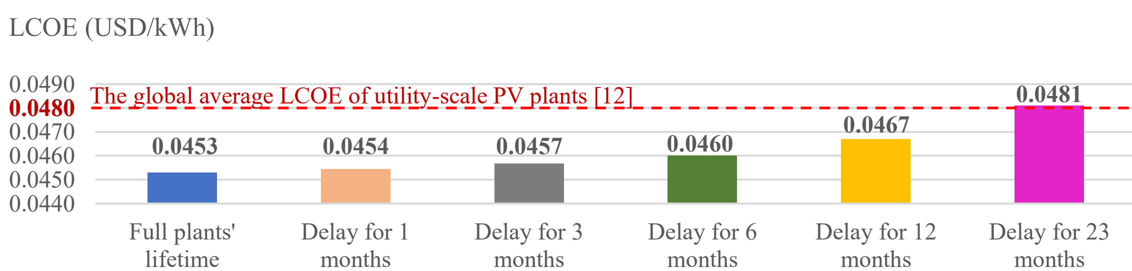

Fig. 5 Sensitivity of LCOE to the changes in the delay in starting the operation.

Secondly, the data shows that the operation of only four wind energy farms could be started on schedule. The delay in starting the operation of the other 25 wind energy farms caused the average LCOE of wind energy farms in Thailand to be 1.33% higher. The study's results also show that if all 29 wind energy farms delay starting the operation for 12 months, the average LCOE of wind energy farms increases by just 3.07%. These findings show that delay in starting operation would not cause the LCOE of wind energy farms to be significantly higher. However, suppose all wind energy farms delay operating for 23 months. In that case, the LCOE of utility-scale PV plants is lower, as presented in Fig. 5, and would be a better option for electricity generation from renewable energy than wind energy farms. Nevertheless, this long delay is hard to occur because the most extended delay is around 11 months, as shown in Table 2.

Lastly, this study proposes the average LCOE of the wind energy farms in Thailand based on the average capital expenditure, the 25-year plants' lifetime, and the average electricity generation of the

29 wind energy farms. The results can be different if the LCOE is analyzed based on different assumptions. For instance, [23] analyzed the LCOE of a 15MW wind energy farm in central Thailand with a specific loan rate of around 7%, the 20-year plant's lifetime, and the moderate AEP of this wind energy farm. Compared to the global average LCOE of new onshore wind energy farms at 0.033 USD/kWh, the LCOE at 0.093 USD/kWh, proposed in the study of [23], is relatively high. The shorter plants' lifetime and lower AEP can result in a higher LCOE.

5. Conclusions

The life cycle cost analysis was conducted to find the cost of wind power in Thailand. The results show that the total LOCE of the 29 wind energy farms in Thailand over the whole lifetime of the plant is around 2,718 million USD, whereas the capacity-weighted average of LCC is around 1.803 million USD/MWp. The result of the study shows that the delay in starting the operation of the 25 wind energy farms caused the average LCOE to increase from 0.0453 to 0.0459 USD/kWh. The study's findings show that delay in starting operation would not cause the LCOE of wind energy farms to change significantly.

6. Recommendations for further studies

The LCC analysis in this study includes neither the damage cost of the pollutants coming from wind energy farms in the life cycle nor the environmental cost avoided by fossil energy saving. Although wind energy farms do not come at high environmental costs compared with fossil fuel power plants [1], estimation of LCC with the damage cost of the pollutants can make the LCOE of wind energy farms more precise. Also, studies on the environmental cost that can be avoided by electricity generation from wind power in the life cycle cost of wind energy farms can contribute to Thailand's government to formulate of relevant carbon tax policies.

Finally, the LCE results from the simplified estimation in this study. The failure rates, downtime, and possible sources of uncertainty for wind turbines were not assumed. The reliability of wind turbines is interesting for further studies on life cycle cost analysis to demonstrate how wind turbine reliability impacts LCOE [24].

References

[1] Waewsak, J. (2015). *Wind Energy Technology*. Bangkok, Thailand: ChulaPress

[2] Gamonwet, P., Dhakal, S., & Thammasiri, K. (2017). The impact of renewable energy pricing incentive policies in Thailand. *GMSARN International Journal*, *11*(2), 51–60. Retrieved December 6, 2022, from http://gmsarnjournal.com/home/wp-content/uploads/2017/07/vol11no2-1.pdf

[3] Taylor, M. (2020). *Energy subsidies evolution in the global energy transformation to 2050*. (2020). Abu Dhabi, UAE: IRENA. Retrieved December 6, 2022, from https://www.irena.org/publications/2020/Apr/Energy-Subsidies-2020

[4] Thailand Greenhouse Gas Management Organization (Public Organization). (2017). *Project design document.* Retrieved December 6, 2022, from https://ghgreduction.tgo.or.th/th/tver-database-and-statistics/t-ver-registered-project/download/763/836/118.html

[5] A Siemens SWT-2.3-101 wind turbine generator [Photograph]. (n.d.). Retrieved December 6, 2022, from https://www.demco.co.th/storage/business/service-business/renewable-energy-works/west-huaybong -3-wind-farm/west-huaybong-3-wind-farm-3.jpg

[6] A Gamesa G145-4.0 wind turbine generator [Photograph]. (n.d.). Retrieved December 6, 2022, from https://www.bgrimmpower.com/storage/content/power_plants/Renewable_ Power_Plant/In%20Development/bo-thong-wind-farm-co-ltd.jpg

[7] B.GRIMM POWER. (2021). Bo Thong wind farm. Retrieved December 6, 2022, from https://bgrim.listedcompany.com/newsroom/images/20210819-161835-1.jpg

[8] Vorarat, S. (2019). Total cost of ownership analysis for alternative gasoline and gasoline hybrid electrical vehicle in Thailand. *International Journal of Engineering Science and Innovative Technology (IJESIT)*, *8*(2), 23–28. Retrieved December 6, 2022, from http://www.ijesit.com/Volume%208/Issue%202/IJESIT201902_04.pdf

[9] Short, W., Packey, D., & Holt, T. (1995). *A manual for the economic evaluation of energy efficiency and renewable energy technologies*. Colorado, USA: National Renewable Energy Laboratory. Retrieved December 6, 2022, from https://www.nrel.gov/docs/legosti/old/5173.pdf

[10] Comello, S., Glenk, G., & Reichelstein, S. (2017). *Levelized cost of electricity calculator: a user guide*. California, USA: Stanford Graduate School of Business. Retrieved December 6, 2022, https://web.stanford.edu/dept/gsb_circle/cgi-bin/sustainableEnergy/GSB_LCOE_User%20Guide_0517.pdf

[11] International Energy Agency, Nuclear Energy Agency, & Organisation for Economic Co-operation and Development. (2010). *Projected costs of generating electricity 2010 edition*. Paris, France: International Energy Agency, Nuclear Energy Agency, & Organisation for Economic Co-operation and Development. Retrieved December 6, 2022, from https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/6819-projected-costs.pdf

[12] The International Renewable Energy Agency. (2022). *Renewable power generation costs in 2021.* Abu Dhabi, UAE: IRENA. Retrieved December 6, 2022, from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf?rev=34c22a4b244d434da0accde7de7c73d8

[13] International Energy Agency. (2021). *Thailand power system flexibility study*. Paris, France: International Energy Agency. Retrieved December 6, 2022, from https://iea.blob.core.windows.net/assets/19f9554b-f40c-46ff-b7f5-78f1456057a9/ThailandPowerSystemFlexibilityStudy.pdf

[14] Wiser, R., Boilinger, M., & Lantz, E. (2019). Assessing wind power operating costs in the United States: results from a survey of wind industry experts. *Renewable Energy Focus*, *30*(00), 46-57. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/abs/pii/S1755008419300092

[15] Tantawat, W., Vorarat, S., & Phdungsilp, A. (2022). Assessment of CO_2 emissions and costs of decommissioning of commercial onshore wind farms in Thailand. *International Energy Journal*, *22*(4), 415–424. Retrieved December 6, 2022, from http://www.rericjournal.ait.ac.th/index.php/reric/article/view/2990

[16] Vorarat, S. (2017, January 19-21). *Life cycle cost model for estimating and forecasting future budget needs for machinery*. ACENS 2017, Asian Conference on Engineering and Natural Sciences, Hokkaido, Japan.

[17] Yeter, B., Garbatov, Y., & Guedes Soares, C. (2019). Risk-based life-cycle assessment of offshore wind turbine support structures accounting for economic constraints. *Structure Safety*, *81*, 101867. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/abs/pii/S0167473018300316

[18] Myhr, A., Bjerkseter, C., Ågotnes, A., & Nygaard, T. (2014). Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable Energy, 66*, 714–728. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/pii/S0960148114000469

[19] Ioannou, A., Angus, A., & Brennan, F. (2018). Parametric CAPEX, OPEX, and LCOE expressions for offshore wind farms based on global deployment parameters. *Energy Sources Part B: Economics, Planning, and Policy*, *13*(5), 281–289. Retrieved December 6, 2022, from https://www.tandfonline.com/doi/full/10.1080/15567249.2018.1461150

[20] Filimonova, I., Kozhevin, V., Provornaya, I., Komarova, A., & Nemov, V. (2022). Green energy through the LCOE indicator. *Energy Reports*, *8*, 887–893. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/pii/S235248472202100X

[21] Abu-Rumman, A., Muslih, I., & Barghash, M. (2017). Cycle costing of wind generation system. *Journal of Applied Research on Industrial Engineering*, *4*(3), 185–191. Retrieved December 6, 2022, from http://www.journal-aprie.com/article_54726.html

[22] Staffell, I., & Green, R. (2014). How does wind farm performance decline with age?. *Renewable Energy*, *66*, 775–786. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/pii/S0960148113005727

[23] Niyomtham, L., Waewsak, J., Kongruang, C., Chiwamongkhonkarn, S., Chancham, C., & Gagnon, Y. (2022). Wind power generation and appropriate feed-in-tariff under limited wind resource in central Thailand. *Energy Reports*, *8*, 6220-6233. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/pii/S2352484722008344

[24] Liao, D., Zhu, S., Correia, J., Jesus, A., Veljkovic, M., & Berto, F. (2022). Fatigue reliability of wind turbines: historical perspectives, recent developments and future prospects. *Renewable Energy*, *200*, 724–742. Retrieved December 6, 2022, from https://www.sciencedirect.com/science/article/abs/pii/S0960148122014525