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Land use in onshore wind power-based hydrogen production scenarios: the case of Finland

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Abstract

Background The transition to low-carbon energy systems is essential for climate change mitigation, but it involves new land use pressures, posing potential risks to biodiversity and local communities. This study estimates the land area required for six onshore wind power-based hydrogen production scenarios in Finland, using empirical data from existing wind power plants. By doing so, it contributes to broader discussions on the socio-ecological impacts of energy transitions. It emphasizes the importance of better understanding and addressing land use pressures affecting ecosystems and communities in decision-making, in an effort to build sustainable, low-carbon societies.

Results The analysis is based on 24 wind power areas in Finland, with capacities ranging from 90 to 416 MW. Their direct land use (km^2), turbine spacing area (km^2), installed capacity density (MW/km^2), length of the edge between industrial production sites and their surroundings (km and m/MW), and annual energy production potentials (TWh) were calculated. Using the calculated installed capacity densities and comparing them with the capacity density values obtained from literature, we analyzed the hydrogen value chain from variable wind power production to pressurized hydrogen. Since there are losses at each conversion step, much more wind power, and thus land area, is needed than what the hydrogen output alone indicates. When scaling these findings to fit hydrogen economy scenarios, the land area required for wind power and the infrastructure associated with hydrogen production becomes substantial. To achieve the hydrogen production targets set by the Finnish government using onshore wind power, it might be necessary to install wind power plants covering more than 8% of Finland's total land area, including the spacing area, a figure comparable to the country's arable land area.

Conclusions These findings highlight the scale of land use change associated with hydrogen production powered by onshore wind energy. Standardized, transparent land use assessments, distinguishing between direct, spacing, and total land use, are needed to understand socio-ecological impacts across scales. Expanding assessments beyond techno-economic considerations and individual projects to landscape scales, along with prioritizing energy efficiency, is essential to aligning renewable energy expansion with socio-ecological sustainability and broader sustainable development.

Keywords Onshore wind power, Land use, Socio-ecological impacts, Spatial analyses, Hydrogen, Hydrogen economy, Water electrolysis, Energy transition

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Background

Climate change and the loss of biodiversity are interlinked existential threats that require integrated solutions [1]. While the transition to low-carbon energy systems is urgently needed to address climate change, it involves new forms of land use and land-use changes, a process that, more broadly, is among the main drivers of biodiversity loss [2]. Achieving climate targets involves major transitions in the energy sector, including phasing out fossil fuel use, widespread electrification, improved energy efficiency, and the adoption of alternative fuels such as hydrogen and its derivatives [3]. This transition essentially marks a new phase of reindustrialization, highlighting the need to address emerging socio-ecological issues, often related to land use. These include impacts on biodiversity [4, 5], competition with existing land-based economies [6], and effects on local communities, livelihoods, and cultural landscapes [7–10], all of which are linked to social acceptability [11, 12]. While climate change can create conflicts over land use by driving environmental degradation, resource scarcity, and migration, efforts to mitigate and adapt to climate change, such as large-scale renewable energy development, can also cause conflicts over land. These conflicts vary depending on the context, showing different patterns between developed and low- and middle-income countries, and in some cases have resulted in serious community rights violations and security threats [7, 8]. The production of renewable energy from solar and wind power, or biomass generally requires more land than the production of fossil or nuclear energy [13–15]. Moreover, over 80% of current mineral extraction, often occurring in or near protected areas and wilderness regions, targets minerals that are also needed for renewable energy technologies [16]. However, there are considerable differences within the same energy technology, with wide variation between the minimum and maximum land footprint, highlighting the fact that land use is also highly dependent on deployment and local context. Large-scale land conversion may challenge both climate and biodiversity goals, as land-use change is responsible for over one-third of global greenhouse gas emissions [17]. At the same time, intact ecosystems play a vital role as carbon sinks and storage systems [1, 18]. Without strategic planning, these pressures could outweigh the benefits of climate mitigation, increasing risks to biodiversity and social justice, and potentially undermining broader sustainability objectives, including the UN Sustainable Development Goals [5, 14, 16].

This article estimates the land area required for industrial-scale onshore wind power development combined with electrolyzers under various hydrogen economy scenarios. These land use estimates provide an important indication of the potential socio-ecological impacts associated with this scale of industrial expansion. However, to fully understand and address these impacts, holistic and multidisciplinary research is needed that examines not only the spatial extent but also the other dimensions of land use change, such as effects on biodiversity, ecosystem functions, local livelihoods, and cultural landscapes. We use Finland as an illustrative case, as its stable electricity grid, favorable wind conditions, and low population density provide a technically advantageous setting for large-scale wind-based hydrogen production. In 2023, Finland ranked second among EU member states in terms of the share of gross final energy consumption derived from renewable sources, achieving 50.8% [19]. Within the country's renewable energy portfolio, wind power accounted for approximately 24% of electricity generation in 2024, making it the second most important source of electricity after nuclear power [20]. Finland's total energy consumption (power and heat) in 2024 was 359 TWh, of which electricity consumption accounted for 83 TWh. Of this electricity, 31.2 TWh was generated by nuclear power, 19.9 TWh by wind, 14.2 TWh by hydropower, and 9.5 TWh by biomass combustion. While wind energy constitutes a notable share of electricity production, its contribution represents only around 4% of total energy consumption. Consequently, the decarbonization of the entire energy system and the replacement of fossil fuels with renewable or other low-carbon energy carriers require a substantial expansion of wind, solar, and/or nuclear capacity. Finland has set itself the strategic goal of becoming a major hydrogen producer within the European Union (EU), further reinforcing its relevance as a leading example in this context. Firstly, we analyze the largest existing modern wind power plants, with capacities ranging from 90 to 416 MW, in terms of their total land use (km^2), installed capacity density (MW/km^2), distances between the turbines, edge length (km and m/MW), and annual energy production potential (TWh) (see locations in Fig. 2). Secondly, by applying the capacity density values calculated in this study, along with capacity density figures retrieved from other recent research, we analyze the hydrogen value chain, from variable wind power generation to pressurized hydrogen for industrial use, in order to estimate energy losses at each conversion step and to assess how these losses increase the total wind power capacity needed to produce the target amount of hydrogen. Finally, we translate this into an estimate of the land use required for such hydrogen production.

Low-emission hydrogen, produced mainly from wind and solar power, is widely seen as a key solution for decarbonizing sectors that are difficult to electrify, such as heavy industry and aviation, and for enhancing energy security [21, 22]. This is also true for Finland, where potential applications for hydrogen include industrial processes in which it serves as a raw material for chemicals and a reducing agent (e.g., steel and chemical production), transport (heavy-duty, rail, and maritime), power generation and energy storage, synthetic fuel production, and emerging uses in construction [23]. In addition, the development of hydrogen infrastructure, including production and distribution networks, is needed [23]. In 2023, global hydrogen production was 97 Mt, of which 99% was produced using fossil fuels. It is estimated that low-emission hydrogen could reach an annual production of 49 Mt by 2030 [22]. This implies increased land use pressure from renewable energy installations, but also from the development of supporting infrastructure, such as electricity grids and hydrogen transport networks [24, 25]. Tonelli et al. [26] estimated the global land use impacts of hydrogen production for the year 2050. Their maximum demand scenario, 646 Mt per year, aligns with, or slightly exceeds, the International Renewable Energy Agency's (IRENA) 1.5 °C pathway [27], in which hydrogen and its derivatives are projected to account for up to 14% of total final energy consumption by 2050. This scenario would require 13.5 million km^2 of land if electricity demand were powered by wind energy, which is more than three times the total land area of the European Union (4.23 million km^2). In this context, it is easy to understand that competing uses of renewable electricity, along with its materials, food production, and land and water availability, are considered the most significant limiting factors for a low-emission hydrogen economy [26, 28]. This requires not only improving energy efficiency and savings, but also rethinking how electricity and materials are distributed and managed, potentially through more decentralized approaches, such as partially or entirely off-grid energy systems. For example, Bampaou and Panopoulos [29] summarized in their review, covering around 100 hydrogen valleys, that partially or fully off-grid hydrogen systems include several benefits, such as the ability to optimize production and consumption without the technical or economic constraints of national grids, and the creation of opportunities for local communities to invest in and shape their own energy landscapes. Estimates of the hydrogen economy are often designed with a narrow focus on techno-economic optimization only. Consequently, ecological, social, and cultural criteria are rarely integrated into land use assessments, despite growing recognition of their role as key bottlenecks in the energy transition. In fact, Bampaou and Panopoulos [29] made no mention of land use, ecological impacts, or social values in their review. The same is true of assessments assessing the opportunities for the hydrogen economy in Finland [23, 30, 31]. On the contrary, the green transition within the EU is being accelerated by the weakening of legal protections for nature, permitting green energy development in or near ecologically valuable areas [32]. This trajectory is unfolding despite the fact that the aim of the EU Green Deal, the Union's growth strategy, is to ensure not only carbon neutrality of the EU by 2050, but also that socioeconomic systems remain within planetary boundaries and that nature is restored [33].

The EU's net-zero target and decarbonization of energy-intensive industrial processes and the transport sector rely on hydrogen produced using renewable electricity, known as "green hydrogen". The aim is that, by 2050, green hydrogen will cover around 10% of the EU's energy needs [34]. Finland aims to produce 10% of this EU target by 2030 [23, 35], mainly by using onshore wind power. At present, wind power occupies a relatively modest land area in Finland; however, the pursuit of green hydrogen production, combined with large-scale onshore wind deployment, may significantly increase land-use pressures, intensify impacts on nature, and challenge social acceptance. Wind power capacity in Finland, both on- and offshore, was 8.4 GW at the end of 2024, and is forecasted to grow to 19 GW by 2030 [36]. Electricity consumption is expected to increase from approximately 83 TWh in 2022–2023 to 126 TWh by 2030 and 160 TWh by 2035, primarily driven by industrial electrification, hydrogen production, and data centers [36]. The renewable electricity needed for the green hydrogen economy depends on its ambition level. Sivill et al. [23] analyzed five scenarios, describing alternative pathways for developing Finland's hydrogen economy, which differed in terms of scale, industrial integration, and export ambitions. The Business-as-usual scenarios A and B, requiring 1.1 and 8.8 GW of additional onshore wind capacity, represent conservative pathways focused mainly on hydrogen use in transport. Scenario B also includes hydrogen-based steel production and refinery transformation. The Moderate scenario, which requires 24 GW of additional wind capacity, expands hydrogen use to industrial applications and includes limited European e-fuel exports. The Maximum scenarios A and B, which both require 53 GW of additional wind capacity, describe high-growth pathways with extensive hydrogen use in steel production, refining, and exports. Maximum A assumes that exports are constrained by European demand, whereas Maximum B represents the most ambitious pathway, targeting a 10% European e-fuel market share and assuming that hydrogen infrastructure expansion is not limited by demand. However, based on our results, the required onshore wind power capacities are likely to be slightly higher than what was calculated by Sivill et al. [23]. Moreover, Hydrogen Cluster Finland [30] estimated that by 2045, the available surplus of clean electricity for hydrogen production could range from 80 to 212 TWh (2.4–6.4 Mt/y). However, the corresponding wind power capacity required to meet this demand was not calculated in their report. This article addresses that gap by providing an estimate of the corresponding wind power capacity. Meeting these demands will be in addition to broader electrification needs, thereby intensifying land use pressures related to renewable energy expansion in Finland as well.

Globally, energy systems use only around 0.4%, or 720,000 km^2, of the ice-free land area. However, the projection is that with the ongoing energy transition and growing demand for electricity, this figure will increase by a factor of 2 to 10 by 2050 [15], which would represent more than 10% of the Earth's habitable area. Methodological choices and the underlying assumptions behind them can shape expectations about the energy transition and its land use. These choices can influence how opportunities such as those related to the hydrogen economy are perceived by individuals, communities, industry, or policymakers, affecting both land use policy and energy system planning outcomes. For example, in the United States, around 33% of the land area is considered suitable for wind power development, enabling the installation of 7.3–81.6 TW of wind power plant capacity, depending on the methodological choices [37]. Moreover, Lovering et al. [15] explain that the land-use intensity of electricity (LUIE) is often based on a single or a small number of facilities, or on modelled data. The total land use associated with energy supply, land use change, and resulting socio-ecological impacts are not usually taken into account in assessments of decarbonization pathways, except in the case of land use-intensive bioenergy [38–40]. Furthermore, life cycle assessments of renewable energy also tend to only consider directly impacted areas [41], which carries the risk of underestimating the total land use impacts of wind power, potentially misleading decision-makers and triggering opposition that ultimately slows down the green transition. Moreover, environmental impact assessments are often applied to a limited spatial scope, failing to capture impacts at relevant ecological scales and cumulative effects [42]. To provide a clear understanding of impacts at various scales, Denholm et al. [43] have proposed distinguishing between direct, indirect, and total impact areas when discussing the land use of renewable energy systems. In this study, direct impact refers to the area occupied by the turbines and their share of maintenance roads, the spacing area refers to the area required for the entire power plant, and the total area (not discussed in the article) for all land-use impacts, including power lines and material extraction.

Varying methodologies and assumptions are used to calculate land use (LU). Typically, wind-power plants have a relatively small direct land use impact, in the order of 1 m^2/MWh, depending on wind conditions and topography [44]. A commonly used estimate in Finland for the direct land use impact of a wind turbine, including the cleared area for access roads and the installation site, is 0.02 km^2 per turbine (for example, see [45]). However, while this figure is widely applied in environmental assessments and planning practice, there is no officially published reference or government guideline that formalizes its use. For context and comparable figures, see Denholm et al. [43], Zimmerling et al. [46], and Balotari-Chiebáo and Byholm [47]. The area required for a wind power plant, here referred to as the 'spacing area', is determined by technical site specifications, including wind conditions, topography, and the need to avoid interference between turbines. As modern onshore wind turbines have increased in size and capacity, the spacing required between them has also increased to minimize wake effects, since the wind flow becomes turbulent and slows down after passing through a rotor [48]. When only the immediate, direct land use impact of wind power infrastructure is considered, without accounting for the additional land required for turbine spacing, wind energy stands out as one of the most efficient renewable energy technologies in terms of land use. However, when the spacing area is considered, wind becomes one of the least land-use efficient sources of electricity [14, 15, 38]. Therefore, understanding the land-use associated with wind power and its socio-ecological impacts requires navigating the methodological and definitional differences across spatial scales, as highlighted by several key studies that offer complementary, yet sometimes conflicting, perspectives. A central source of differences between studies is the definition of land use, particularly the distinction between direct land use and spacing area; other differences stem from methodological choices.

Both Trainor et al. [38] and Lovering et al. [15] address the distinction between direct area and spacing area in their studies. Trainor et al. projected the U.S. energy expansion by 2040, estimating that over 200,000 km^2 would be directly impacted by various energy production facilities, and over 800,000 km^2 if the spacing area is included, which is equivalent to nearly 8.5% of the U.S. land area. For wind energy, the intensity of direct land use ranged from 0.34 to 1.37 km^2/TWh, while the inclusion of the spacing area resulted in 126.92 km^2/TWh. Lovering et al. conducted a methodological comparison of LUIE between different energy sources and obtained similar figures for wind power: a median direct land use of 1.30 ± 0.18 km^2/TWh and a spacing area-based impact of 120 ± 17 km^2/TWh. Comparison with other energy sources showed that the land use impact was lowest for nuclear power, at 0.071 km^2/TWh, and highest for dedicated biomass, at 580 km^2/TWh, which also illustrates how methodological clarity is essential for cross-technology assessments.

The complexity highlighted above and the variability in the reported values are discussed in greater detail by

Turkovska et al. [37]. Their review focuses on inconsistencies in land-use (LUR) calculations, especially for wind power. They found that installed capacity densities range from 0.4 to 4950 MW/km^2, with a median of 3.9 MW/km^2, reflecting a spread of values so vast that it results in fundamentally different assumptions about what counts as "used" land. These findings align with those by Lovering et al. [15] in that metrics such as LUIE are only meaningful when the underlying assumptions are standardized. Turkovska et al. [37] warn that such inconsistencies pose a major risk to decarbonization modeling, as projections become highly sensitive to methodological choices. They emphasize the need for transparent, scenario-sensitive metrics to guide land use planning in the transition to renewable energy.

While previous studies largely rely on models or syntheses from literature, Miller and Keith [49, 50] offer empirical validation. After analyzing real-world wind installations in the U.S., they reported an average capacity density of 2.8 MW/km^2, which is consistent with the lower end of the range reported by Turkovska et al. [37], and somewhat below Rinne et al.'s [51] estimates for Finland. Rinne et al. applied a spatial analysis to Finland to evaluate, first, the available land and, second, the area required to generate 50 TWh of wind electricity. Their estimated land area (2,416–2,636 km^2) equated to just under 1% of Finland's land area, with capacity densities of 5.3–7.2 MW/km^2 based on 2015 turbine technologies. These values are higher than those provided by Miller and Keith [49, 50], suggesting that geography, turbine design, and land-use policies significantly affect land-use outcomes. Interestingly, Miller and Keith also found that larger wind projects tend to have lower installed densities, possibly due to land constraints or siting practices. This suggests a scale-efficiency trade-off that is not fully captured in theoretical studies. Taken together, these two studies demonstrate the importance of empirical observations and local conditions for broader land-use modeling.

Finally, Kiesecker and Naugle [14] introduce a broader ecological perspective, emphasizing that renewable energy systems, particularly wind power, can have a greater impact on land use than conventional energy systems when spacing areas are also considered. They estimate a global LUIE for wind of 72.1 km^2/TWh, which falls between the direct and spacing-based estimates of Lovering et al. [15] and Trainor et al. [38]. More importantly, Kiesecker and Naugle argue that 20% of remaining natural lands are at high risk from future energy development, highlighting that the trade-off between land use and biodiversity is at the core of the renewable energy transition. These concerns are also in line with the findings of Turkovska et al. [37] and Miller and Keith [49, 50] that land-use planning must balance not just techno-economic feasibility but also ecological and social integrity. Kiesecker and Naugle call for proactive land-use zoning and mitigation policies, just as Rinne et al. [51] recommend the use of empirical data in spatial analyses and planning. Table 1 presents a compact summary of these results.

In addition to being influenced by methodological choices and underlying assumptions, the socio-ecological impacts of land use resulting from wind power development are highly context-specific, shaped by local conditions, and therefore inherently carry a degree of uncertainty. Typically, less than 10% of the wind power plant project area is occupied by wind turbines and related infrastructure, and much of the area remains available for other land uses [38, 39, 52], a flexibility that is often not possible in many other energy landscapes.

Table 1 Comparison of key studies referenced in this study

Study	Focus	Direct LU (km^2/TWh/a)	Spacing Area (km^2/TWh/a)	Installed Capacity Density (MW/km^2)	Methodology
Trainor et al. [38]	U.S. land projection; direct vs. spacing area	0.34–1.37	126.9	–	National-scale spatial modeling
Lovering et al. [15]	Cross-technology LUIE analysis	1.30 ± 0.18	120.0 ± 17	–	Literature synthesis; standardized comparison across energy types
Turkovska et al. [37]	Methodological inconsistency in LUR	–	–	0.4–4950 (median 3.9)	Meta-review of land use studies
Rinne et al. [51]	Empirical data, Finland: wind potential & land needs	–	48.3–52.7	5.3–7.2	Spatial analysis of wind power plants in Finland; policy scenario modeling
Balotari-Chiebáo and Byholm [47]	Land use metrics, direct and indirect land use	–	–	4.3	Spatial analysis of wind power plants in Finland, Ostrobothnia region
Miller and Keith [49, 50]	Empirical data, U.S.: land-use density	–	126.8	2.8	Spatial analysis of wind power plants in the U.S.
Kiesecker and Naugle [14]	Energy land use vs. biodiversity conservation	–	72.1	–	Global spatial overlay of energy and nature conservation data

However, as wind power deployment grows, there is an increased risk of cumulative ecological or social impacts, such as habitat disruption, species displacement, and landscape change, particularly if projects are concentrated in certain regions [53]. Land use may be restricted, for example, due to noise disturbance [54], land use conflicts [11], and both onshore and offshore wind developments can create conflicts with biodiversity, such as the maintenance of ecosystem integrity, species protection, and sustainable land or seascape management [55–58]. Moreover, there are livelihoods, such as reindeer herding in the Nordic countries, including Finland, that can be affected by wind power development. The construction and operation of wind power can reduce the size of available grazing areas, alter reindeer migration routes, and fragment calving areas. This occurs through barriers such as roads and by causing animals to avoid wind power production sites [9], potentially affecting both the economic viability of herding communities and the preservation of their cultural heritage. Similar avoidance behavior has been observed in a range of other animal species (see, for example, the reviews by Tolvanen et al. [59] and Paulomäki and Pansch [58]). Furthermore, differences in land ownership structures, political stability, and levels of societal development contribute to the unequal distribution of wind power benefits across communities and countries. The size of the spacing area and the number and height of wind turbines directly impact the cultural landscape, which is often measured by distance and visibility; however, as Jerpåsen and Larsen [10] show, the cultural value and deeper significance of the area should also be considered. However, studies that identify changes in the cultural value of the land in wind power areas are scarce. Therefore, defining standardized terminology to discuss the land use impact of wind power at different scales would benefit project comparability, facilitate better landscape-level planning, improve communication between stakeholders, and enable a more consistent assessment of cumulative socio-ecological impacts.

This article contributes to the ongoing discussion on the impacts of renewable energy expansion on land use from a techno-socio-ecological perspective. The aim is to provide numerical references for evaluating the direct and spacing land use impacts of wind power and the potential implications of this for socio-ecological systems. This is done by studying the land use impacts of the forecasted hydrogen scenarios in Finland [23, 30]. The calculations are based on data from operational wind power projects, and we estimate the expected land use impacts by quantifying both the direct land use and the spacing area required in the hydrogen production scenarios evaluated. The separation between direct and spacing impact areas is made for the reasons discussed above. First, due to technical constraints, e.g., wake-effect, turbines cannot be sited closer to each other, which sets a limit on the potential expansion of wind power. Second, the ecological and social impacts of wind power development are closely associated with the entire project area, extending beyond the immediate vicinity of the turbines themselves. Finally, we offer recommendations for advancing a sustainable and just energy transition, paying particular attention to land use considerations and the role of spatial and socio-ecological data in guiding decision-making.

Methods

To enable a meaningful assessment of installed capacity densities and their associated land use impacts, it is essential to address the current lack of standardization in calculation methods and terminology. Different studies and projects often use varying methodologies and assumptions to define project boundaries and capacity ranges, making direct comparisons challenging. In this study, we adopt a transparent and clearly defined methodological approach to improve comparability and provide robust estimates of direct land use intensity and spacing area related to wind power development (Fig. 1). Installed capacity densities can be estimated using different approaches. These include empirical methods using data from existing wind power plants, as well as theoretical models that estimate turbine spacing as a multiple of the rotor diameter (typically 5–7 times the rotor diameter) [37]. Empirical methodologies include the convex hull method [53], Voronoi polygons [49, 50], buffered or buffer–spacing–cluster approaches [37], and the use of reported figures from official documents [43]. According to Turkovska et al. [37], the convex hull, Voronoi polygon, and reported-figure methods produce results of similar magnitude. In this study, the convex hull and Voronoi polygons were employed to calculate land use and installed capacity densities. To account for the spacing area of wind power projects, a 500-meter buffer was applied beyond the outermost turbines. For comparison purposes, the land use was also calculated using the commonly applied direct land use impact of 0.02 km^2 per turbine.

Wind power plants larger than 90 MW were selected for the study in order to obtain a representative selection of the largest and most modern wind power production sites in Finland. In January 2025, there were a total of 32 wind power plants in Finland with a nominal capacity of more than 90 MW. However, spatial data were not available for all of these sites. In some cases, areas with spatially uniform turbine distributions were operated by multiple companies and recorded as separate power plants in official data. For the purposes of this analysis, these areas were treated as a single power production

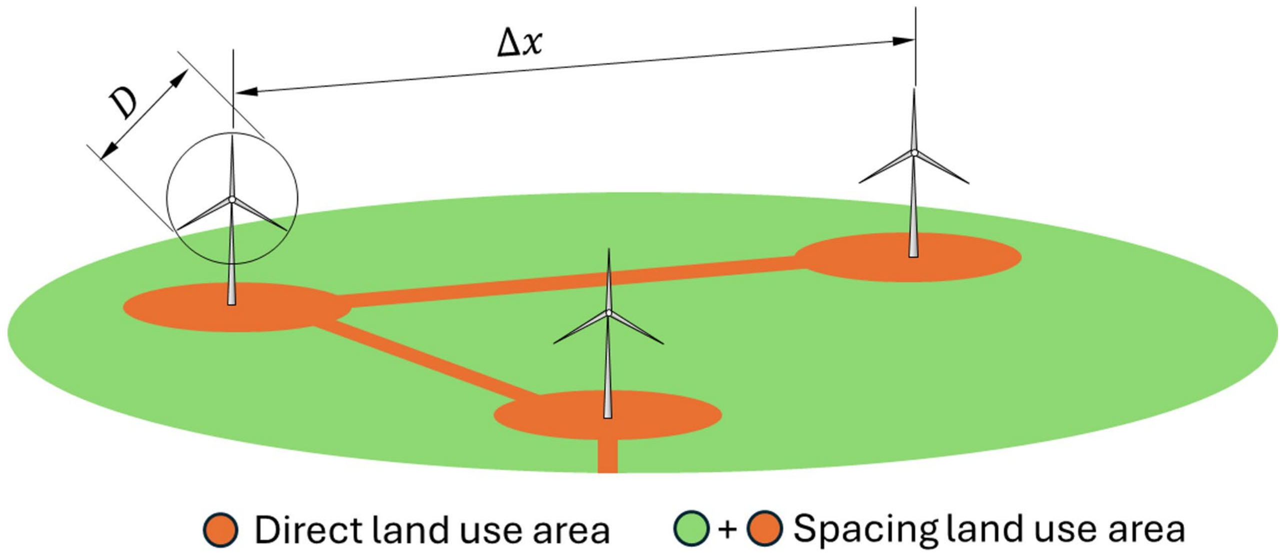

Fig. 1 Direct and spacing land use areas used in this research. D is the rotor diameter, and Δx is the distance between the turbines

area, resulting in 24 distinct wind power areas. These areas included a total of 750 turbines, accounting for approximately 42% of the 1,778 wind turbines installed in Finland as of January 2025. Spatial data for wind turbines were retrieved from a database maintained by the Finnish Transport and Communications Agency [60]. The studied wind power areas are distributed along the western side of Finland, extending from south to north, providing broad geographical coverage (see Fig. 2).

We used the concepts of installed capacity density (MW/km^2) and energy density (TWh/km^2), a_P and a_E, respectively, to analyze the land use of wind power plants in Finland. Installed capacity density is the total installed rated power, P_0, of N turbines per used land area of the power plant site, A_t.

$$a_P = \frac{P_0}{A_t} = \frac{\sum_{i=1}^{N} P_{0.i}}{A_t}$$

Installed capacity density does not reflect the actual energy output of a wind power plant; rather, it indicates the theoretical maximum power that could be generated if all turbines were operating continuously at wind speeds above their rated capacity. A_t is the land area required to secure optimal wind conditions for all turbines in the power plant, including the buffer defined above. This is called the spacing area. If turbines are installed too close to each other, significant wake losses can occur, leading to reduced power generation. Energy density is the electrical energy that can be generated from a given area over the course of a full year, 8,760 h.

$$\begin{aligned} a_E &= \frac{E}{A_t} = \frac{1}{A_t} \sum_{i=1}^{N} \int_{t=0}^{8760\,h} P_i(t)\,dt \\ &= \frac{P_0 \times 8760 \times C_f \times \eta_A \times \eta_O}{A_t} \\ &= a_P \times 8760 \times C_f \times \eta_A \times \eta_O \end{aligned}$$

The capacity factors listed in Wind Atlases refer to a single, free turbine, not including wake losses in the turbine grid. To calculate the energy densities in Table 2, we assumed a constant turbine array efficiency, $\eta_A = 0.9$, and operational efficiency, $\eta_O = 0.9$, including availability and icing losses [51, 61]. Both installed capacity density and energy density were calculated for the 24 largest wind power areas in Finland. With this information, we were then able to estimate how much land would be needed if the hydrogen scenarios using onshore wind power in Finland were implemented.

Installed capacity densities based on the buffered convex hull

A buffered convex hull represents an adjusted, minimum spatial boundary around wind turbines and can be used to calculate the installed capacity densities for wind power areas [37, 54]. It reflects the operational spacing area of each wind power plant. Convex hulls were generated using ArcGIS Pro, enclosing the buffered turbines and creating a boundary that reflects the spatial extents of the 24 wind power production areas. The installed capacity density was calculated for each power production area defined by the set of turbines and their rated power.

Initially, each turbine was assigned a 500-meter buffer zone, accounting for its potential influence area. This

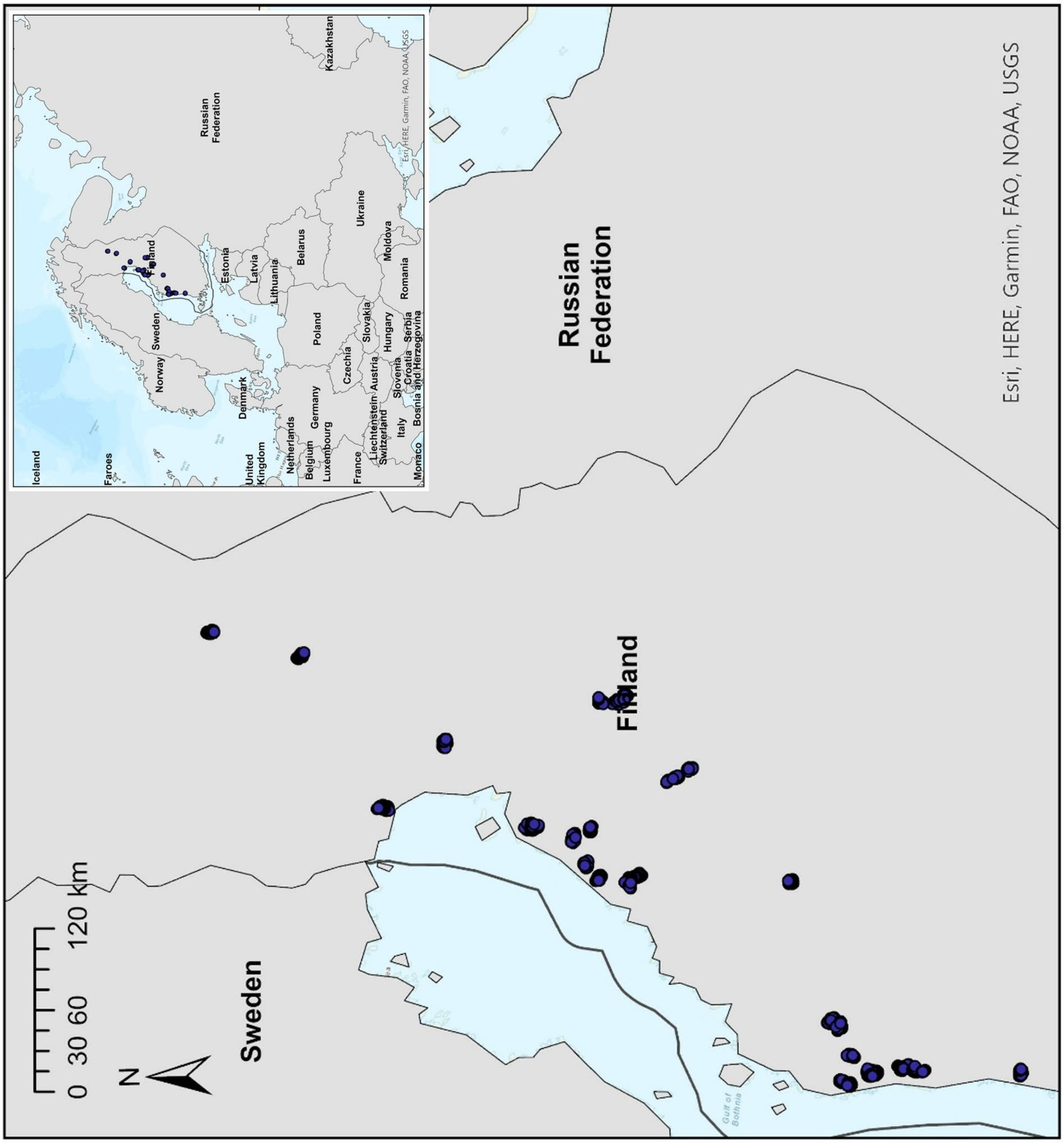

Fig. 2 Map of Finland and study locations

Table 2 Summary of results, in descending order according to installed plant capacity

ID	P_0	C_f	E_t	N	A_t	$a_{P.t}$	$a_{P.V}$	$a_{E.t}$	LUIE	$\Delta x/D$	L	L/P_0
–	MW	–	TWh/a	–	km^2	MW/km^2	MW/km^2	GWh/a/km^2	km^2/TWh/a	–	km	m/MW
1	416	0.36	1.064	69	82	5.06	8.74 ± 6.05	12.9	77.4	N/A	37.6	90
2	381	0.36	0.973	56	47	8.11	8.68 ± 2.23	20.7	48.3	6.06 ± 1.93	26.2	69
13	360	0.35	0.893	58	54	6.70	7.65 ± 2.62	16.6	60.1	6.33 ± 2.38	28.4	79
3	242	0.38	0.652	39	33	7.42	8.65 ± 3.12	20.0	50.0	5.16 ± 1.84	23.6	97
5	215	0.29	0.442	44	35	6.16	6.97 ± 2.83	12.7	78.9	N/A	24.1	112
4	211	0.37	0.555	41	58	3.67	5.23 ± 2.88	9.6	103.7	N/A	32.0	152
6	188	0.34	0.454	33	20	9.24	9.71 ± 2.31	22.3	44.9	4.86 ± 1.40	17.4	92
7	186	0.34	0.449	30	27	6.80	7.33 ± 2.01	16.4	61.0	N/A	20.2	109
20	174	0.46	0.567	28	18	9.51	10.40 ± 3.36	31.1	32.2	5.03 ± 1.59	16.6	96
8	165	0.45	0.527	30	20	8.16	8.94 ± 2.59	26.1	38.4	N/A	17.9	108
9	154	0.46	0.503	28	26	5.90	6.80 ± 2.34	19.3	51.9	N/A	20.1	131
11	143	0.38	0.384	23	16	8.70	9.13 ± 2.40	23.4	42.6	5.30 ± 1.61	15.1	106
23	139	0.33	0.326	29	26	5.45	6.04 ± 2.07	12.8	78.3	6.53 ± 2.43	20.3	146
12	132	0.34	0.318	24	17	7.78	8.84 ± 3.29	18.8	53.3	5.20 ± 2.15	16.5	125
14	130	0.37	0.342	21	21	6.17	7.16 ± 2.55	16.2	61.8	6.14 ± 2.26	18.5	142
15	124	0.39	0.343	23	16	7.92	8.80 ± 3.12	21.9	45.6	N/A	16.3	131
16	119	0.35	0.296	34	39	3.08	4.85 ± 2.60	7.6	130.9	7.75 ± 7.29	25.5	214
10	106	0.33	0.249	18	15	7.00	7.51 ± 1.93	16.4	61.0	N/A	15.1	142
17	103	0.39	0.286	24	27	3.85	5.14 ± 1.76	10.7	93.8	6.60 ± 4.01	26.7	259
18	102	0.39	0.282	17	11	9.35	9.99 ± 2.66	25.9	38.7	6.48 ± 1.89	12.4	122
19	97	0.42	0.289	17	17	5.83	7.21 ± 3.59	17.4	57.5	6.43 ± 3.12	16.0	165
21	93	0.37	0.244	15	13	7.04	7.46 ± 1.86	18.5	54.1	6.00 ± 1.69	14.0	151
22	92	0.39	0.256	28	18	5.01	5.25 ± 1.14	13.9	72.1	6.48 ± 1.63	16.8	182
24	90	0.39	0.250	21	13	7.04	7.15 ± 0.87	19.5	51.3	5.36 ± 1.32	13.1	145

ID: identification number of the wind power plant; P_0: rated power (MW); C_f: capacity factor; E_t: annual electricity production (TWh/a); N: number of turbines; A_t: total (spacing) area (km^2); $a_{P.t}$: total installed capacity density (MW/km^2); $a_{P.V}$: turbine specific installed capacity density (MW/km^2); $a_{E.t}$: total energy density (GWh/km^2/a); LUIE: land use intensity of electricity production (km^2/TWh/a); $\Delta x/D$: spacing/rotor diameter ratio; L: perimeter of the wind power plant area (km); L/P_0: edge length per installed capacity (m/MW). The total installed capacity of the 24 wind power areas studied is 4.16 GW, the electricity generation potential 10.9 TWh/a, the area is 669 km^2, the energy density 61.1 km^2/TWh/a, and the installed capacity density is 6.2 MW/km^2, respectively. Capacity densities were obtained from the Global Wind Atlas [63] buffer zone was applied for three main reasons. First, wind turbines cannot typically be sited at a shorter distance due to technical and safety constraints; the figure of 500 m was also supported by the distance calculations conducted in this study (see results, which are in the order of 50% turbine spacing). Second, the environmental and land use impacts of wind turbines extend beyond their immediate footprint, making the buffer a justified means of accounting for their broader spatial influence. Third, in the analysis of installed capacity density, a buffered convex hull approach accounts for turbine spacing constraints, providing a more realistic estimate of the land area per unit of power produced compared with relying solely on turbine point locations.

Installed capacity densities based on Voronoi triangulation

Installed capacity densities were also calculated using the Voronoi triangulation method [49, 50]. Voronoi triangulation was conducted in ArcGIS Pro using Thiessen polygons, which partition the space within the 24 wind power production areas so that each polygon represents the area closest to a single turbine. Unlike convex hulls, which simply define the smallest convex boundary enclosing all turbines, Voronoi polygons can extend indefinitely into the surrounding space when turbines are not evenly distributed, leading to unreasonably large areas for edge turbines. To address this issue, Voronoi polygons were clipped using the convex hull of each wind power production area, ensuring comparable spatial boundaries for installed capacity density calculations. This approach prevents distortions in density estimates and reflects the actual operational footprint of each wind power production area more accurately.

Each Voronoi polygon gives an estimate of the land area allocated to a specific turbine. By dividing the turbine's power by its corresponding Voronoi area, a localized installed capacity density (MW/km^2) is obtained. Voronoi polygons also give information on the spatial distribution of turbines. If the polygons vary greatly in size, this indicates uneven turbine distribution; larger polygons suggest sparse turbine placement, while smaller ones indicate denser clusters.

Unlike convex hull-based capacity density calculations, which average installed capacity over a broader area, Voronoi-based densities highlight localized variations, showing where power production is most concentrated within individual power plants. Overall, Voronoi-based installed capacity densities provide a spatially detailed view of power distribution, complementing the broader perspective given by convex hull-based calculations.

Distances between turbines

To complement the installed capacity density calculations, the distances between neighboring turbines were analyzed. This was achieved by performing a spatial join to identify turbines that share a Voronoi polygon vertex, followed by calculating the distances between neighboring turbines using the Haversine equation in Python [62].

Turbine spacing plays a critical role in determining annual energy generation within wind power plants. Distance calculations complement installed capacity density assessment with a more detailed understanding of how turbine placement affects energy output per unit area and, consequently, power plant layouts and land use efficiency. The minimum spacing is influenced by technical constraints [48], ensuring that turbines operate efficiently without excessive wake loss effects. Additionally, factors such as wind resources, topography, and competing land uses impact turbine placement, ultimately affecting the total area allocated to wind power development and the resulting installed capacity density values.

For distance calculations, only power plants with one turbine type were selected to ensure that the rotor diameter was included correctly. This resulted in a total of 20 wind power production areas, which were further reduced to 16 due to the limited availability of data on rotor diameter.

Analysis of the energy value chain from variable wind power to a pressurized constant mass flow rate of hydrogen for industrial use

The objective of this section is to estimate how much installed wind power capacity and land are required to reach the existing hydrogen production scenarios for Finland, 6–113 TWh (0.2–3.4 Mt) [23] and 212 TWh (6.4 Mt) of hydrogen [30]. In addition, we compare our results with the global land area estimates provided by Tonelli et al. [26], who evaluated the space required to meet a high-end hydrogen production scenario of 21,500 TWh (646 Mt).

Only a fraction of the installed rated capacity of the wind turbine fleet can be used, defined by the product of capacity factor, turbine array efficiency, and the operational efficiency of the whole power plant. In this research, we are interested in unlimited production potentials and not realized production as part of the current national and Nordic electricity system, with curtailment and cannibalization effects. Therefore, instead of using actual production figures, we obtained the maximum capacity factors for the study areas using the Global Wind Atlas [63] for a single free turbine (Table 2).

Considering the wake losses and turbine array efficiency, η_A; efficiencies in plant operation, η_O; in the electrolyzers, η_E; transformers and rectifiers, η_{ACDC}; and the balance of the plant, η_{BoP}, we can calculate the energy converted into the chemical energy of hydrogen, E_{H_2}.

$$E_{H_2} = P_0 \times 8760 \times C_f \times \eta_A \times \eta_O \times \eta_{ACDC} \times \eta_E \times \eta_{BoP} = m_{H_2} LHV_{H_2}$$

From this, the required installed wind capacity P_0 can be calculated as follows:

$$P_0 = \frac{E_{H_2}}{8760 \times C_f \times \eta_A \times \eta_O \times \eta_{ACDC} \times \eta_E \times \eta_{BoP}} = \frac{m_{H_2} LHV_{H_2}}{8760 \times C_f \times \eta_A \times \eta_O \times \eta_{ACDC} \times \eta_E \times \eta_{BoP}}$$

Thus, the required land area for this directly follows from:

$$A = \frac{P_0}{a_P}$$

Ensuring a continuous supply of hydrogen to an industrial facility necessitates a stable grid connection, the integration of electrical energy storage systems (e.g., battery energy storage), and/or hydrogen storage infrastructure to buffer the variability between wind power generation and electrolyzer operation. Alternating current (AC) power generated from variable wind sources and the grid must first be converted to direct current (DC) to be compatible with electrolyzer operation. Based on Godula-Jopek [64], we assume for transformer + AC-DC a conversion efficiency of $\eta_{ACDC} = 0.95$. Furthermore, we assume that a proton exchange membrane (PEM) electrolyzer is used at 30 bars pressure with an efficiency of $\eta_E = 0.63$ ([65] for 10 MW PEM electrolyzers, model PSM units). In addition, we assume that H_2 is also used at 30 bars for the industrial customer. Pressurized hydrogen storage is assumed to operate at a maximum of 300 bars, with an efficiency (LHV-basis) of 98.5% (isentropic and mechanical efficiencies were assumed to be 0.75 and 0.95, respectively, for both compression and expansion, assuming no H_2 leakage). The balance of the electrolysis plant, including a compressed gas energy storage system and other auxiliaries, is assumed to be 7.5%, i.e., η_{BoP} = 0.93 [64, 65]. We assume that these efficiencies do not depend on the system load. However, the efficiencies of electrolyzers and compression systems are greatly affected by load, and in variable renewable energy systems, the share of partial loads is significant. Therefore, in reality, this might result in a larger consumption of energy, and the actual land use impact would be even greater than predicted here.

Results

Table 2 presents a summary of the results, providing an overview of the wind power production areas and illustrating how their spatial configuration, installed capacity, and turbine layout relate to land use intensity. A_t captures the broader spatial impact zone and represents the area effectively influenced by the wind power plant. Installed capacity densities were calculated using two methods: convex hull and Voronoi triangulation. The convex hull method yielded an average installed capacity density of 6.7 MW/km², while the Voronoi approach resulted in a higher average of 7.7 MW/km². The weighted average installed capacity density using both methodologies is 6.23 MW/km², reflecting the actual spatial performance across all wind power production areas. See Fig. 3 for examples illustrating the varying spatial extents of the wind power production areas.

The total installed capacity density, $a_{P.t}$, reflects the intensity with which the land is used for power production. The turbine-specific installed capacity density, $a_{P.v}$ ± SD, gives insight into the variability of siting within power plants; it assesses the spatial uniformity and

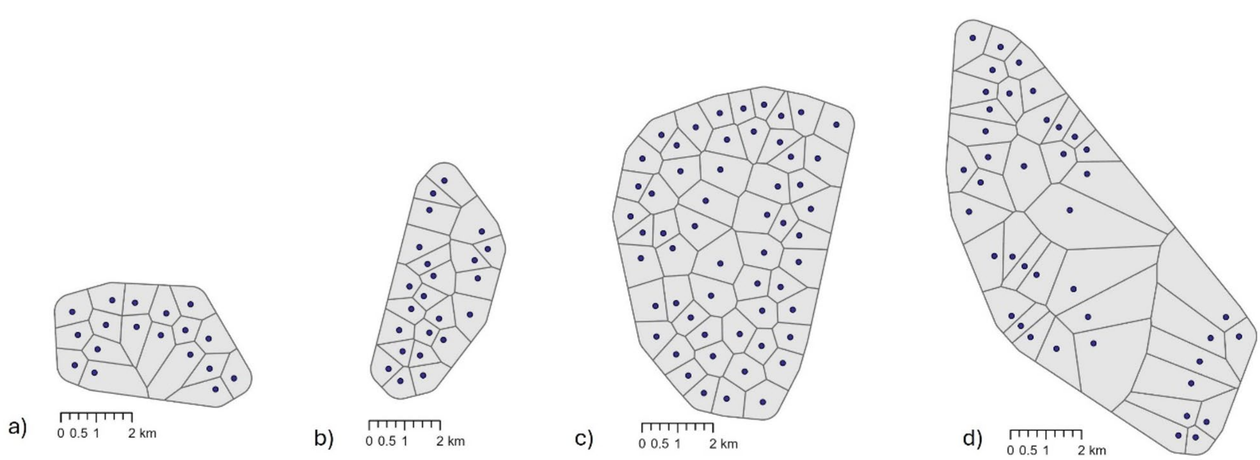

Fig. 3 Examples of the distribution of turbines in four study areas: **a** power plant ID 10, capacity density 7.0 MW/km^2, **b** power plant ID 15, capacity density 7.92 MW/km^2, **c** power plant ID 2, capacity density 8.11 MW/km^2, and **d** power plant ID 4, capacity density 3.67 MW/km^2. The outer boundary of each wind power production area, shown as a convex hull, encloses all turbines, while the Voronoi polygons for individual turbines illustrate the area within the site that is closest to each turbine

efficiency of power production at the turbine level. The same can also be assessed based on the distance between the nearest turbines, $\Delta x / D \pm SD$, where larger ratios imply more dispersed layouts, which reduces the wake effect but can increase land use and potential environmental disturbance. Finally, the edge length, L, and the edge length per installed capacity, L/P_0, describe the spatial footprint and linear extent of the power plant.

For optimal power generation, neighboring turbines must be spaced sufficiently to allow for wake recovery at the prevailing wind speed. In addition, in the direction of the dominating wind, spacing is typically greater than in the perpendicular direction. Because of this, the distance between wind turbines is usually at least 600 to 1,000 m (5 to 9 × the rotor diameter) [48]. Thus, although the land area cleared for a single wind turbine is small, the spacing required between turbines means that the entire wind power plant area can extend over a very large area, depending on the number of turbines. In this research, the mean distances varied between 792 and 1,054 m (4.9–7.8 × the rotor diameter), and the median distances between 738 and 967 m (4.5–6.6 × the rotor diameter), with considerable variation within some individual wind power production areas (Fig. 4).

Assessment of land use impacts using various metrics

Table 3 presents the estimated installed wind power capacity, direct and spacing-related land use, and the share of Finland's land area (excluding lakes) needed to meet different hydrogen production scenarios (6–212 TWh) using the metrics from various studies and land use figures calculated in this research. The calculations are based on 7.2 MW turbines and a range of installed capacity densities (3.08–9.51 MW/km²), demonstrating how land use estimates vary depending on assumptions about spatial efficiency. As the table shows, the direct land use remains relatively low, even in the most ambitious scenario of producing 6.4 Mt (212 TWh) of hydrogen. In contrast, the spacing area is projected to be substantial, ranging from 15,300 to 47,400 km².

To better understand the impact of wind conditions and the efficiency of the different process components, Fig. 5 presents the reduction of land use by improving different efficiencies (C_f, η_O, η_{ACDC}, η_E, η_{BoP}) one at a time while keeping others constant, and the effect of improving the performance of all components at the same time (η_T). We did not study the impact of installed capacity density and turbine array efficiency, since they are strongly coupled and it is not possible to simply present the $\eta_A(a_R)$ correlation. However, increasing installed capacity density decreases land use and therefore has a significant impact on the amount of land required, as already shown in Table 3.

Discussion

The results demonstrate how spatial configuration, installed capacity, and turbine layout determine the land use intensity of wind power production areas. The spacing area (A_t) covers the broadest impact zone of a wind power plant, representing the land affected by electricity production, although most of the land area remains available for other uses, such as forestry. These large projects may nonetheless increase the risks of landscape fragmentation, induce impacts on biodiversity and wildlife, and

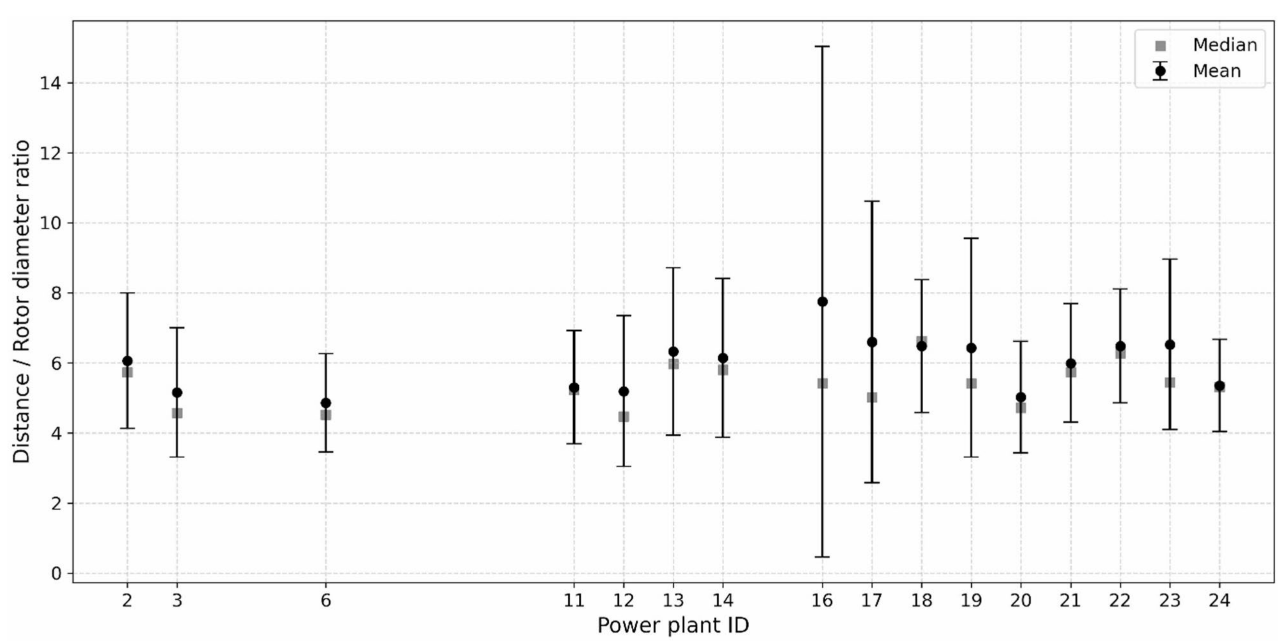

Fig. 4 Mean and median distances between neighboring wind turbines across 16 wind power areas

Table 3 Installed wind power capacity, turbine count, and land use for various hydrogen production scenarios (6–212 TWh/a)

Hydrogen scenarios					Spacing LU (km^2) and fraction of Finland's land area (%)					
					Literature			This research		
H_2	H_2	P_0	N	A_d	Turkovska	Lovering	Kiesecker & Naugle	Low	Ave.	High
TWh/a	Mt	GW	-	km^2	3.90	3.17	5.28	9.51	6.20	3.08
6	0.19	4	612	12	1,129	1,389	834	463	710	1,430
					0.4%	0.5%	0.3%	0.2%	0.2%	0.5%
14	0.43	10	1,357	27	2,505	3,081	1,851	1,027	1,576	3,172
					0.8%	1.0%	0.6%	0.3%	0.5%	1.0%
61	1.83	42	5,829	117	10,761	13,235	7,952	4,413	6,769	13,626
					3.5%	4.4%	2.6%	1.5%	2.2%	4.5%
111	3.33	76	10,607	212	19,582	24,084	14,470	8,030	12,317	24,795
					6.4%	7.9%	4.8%	2.6%	4.1%	8.2%
113	3.39	78	10,798	216	19,934	24,518	14,731	8,175	12,539	25,242
					6.6%	8.1%	4.8%	2.7%	4.1%	8.3%
212	6.36	146	20,258	405	37,399	45,997	27,637	15,337	23,525	47,356
					12.3%	15.1%	9.1%	5.0%	7.7%	15.6%

The left side of the table presents the required installed turbine capacity (using 7.2 MW turbines), the number of turbines (N), and direct land use A_d(calculated at 0.02 km^2 per turbine). The right side of the table presents the spacing land use (km^2) and the fraction of Finland's land area (304,000 km^2) based on capacity densities from the literature (3.17–5.28 MW/km^2) and installed capacity densities (3.08–9.51 MW/km^2) calculated in this research

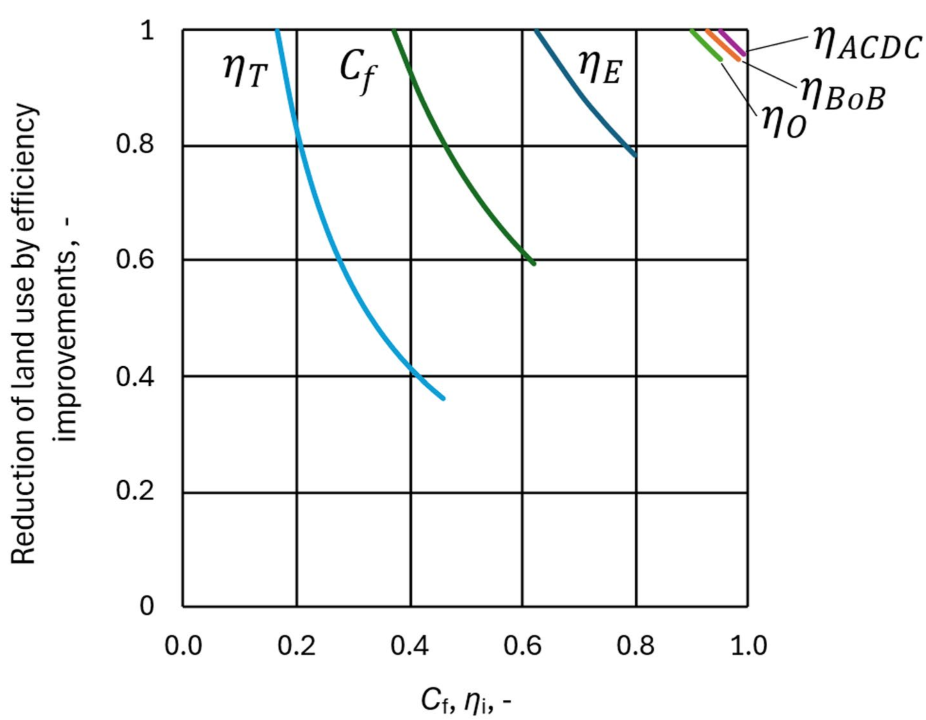

Fig. 5 Reduction in required land area through component efficiency improvements, first by varying each component individually while keeping the others constant, and then by applying them simultaneously, η_T. The efficiencies were varied as follows: $C_f = 0.37 \rightarrow 0.62$, $\eta_E = 0.63 \rightarrow 0.80$, $\eta_O = 0.9 \rightarrow 0.95$, $\eta_{BoP} = 0.93 \rightarrow 0.98$, and $\eta_{ACDC} = 0.95 \rightarrow 0.99$, respectively

generate conflicts with other land uses. This underlines the importance of aligning planning and siting decisions with the local context, also taking into account the cumulative effects of other developments and implementing mitigation measures to reduce adverse impacts.

Installed capacity densities were estimated using two complementary methods: convex hull and Voronoi triangulation. The convex hull method resulted in an average installed capacity density of 6.7 MW/km^2, whereas the Voronoi method produced a higher value of 7.7 MW/km^2. The difference is due to the way each method represents the spatial extent of a project. The convex hull is more suitable for capturing the full land area associated with a power plant (e.g., for zoning or environmental impact assessments). In contrast, the Voronoi approach better reflects functional turbine spacing and reveals how local conditions shape turbine clustering. The weighted average across both methods was 6.23 MW/km², showing that smaller, high-density areas tend to skew unweighted averages, while the weighted mean more accurately represents the overall spatial performance across sites (see Fig. 3 for examples).

Figure 4 shows relatively consistent turbine spacing across the areas, with mean distances of 4.9–7.8D and medians of 4.5–6.6D, largely within typical ranges. In most areas, the mean spacing exceeds the median, indicating slightly right-skewed distributions. This implies that while most turbines are spaced relatively uniformly, some are located at substantially greater distances. This can reflect boundary effects, where turbines at the edge of the site have fewer neighboring turbines, or irregular site geometry, or environmental or other land use constraints. The largest variability (e.g., ID 16) suggests heterogeneous layouts, potentially due to fragmented land availability or complex terrain.

Looking at installed capacity density, we see that the total, $a_{P.t}$, is a useful measure for understanding the intensity with which land is used for power production. The observed variation across sites means that these are different and that there is no single value for capacity density that could be used in land use estimation, particularly at smaller spatial scales. Lower densities suggest greater land use impact per MW, while higher densities point to more efficient spatial land use. At the turbine level, turbine-specific installed capacity densities, $a_{P.v}$ ± SD, provide additional insights into the uniformity with which turbines are sited within individual power plants. This measure reflects the internal spatial efficiency of power production and points to differences in layout strategies. Similar insights are gained from the ratio of nearest-neighbor distances to rotor diameter, Δx /D ± SD. Higher values signify dispersed layouts, which may mitigate wake effects but at the cost of increased land use and potential ecological disturbance.

Finally, the edge length (L) and edge length per installed capacity (L/P_0) quantify the spatial footprint and linear extent of wind power plants. A high L/P_0 ratio indicates fragmented layouts, which can increase infrastructure needs (e.g., roads, cabling) and intensify edge-related ecological and social impacts per unit of installed capacity, due to greater habitat fragmentation or visual and noise disturbance. Taken together, these findings demonstrate how turbine layout, spacing, and overall configuration not only determine the energy output and land use efficiency of wind power plants, but also the spatial extent of their socio-ecological impact.

Land use metrics therefore play a critical role in shaping the outcomes and expectations related to the land demand of wind power. The choice of metrics influences how spatial extent and energy efficiency are calculated, and what kinds of figures are reported regarding land use intensity. Different methodological approaches can lead to varying interpretations of land use, which in turn affect planning decisions, broad-scale ecological and social sustainability assessments, and public perceptions of wind power development plans. Terminological and methodological variability complicates comparisons between studies and can also shape and even mislead political decision-making by framing the perceived trade-offs and benefits of wind energy deployment.

The potential land use in different hydrogen production scenarios (6–212 TWh) calculated in this research illustrate how estimates vary and emphasize the importance of careful interpretation when assessing the spatial implications of wind power expansion (Table 3). As shown in this research, direct land use remains relatively low, even in the most ambitious hydrogen scenario, with a production of 6.4 Mt (212 TWh). In contrast, the spacing area is projected to be substantial, ranging from 15,300 to 47,400 km², accounting for nearly twice the total size of Finland's arable land (22,500 km²) at the maximum end of the range. Based on the metrics from this study, the spacing area of Finland's current installed wind capacity (8.902 GW) is estimated at 1,400–1,500 km², or about 0.4% of the country's total land area.

The question of land use change associated with renewable energy development is particularly important for Finland's forests, which cover approximately 75% of the country's total land area. Although the area directly occupied by forest clearings for roads and turbine installation sites is relatively small compared to other commercial forest uses and the overall extent of forests in Finland, the concern remains relevant. Most wind power projects are located on forested land, and with the spacing area, wind power affects extensive areas beyond the direct construction zones. Balotari-Chiebáo and Byholm [47] found that deforestation rates in wind power project areas in Finland were substantially higher than in control areas, and that turbine micro-siting showed little avoidance of mature forests, with a minimal preference for areas of lower ecological value, such as transitional forests. However, while restrictive land use policies reduce the land area available for wind power development, this can be, according to Rinne et al. [51], at least partly offset by technological improvements that allow for greater energy output from smaller areas, as also demonstrated in this research. This discussion is topical, as demonstrated by a recent statement by the Finnish government

[66] proposing that, unless a wind power plant is in an area specifically designated for wind power development in regional land use plans, turbines should be placed at least eight times their total height away from existing residential buildings. If the proposal is passed, this would result in a minimum distance of 2–3 km between wind turbines and residential areas. Such a policy could push wind power development further away from settlements, but could simultaneously increase environmental pressures on remote and natural areas, such as continuous forests. The proposal exceeds the typical setback distances in many other European countries, which generally range from 500 to 1,500 m, depending on national and regional regulations [67]. For instance, typical minimum distances range from 1,000 to 1,500 m in Austria, 600–700 m in Belgium, and 400–1.100 m in Germany.

There is only limited scientific knowledge available concerning the impacts of wind power development on boreal forest species. Based on available literature reviews, we know that the spacing area represents a broader zone of influence that can have varying effects on forest species, some negligible or short-term, but others more lasting and potentially extending over several kilometers beyond the boundaries of the wind power plant [58, 59]. Taking these aspects into account, and considering that the range of areas required based on the installed capacity density of the 24 largest wind power plants in Finland varies from 15,300 km^2 to 47,400 km^2, the importance of conducting a thorough siting analysis, from broad, power plant scale plans to individual turbine siting considerations within power plants, is emphasized (see Fig. 3 for examples of plants with high and low installed capacity density).

The need to clarify methodologies and terminology related to land use of renewable energy expansion is further highlighted when comparing our results with those of a recent study on wind power potential in Finland. Karjunen et al. [68] projected a theoretical, technological maximum wind power production scenario of 2,500 TWh, corresponding to about 952 GW of installed wind power (assuming a capacity factor of 0.37, a wake array efficiency of 0.9, and a combined icing and availability efficiency of 0.9). Using the range of installed capacity densities calculated in this research, 3.08–9.51 MW/km^2, the production scenarios of Karjunen et al. [68] result in spacing areas between 100,000 and 309,000 km^2, implying that approximately 33% to over 100% of Finland's land area would be allocated to industrial wind power production. The direct land use area needed for approximately 132,000 7.2 MW turbines would be 2,644 km^2. This underscores that technical potential assessments alone are insufficient to fully capture or understand the land use implications of wind power development. Finally, as discussed in relation to global impacts, Tonelli et al. [26] estimated a land area of 13.5 million km^2 to meet the maximum global hydrogen production scenario of 646 Mt using wind power. Based on our results, excluding de-icing-related production losses, the corresponding land area ranges from 1.5 to 4.6 million km^2, depending on the assumed installed capacity densities (ranging from 3.1 to 9.5 MW/km^2). These results are rough estimates, and when extrapolating them to other countries or locations, it is important to note that geography, turbine technology, and land use policies can significantly influence achievable capacity densities. Furthermore, our estimate covers only the land needed to produce pressurized hydrogen from wind power. If refined e-fuels, such as e-methane or e-methanol, were to be produced, as considered by Tonelli et al. [26], the land area required for wind power generation would increase substantially.

We identify three main pathways to improve efficiency and thereby reduce land use impacts. First, the largest reduction in land use can be obtained by increasing the capacity factor. By installing turbines at the best wind locations, we can efficiently save land or sea area. The highest capacity factors are available offshore [63]. Second, land use area can be reduced by investing in the greatest electrolyzer efficiency, which can have an impact of up to 0.8 on efficiency in land use. Third, the most modest way to reduce land use is to balance the plant and auxiliary systems, which are already quite efficient today, and their further development has only a minor impact on land use in comparison to the first two pathways. However, if all improvement options were implemented, land use could be reduced by more than 60% (See Fig. 5). Similar efficiency analyses for all renewables, including PV, wind, hydro, geothermal energy, and biomass, would be highly valuable, as energy yield per area differs considerably between sources.

To effectively balance and decrease the overall land use impacts of renewable energy expansion, measures and policies addressing energy saving and efficiency become increasingly vital, as they can substantially reduce the overall land use of renewable energy. Trainor et al. [38] demonstrate that energy conservation measures can prevent more land from being allocated to energy use than nearly any other single policy measure, with land-saving effects comparable to or exceeding those of major land use drivers, such as urbanization and agriculture. This highlights the critical role of energy savings and efficiency via technological improvements in reducing the spatial pressures associated with energy transitions. However, these benefits must be viewed in light of the Jevons paradox, which suggests that savings and improvements in land use efficiency can, paradoxically, lead to increased overall energy consumption if they are not coupled with sufficiency-oriented policies. Therefore, maximizing the land-saving potential of energy efficiency requires not only technological improvements, but also demand-side measures that promote sufficiency and limit total energy use. Energy systems of the future are also expected to become more and more decentralized, with an increasingly important role for off-grid solutions and energy communities. These developments can improve land use efficiency, enhance energy resilience, enable local ownership, and support the integration of renewable energy sources at multiple scales, which also allows for better integration of ecological, societal, and local landscape values into planning.

Conclusions

The transition to a green hydrogen economy, as outlined in the EU Hydrogen Strategy and pursued nationally in Finland, entails extensive spatial demands associated with renewable electricity generation, namely wind power, as demonstrated in this research and supported by previous studies. Moreover, estimates of land use can vary by orders of magnitude depending on the chosen methodology. The expansion of wind power to meet growing demands for low-emission electricity, including green hydrogen production, can have wide-ranging impacts on nature and local communities, depending on siting decisions and mitigation efforts.

The choice of methodology can substantially affect land use estimates for future low-carbon energy systems, potentially leading to over- or underestimation of land demands. Moreover, using data from a single installation or a small, non-random sample, or modelled rather than real-world generation data, can misrepresent the true distribution and extent of land use [15, 51]. On the other hand, other methodological choices, such as accounting only for the direct impact of turbines and access roads or the entire spacing area within a project's boundaries, can dramatically affect land use estimates. Using only the direct area underestimates the true spatial influence of wind energy, while using the spacing area may overstate the exclusive land use area [14, 15, 37]. Reporting both direct and spacing areas is therefore essential, as land within the spacing area is often available for other uses, such as agriculture, forestry, or grazing. Even so, turbines cannot be sited any closer due to technical constraints, and the spacing area defines the minimum boundary necessary to assess ecological, social, and landscape impacts. Although renewable energy systems, such as wind power, are land-intensive at the local scale, there are significant opportunities to develop wind energy in locations that minimize harm to biodiversity [6] and local communities. By integrating spatial conservation prioritization with renewable energy planning, it is possible to identify areas where wind energy can be expanded with minimal overlap with high-priority conservation lands [4]. Taking into account different land uses at appropriate scales during the planning process further supports the alignment of energy development with existing land uses, helping to minimize impacts on biodiversity while maximizing potential co-benefits. Neglecting this consideration may result in land use emerging as a critical bottleneck to achieving urgent decarbonization targets.

If land use assessments are too narrowly defined and the total spacing area is inadequately analyzed or not properly discussed with local communities, the actual socio-ecological impacts of wind power development may be far greater than anticipated during the permitting phase, potentially leading to widespread public resistance [7, 11]. Rapid acceleration of the energy transition, if not accompanied by adequate social participation and inclusive planning processes, may risk weakening public acceptance and engagement. In addition, efforts to reduce the spatial impacts of wind power through policy restrictions and technological development can create trade-offs. Concentrating turbines within smaller areas may require taller structures to access higher wind speeds, which can improve efficiency but may also increase landscape and visual impacts.

The following limitations should be considered when interpreting the results. First, capacity densities vary substantially between large wind power plants and are highly site-specific, depending on terrain, ecological, and societal conditions; therefore, the estimates reflect a range of possible land-use outcomes rather than precise projections. Second, the analysis assumes constant efficiencies for system components such as electrolyzers, although in practice efficiency varies with load and is typically lower outside the design point, meaning that installed wind capacity and land use may be underestimated. Third, the research did not consider potential interactions with ecological and social systems, or the cumulative socio-ecological impacts of increased wind power capacity. A saturation point for the maximum land area for wind power likely exists, reflecting both technical constraints and socio-ecological limitations, and will be examined in more detail in future work.

To conclude, the transition to low-carbon energy production is essential for bringing atmospheric carbon levels back within safe limits, but it is far more than a technical undertaking. The methodologies used to calculate the land use of energy projects are not mere technical details; the decisions taken fundamentally shape the resulting energy landscapes, with impacts on local biodiversity and communities. Distinguishing between direct, spacing, and total land use is essential for evaluating the full implications of renewable energy deployment and avoiding misleading conclusions about the land use impacts of different energy technologies. Accurate, transparent, and standardized methodologies are also necessary to inform policy decisions and guide the deployment of low-carbon technologies. Equally important is placing greater emphasis on energy saving and efficiency, which can significantly reduce overall demand and ease pressure on land and ecosystems if coupled with supportive policies. There is a need for improved understanding of the broader, landscape-scale impacts of wind power development. Currently, assessments of land use and the resulting environmental and social impacts are often limited to individual projects and narrow spatial scopes, limiting their ability to capture relevant ecological scales and account for cumulative effects across larger areas. The application of a consistent and transparent methodological approach to calculating land use at different scales is essential to ensure that the expansion of renewable energy aligns with broader sustainable development goals, supporting biodiversity protection and sustainable land-use.

List of symbols

A	Area, km^2
a_P	Installed capacity density, MW/km^2
a_E	Energy density, TWh/a/km^2
C_f	Capacity factor
m_{H_2}	Mass of hydrogen, Mt, million tons
E_t	Annual electricity production, TWh/a
E_{H_2}	Energy in hydrogen (LHV basis), TWh/a
η_A	Wind turbine array efficiency
η_O	Operational wind power plant efficiency, availability, and icing losses
η_{ACDC}	AC to DC conversion efficiency
η_E	Electrolyzer efficiency (LHV basis)
η_{BoP}	Balance of plant efficiency
LHV_{H_2}	Lower heating value of hydrogen 120 MJ/kg
L	Perimeter of the wind power plant area, km
LU	Land use
LUIE	Land use intensity of electricity production, km^2/TWh/a
P_0	Rated power, MW
$\Delta x/D$	Spacing/rotor diameter ratio

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Author contributions
Original idea, conception, and design of the work: MJ and HP; Acquisition, analysis, and interpretation of data: HP and MJ; Writing of the original draft: HP and MJ; Writing, editing, and revision: MJ, HP, and ELA. All authors have approved the submitted version.

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Data availability
The wind turbine dataset that was used to generate spatial files and used for analyses during the current study was retrieved from a database maintained by the Finnish Transport and Communications Agency (Traficom), available in: www.ais.fi/en/obstacle-data-csv-files. Data used in this study was retrieved on 26 December 2024.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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