

Quantifying Land Use from Commercial Onshore Wind Energy Farms in Thailand Utilizing Geo-Informatics Technology

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ABSTRACT

This study quantifies the spatial footprint of 29 commercial onshore wind energy farms in Thailand (263 km² in total) using Geo-Informatics Technology which integrates remote sensing and GIS. Satellite imagery before and after construction was analyzed to compute the Land Use Intensity of Electricity (LUIE), defined as direct area per unit of generated electricity. Before construction, agricultural lands were the dominant land cover within wind energy farms (80.63 %), followed by forest lands (8.89 %), miscellaneous lands (5.7%), urban and built-up lands (2.71%), water bodies (1.10%), and roads (0.98%). After construction, agricultural lands remained dominant (79.06%), with forest lands (7.81%), water bodies (6.57%), urban and built-up lands (3.0%), roads (1.54%), miscellaneous lands (1.38%), and land use from the infrastructure of the wind energy farms (0.64%). The most notable changes were that water bodies significantly increased from 1.10% to 6.57% while built-up areas and roads slightly increased from 2.71% and 0.98% to 3.00 % and 1.54 %, respectively. Wind farm infrastructure directly occupied 3.19 km² (1.21% of the 263 km²). Wind turbine foundations and hardstands accounted for most of the land use (50.25% of 3.19 km²), followed by new roads (46.80% of 3.19 km²), and substations and other facilities (2.9% of 3.19 km²). The median LUIE was 42.6 m²/GWh, demonstrating high spatial efficiency. The findings of the study demonstrate the minimal agricultural land decrease (from 80.63% to 79.06%). This confirms compatibility between wind energy development and agricultural co-use in Thailand's rural landscapes, providing empirical data for future wind energy farm planning and land use policy.

1. Introduction

According to clean energy policy goals [1-2], Thailand has greatly increased its production of onshore wind energy in the past ten years. The electricity infrastructure has gradually shaped land use patterns throughout the country. Unlike fossil fuel power plants that are usually built in industrial areas, wind energy farms are often built in rural areas with abundant wind resources that also happen to be agricultural areas. This raises concerns about land competition and land cover changes in rural areas [3]. Although wind energy is recognized for its environment benefits, Thailand has not systematically quantified the spatial footprint of its wind energy infrastructure [4]. Understanding the land use of wind farms includes not only the foundations of the turbines, but also access roads, substations, service buildings, and safety buffers that delineate each project's operational boundary. This study is essential as renewable infrastructure expands in multifunctional rural landscapes where agricultural production and electricity generation must coexist.

Onshore wind farms refer to land-based wind energy installations, as distinguished from offshore developments [5]. These facilities employ multiple wind turbines strategically placed to harness kinetic energy from atmospheric wind flows and transform it into electrical energy via electromagnetic induction [6]. A standard commercial onshore wind farm comprises various interconnected infrastructure components that define collectively constitute its physical footprint. The core components include wind turbine

generators mounted on steel or concrete towers, which typically range from 80 to 120 meters in hub height for modern setups. Supporting these towers are turbine foundations and hardstands constructed from reinforced concrete to ensure structural stability and maintenance access. Furthermore, the system includes internal access roads connecting individual turbines to facilitate construction and operations, along with electrical collection systems using underground or overhead cables. Finally, the facility incorporates substations for voltage transformation and grid interconnection, as well as ancillary facilities such as control buildings, meteorological towers, and temporary construction areas [7].

According to [8], the land use characteristics of onshore wind farms differ fundamentally from conventional thermal power plants in three key aspects. The first distinction is that the spatial distribution is dispersed, rather than concentrated as in conventional power plants. Turbines are typically spaced 3 to 5 rotor diameters apart to minimize wake interference effects. This spacing results in project areas spanning several square kilometers, although the physical infrastructure occupies only a small fraction of this total extent. The second aspect involves the nature of land occupation, which is predominantly temporary and reversible. Unlike permanent industrial facilities, wind farm components can be decommissioned, and sites can be restored to pre-construction conditions at the end of the operational lifetime of 20 to 30 years. This characteristic leads to low land-use intensity over the full project lifecycle. The third factor is that the infrastructure exhibits high spatial compatibility with pre-

existing land uses, particularly agriculture. The dispersed turbine layout allows continued farming and grazing activities in the spaces between turbines. Consequently, this enables effective dual land use with minimal disruption to agricultural land functions [9].

Wind farms in Thailand's Chaiyaphum, Nakhon Ratchasima, and Phetchabun provinces occupy agricultural lands including rice paddies and cassava fields, raising questions about land use trade-offs [10]. However, the actual spatial footprint of these installations has not been systematically quantified. This research addresses that gap by using Geo-Informatics to measure real land occupancy in 29 commercial developments, thereby providing empirical data for policy and planning.

Despite the importance of land use studies, this topic has received limited scholarly attention in Thailand's renewable energy sector. The majority of onshore wind farm research in Thailand focuses on economic feasibility, technical performance, or life cycle environmental impact studies, with little attention paid to wind farm spatial requirements. This information gap constrains policymakers, planners, and developers from making fully informed decisions regarding project siting, land allocation, and environmental impact mitigation. Foundational studies introduced the Land Use Intensity of Electricity (LUIE) metric (ha/TWh-yr) as a standardized indicator linking spatial extent with energy output [11]. Subsequent analyses demonstrated that variations in LUIE are driven not only by turbine design and capacity factor but also by institutional arrangements and land-use regulation. As renewable energy increasingly intersects with multifunctional rural landscapes, scholars have redefined land as an ecological, institutional, and cultural asset, transforming LUIE from an engineering ratio into a governance-sensitive metric.

Finally, effective action to ensure the long-term sustainable use of forest and land resources is essential for implementing the United Nations Sustainable Development Goals (SDGs) [12]. This research contributes to achieving SDG 15: Life on Land. It supports protection, restoration, and promotion of sustainable use of terrestrial ecosystems by sustainably managing forests, combating desertification, halting and reversing land degradation, and halting biodiversity loss.

This research utilizes Geo-informatics technologies to estimate land use related to the 29 commercial onshore wind energy farms in Thailand, addressing the identified gap. These wind energy farms account for more than 90% of the total installed capacity of all wind energy farms in Thailand at present. Therefore, the results of this research can be representative of wind energy farms in Thailand. This study addresses the research question: What is the quantitative extent of direct land use from commercial onshore wind farms in Thailand, and which infrastructure components contribute most to the total footprint?

2. Experimental detail

2.1 Geo-informatics technology

Geo-informatics integrates Remote Sensing (RS), GIS, and Global Navigation Satellite System (GNSS), enabling spatially explicit analysis of environmental change. This study applied Geo-informatics to compare pre- and post-construction imagery of wind farms, detecting land cover changes through overlay and visual interpretation. Geo-informatics technology also facilitates efficient management and analysis of spatial data, thereby supporting the effective planning and management of natural resources. Consequently, it has been applied across various sectors

in support of national development, including natural resources and environmental management [13].

Remote sensing is a widely used method for surveying large areas using satellite imagery. This technology enables rapid and accurate investigation of changes. Satellites periodically return to capture images of the same location, enabling direct comparison of Earth surface conditions across different time periods. Using remote sensing to study land cover patterns through visual interpretation is a popular approach for analyzing land cover changes. This study analyzed land use data from before and after the construction of wind energy farms by employing a data overlay analysis to compare the two datasets. This approach examines how the original land cover is classified and how it was changed into the infrastructure of wind turbine generators [14].

GIS is a computer-based system for working with spatial data and associated information. It links data to specific locations on the Earth's surface. For example, a GIS can associate an address or house number with a particular map coordinate (latitude and longitude). Data and maps in a GIS are organized into data tables and databases that include spatial information. GIS can be used to analyze spatial data structures and relationships, thereby enabling the interpretation of changes over time [15]. In this research, GIS was used to investigate the exact locations of all 610 commercial wind turbines being operated in Thailand.

2.2 A land use classification system

The Land Development Department standard classification [16] was used for visual interpretation. This research applied Level I categories to quantify changes, ensuring consistency with Thailand's fundamental geographic data framework as presented in Table 1. The land use classification system is basically divided into level I and level II. However, the land use quantified in this research was classified at level I only.

2.3 Land use associated with wind farm development

Measurement of land use from onshore wind energy farms relies on a critical distinction between direct and indirect footprints. The direct footprint covers land permanently occupied by physical infrastructure. This includes wind turbine foundations, hardstands, access roads, substations, and maintenance buildings. Furthermore, wind farms occupy space beyond these infrastructure elements. The indirect footprint refers to the larger area defined by turbine spacing, which the physical infrastructure does not occupy. Wind project developers must decide whether this area counts as land use.

Following [17], two analytical boundaries were defined in this study. They are Direct Impact Area (infrastructure-only) and Total Farm Area. This consideration is based on the environmental impact assessment perspective.

The Direct Impact Area of the 29 onshore wind energy farms includes turbine foundations, hardstands, roads, substations, and other impervious infrastructure that physically occupies land. This is because the infrastructure physically occupies land area or create impervious surfaces. Also, for construction in forested areas, land must be cleared around each wind turbine.

The Total Farm Area covers the perimeter enclosing all wind turbines. There is no standardized definition of the boundary surrounding a wind energy farm. Nonetheless, the boundary varies with the required turbine spacing [18] or standardized setback from turbines at the edge of a project [17].

Table 1 Land use classification system [23].

Level I	Code	Level II	Code
1. Urban and built-up land	U	Urban and Commercial area	U1
		Residential area	U2
		Governmental and institutional land	U3
		Transportation, communications and utilities	U4
		Industrial land	U5
		Other built-up land	U6
		Golf course	U7
2. Agricultural land	A	Paddy field	A1
		Field crop	A2
		Perennial	A3
		Orchard	A4
		Horticulture	A5
		Swidden cultivation	A6
		Pasture and farm house	A7
		Aquatic plant	A8
		Aquacultural land	A9
		Integrated farm	A0
3. Forest land	F	Evergreen forest	F1
		Deciduous forest	F2
		Mangrove forest	F3
		Swamp forest	F4
		Forest plantation	F5
		Agro-forestry	F6
		Beach forest	F7
4. Water body	W	Natural Water body	W1
		Artificial water body	W2
5. Miscellaneous land	M	Rangeland and scrub	M1
		Marsh and swamp	M2
		Mine and pit	M3
		Other miscellaneous land	M4
		Salt flat	M5
		Beach	M6
		Garbage dump	M7

2.4 Land use intensity of electricity generation from wind

The land use intensity metric quantifies the concept of the Direct Impact Area to describe direct land usage relative to lifetime energy generation. The land use intensity for onshore wind is calculated as either capacity density (rated capacity per unit area) or as land required per unit generation, complemented by environmental impact assessments (EIA) and ecosystem-service perspectives. The energy-density concept quantifies the electricity generation rate per surface area. Ecosystem and life cycle assessment approaches further quantify the directly impacted area, which is used for the infrastructure of wind turbine generators, plus indirect land impacts [19, 20, 21]. The land use intensity is applied across EIA, strategic spatial planning, and energy-system modeling to balance generation targets and environmental constraints [17]. Land use can be calculated with Equation (1) [8].

$$LUIE = \frac{\sum A_D}{C \times cf \times H \times y} \quad (1)$$

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

LUIE	is	Land Use Intensity of Electricity (m ² /GWh)
A _D	is	Each Land use from infrastructure components (m ²)
C	is	The installed capacity (MW)
cf	is	The capacity factor of a wind turbine
H	is	The number of hours in an average year (8,766)
y	is	The generating lifetime of a wind turbine in years

2.5 Safety distance of wind energy farms

The announcement of the Office of Energy Regulatory Commission (ERC) for safety distance and installed capacity for wind electricity producers, is in the Thai Government Gazette of 26 June 2015 [22], where safety distance of wind energy farms can be defined as “the safe separation between wind turbine towers within the project area, within which the construction of residential dwellings is prohibited”. According to this regulation, the distance from the tower base to the project boundary of an onshore wind energy farm is stipulated to be not less than 1.2 times the sum of the tower height plus the rotor radius. Considering this regulation, not only does wind energy farm infrastructure directly cause land use change, but the safety distance also indirectly affects the original land use.

The safety distance at each wind turbine is presented in Fig. 1. It can be calculated with Equations (2) and (3). This research used areas within a perimeter drawn with a safety distance surrounding all of the turbines in the wind to set the project boundary of each wind energy farm.

$$H_T = H_H + L \quad (2)$$

$$S_S = 1.2 \times H_T \quad (3)$$

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

H _H	is	Hub height of a wind turbine (m)
L	is	Length of a wind turbine blade (m)
H _T	is	Tip height of a wind turbine (m)
S _S	is	Safety distance (m)

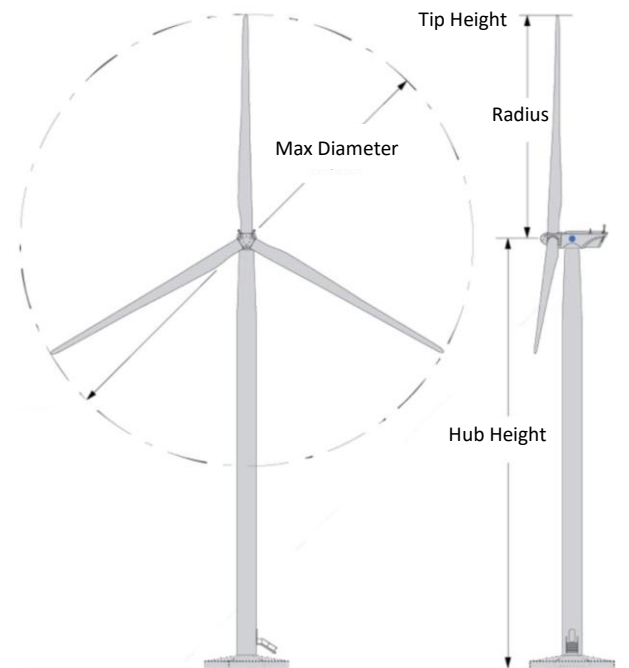


Fig. 1 The tip height of a wind turbine.

3. Data collection and research methods

3.1 Data collection

This study compiled data for the 29 existing commercial onshore wind energy farms operating in Thailand, including installed capacities, lifetime electricity generation, locations, the number of wind turbines, hub height, tip height of wind turbines, and commercial operation dates (the official date on which the plant begins generating electricity). The data are presented in Table 2. These data were collected from the ERC as cited in [24].

The total electricity generation over the lifetime of each wind energy farm used to calculate land use intensity is referred to in [25]. The coordinates of the approximate center of each wind energy farm and of each wind turbine were measured by the researcher. The wind speed at the rough center of each wind energy farm was collected from <https://globalwindatlas.info>, which is a well-known source providing data on wind power throughout the world. Table 2 also presents the green field period referred to in [26] and the calculated safety distance of each wind energy farm.

Table 2 Data of commercial onshore wind energy farms in Thailand [25-26].

Wind energy farm no.	Total electricity generation over the wind energy farm's lifetime (kWh)	Location of wind energy farm (coordinates)	Installed capacity per wind turbine (MW)	Number of wind turbines installed	Hub height of wind turbines (m)	Tip height of wind turbines (m)	Commercial operation dates	Green field period	Safety distance (m)
1	4,279,833,625	15.19460N 101.45271E	2.3	45	80	131	14th November 2012	Before 14th November 2010	157
2	3,571,810,813	15.19460N 101.45271E	2.3	45	80	131	8th Feb 2013	Before 14th November 2010	157
3	2,146,580,988	16.697557N 100.985226E	2.5	24	85	145	5th August 2016	Before 5th August 2014	174
4	3,112,098,750	15.608014N 101.548727E	2.5	32	120	181	16th December 2016	Before 16th December 2014	217
5	3,547,721,538	15.414156N 101.468333E	2.1	30	80	138	24th December 2016	Before 24th December 2014	166
6	2,025,154,250	15.135212N 101.481218E	2.0	25	108	164	29th December 2016	Before 29th December 2014	197
7	1,806,857,150	8.06733N 100.30607E	1.8	20	137	192	3rd March 2017	Before 3rd March 2015	231
8	2,343,017,825	8.06733N 100.30607E	1.8	25	137	192	10th June 2017	Before 3rd March 2015	231
9	2,268,450,325	8.06733N 100.30607E	1.8	25	137	192	23rd June 2017	Before 3rd March 2015	231
10	3,169,517,875	15.175983N 101.500744E	2.1	33	153	209	27th March 2018	Before 27th March 2016	251
11	2,811,526,888	14.954110N 101.444427E	2.5	20	137	199	20th June 2018	Before 20th June 2016	239
12	6,061,075,563	15.33988N 101.46924E	3.0	30	132	200	28th September 2018	Before 28th September 2016	240
13	5,928,140,750	15.37017N 101.44549E	3.0	30	132	200	28th September 2018	Before 28th September 2016	240
14	6,172,756,063	15.28055N 101.47440E	3.0	30	134	199	21st November 2018	Before 28th September 2016	239
15	5,414,908,113	15.07904N 101.50155E	3.0	30	134	199	28th December 2018	Before 28th December 2016	239
16	1,687,058,023	15.629709N 101.651005E	2.5	18	153	216	25th January 2019	Before 25th January 2017	260
17	1,662,130,865	15.659124N 101.694138E	2.5	18	153	216	25th January 2019	Before 25th January 2017	260
18	2,471,582,308	15.464689N 101.413719E	2.5	19	153	216	22nd March 2019	Before 22nd March 2017	260
19	1,741,331,695	15.47826N 101.45016E	2.5	16	153	216	30th March 2019	Before 22nd March 2017	260
20	1,681,540,400	16.374614N 104.418739E	3.45	13	136	203	1st April 2019	Before 1st April 2017	243
21	3,385,189,135	15.53198N 101.55513E	2.5	32	153	216	13th April 2019	Before 13th April 2017	260
22	5,193,966,250	15.236577N 101.502730E	3.0	30	134	199	16th March 2019	Before 16th March 2017	240
23	371,985,903	15.395707N 101.432335E	2.5	3	90	145	18th July 2013	Before 18th July 2011	174
24	360,753,425	8.336625N 100.251719E	2.5	4	90	149	6th November 2015	Before 6th November 2013	179
25	396,784,963	15.135212N 101.481218E	2.0	4	125	182	17th March 2016	Before 17th March 2014	219
26	99,196,241	15.135212N 101.481218E	2.0	1	125	182	17th March 2016	Before 17th March 2014	219
27	243,299,575	8.302096N 100.240412E	2.5	4	90	151	11th April 2019	Before 11th April 2017	181
28	396,784,963	16.387342N 104.412260E	4.0	2	157	230	16th August 2021	Before 2nd August 2019	276
29	396,784,963	16.387342N 104.412260E	4.0	2	157	230	2nd August 2021	Before 2nd August 2019	276

3.2 Utilizing Geo-informatics technology

ArcGIS, which is a robust GIS software for the investigation of land use [27], was used to identify the precise locations of all wind turbines within the 29 wind energy farms from the locations of these wind energy farms, as shown in Table 2. Moreover, ArcGIS was used to analyze the land cover change before and after the development of the 29 wind energy farms in Thailand. The satellite imagery of land use in Phetchabun province in 2013, Nakhon Ratchasima province in 2014, Chaiyaphum province in 2013, Mukdahan province in 2018, and Nakhon Si Thammarat in 2016 are the data of land cover before construction. They were collected from [28], whereas the data after construction refer to Google Satellite imagery in the year 2024. The data were input at a scale of 1:4,000. The GIS overlay technique was used to analyze the land cover by visual interpretation. In addition, ArcGIS version Pro 3.3.2 and its GIS database used in this research were legally subscribed to by the authors.

3.3 Setting the land use area of each wind energy farm

In this research, the circles with a radius equal to S_s at each wind turbine location are considered as a safety distance buffer. The safety distance buffers were connected to delineate the project boundary. The area inside the project boundary was considered to be the land use area. For example, the land use area of wind energy farm nos. 1&2 is presented in Fig. 2 as the total wind energy farm area considered.

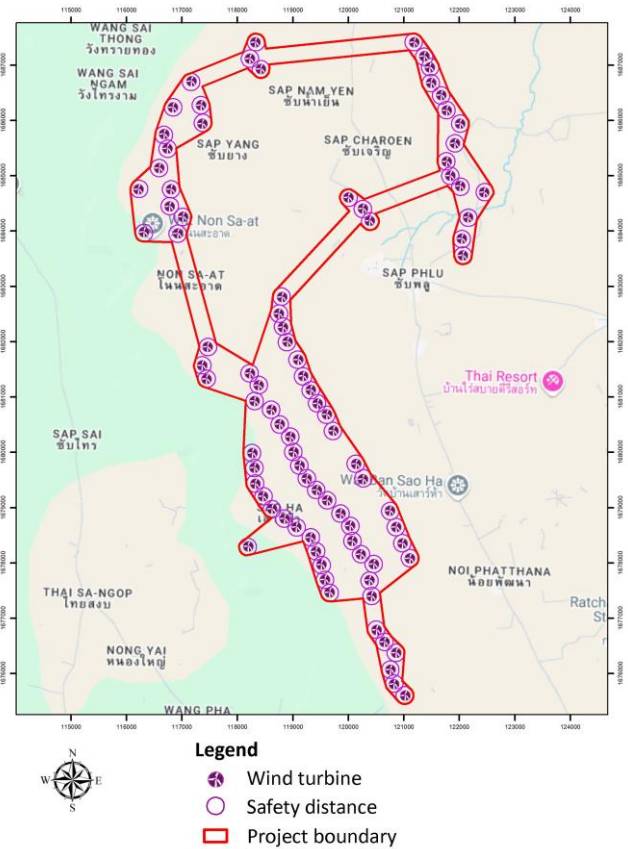


Fig. 2 The considered land use of wind energy farms no. 1&2.

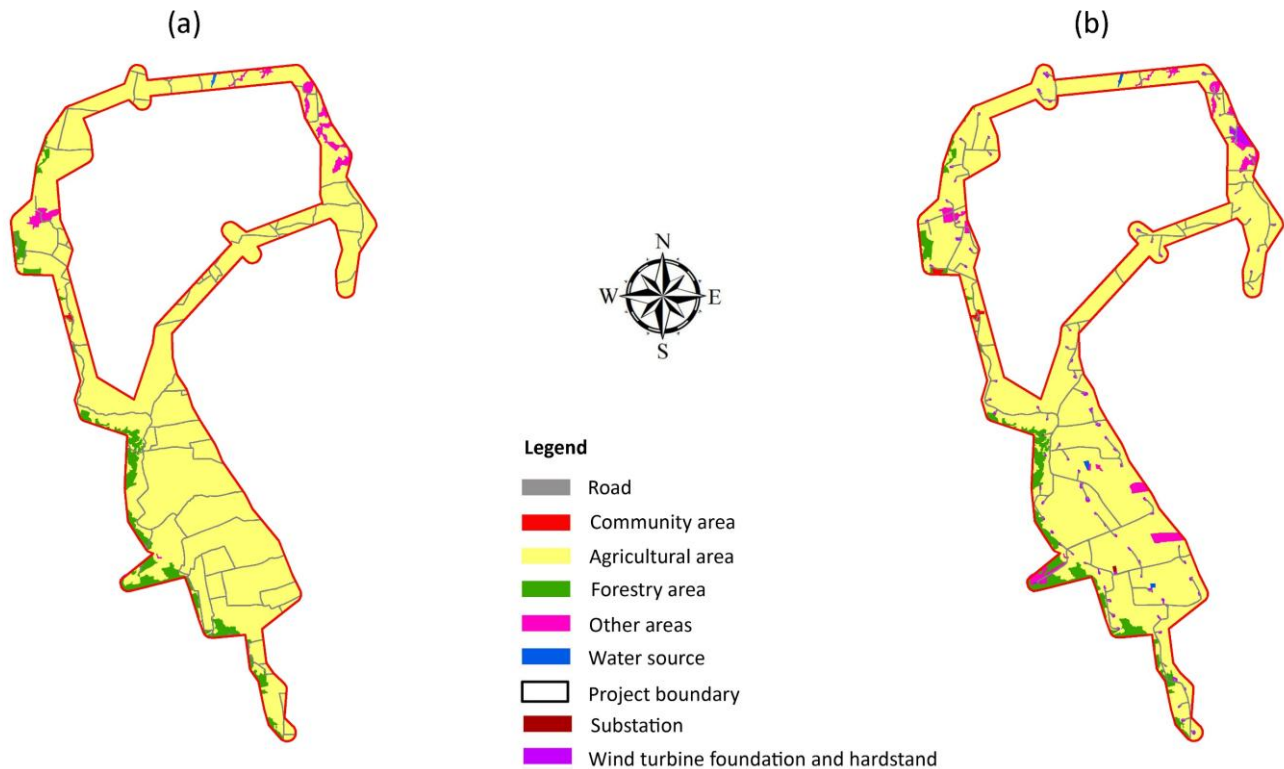


Fig. 3 (a) The land before and (b) after the development of wind energy farm no. 1+2.

4. Results and discussions

4.1 Land use from wind energy farms in Thailand

Fig. 3 presents the details of the land before the development (green field periods) and after the development (after commercial operation dates) of wind energy farm no. 1, combined with wind energy farm no. 2 as a sample comparison. Fig. 4 illustrates the land before and after the development of the other 27 wind energy farms. The legends used in Fig. 4 are identical to those of Fig. 3. Moreover, the detailed close-up figures of all 29 wind energy farms are provided in the full master's thesis, of which this study is a part.

The Land use and land cover classification followed the Land Development Department's land use classification system [23], summarized in Tables 4-7. These results show before/after comparison for all 29 wind energy farms.

Land use analysis of the total project area revealed that before construction, agricultural lands dominated areas of wind energy farms (80.63 %), followed by forest lands (8.89 %), miscellaneous lands (5.7%), urban and built-up lands (2.71%), water bodies (1.10%), and roads (0.98%). After construction, agricultural lands remained dominant (79.06%), with forest lands (7.81%), water bodies (6.57%), urban and built-up lands (3.0%), roads (1.54%), miscellaneous lands (1.38%), and land use from the infrastructure of the wind energy farms (0.64%). The most notable changes were that water bodies significantly increased from 1.10% to 6.57% where built-up areas and roads slightly increased from 2.71% and 0.98% to 3.00 % and 1.54 %, respectively.

Tables 6 and 7 revealed that wind farm infrastructure directly occupied 3.19 km² (1.21% of the 263 km²). Wind turbine foundations and hardstands account for most of the land use (50.25% of 3.19 km²), followed by new roads (46.80% of 3.19 km²), and substations and other facilities (2.9% of 3.19 km²). The installed capacity density ranged from 0.000225 to 0.002336 MW/m² (median 0.0015 (MW/m²), showing high spatial efficiency relative to international averages. Similarly, LUIE varied from 7 to 100 m²/GWh (median 42.6 m²/GWh).

4.2 Discussion

The empirical findings of this study indicate that commercial onshore wind energy farms in Thailand exhibit relatively low LUIE values, with a median of 42.6 m²/GWh across 29 projects. This metric demonstrates high spatial efficiency in wind energy development, as the direct infrastructure footprint occupies only 1.21% of the total 263 km² project area. The remaining 98.79% of project boundaries retain their original land use classifications, predominantly agricultural lands (79.06% post-construction) and forest lands (7.81% post-construction).

The analysis reveals that wind farm development caused minimal landscape conversion. Agricultural lands decreased by only 1.57% (from 80.63% to 79.06%), and forest lands declined by 1.08% (from 8.89% to 7.81%), demonstrating that wind energy infrastructure can be deployed with limited disruption to existing land cover patterns. This finding is particularly significant for Thailand's renewable energy planning, as it confirms that wind farm development is compatible with ongoing agricultural activities and forest conservation objectives.

Within the 3.19 km² direct footprint, wind turbine foundations and hardstands account for 50.25% of the land use, followed by access roads (46.80%) and other infrastructure such as substations and control buildings (2.94%).

This composition indicates that the majority of permanent land conversion is attributable to turbine foundations and the road network required for construction, operation, and maintenance access. The relatively small proportion allocated to substations and ancillary facilities reflects efficient infrastructure design that minimizes unnecessary land occupation.

The most notable land cover change observed was an increase in water bodies from 1.10% to 6.57% of the total project area. Spatial and visual analysis reveals that this increase of water bodies is attributable to the construction-related water management features, which are retention ponds and sedimentation basins, rather than environmental degradation or genuine hydrological change. These engineered features serve erosion control and water management functions during and after construction. The presence of new water bodies near wind farm infrastructure suggests that these features were planned components of wind energy farms rather than unintended environmental impacts. However, these findings highlight the need to distinguish between natural and artificial water bodies. Future studies should consider classifying construction-related water features within the wind energy farm infrastructure category to provide clearer accounting of wind farm land use impacts.

Comparison between Thailand's two wind energy regions reveals differences in spatial efficiency. The North-East region (24 wind energy farms) exhibits an average LUIE of 37.47 m²/GWh with 1.22% average land use, while the South region (5 wind energy farms) shows an average LUIE of 92.52 m²/GWh with 1.19% average land use. Despite similar land use percentages, the South region's higher LUIE indicates lower spatial efficiency, likely attributable to differences in installed capacity, turbine specifications, or site-specific characteristics. This regional variation suggests that spatial efficiency is influenced by factors beyond total land area, including energy yield per turbine and project design parameters.

The installed capacity density across all projects ranges from 0.000225 to 0.002336 MW/m² (median 0.0015 MW/m²), demonstrating considerable variation among individual wind farms. This variation reflects differences in turbine spacing, project layout, and site-specific constraints. Projects with higher capacity density achieve greater energy output per unit area, contributing to lower LUIE values and more efficient land use.

These findings provide quantitative evidence that onshore wind energy farm development in Thailand can achieve high spatial efficiency while maintaining compatibility with existing land uses. The minimal conversion of agricultural and forest lands, combined with the small direct infrastructure footprint (1.21% of project area), suggests that wind energy expansion can proceed without significant competition for land resources. This is particularly relevant for Thailand's renewable energy targets, as it indicates that wind power can contribute substantially to the national energy mix without requiring extensive land reallocation or causing major landscape transformation. The LUIE values and installed capacity density metrics established in this study provide baseline data for evaluating future wind farm proposals and comparing spatial efficiency across projects. These metrics can inform site selection, project design, and environmental impact assessment processes to optimize land use efficiency in subsequent wind energy developments.

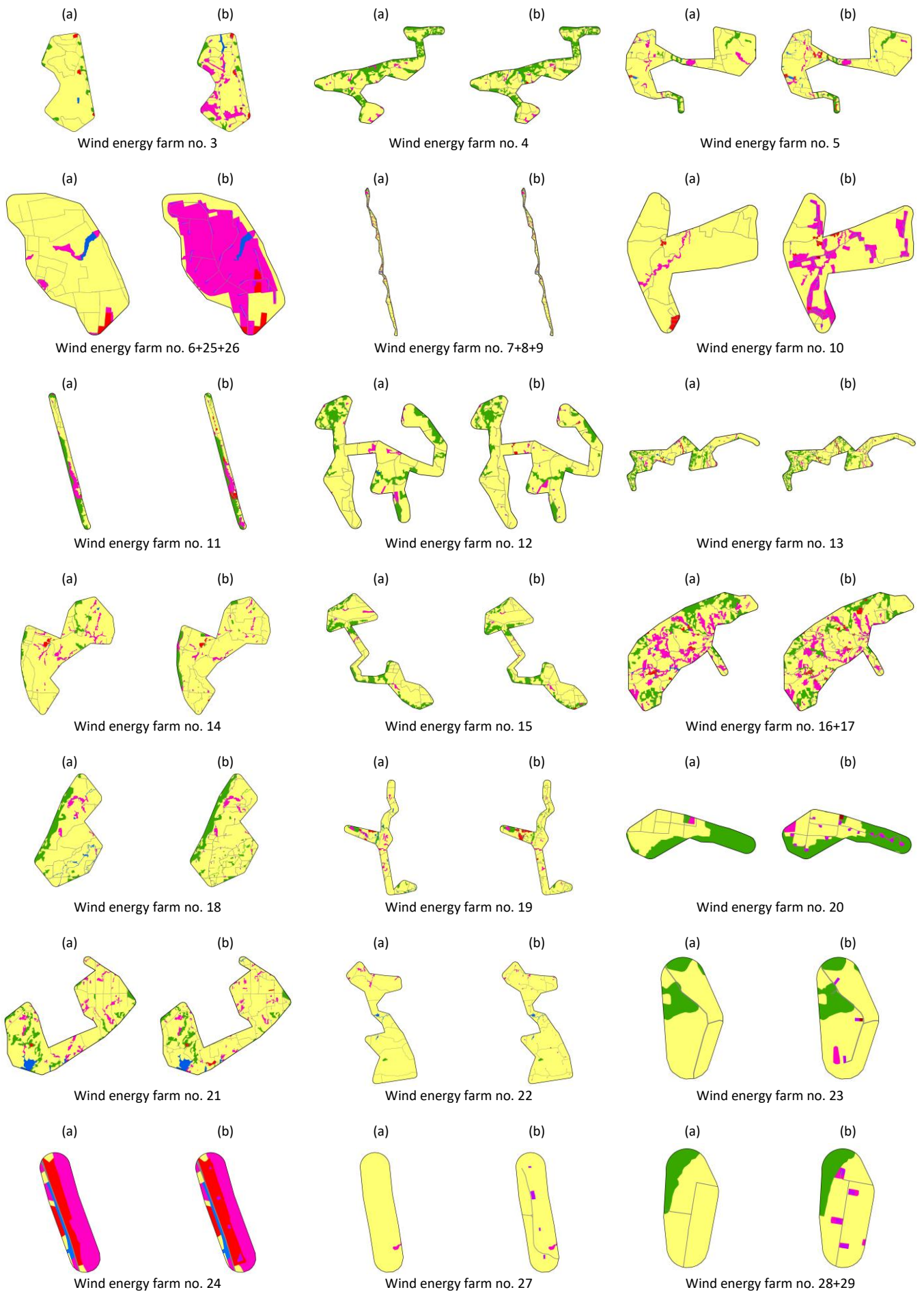


Fig. 4 (a) The land before and (b) after the development of wind energy farm no. 3 to 29.

Table 4 The classification of land use and land cover in the project boundaries of the 29 wind energy farms before construction.

Region	Wind energy farm no.	Total wind energy farm area (m ²)	Urban and built-up lands (m ²)	Roads (m ²)	Agricultural Land (m ²)	Forest Lands (m ²)	Water bodies (m ²)	Miscellaneous lands (m ²)
North-East	1+2	17,747,492 (100%)	13,926 (0.08%)	291,231 (1.64%)	16,043,945 (90.40%)	1,037,065 (5.84%)	13,705 (0.08%)	347,620 (1.96%)
North-East	3	4,141,742 (100%)	41,390 (1.00%)	64,564 (1.56%)	3,862,009 (93.25%)	160,839 (3.88%)	12,941 (0.31%)	-
North-East	4	8,651,268 (100%)	5,619 (0.06%)	41,380 (0.48%)	5,734,032 (66.28%)	2,623,435 (30.32%)	-	246,801 (2.85%)
North-East	5	12,257,919 (100%)	26,037 (0.21%)	111,522 (0.91%)	10,907,469 (88.98%)	625,566 (5.10%)	65,260 (0.53%)	522,064 (4.26%)
North-East	6+25+26	4,408,467 (100%)	54,000 (1.22%)	100,345 (2.28%)	4,054,311 (91.97%)	-	58,426 (1.33%)	141,385 (3.21%)
North-East	10	9,136,628 (100%)	110,199 (1.21%)	101,907 (1.12%)	8,730,359 (95.55%)	-	-	194,164 (2.13%)
North-East	11	4,970,571 (100%)	17,405 (0.35%)	31,275 (0.63%)	2,648,723 (53.29%)	1,487,425 (29.92%)	-	785,743 (15.81%)
North-East	12	9,202,378 (100%)	1,233 (0.01%)	111,346 (1.21%)	7,405,703 (80.48%)	1,448,125 (15.74%)	15,142 (0.16%)	220,828 (2.40%)
North-East	13	18,305,457 (100%)	234,363 (1.28%)	161,930 (0.88%)	13,829,315 (75.55%)	3,341,138 (18.25%)	222,712 (1.22%)	515,999 (2.82%)
North-East	14	21,448,609 (100%)	145,470 (0.68%)	154,478 (0.72%)	19,222,672 (89.62%)	832,277 (3.88%)	31,982 (0.15%)	1,061,730 (4.95%)
North-East	15	12,251,712 (100%)	5,904 (0.05%)	168,075 (1.37%)	9,690,372 (79.09%)	2,147,943 (17.53%)	4,056 (0.03%)	235,362 (1.92%)
North-East	16+17	30,147,104 (100%)	401,199 (1.33%)	176,756 (0.59%)	19,839,197 (65.81%)	4,415,211 (14.65%)	178,949 (0.59%)	5,135,791 (17.04%)
North-East	18	8,588,800 (100%)	-	85,448 (0.99%)	7,175,326 (83.54%)	915,070 (10.65%)	146,754 (1.71%)	266,203 (3.10%)
North-East	19	7,329,330 (100%)	99,542 (1.36%)	73,703 (1.01%)	6,239,443 (85.13%)	345,856 (4.72%)	185,172 (2.53%)	385,614 (5.26%)
North-East	20	2,574,973 (100%)	-	28,698 (1.11%)	1,444,372 (56.09%)	1,072,827 (41.66%)	-	29,076 (1.13%)
North-East	21	21,579,205 (100%)	33,287 (0.15%)	152,321 (0.71%)	17,866,546 (82.80%)	1,851,701 (8.58%)	468,829 (2.17%)	1,206,521 (5.59%)
North-East	22	14,400,237 (100%)	-	107,409 (0.75%)	14,004,741 (97.25%)	38,212 (0.27%)	83,365 (0.58%)	166,510 (1.16%)
North-East	23	358,437 (100%)	-	7,011 (1.96%)	286,074 (79.81%)	65,352 (18.23%)	-	-
North-East	28+29	895,181 (100%)	-	10,596 (1.18%)	731,042 (81.66%)	153,543 (17.15%)	-	-
South	7+8+9	53,648,842 (100%)	5,801,749 (10.81%)	575,702 (1.07%)	41,836,053 (77.98%)	836,656 (1.56%)	1,364,255 (2.54%)	3,234,427 (6.03%)
South	24	505,099 (100%)	146,103 (28.93%)	18,659 (3.69%)	34,457 (6.82%)	-	30,398 (6.02%)	275,481 (54.54%)
South	27	515,864 (100%)	-	-	511,904 (99.23%)	-	-	3,959 (0.77%)
Total		263,065,315 (100%)	7,137,425 (2.71%)	2,574,356 (0.98%)	212,098,066 (80.63%)	23,398,240 (8.89%)	2,881,946 (1.10%)	14,975,282 (5.69%)

Table 5 The classification of land use and land cover in the project boundaries of the 29 wind energy farms after construction.

Region	Wind energy farm no.	Urban and built-up lands (m ²)	Roads (m ²)	Agricultural Land (m ²)	Forest Lands (m ²)	Water bodies (m ²)	Miscellaneous lands (m ²)	Total land use from wind energy farm infrastructure (direct impact area) (m ²)
North-East	1+2	41,120 (0.23%)	299,116 (1.69%)	15,493,279 (87.30%)	1,017,073 (5.73%)	32,530 (0.18%)	501,894 (2.83%)	362,480 (2.04%)
North-East	3	49,969 (1.21%)	100,506 (2.43%)	3,075,101 (74.25%)	190,752 (4.61%)	52,994 (1.28%)	578,736 (13.97%)	93,685 (2.26%)
North-East	4	25,240 (0.29%)	132,671 (1.53%)	5,785,283 (66.87%)	2,482,313 (28.69%)	18,705 (0.22%)	166,980 (1.93%)	40,076 (0.46%)
North-East	5	173,679 (1.42%)	214,693 (1.75%)	10,717,686 (87.43%)	524,733 (4.28%)	150,015 (1.22%)	436,675 (3.56%)	40,439 (0.33%)
North-East	6+25+26	124,439 (2.82%)	88,142 (2.00%)	1,180,491 (26.78%)	-	58,595 (1.33%)	2,807,938 (63.69%)	148,863 (3.38%)
North-East	10	78,882 (0.86%)	129,027 (1.41%)	6,979,378 (76.39%)	-	-	1,684,365 (18.44%)	264,975 (2.90%)
North-East	11	293,526 (5.91%)	78,903 (1.59%)	2,294,801 (46.17%)	1,397,344 (28.11%)	-	873,262 (17.57%)	32,735 (0.66%)
North-East	12	31,413 (0.34%)	129,065 (1.40%)	7,715,969 (83.85%)	1,066,570 (11.59%)	31,302 (0.34%)	174,506 (1.90%)	53,554 (0.58%)
North-East	13	294,080 (1.61%)	270,649 (1.48%)	13,891,539 (75.89%)	3,026,020 (16.53%)	407,638 (2.23%)	356,130 (1.95%)	59,402 (0.32%)
North-East	14	127,044 (0.59%)	262,110 (1.22%)	19,508,297 (90.95%)	747,060 (3.48%)	42,564 (0.20%)	722,901 (3.37%)	38,633 (0.18%)
North-East	15	26,334 (0.21%)	155,355 (1.27%)	9,833,159 (80.26%)	2,037,172 (16.63%)	4,056 (0.03%)	157,112 (1.28%)	38,523 (0.31%)
North-East	16+17	580,574 (1.93%)	367,746 (1.22%)	21,576,762 (71.57%)	3,220,532 (10.68%)	454,277 (1.51%)	3,886,915 (12.89%)	60,296 (0.20%)
North-East	18	-	162,476 (1.89%)	7,015,512 (81.68%)	962,166 (11.20%)	193,654 (2.25%)	221,658 (2.58%)	33,335 (0.39%)
North-East	19	254,816 (3.48%)	132,821 (1.81%)	6,202,692 (84.63%)	274,738 (3.75%)	238,319 (3.25%)	203,145 (2.77%)	22,800 (0.31%)
North-East	20	-	37,557 (1.46%)	1,222,240 (47.47%)	1,107,184 (43.00%)	-	139,698 (5.43%)	68,294 (2.65%)
North-East	21	126,625 (0.59%)	279,333 (1.29%)	18,400,961 (85.27%)	1,409,539 (6.53%)	489,026 (2.27%)	820,943 (3.80%)	52,778 (0.24%)
North-East	22	1,768 (0.01%)	139,545 (0.97%)	14,013,794 (97.32%)	38,212 (0.27%)	85,936 (0.60%)	58,892 (0.41%)	62,090 (0.43%)
North-East	23	-	6,779 (1.89%)	278,822 (77.79%)	62,447 (17.42%)	-	6,330 (1.77%)	4,059 (1.13%)
North-East	28+29	-	9,980 (1.11%)	683,334 (76.33%)	153,656 (17.16%)	-	29,630 (3.31%)	18,582 (2.08%)
South	7+8+9	5,462,932 (10.18%)	1,016,300 (1.89%)	41,583,064 (77.51%)	835,720 (1.56%)	1,336,892 (2.49%)	3,229,820 (6.02%)	184,113 (0.34%)
South	24	190,547 (37.72%)	18,659 (3.69%)	33,664 (6.66%)	-	30,398 (6.02%)	223,421 (44.23%)	8,410 (1.67%)
South	27	-	9,029 (1.75%)	495,303 (96.01%)	-	-	3,959 (0.77%)	7,572 (1.47%)
Total		7,882,989 (3.00%)	4,040,461 (1.54%)	207,981,130 (79.06%)	20,553,230 (7.81%)	3,626,902 (6.57%)	17,284,910 (1.38%)	1,695,693 (0.64%)

Table 6 The classification of the land use from the infrastructure of the 29 wind energy farms.

Region	Wind energy farm no.	Estimated wind speed at the hub height (m/s)	Total wind energy farm area (m ²)	Actual land use				Land use from wind energy farm (%)	Average installed capacity density (MW/m ²)	LUIE (m ² /GWh)
				Wind turbine foundations and hardstands (m ²)	New roads (m ²)	Other infrastructure (m ²)	Total actual land use (m ²)			
North-East	1+2	6.18	17,747,492	356,195 (96.17%)	7,886 (2.13%)	6,284 (1.70%)	370,366 (100%)	2.09	0.000571	47.17
North-East	3	5.59	4,141,742	88,176 (68.02%)	35,942 (27.73%)	5,509 (4.25%)	129,627 (100%)	3.13	0.000648	60.39
North-East	4	5.99	8,651,268	33,866 (25.78%)	91,290 (69.49%)	6,210 (4.73%)	131,366 (100%)	1.52	0.001996	42.21
North-East	5	6.19	12,257,919	40,439 (28.16%)	103,170 (71.84%)	-	143,609 (100%)	1.17	0.001484	40.48
North-East	6+25+26	6.53	4,408,467	148,863 (100%)	-	-	148,863 (100%)	3.38	0.000470	59.05
North-East	10	6.84	9,136,628	257,206 (88.06%)	27,121 (9.28%)	7,769 (2.66%)	292,096 (100%)	3.20	0.000684	92.16
North-East	11	6.82	4,970,571	28,728 (35.75%)	47,628 (59.27%)	4,006 (4.99%)	80,363 (100%)	1.62	0.000255	28.58
North-East	12	7.13	9,202,378	53,554 (75.14%)	17,719 (24.86%)	-	71,273 (100%)	0.77	0.001527	11.76
North-East	13	6.80	18,305,458	59,402 (35.33%)	108,719 (64.67%)	-	168,121 (100%)	0.92	0.001681	28.36
North-East	14	6.88	21,448,609	34,941 (23.89%)	107,632 (73.59%)	3,692 (2.52%)	146,265 (100%)	0.68	0.001515	23.70
North-East	15	6.53	12,251,712	38,523 (100%)	-	-	38,523 (100%)	0.31	0.002336	7.11
North-East	16+17	6.25	30,147,104	60,296 (24.00%)	190,990 (76.00%)	-	251,286 (100%)	0.83	0.001493	75.03
North-East	18	6.60	8,588,800	33,335 (30.20%)	77,029 (69.80%)	-	110,364 (100%)	1.28	0.001425	44.65
North-East	19	6.82	7,329,330	22,800 (27.83%)	59,118 (72.17%)	-	81,918 (100%)	1.12	0.001754	47.04
North-East	20	6.79	2,574,973	55,677 (72.16%)	8,859 (11.48%)	12,617 (16.35%)	77,153 (100%)	3.00	0.000657	45.88
North-East	21	6.48	21,579,205	52,778 (29.36%)	127,012 (70.64%)	-	179,790 (100%)	0.83	0.001516	53.11
North-East	22	6.74	14,400,237	58,355 (61.93%)	32,136 (34.11%)	3,734 (3.96%)	94,226 (100%)	0.65	0.001450	18.14
North-East	23	6.09	358,437	3,400 (83.77%)	-	659 (16.23%)	4,059 (100%)	1.13	0.001848	10.91
North-East	28+29	6.96	895,181	18,582 (100%)	-	-	18,582 (100%)	2.08	0.000861	23.42
South	7+8+9	4.69	53,648,842	140,768 (22.53%)	440,598 (70.53%)	43,345 (6.94%)	624,711 (100%)	1.16	0.000684	97.33
South	24	4.23	505,099	8,410 (100%)	-	-	8,410 (100%)	1.67	0.001189	23.31
South	27	4.12	895,181	7,572 (45.61%)	9,029 (54.39%)	-	16,601 (100%)	3.22	0.001321	68.23
Total			263,065,315	1,601,867 (50.25%)	1,491,877 (46.80%)	93,836 (2.94%)	3,187,570 (100%)	1.21	0.020296	42.64

Table 7 The actual amount of land use in each region of Thailand.

Region	Wind energy farm no.	Total wind energy farm area (m ²)	Total actual land use (m ²)	Land use from wind energy farms (%)	Average installed capacity density (MW/m ²)	Land use intensity (m ² /GWh)
North-East	1, 2, 3, 4, 5, 6, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 28, 29	208,395,511	2,537,849	1.22	0.020245	37.47
South	7, 8, 9, 24, 27	54,669,804	649,722	1.19	0.020791	92.52

5. Conclusion

This study used Geo-Informatics Technology, which combined RS, GIS, and GNSS, to quantify land use across 29 commercial onshore wind energy farms, covering a total project area of 263 km² in Northeast and Southern Thailand. The analysis reveals that wind power development achieves high spatial efficiency with minimal land conversion.

Wind energy infrastructure occupies only 3.19 km² (1.21% of total project areas), with 98.79% of project boundaries retaining their original land use classifications. The LUIE exhibits a median value of 42.6 m²/GWh across all projects, ranging from 7 to 100 m²/GWh, demonstrating efficient land utilization relative to energy output. The installed capacity density ranges from 0.000225 to 0.002336 MW/m² (median 0.0015 MW/m²), reflecting considerable variation in spatial efficiency among individual projects.

The analysis of pre-construction and post-construction satellite imagery demonstrates minimal land use change. Agricultural lands decreased from 80.63% to 79.06% (1.57%), and forest lands declined from 8.89% to 7.81% (1.08%), confirming that wind farm development preserves existing land uses. Built-up areas increased modestly from 2.71% to 3.00%, and roads expanded from 0.98% to 1.54% to accommodate wind farm access requirements. The most notable change was a substantial increase in water bodies from 1.10% to 6.57%, attributed to construction-period ponds and drainage features in post-construction imagery. Within the 3.19 km² direct footprint, wind turbine foundations and hardstands account for 50.25% of land use, access roads comprise 46.80%, and other infrastructure (substations, control buildings) occupies 2.94%. This composition indicates that permanent land conversion is primarily attributable to turbine foundations and the road network required for construction, operation, and maintenance access.

These findings provide quantitative evidence that onshore wind energy farm development in Thailand can proceed with minimal competition for land resources. The combination of low LUIE values (median 42.6 m²/GWh), minimal agricultural and forest conversion (1.57% and 1.08%, respectively), and a small direct footprint (1.21% of the project area) demonstrates that wind energy expansion is compatible with existing agricultural activities and forest conservation objectives. The LUIE values and installed capacity density metrics established in this study provide baseline data for evaluating future wind farm proposals and optimizing land use efficiency in developments of new onshore wind energy farms.

6. Recommendations for further studies

This study's empirical dataset provides a foundation for forecasting models aimed at optimizing future wind farm siting. The dataset, which correlates land-use intensity with design parameters, terrain characteristics, and governance conditions, allows for a predictive assessment of spatial efficiency under varying regulatory and ecological scenarios. Future research should extend this work by developing machine-learning models that leverage turbine configuration and LUIE to discover the optimal spatial layouts.

Moreover, future analysis could integrate Social Return on Investment (SROI), which is a framework measuring the broader social, environmental, and economic value created per unit of investment [29], to balance land-use efficiency with community well-being. By incorporating SROI metrics, spatial optimization could be grounded in principles of social equality and sustainable development, ensuring that wind farm development generates benefits beyond electricity production, including employment creation, infrastructure enhancement, and agricultural co-use opportunities.

Additionally, this study quantifies land cover patterns and spatial efficiency metrics but does not investigate the causal factors underlying the observed regional variations or the specific design decisions that influence LUIE values. Future research could examine the relationships between turbine specifications, spacing configurations, terrain characteristics, and spatial efficiency to identify best practices for minimizing land use intensity. Longitudinal monitoring of land cover changes throughout project lifecycles would provide insights into temporal dynamics and long-term land use impacts, enabling adaptive management strategies that optimize both spatial efficiency and environmental outcomes.

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The authors used SciSpace [https://scispace.com/], ChatGPT [https://openai.com/], Google Gemini [https://gemini.google.com/],

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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