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Assessment of CO_2 Emissions and Costs of Decommissioning of Commercial Onshore Wind Farms in Thailand**

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ARTICLE INFO

Article history:
Received 15 July 2022
Received in revised form
15 November 2022
Accepted 21 November 2022

Keywords:
Carbon intensity
CO_2 emission assessment
Decommissioning costs
Emissions from decommissioning
Onshore wind farms

ABSTRACT

This study assesses the CO_2 emissions associated with decommissioning of 29 commercial onshore wind farms in Thailand. The decommissioning of the onshore wind farms consists of the disassembly and transport of wind turbines and the demolition and disposal of concrete foundations. Access roads and transmission cables are not included in the assessment due to the conditions of wind farm development in Thailand. Data on 29 wind farms in Thailand were collected from the Energy Regulatory Commission of Thailand (ERC) and the Electricity Generating Authority of Thailand (EGAT). Carbon emission factors of a wind turbine is used to estimate CO_2 emissions from the decommissioning. This study also assesses the CO_2 emission reductions from recycling wind turbine materials and concrete foundations. The cost of decommissioning per installed capacity is used to estimate each wind farm's cost of decommissioning. Results are shown that total carbon emissions from decommissioning are 779,479.3 tCO_2eq. The average carbon intensity of decommissioning is 10.095 gCO_2eq/kWh and the average cost of decommissioning is 0.0014 USD/kWh. Findings are also shown that CO_2 emissions of decommissioning are minor when compared with other carbon emissions of electricity generation from wind power.

1. INTRODUCTION

Commercial electricity generation from onshore wind power in Thailand began in 2012. There are 29 onshore wind farms in six Thailand's provinces, including Nakhon Ratchasima, Chaiyaphum, Nakhon Si Thammarat, Petchabun, Songkla, and Mukdahan. These wind farms have sold more than three GWh of electricity per year to the Electricity Generating Authority of Thailand (EGAT) and the Provincial Electricity Authority (PEA) [1]. The total number of installed wind turbines for commercial wind farms is 610, as presented in Figure 1.

Currently, Wind Energy Holding Co., Ltd. is the largest wind power producer in Thailand, as presented in Figure 2. The plant's lifetime of all commercial wind farms in Thailand is considered 25 years by the period of power purchasing agreements (PPAs) between commercial power producers and EGAT/PEA. At present, all wind farms are in the operation stage. When the period of the PPA ends, the next life cycle stage of the wind farms is the decommissioning phase, as presented in Figure 3. The reason is that the PPAs did not state conditions for repowering to extend the plant's lifetime. Therefore, wind power producers expect to restore sites to green fields. Accordingly, studies on the decommissioning phase of wind farms in the context of Thailand can be beneficial to wind power producers. However, studies on the Life Cycle Assessment (LCA)-based approach for estimating carbon emissions from the decommissioning of wind farms in Thailand are limited.

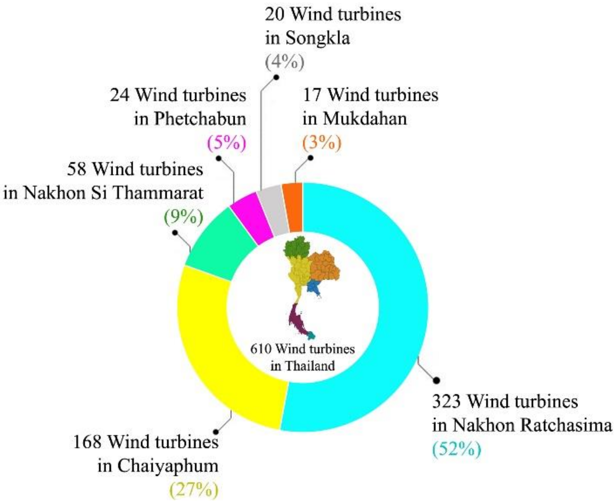

Fig. 1. Commercial wind turbines installed in Thailand.

This study aims to fulfill research gaps in the literature by assessing carbon emissions related to wind

**This paper was presented at the *ICUE 2022 International Conference on Energy, Environment, and Climate Change* held at Pattaya City, Thailand from 26-28 October 2022.

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farms in Thailand. The calculation tool adopts the basics of the LCA approach but avoids using specific LCA software for better transparency in the calculation. A comparison of the environmental performance of each wind energy farm presents in terms of carbon intensity. This study assesses the CO_2 emission reductions from recycling concrete foundation materials because of the improvement of concrete technology in Thailand. According to the PPAs, the wind power producers in Thailand must bear the costs of decommissioning wind farm assets. The cost of decommissioning in USD/kWh which is founded from this study would contribute not only the investment in wind farms in Thailand but also assessing the environmental performance of wind technology.

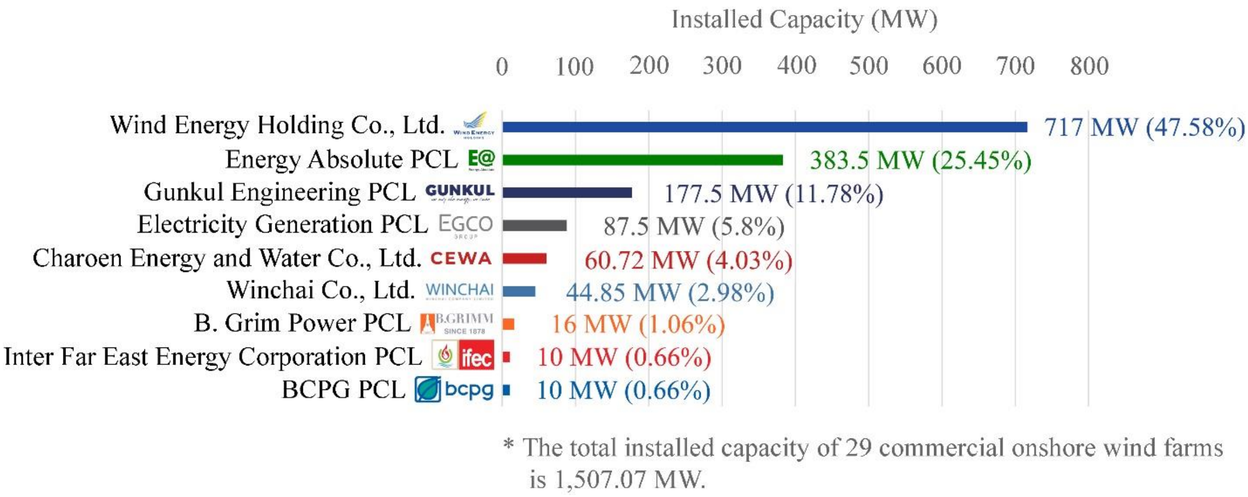

Fig. 2. Commercial wind power producers in Thailand.

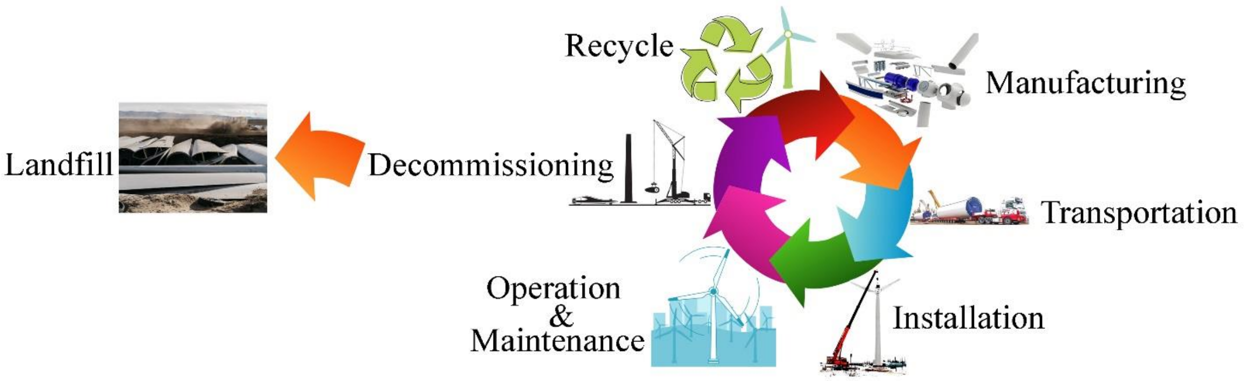

Fig. 3. Life cycle assessment stages of a wind energy system.
Source: [2]

2. DATA COLLECTION AND METHOD

The flowchart methodology of this research is presented in Figure 4.

2.1 Data Collection

In this study, data related to installed capacities, number of wind turbines, models of wind turbines, and locations of 29 existing commercial onshore wind farms in Thailand collected from the Energy Regulatory Commission of Thailand (ERC). Hub heights and blade diameters of wind turbines collected from WindPro software, which is a well-known wind energy software for wind energy simulation [3]. The relevant data from 29 wind farms are presented in Table 1. The number of each wind farm is shown in Table 1, from the oldest wind farm to the newest wind farm.

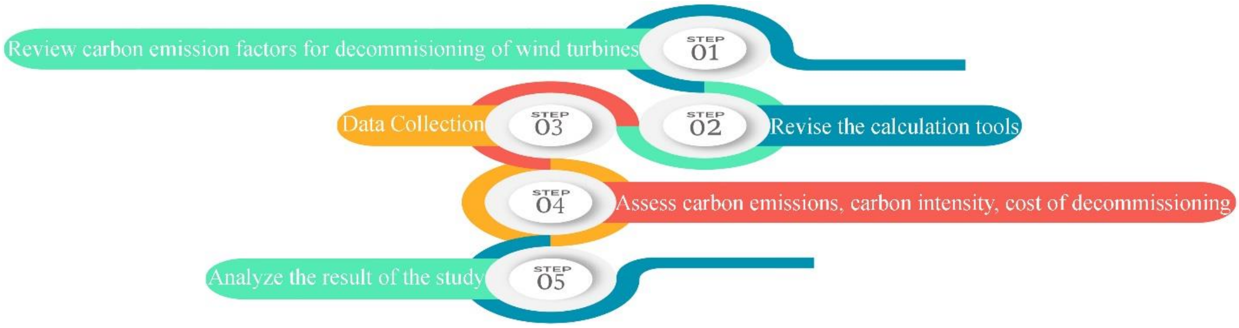

Fig. 4. The flowchart methodology.

Table 1. Data of the 29 existing commercial onshore wind farms in Thailand.

Wind Farm No.	Wind Power Producer	Collected from ERC				Collected from WindPRO	
		Location of Wind Farm (Coordinates)	Installed Capacity of Wind Turbines (MW)	Number of Wind Turbines	Model of Wind Turbines	Hub Height (m)	Blade Diameter (m)
1	First Korat Wind Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.113N 101.505E	103.50	45	Siemens SWT-2.3-101	80.0	101
2	K.R. Two Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.113N 101.505E	103.50	45	Siemens SWT-2.3-101	80.0	101
3	Khao Kor Wind Power Co., Ltd. (a subsidiary of Charoen Energy and Water Asia Co., Ltd.)	16.685N 100.993E	60.72	24	GE 2.5-120	85.0	120
4	Chaiyaphum Wind Farm Co., Ltd. (a subsidiary of Electricity Generating PCL)	15.605N 101.547E	80.00	32	Goldwind GW121/2500	120.0	121
5	Watabak Wind Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.425N 101.489E	60.00	30	GE 120-2.1	80.0	116
6	Wind Energy Development Co., Ltd. (a subsidiary of Gunkul Engineering PCL)	15.119N 101.488E	50.00	25	Gamesa 114-2.0	108.0	112
7	EA Wind Hadkanghan 3 Co., Ltd. (a subsidiary of Energy Absolute PCL)	7.997N 100.322E	36.00	20	Vestas V110-1.8	80.0	100
8	EA Wind Hadkanghan 3 Co., Ltd. (a subsidiary of Energy Absolute PCL)	7.997N 100.322E	45.00	25	Vestas V110-1.8	80.0	100
9	EA Wind Hadkanghan 3 Co., Ltd. (a subsidiary of Energy Absolute PCL)	7.997N 100.322E	45.00	25	Vestas V110-1.8	80.0	100
10	Greenovation Power Co., Ltd. (a subsidiary of Gunkul Engineering PCL)	15.174N 101.492E	67.50	33	Gamesa G114-2.0/2.1	153.0	112
11	Korat Wind Energy Co., Ltd. (a subsidiary of Gunkul Engineering PCL)	14.932N 101.515E	50.00	20	Gamesa G126-2.5	137.0	124
12	Tropical Wind Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.338N 101.482E	90.00	30	Vestas V136-3.0	132.0	136
13	K.R.S. Three Co., Ltd. (a subsidiary of Wind Energy Holding	15.366N 101.450E	90.00	30	Vestas V136-3.0	132.0	136

	Co., Ltd.)						
14	Theparak Wind Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.275N 101.465E	90.00	30	GE 137-3.0	134.0	130
15	Krissana Wind Power Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.087N 101.510E	90.00	30	GE 137-3.0	134.0	130
16	Nayangklak Wind Power Co., Ltd. (a subsidiary of Energy Absolute PCL)	15.633N 101.649E	45.00	18	Gamesa G126-2.5	127.5	145
17	Nayangklak Developement Co., Ltd. (a subsidiary of Energy Absolute PCL)	15.667N 101.692E	45.00	18	Gamesa G126-2.5	127.5	145
18	Pongnok Development Co., Ltd. (a subsidiary of Energy Absolute PCL)	15.468N 101.413E	47.50	19	Gamesa G126-2.5	127.5	145
19	Benjarat Development Co., Ltd. (a subsidiary of Energy Absolute PCL)	15.500N 101.448E	40.00	16	Gamesa G126-2.5	127.5	145
20	Winchai Co., Ltd.	16.378N 104.414E	44.85	13	Vestas V136-3.45	132.0	136
21	Banchuan Development Co., Ltd. (a subsidiary of Energy Absolute PCL)	15.541N 101.559E	80.00	32	Gamesa G126-2.5	127.5	145
22	K.R. One Co., Ltd. (a subsidiary of Wind Energy Holding Co., Ltd.)	15.224N 101.505E	90.00	30	GE 137-3.0	134.0	130
23	Theppana Wind Farm Co., Ltd. (a subsidiary of Electricity Generating PCL)	15.712N 101.479E	7.50	3	Goldwind GW109/2500	90.0	109
24	Inter Far East Wind International Co., Ltd. (a subsidiary of Inter Far East Energy Corporation PCL)	8.332N 100.252E	10.00	4	Goldwind GW121/2500	90.0	121
25	Wind Energy Development Co., Ltd. (a subsidiary of Gunkul Engineering PCL)	15.119N 101.488E	8.00	4	Gamesa G114-2.0	125.0	114
26	Wind Energy Development Co., Ltd. (a subsidiary of Gunkul Engineering PCL)	15.119N 101.488E	2.00	1	Gamesa G114-2.0	125.0	114
27	Lomlikor Co., Ltd. (a subsidiary of BCPG PCL)	8.355N 100.206E	10.00	4	Goldwind GW121/2500	90.0	121
28	Bo Thong Wind Farm Co., Ltd. (a subsidiary of B. Grimm Power PCL)	16.390N 104.416E	8.00	2	Gamesa G145-4.0MW	157.5	145
29	Bo Thong Wind Farm Co., Ltd. (a subsidiary of B. Grimm Power PCL)	16.390N 104.416E	8.00	2	Gamesa G145-4.0MW	157.5	145
	Total		1,507.07	610			

2.2 *Estimation of Electricity Generated from Wind Energy*

In this study, the electricity generation of wind farms no. 1 to 22 refers to the yearly purchased electricity of each wind farm in the previous year. The actual yearly purchased electricity in kWh/year of 2020 of the 22 wind farms was collected from EGAT. The study assumed that a wind farm could generate the same annual electricity output as 2020 for 25 years. The estimated electricity generation of wind farms no. 1 to 22 is presented in Table 1.

However, the actual yearly purchased electricity of wind farm no. 23 to 29 could not be collected. The wind power model in the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM) was used to estimate the electricity generation of these seven wind farms. SAM's wind power model can simulate a single wind turbine or a wind farm with more than one turbine. SAM's wind power model does not strictly require wind farm layouts [4]. The study could not collect wind farm layouts of all 29 wind farms because they are commercial in confidence data. Therefore, SAM's wind power model is suitable for this study.

The electricity generation over the plant's lifetime (25 years) of each wind farm estimated the carbon intensity of decommissioning of the wind farm. However, the electricity generations of wind farms no. 23 to 29 were not used to calculate the weighted average of the carbon intensity to avoid inaccuracy. The weighted average intensity of all carbon intensities calculated using the yearly purchased electricity of wind farms no. 1 to 22. The reason is that the wake effect of wind farms was not calculated. Instead, the electricity generation is approximately estimated by multiplying the simulated power generation of a single wind turbine by the number of wind turbines installed. In addition, the wake effect of wind farms is also explained in the study's limitation.

2.3 Assessment of CO_2 Emissions from the Decommissioning of Wind Farms

The decommissioning of transmission cables and the access roads of wind farms were not assessed due to the conditions of wind farm development in Thailand. Even though the commercial wind power producers constructed the transmission cables and access roads, they have not belonged to commercial wind power producers but to local administrative organizations such as Subdistrict Administrative Organizations and the Department of Rural Roads [5]. Therefore, the CO_2 emissions of the decommissioning of only wind turbines, concrete foundation disposal, and earthwork backfilling were assessed in this study.

The calculation of the carbon emissions of wind farms developed by [6] was adopted in this study. The calculation used correlations from LCA studies to estimate the CO_2 emissions of individual wind farms. It was chosen for this study because less inputs are needed and data available from public sources. The turbine tower height (H) in meters and blade diameter (D) in meters of each wind turbine were collected from WindPRO software (see Table 1). They were used to calculate each wind turbine's and concrete foundation's mass. Accordingly, carbon emission factors were used to calculate the CO_2 emissions of the decommissioning of 29 wind farms.

Dismantling Wind Turbines

The carbon emissions of manufacturing are estimated with the mass associated with wind turbine components shown in Table 2, the carbon emissions of dismantling wind ($C_{dismantling}$) is 90% of the carbon emissions of manufacturing [7]. The weight or mass (m) of wind turbine materials were derived from Equations (1) to (2). Accordingly, $C_{dismantling}$ is estimated using Equation (3).

$$m_{structural\ steel}(t/turbine) = 0.0214H^2 + 0.0845H + 87 \quad (1)$$

$$m_{blade}(t/turbine) = 1.37x10^{-6}D^{3.44} \quad (2)$$

where: H represents the turbine tower height and D represents blade diameter. H and D of each wind turbine were collected from WindPRO software (see Table 1).

$$C_{decommissioning}(tCO_2eq) = 0.9[CF_{s,s}\ x\ m_{structural\ steel} + CF_{GB} + CF_{GN}CF_F\ x\ m_{blade}] \quad (3)$$

Nevertheless, the recycling credit of wind turbine materials was not considered because manufacturing technology and recycling technology for wind turbines in Thailand are limited.

Concrete Foundation Disposal

The carbon emissions of manufacturing are estimated with the mass associated with concrete foundation shown in Table 3, The weight or mass (m) of wind turbine foundation was derived from Equation (4). Accordingly, the carbon emissions of concrete foundation disposal ($C_{disposal}$) is estimated using Equation (5).

$$m_{concrete}(t/turbine) = 0.163H\ x\ D \quad (4)$$

$$C_{disposal} = [(CF_c - RC_c)\ x\ m_{concrete} \quad (5)$$

Table 2. Carbon emission factors of a wind turbine.

Components	Carbon Emissions	
Structural steel	$CF_{S,S}$	1.24 tCO_2eq/t
Gearbox	CF_{GB}	54.46 tCO_2eq/turbine
Generator	CF_{GN}	54.55 tCO_2eq/turbine
Fiberglass (blade)	CF_F	0.69 tCO_2eq/t

Source: [6] and [8].

Table 3. Carbon emission factors of concrete.

Components	Carbon Emissions	
Disposal	$CF_{Disposal}$	0.01 tCO_2eq/t
Recycling credit	RC_C	0.00271 tCO_2eq/t

Source: [9] and [10].

Earthwork Backfilling

As referred to [6], the carbon emissions of earthworks of a wind turbine ($C_{earthworks}$) is 5,600 $kgCO_2eq$/turbine.

2.4 Carbon Intensity Index

The carbon intensity index, calculated in $kgCO_2eq/kWh$ by using the estimated electricity generation over the plant's lifetime (25 years), was used to compare CO_2 emissions from the decommissioning of each wind farm.

2.5 Costs of Decommissioning of Wind Farms

According to [11], the costs of decommissioning wind farms are 5% of the capital costs of wind farms. Referred to [12], the global weighted average total installed costs of onshore wind farms in 2021 are 1,325 USD/kW. Accordingly, the costs of decommissioning are 66.25 USD/kW. The costs of decommissioning calculated in USD/kWh were used to compare each wind farm's decommissioning costs. However, the electricity generations of wind farms no. 23 to 29 were not used to calculate the weighted average of the costs per kWh to avoid inaccuracy.

3. RESULTS

The assessment of CO_2 emissions from decommissioning and related costs of decommissioning of 29 commercial onshore wind farms in Thailand are presented in Tables 4 and 5.

3.1 CO_2 Emissions from Decommissioning

The total CO_2 emissions of the decommissioning of the 29 wind farms are 779,479.3 $tonCO_2eq$, as shown in Table 4. The weighted average carbon intensity of the decommissioning of onshore wind farms in Thailand is 10.095 gCO_2eq/kWh. The carbon intensity of wind farms ranges from 5.00 gCO_2eq/kWh for wind farms no. 28 and 29 to 25.95 gCO_2eq/kWh for wind farm no. 27.

Table 4. The CO_2 emission of decommissioning of 29 wind farms.

Wind Farm No.	Mass of Turbine Materials (ton/turbine): Structural Steel	Blade	Concrete	Reinforcing Steel	CO_2 Emissions from Decommissioning ($kgCO_2eq$): Dismantling Wind Turbines	Concrete Foundation Disposal	Earthwork Backfilling	Total CO_2 Emissions from Decommissioning ($kgCO_2eq$)
1	230.72	10.76	1,317.04	51.28	42,200,719.81	432,054.97	252,000.00	42,884,774.78
2	230.72	10.76	1,317.04	51.28	42,200,719.81	432,054.97	252,000.00	42,884,774.78
3	248.80	19.46	1662.60	64.67	25,097,281.44	290,888.50	134,400.00	25,522,569.93
4	267.95	20.02	1,775.07	69.04	34,255,632.41	414,088.33	179,200.00	34,848,920.74
5	230.72	17.32	1,512.64	58.84	30,170,409.75	330,814.37	168,000.00	30,669,224.12
6	345.74	15.35	1,971.65	76.69	27,476,776.40	359,333.21	140,000.00	27,976,109.61
7	230.72	10.39	1,304.00	50.72	18,680,997.86	190,123.20	112,000.00	18,983,121.06
8	230.72	10.39	1,304.00	50.72	23,351,247.32	237,654.00	140,000.00	23,728,901.32
9	230.72	10.39	1,304.00	50.72	23,351,247.32	237,654.00	140,000.00	23,728,901.32
10	345.74	15.35	1,971.65	76.69	36,269,344.85	474,319.84	184,800.00	36,928,464.69
11	445.66	37.31	3,013.46	117.21	28,502,410.91	439,362.47	112,000.00	29,053,773.38
12	471.03	29.93	2,926.18	113.82	41,215,633.24	639,955.57	168,000.00	42,023,588.80
13	471.03	29.93	2,926.18	113.82	41,215,633.24	639,955.57	168,000.00	42,023,588.80
14	482.58	25.63	2,839.46	110.44	40,223,010.69	620,989.90	168,000.00	41,012,000.59
15	482.58	25.63	2,839.46	110.44	40,223,010.69	620,989.90	168,000.00	41,012,000.59
16	445.66	37.31	3,013.46	117.21	25,652,169.82	395,426.22	100,800.00	26,148,396.04
17	445.66	37.31	3,013.46	117.21	25,652,169.82	395,426.22	100,800.00	26,148,396.04
18	445.66	37.31	3,013.46	117.21	27,077,290.36	417,394.34	106,400.00	27,601,084.71
19	445.66	37.31	3,013.46	117.21	22,801,928.73	351,489.97	89,600.00	23,243,018.70
20	471.03	29.93	2,926.18	113.82	17,860,107.74	277,314.08	72,800.00	18,210,221.81
21	445.66	37.31	3,013.46	117.21	45,603,857.46	702,979.95	179,200.00	46,486,037.40
22	482.58	25.63	2,839.46	110.44	40,223,010.69	620,989.90	168,000.00	41,012,000.59
23	267.95	13.98	1,599.03	62.20	7,498,569.86	34,970.79	16,800.00	7,550,340.64
24	267.95	20.02	1,775.07	69.04	10,924,376.86	51,761.04	22,400.00	10,998,537.90
25	431.94	16.31	2,322.75	90.35	13,551,669.90	67,731.39	22,400.00	13,641,801.29
26	431.94	16.31	2,322.75	90.35	3,387,917.48	16,932.85	5,600.00	3,410,450.32
27	267.95	20.02	1,775.07	69.04	10,924,376.86	51,761.04	22,400.00	10,998,537.90
28	631.16	37.31	3,722.51	144.79	10,309,409.39	54,274.20	11,200.00	10,374,883.59
29	631.16	37.31	3,722.51	144.79	10,309,409.39	54,274.20	11,200.00	10,374,883.59
Total					766,210,340.07	9,852,964.98	3,416,000.00	779,479,305.06

3.2 Assessment of Costs of Decommissioning of Wind Farms

The total costs of the decommissioning of the 29 wind farms are 99,843,387 USD, as shown in Table 5. Thailand's weighted cost of decommissioning onshore wind farms is 0.0014 USD/kWh. The costs of decommissioning wind farms range from 0.00026 USD/kWh for wind farm no. 28 and 29 to 0.00192 USD/kWh for wind farm no. 2.

Table 5. The carbon intensity and costs of decommissioning of 29 wind farms.

Wind farm No.	Electricity generation over the plant's lifetime (kWh)	Carbon intensity of decommissioning (gCO_2eq/kWh)	Costs of decommissioning	
			USD/wind farm	USD/kWh
1	4,279,833,625	10.020197	6,856,875	0.00160
2	3,571,810,813	12.006452	6,856,875	0.00192
3	2,146,580,988	11.889870	4,022,700	0.00187
4	3,112,098,750	11.197884	5,300,000	0.00170
5	3,547,721,538	8.644766	3,975,000	0.00112
6	2,025,154,250	13.814310	3,312,500	0.00164
7	1,806,857,150	10.506155	2,385,000	0.00132
8	2,343,017,825	10.127495	2,981,250	0.00127
9	2,268,450,325	10.460402	2,981,250	0.00131
10	3,169,517,875	11.651130	4,471,875	0.00141
11	2,811,526,888	10.333806	3,312,500	0.00118
12	6,061,075,563	6.933355	5,962,500	0.00098
13	5,928,140,750	7.088831	5,962,500	0.00101
14	6,172,756,063	6.644034	5,962,500	0.00097
15	5,414,908,113	7.573905	5,962,500	0.00110
16	1,919,481,125	13.622638	2,981,250	0.00155
17	1,905,801,000	13.720423	2,981,250	0.00156
18	2,703,471,688	10.209496	3,146,875	0.00116
19	1,908,225,125	12.180438	2,650,000	0.00139
20	1,681,540,400	10.829488	2,971,312	0.00177
21	3,650,760,563	12.733247	5,300,000	0.00145
22	5,193,966,250	7.896085	5,962,500	0.00115
23	886,616,625	8.515902	496,875	0.00056
24	475,126,700	23.148642	662,500	0.00139
25	1,744,030,900	7.821995	530,000	0.00030
26	436,007,725	7.821995	132,500	0.00030
27	423,807,900	25.951706	662,500	0.00156
28	2,073,650,350	5.003198	530,000	0.00026
29	2,073,650,350	5.003198	530,000	0.00026
Total	81,735,587,212		99,843,387	
Weighted average		10.095		0.0014

4. DISCUSSION

The weighted average carbon intensity of decommissioning of wind farms in Thailand compared to other carbon intensities is shown in Figure 5. The different carbon intensities of wind farms were calculated from the carbon emissions assessed by [1]. The weighted average intensity of other carbon intensities was also calculated by using the actual wind farm no. 1 to 22 only. The electricity generations of wind farm no. 23 to 29 were not used to estimate different carbon intensities to avoid inaccuracy. The breakdown of the carbon intensity of onshore wind farms is presented in Figure 5. The results showed that the combined average carbon intensity of wind farms in Thailand is 73.57 gCO_2eq/kWh. Compared with carbon emissions from fossil fuels in Thailand, presented in Figure 6, the carbon emissions of electricity generation from wind farms are low. The results of this study also showed that the CO_2 emissions of decommissioning are minor compared to other carbon emissions of electricity generation from wind power. The results corresponded with the carbon emission proportion presented in the study of [13], [14], [15], and [16].

In this study, the weighted average cost of decommissioning wind farms in Thailand is 0.0014 USD/kWh. The cost of decommissioning the second oldest wind farm is the highest, whereas the cost of decommissioning the newest wind farm is the lowest. This study shows that wind technology improvements can reduce the levelized cost of electricity (LCOE) of wind farms. New wind farms can install a smaller number of new technology wind turbines but generate higher electricity than before. Nevertheless, wind power producers cannot only perform decommissioning of wind farms but also repower wind turbines to extend the plant's lifetime. Due to wind technology improvements, onshore wind's global average LCOE has continued to reduce. Therefore, existing wind farms performing repowering to extend the plant's lifetime might have an LCOE lower than new wind farms. Further study should compare the LCOE of wind farms performing decommissioning and the LCOE of wind farms performing repowering.

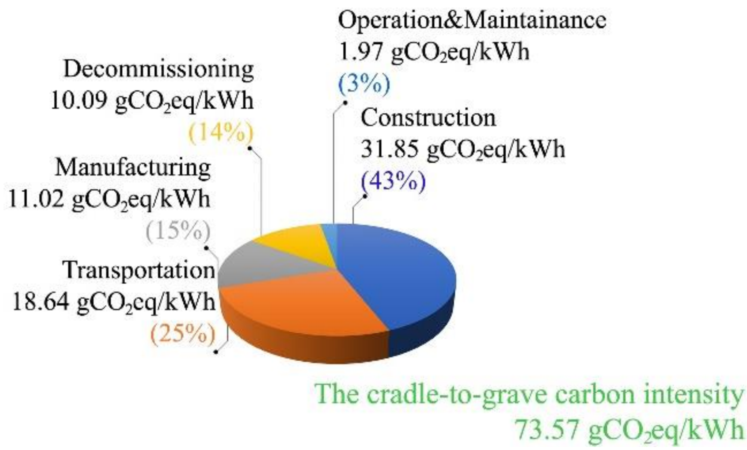

Fig. 5. The breakdown of CO_2 emissions from onshore wind farms in Thailand.

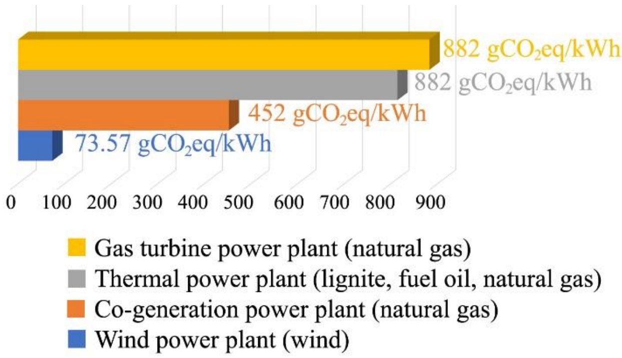

Fig. 6. Carbon emissions of electricity generation from fossil fuels power plants in Thailand.
Source: [17]

5. CONCLUSIONS

The CO_2 emissions of decommissioning and the costs of decommissioning for 29 existing commercial onshore wind farms in Thailand were assessed. This study compares the environmental performance of each wind energy farm in terms of the carbon intensity index. The CO_2 emissions of decommissioning were dismantling wind turbines, concrete foundation disposal, and backfilling. Results are shown that total CO_2 emissions of decommissioning the 29 wind farms in Thailand are 779,479.3 tonCO_2eq. The weighted average carbon intensity is 10.095 gCO_2eq/kWh, which is in the range of 5.00 gCO_2eq/kWh to 25.95 gCO_2eq/kWh. This study suggests that the CO_2 emissions of decommissioning are minor compared to other carbon emissions of electricity generation from wind power.

The study also compared the costs of decommissioning each wind farm in USD/kWh. The weighted average cost of decommissioning wind farms in Thailand is 0.0014 USD/kWh, with the highest costs being 0.00192USD/kWh for the second oldest wind farm, while the lowest costs are 0.00026 USD/kWh for the newest wind.

6. LIMITATIONS

The electricity generation of wind farm no. 23 to 29 were calculated by multiplying the simulated electricity generated from a free-standing wind turbine by the number of wind turbines installed at each wind farm. This study used this method because the layouts of these seven wind farms are commercial in confidence data that could not be collected.

This calculation method did not consider the wake effect. According to [18], the wake effect is power loss resulting from lower wind speed due to turbulent flow occurs. When a turbine is located in a relatively close spacing with others, the wind speed entering a turbine is higher than that leaving it in the area behind a turbine. Downstream wind turbines generate low power because turbulent flow occurs. The wake effect can significantly influence the electricity generation of wind farms. Because the method used to calculate the electricity generations of wind farm no. 23 to 29 did not consider the wake effect of other wind turbines. The estimated electricity generations of these wind farms were inaccurate. For this reason, the electricity generations of these wind farms were not used to calculate the weighted average of the carbon intensity and cost per kWh to avoid inaccuracy.

7. RECOMMENDATIONS FOR FURTHER STUDIES

Currently, in European countries, such as Germany, Italy, Spain, repowering potential of wind farms that reach the end-of-life are also studied instead of considering for only decommissioning [19]–[21]. Repowering wind farms with new wind turbine technologies appears to be feasible for old wind farms with wind resource greater than those recently made. Studies on repowering existing wind farms in Thailand can help EGAT and ERC to better understand the main features of repowering initiative and could support them to set a policy framework for repowering wind farms in future.

Also, compared to carbon emissions of electricity generation from fossil fuels, wind power owes potential for carbon emission reduction as shown in Figure 6. Studies on carbon emission reduction benefit of wind farms can provide decision support for clean energy policy making to EGAT and ERC [16]. The energy return on carbon investment which express the electricity generation per unit of carbon footprint [6] is one of suitable parameters used for measuring environmental benefits from wind farms.

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