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Beyond the Footprint: Empirical Land Use and Environmental Patterns of Wind Energy in Mountainous Landscapes

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Abstract

In a world of over 8.2 billion people, the land footprint of any infrastructure has become a critical factor in sustainable spatial planning. In the case of wind energy deployment, land use primarily involves hardstands, access roads, and interconnection infrastructure. This study focuses on Greece, a country with complex mountainous terrain, where Wind Power Stations are predominantly installed along ridgelines and slopes. Using GIS analysis based on digitization of actual on-site infrastructure, we measured the land coverage of wind energy facilities with a total installed capacity of nearly 2.6 GW. We found an average land-use intensity of 0.33 hectares per megawatt (ha/MW), placing it near the lower end of the range reported in international literature. For the subset of projects with available energy yield data, the value was 1.58 square meters per megawatt-hour (m^2/MWh). This approach provides one of the largest, nationally representative, infrastructure-based estimates of actual wind energy land use in complex terrain. Applying these findings to the onshore wind deployment targets of Greece's National Energy and Climate Plan (NECP) for 2030 and 2050, we estimate that only 0.02–0.03% of the country's land area will be occupied by wind energy infrastructure. By comparison, lignite mining has already transformed approximately 0.13% of the national territory—almost four times more land than projected for wind energy use in 2050. Further spatial analysis was conducted to identify the land use categories associated with wind energy infrastructure, while for the subset of projects located within Natura 2000 protected areas, the types of affected habitats were also examined. Treating land coverage as a standalone proxy for environmental impact should be avoided; the study demonstrates the need for a context-sensitive interpretation of land use, accounting for ecological context, land-use compatibility, and positive co-benefits, such as improved forest accessibility, fire prevention works and recreation parks. Repowering maximizes land efficiency by extending wind farm lifetimes without expanding their footprint.

Keywords: land-use planning; wind energy; renewable energy; complex terrain; Greece; environmental impacts; Geographic Information Systems; compensatory measures; repowering

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1. Introduction

In a world where nearly 40% of the planet's ice-free land is devoted to agriculture (cropland and pasture) for a population that now exceeds 8 billion, the land footprint of every human activity matters [1]. During the 20th century, global population rose 3.7-fold while the harvested cropland area increased by only ~40%; the apparent efficiency gain was achieved through a dramatic increase in energy inputs into farming—on the order of ninety-fold—underscoring how energy underpins modern land use [2].

The climate crisis now necessitates a rapid transition away from fossil fuels towards renewables and widespread electrification; major outlooks project electrification roughly doubling by mid-century [3]. Notably, in the first half of 2025, renewables overtook coal in the global electricity mix for the first time on record [4]. Within this transition, land implications are particularly important, as human activities already affect most of the Earth's ice-free land [5]. Estimates indicate that more than 53% of ice-free land has been directly modified [6], around three-quarters is significantly altered and nearly 95% shows some indication of human influence [5,7]. Yet, the environmental consequences depend not on the extent of modification alone but on the specific ways in which land is transformed [5]. The most extensive altered ecosystems are grazing land and cropland followed by settlements, industries, and transport corridors [8]. Notably, impacts tend to be greater where land is converted to impervious (sealed) surfaces, which alter surface-energy balance and increase flood risk.

Against this backdrop, current global land use for electricity production is about 72 Mha, i.e., on the order of half a percent of ice-free land, with ~80% associated with hydropower reservoirs [9]. Accordingly, the land footprint of the electricity system is, at present, relatively small in global terms yet poses localized siting challenges and trade-offs with ecosystems, agriculture, and conservation, especially as renewable deployment accelerates.

For onshore wind, land occupation arises primarily from hardstands, access roads, and interconnection works (substations, lines, control rooms). Crucially, the vast majority (≈96–99%) of the area within typical wind–plant boundaries is not covered by permanent infrastructure and thus remains available for other uses; sealed areas are largely limited to turbine foundations and small ancillary pads [10].

This sealed-versus-unsealed distinction is central to interpreting "land take". Treating the entire plant envelope (spacing) as "occupied" substantially overestimates direct transformation [11,12], whereas mapping only the actually modified surfaces—such as roads, pads and substations—provides a more accurate measure of physical disturbance [13]. For context, scenario work has even defined the wind "footprint" narrowly as the sealed base of the tower [14], highlighting how definitions alone can shift results by orders of magnitude.

Beyond the definition of direct land occupation, recent high-impact studies have shown that broader spatial and land-use contexts can indirectly shape assessments of wind energy land requirements [15]. At the macro scale, siting constraints and land-eligibility criteria—arising from environmental protection, settlement buffers, or policy exclusions—can substantially influence the spatial distribution of wind development and the total land area required to meet energy targets. These factors can alter the overall extent of development without modifying the underlying types of physical interventions involved [15]. In parallel, life-cycle assessments that explicitly account for land-use change demonstrate that the environmental performance of wind farms depends on pre-existing land cover, as carbon losses from vegetation and soils vary markedly across ecosystems, particularly in forested areas [16].

Greece offers a pertinent test case: complex terrain concentrates viable wind resources in mountainous areas, where roads may be longer than those in flat terrains, but surfaces are largely unsealed and multifunctional [17–19]. Building on national and local datasets, we assembled a sample of 129 Wind Power Stations (WPSs) totaling 2605.5 MW (1245 turbines) and quantified actual land occupation from mapped infrastructure. The average land coverage was 0.33 ha/MW, consistent with ranges reported in the international literature for direct disturbance; for the subset with capacity-factor data, we also express land occupation as area per energy yield with a mean of 1.58 m^2/MWh [11,13,20].

Although this analysis focuses on Greece, the underlying conditions are broadly representative of onshore wind deployment in topographically complex regions worldwide, including parts of southern and central Europe (the Balkans, the Iberian Peninsula, and Austria), Scandinavia, and mountainous areas of Asia and North America [13,21–23]. Unlike flat lowland settings, such terrains typically require longer access roads and more extensive interconnection works, making Greece a representative case for assessing wind energy land use under complex terrain conditions.

Recent studies have examined the land-use implications of onshore wind energy using diverse spatial definitions and methodological approaches, resulting in substantial variation in reported land-use intensities [24,25]. Empirical, infrastructure-based assessments show that actual land transformation is primarily driven by terrain, land cover, and access requirements, rather than turbine spacing alone [13,20]. Other analyses emphasize broader spatial constraints and land eligibility criteria, demonstrating that planning exclusions and siting limitations can markedly increase estimated land requirements without altering the nature of physical interventions [15]. However, the inconsistent treatment of "land occupation"—particularly the frequent conflation of direct physical disturbance with spacing or eligible areas—limits comparability across studies and hampers interpretation for planning and policy. Addressing this gap, the present study provides a nationally representative, GIS-based quantification of actual wind energy land occupation in a topographically complex setting, offering harmonized metrics directly applicable to spatial planning and environmental assessment.

We argue that the "land take per MW (or per MWh)" is not a sufficient index of a wind energy project's environmental impacts; a multi-criteria assessment is required for such a purpose. Precisely because land take from wind energy is limited—its global land footprint is small in absolute terms—careful siting and minimization of direct disturbance can substantially reduce environmental impacts while accommodating large-scale decarbonization.

We review Greek legal provisions [26] and mitigation practices that minimize and offset disturbance (e.g., legally mandated reforestation as a positive-balance measure) and formulate practical recommendations to reduce land occupation in complex terrain (e.g., road reuse and optimized turbine micro-siting to minimize new disturbance). Throughout, we clearly distinguish between actual modified area and total (spacing) area.

In Greece, as in many regions [27–29], surveys indicate that onshore wind energy enjoys broad public support, while opposition to specific projects tends to arise from smaller groups concerned about landscape change, biodiversity impacts, and local disturbances (e.g., noise, shadow flicker, construction-related dust, and close-range visual impacts) [30–32]. Several studies also note that these concerns can, in some cases, be influenced by limited information or NIMBY attitudes [30–32]. Empirical environmental assessments nevertheless indicate that, despite localized and mostly moderate impacts, wind farms are widely recognized as contributing positively to climate mitigation and the socio-economic environment [33].

2. Materials and Methods

2.1. Data Collection

The methodological scheme below (Figure 1) presents the structure on which the analysis is based.

To assemble the necessary data for this study, we collaborated closely with the technical and environmental departments of many member companies of the Hellenic Wind Energy Association (HWEA). The Hellenic Wind Energy Association (HWEA) includes nearly all companies active in Greece's wind energy sector (approx. 90% of them).

Specifically, for the land coverage analysis, we gathered data from 129 WPS—122 in operation and 7 under construction—across the Greek territory, sampling across gradients in topography and Wind Turbine Generator capacity (WTG). Regarding the operational projects, those analyzed correspond to 39.5% of the total operational capacity in Greece by the end of 2025 (Table 1).

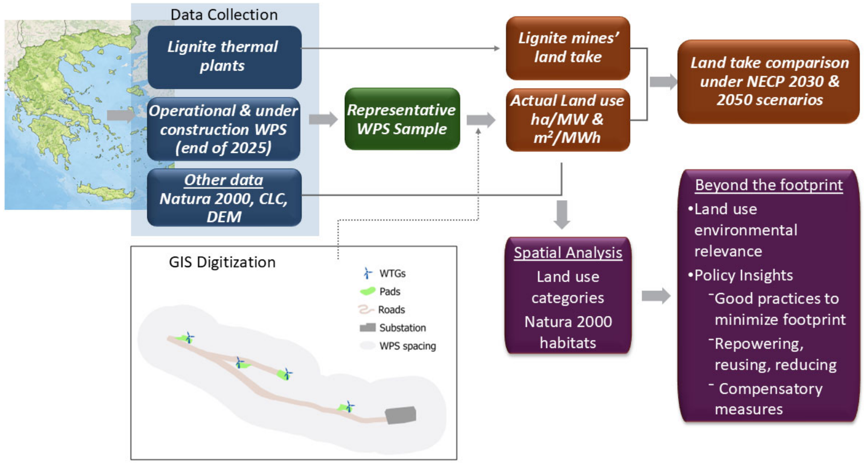

Figure 1. The methodological scheme of the study, summarizing the main analytical steps, from data collection and GIS processing to land-use indicators, comparative analysis, and policy insights. Note: WPS Wind Power Station, CLC Corine Land Cover, DEM Digital Elevation Model, NECP National Energy and Climate Plan, WTGs Wind Turbines.

Table 1. Sample of WPS investigated to calculate land coverage of entire facilities.

		Total Numbers in Greece (End of 2025)	Sample Investigated in the Study
Operational projects	Number of WPS	527	122 (23.2%)
	Number of wind turbines	3093	1178 (38.1%)
	Installed Capacity (MW)	5695	2251.2 (39.5%)
Under construction	Number of WPS	14	7 (50.0%)
	Number of wind turbines	107	67 (62.6%)
	Installed Capacity (MW)	570.5	354.3 (62.1%)

Apart from the size of the sample examined, several other criteria were applied to ensure that robust and representative results are obtained: turbine size (capacity range 600 kW to 6 MW, rotor-diameter range from 44 m to 163 m), topography of the site, altitude of the site (altitude range between 22 m and 2055 m), size of the WPS (expressed as installed capacity in MW), and geographic spread of the sample (both in continental Greece and the islands). The locations of the WPS examined are illustrated in Figure 2.

First, all operational WPS in Greece by the end of 2025 were retrieved from the database of the Hellenic Wind Energy Association (HWEA), also presented in HWEA's GIS application [34]. Specifically, by the end of 2025 there were 3093 operational wind turbines in Greece with a total capacity of 5695 MW. The information provided by the HWEA database included basic data for each WPS: name, geographic location, layout, installed capacity, number and type of wind turbines, year of construction, project company, etc.

For the WPS under construction, we downloaded installation polygons and related wind-turbine points from the online database of the Regulatory Authority for Energy of Greece [35].

As part of the present study, a large amount of additional data was obtained. It included data on interconnection works and access roads to the site, as-built drawings of the projects, annual energy yield, approved land-intervention permits with accompanying drawings, as well as permits related to reforestation works implemented as part of the construction of a wind energy project (Informative Administrative Act) [36].

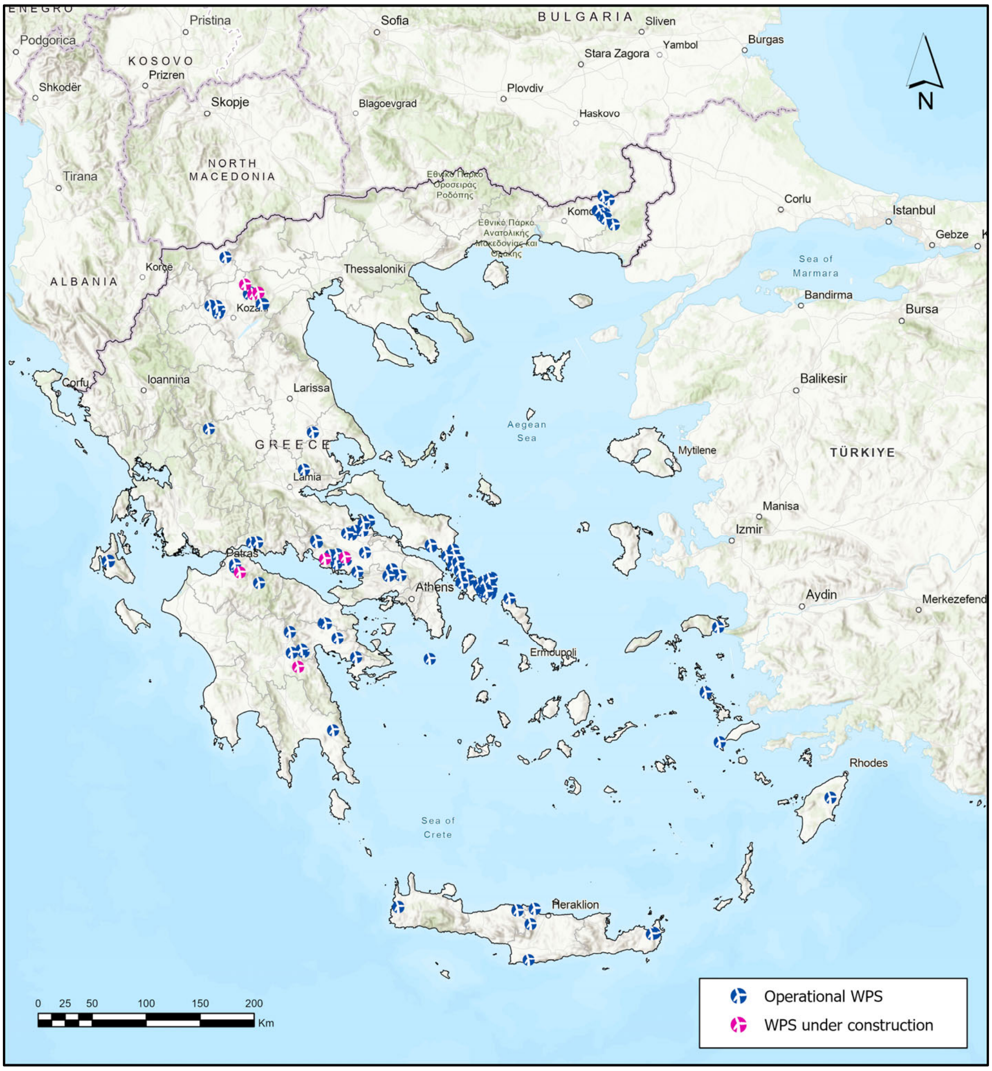

Figure 2. WPS examined in the present study.

For the purposes of this study, the authors collaborated with and coordinated a large multidisciplinary group of scientists working in the environmental and construction departments of wind energy companies operating in Greece, which are members of the HWEA. These teams processed the digital data of their respective projects and provided the authors with detailed analytical information regarding the spatial footprint of their infrastructure. In several cases (corresponding to 984.08 MW of installed capacity), the original GIS footprint files were also made available to the authors. For this subset, in addition to the work already conducted by the companies, high-resolution satellite imagery was used to cross-check the facility footprints provided.

In order to match the locations of the wind turbines with the corresponding altitude, we used the European Copernicus Digital Elevation Model (DEM)—specifically the GLO-30 product, which has a spatial resolution of approximately 30 m, an absolute vertical accuracy of less than 4 m (90% linear error), and an absolute horizontal accuracy of less than 6 m (90% circular error) [37].

Based on the above, we categorized facilities into two turbine-size classes, i.e., with an installed capacity up to 3 MW ($\leq$3.0 MW, or "small" WTGs) and with greater than 3 MW (>3.0 MW or "large" WTGs) and they are presented in Table 2.

Table 2. Distribution of WPS sample by turbine-size categories (in all cases the total sample is 129 WPS).

Variable	Category Classes	
Turbine Size	≤3.0 MW	>3.0 MW
WTG's number	79	50

For the digitized study areas, we also compiled a geospatial database in ArcGIS Pro ver.3.2.2 that included (1) the digitized project polygons; (2) land cover categories from the Corine Land Cover 2012 and 2018 (CLC 2012, CLC 2018) datasets, classified according to typology (Levels 2 and 3) and linked to the corresponding ecosystem types defined by the MAES (Level 2) classification system [38–40]; and (3) the Natura 2000 network of protected areas.

More specifically, for Greece's Natura 2000 network, we used EEA vector boundary datasets [41]. The network covers 58,859 km^2 and comprises 446 terrestrial and marine sites: 215 designated as Special Areas of Conservation (SACs), 181 as Special Protection Areas (SPAs), 24 designated as both SAC and SPA, 24 as Sites of Community Importance (SCIs), and 2 designated as both SCI and SPA [42]. Overall, Natura 2000 spans 27.59% of the country's land area and 19.6% of its marine territory [42].

To identify the habitat types of terrestrial SACs intersected by the sample of WPS, we used the official terrestrial habitat-type polygons produced by the project "Developing large-scale (1:5000) spatial data infrastructure for protected terrestrial areas of the Natura 2000 network" [43]. This ERDF-funded project (Operational Programme Digital Convergence—Partnership Agreement 2007–2013) aimed to refine the outer boundaries of terrestrial SACs and SPAs and to update, describe, and map terrestrial habitat types in 241 SCIs at 1:5000 scale, under the coordination of the Ministry of Environment and Energy [43].

Finally, to compare land coverage between wind facilities and lignite-based electricity generation, we quantified the surface area of lignite mines in Greece. Three major mines were considered, depicted in Figure 3, each subject to Strategic Environmental Assessments under the national de-lignitization process. These assessments delineate expropriation zones as the maximum areas to be excavated [44–47]. Actual mining areas, which represent only a fraction of these zones, were digitized using above mentioned assessments data and satellite imagery in ArcGIS.

2.2. Data Analysis

2.2.1. The Metrics of Land Use by Wind Energy

In the relevant literature, several approaches have been proposed to quantify the land requirements associated with wind energy. These are most often expressed as land area per unit of installed capacity (e.g., ha or km^2 per MW) [13] or, conversely, as installed capacity per unit of land (MW/km^2) [10]. Both metrics essentially represent different expressions of power density [48].

With regards to the area considered, two main methodological approaches can be distinguished. The first includes studies that quantify only the actual land physically transformed by infrastructure elements of wind farms [11,13,49]. Terms such as *"land transformation," "direct impact area," "disturbed area,"* and *"footprint"* are typically used to describe this category.

The second approach involves the estimation of the "total area" [10] or *"spacing"* of a wind plant, defined as the outermost bounds of turbine placement. The actual disturbed area represents only a small fraction of this total area—on average 1.8%, with a maximum of 4.7% [50]. Two main arguments are typically employed to justify the use of this broader metric:

1. a technical argument, related to the minimum distance required between turbines in order to mitigate wake effects and avoid energy yield losses [10];
2. an environmental argument, associated with the extended zone of turbine visibility, noise propagation, light, etc., which is considered relevant to broader landscape impacts [12,21].

However, defining the total area is inherently ambiguous and subject to methodological challenges. Various geometrical techniques—such as fixed buffer zones, prescribed distances based on rotor diameters, or Voronoi polygon methods—produce substantially different results even for the same projects [10,11,48].

In this view, the first approach is the most objective and comparable metric of wind energy land occupation, and thus we adopt this one in the present study focusing exclusively on the actual land altered. This enables consistent comparison with the land footprint of other human activities on a finite planet.

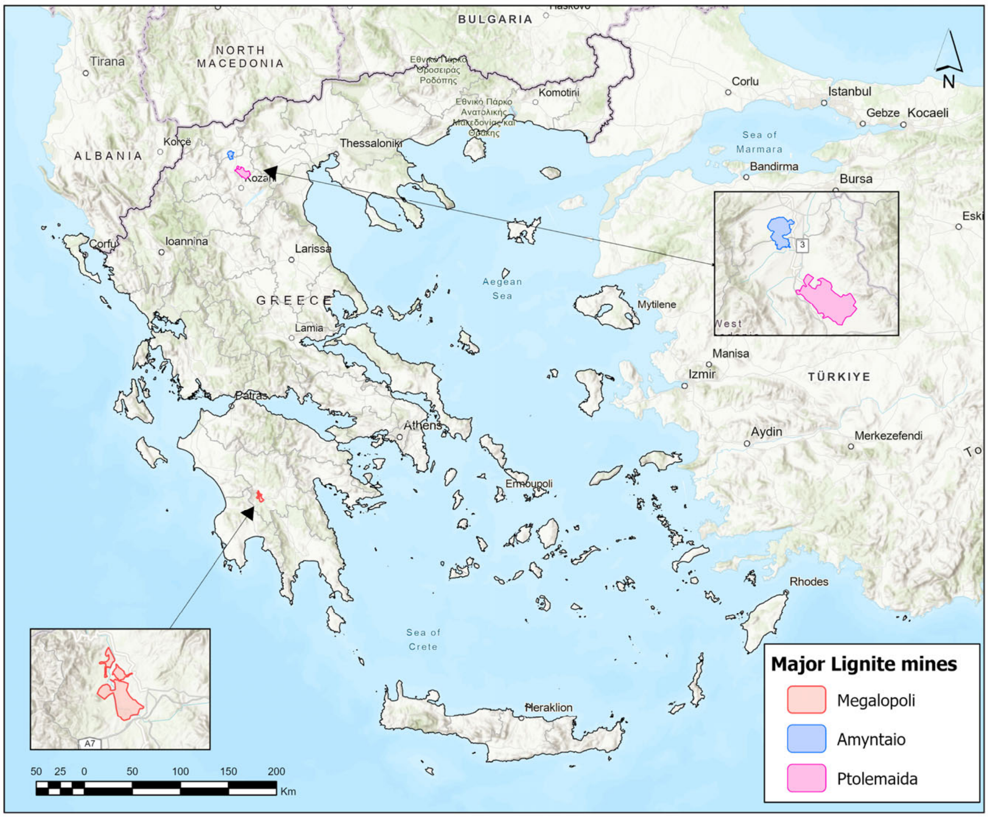

Figure 3. Major lignite mines in Greece and the area they cover in comparison to the total area of Greece.

Accordingly, two complementary indicators are calculated for the WPS examined:

(A) Land Use Intensity per capacity installed (in ha per MW),

$$\mathrm{LUI_P} = \frac{A}{P}$$

where P is the installed capacity of the WPS (in MW) and A corresponds to the cumulative area of all permanent physical interventions (in ha). Specifically, A includes all interventions associated with the construction of a WPS such as crane pads and laydown areas for turbines, newly built or widened roads (subtracting the surface of pre-existing roads), additional ramps for turbine transport (so-called pulling areas), substations, control rooms, high-voltage pylons and their erection platforms.

It is noted that A does not include land indirectly required upstream for component manufacturing (e.g., mining of materials for turbines or cables). This exclusion follows common practice in the literature [10,11,49] and facilitates comparability across studies.

(B) Land-Use Intensity per electricity generated each year (in m^2/MWh/y)

$$\mathrm{LUI_E} = \frac{A}{E_y}$$

where A as previously defined, and E_y is the annual energy yield of a WPS.

2.2.2. Data Processing and Statistical Analysis

First, all land interventions caused by the WPS, as defined above, were considered in the study. As the national industry association, HWEA has gained direct access to owner-verified project data sets. Accordingly, the Land-Use Intensity per installed capacity ($\mathrm{LUI_P}$) was computed from company-provided engineering materials, rather than relying solely on remote sensing, which can introduce errors (e.g., including roads or other facilities not related to the WPS, or missing assets that do belong to the WPS, such as an overhead transmission line). Our dataset covers 2605.51 MW and comprises two main data streams: engineering CAD drawings or GIS shapefiles for 984.08 MW and document-based compilations for 1621.43 MW. Where needed, high-resolution imagery was used only for cross-checks and consistency validation.

For all data, where WPS shared common facilities (e.g., connection to the same substation), the relevant area was allocated proportionally among the participating WPS according to each plant's installed capacity. For digitized data, all the land plots related to a specific WPS were merged into a single polygon feature. For the digitizing process, we used high-resolution imagery and the on-screen digitizing method. We used the World Imagery basemap in ArcGIS Pro 3.2.2 (Esri, Redlands, CA, USA, Maxar, Earthstar Geographics, GIS User Community), which provides approximately 1 m resolution across most of Greece. Consistent with the life-cycle framing of May et al. (2021)—who quantify biodiversity impacts per unit of energy produced rather than capacity alone—we also report a land-use intensity normalized by annual generation (m^2/MWh), alongside the per-MW metric [51].

Accordingly, for the Land-Use Intensity per Electricity generated each year ($\mathrm{LUI_E}$), we took the total land coverage of each WPS as estimated above (converted from hectares to m^2) and divided it by the annual energy yield provided for specific projects. Specifically, the annual energy yield was available for WPS totaling 950.00 MW (775.75 of them correspond to digitized WPS). Within this subset, 653.60 MW corresponds to operational projects and 296.40 MW to under-construction projects. For operational projects, the energy yield corresponds to actual operational data, while for projects under construction the energy yield was taken from detailed on-site wind measurements and the resulting energy studies conducted by the project companies.

While validated annual energy yield data were available only for the 950.00 MW subset described above, we examined whether LUIE estimates could be extended to the full sample (2605.51 MW) by using capacity-factor layers from the Global Wind Atlas [18,19]. Although the Global Wind Atlas provides high-quality mesoscale wind resource estimates, its capacity-factor layers are not intended for project-level yield assessment. In particular, the GWA provides capacity factors for different generic turbine classes (e.g., Class I, II, III), whereas turbine class information was not available for each WPS in our dataset. When compared with verified production data for the 950 MW sub-sample, GWA-based estimates showed substantial deviations, likely due to differences in turbine characteristics, micrositing, and operational conditions. To ensure methodological robustness, $\mathrm{LUI_E}$ calculations were therefore restricted to the subset of 950.00 MW with validated annual energy yields.

For the statistical analysis, project-level actual land take per installed capacity (ha/MW) was computed and summarized using capacity-weighted statistics (weights equal to installed capacity in MW or number of wind turbines), while unweighted project-level values are reported for comparison.

The capacity-weighted mean was calculated as $\bar{x}_w = \sum w_i x_i / \sum w_i$ and dispersion was estimated using the unbiased weighted standard deviation with Bessel correction,

$$s_w = \sqrt{\frac{\sum w_i (x_i - \bar{x}_w)^2}{\sum w_i - \frac{\sum w_i^2}{\sum w_i}}}$$

where x_i denoted the land-take value of each WPS and w_i its corresponding installed capacity.

Ninety-five percent confidence intervals (CIs) for weighted means use the Kish effective sample size $n_{\text{eff}} = \left(\sum w_i\right)^2 / \sum w_i^2$ and two-sided t quantiles. Small ($\leq$3 MW) and Large (>3 MW) turbines were compared by inspecting capacity-weighted means and their corresponding CIs. In addition, the difference between the two weighted means was evaluated using a normal approximation for the difference of independent means, with the standard error of the difference computed as the square root of the sum of the group specific variances.

Second, a spatial intersection was performed between CLC 2018 for Greece and the digitized polygons. This overlay produced a dataset in which each polygon carries a unique CLC code. Where polygons intersected code "121: Industrial or commercial units (artificial surfaces)", we consulted CLC 2012 to identify the pre-installation land-cover class for the specific WPS area; for those portions, the 2018 code 121 was replaced with the corresponding 2012 land-cover class.

For analysis, we matched the CLC categories (Levels 2 and 3) with MAES ecosystem types (Level 2) to consolidate the following high-level classes: (i) Urban ecosystems; (ii) Cropland; (iii) Grassland; (iv) Forest; (v) Heathland and shrub; and (vi) Sparsely vegetated land. Details on all land categories within the digitized project areas are provided in Section 3.2.

Third, a spatial intersection was performed between Greece's Natura 2000 network and the digitized polygons, while the same method was used to identify the terrestrial habitat types intersected by the WPS sample.

Finally, to quantify land disturbance from lignite mining, we first digitized the mining areas using spatial information reported in the relevant studies [45–47]. We then refined these delineations by analyzing satellite imagery in ArcGIS to estimate the actual extent of disturbed land. The mapped mine surfaces correspond only to the actively affected areas and therefore represent a subset of the larger expropriated zones documented in the literature. Importantly, in this digitization process, we excluded land occupied by lignite power plants as well as land required for electricity transmission infrastructure, thereby restricting calculations solely to the mining-affected areas.

3. Results

3.1. Land Transformation

Table 3 summarizes the results of our analysis when grouped by wind turbine size. Across the full sample of 129 WPS, the average actual land coverage was estimated at 0.33 ha/MW. For the subset of 39 WPS for which annual electricity generation data were available, land occupation was additionally expressed per unit of energy output, yielding an average value of 1.58 m^2/MWh.

Table 3. Estimated land coverage of the WPS examined.

WTG Class	Total Capacity (MW)	Total Number of WTGs	LUI_P (ha/MW)	LUI_E * (m^2/MWh)
≤3 MW	1176.55	893.00	0.35 ± 0.17	1.31 ± 0.59
>3 MW	1428.96	352.00	0.32 ± 0.11	1.75 ± 0.59
Total	2605.51	1245.00	0.33 ± 0.14	1.58 ± 0.56

* *Note: for WPS with available energy-yield data.*

Statistical Analysis

To examine the robustness of these estimates, actual land take per installed capacity was summarized using two complementary weighting approaches. When weighted by installed capacity, representing the average land take "per MW" across the fleet, the mean value was 0.311 ha/MW (95% CI: 0.248–0.374). Classification by turbine size, illustrated in Figure 4, indicates that projects with larger turbines (>3 MW) exhibit a slightly lower mean land take of 0.289 ha/MW (95% CI: 0.210–0.368), compared to projects with smaller turbines (≤3 MW), which average 0.335 ha/MW (95% CI: 0.244–0.427). However, the capacity-weighted difference between large and small turbines (−0.046 ha/MW) is not statistically significant.

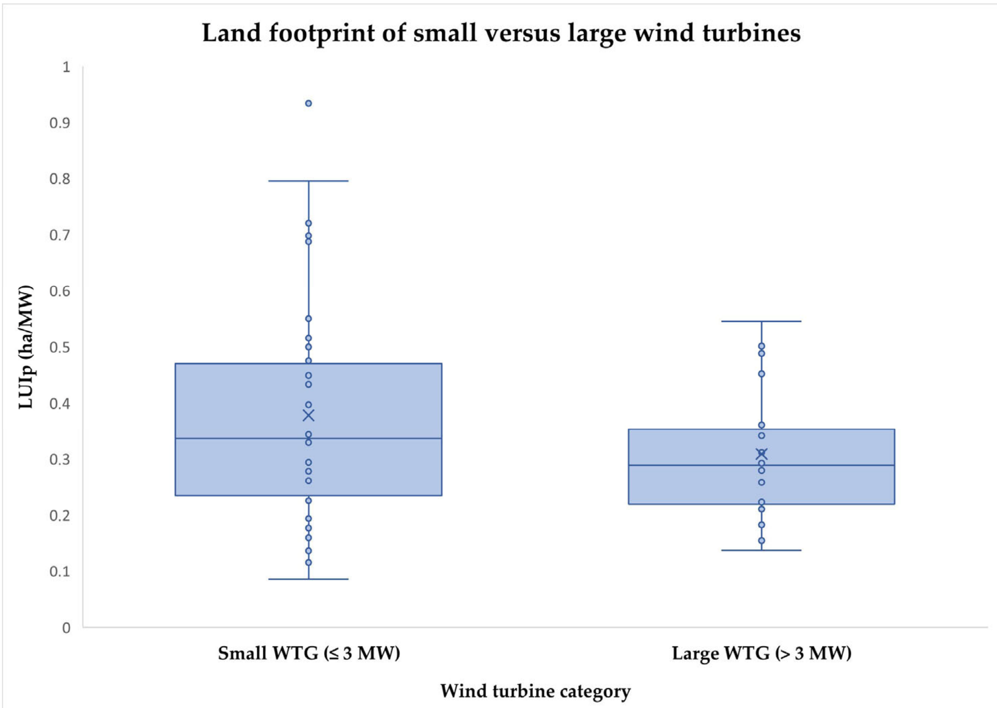

Figure 4. Scatter of land coverage values for small and large wind turbines. Note: The dots represent the sample's values (LUI_p) and the "x" mark in each whisker is the average value (mean LUI_p).

Weighting the observations on the basis of turbine count offers an alternative perspective, reflecting the characteristics of a typical turbine rather than a typical installed megawatt. Under this turbine-weighted approach, the overall mean land take is 0.365 ha/MW (95% CI: 0.276–0.454). Large projects average 0.304 ha/MW (95% CI: 0.208–0.400) while small projects 0.392 ha/MW (95% CI: 0.255–0.528), yielding a non-significant difference of −0.088 ha/MW (95% CI ≈ −0.250 to +0.074). Overall, both weighting schemes consistently suggest a tendency toward slightly lower land take per MW for larger turbines, although the effect remains modest and statistically inconclusive within the present sample.

For the subset of wind farms with available annual electricity generation data (totaling 950 MW), actual land take was further normalized by annual energy output (m^2 per MWh). When weighted by installed capacity, the mean land occupation amounts to 1.293 m^2/MWh (95% CI: 1.052–1.534).

Large-turbine projects average 1.505 m^2/MWh (95% CI: 1.209–1.801), whereas small-turbine projects average 1.028 m^2/MWh (95% CI: 0.785–1.270). Although the capacity-weighted difference (+0.477 m^2/MWh) is not statistically significant, it suggests that, per unit of delivered electricity, newer large-turbine installations show somewhat higher land take, likely reflecting their siting in complex or low-wind terrain requiring denser infrastructure.

A similar pattern emerges under turbine-weighted averaging, where the overall mean land occupation is 1.162 m^2/MWh (95% CI: 0.931–1.393). In this case, large projects average 1.414 m^2/MWh (95% CI: 1.094–1.734), while small projects average 1.007 m^2/MWh (95% CI: 0.774–1.240), giving a non-significant difference of +0.407 m^2/MWh (95% CI: −0.071 to +0.885).

Taken together, these results —centering around approximately 1.3 m^2/MWh— confirm that the actual land occupation of wind energy remains minimal, even when normalized by electricity output, and is comparable to or lower than that reported for most other renewable technologies.

3.2. Type of Land Occupied

Natural, semi-natural, and artificial habitats account for 91.62%, 4.64%, and 3.75% of the digitized footprint, respectively, when grouped by MAES ecosystem types (Table 4). Most of the footprint falls within CLC "321: Natural grasslands" (177.34 ha; 38.55%). The second largest share is CLC "323: Sclerophyllous vegetation" (117.60 ha; 25.56%).

Table 4. Estimated footprint area (ha) of digitized wind-project works by MAES ecosystem and Corine Land Cover (CLC). Columns: Total Area = sum of total interventions (platforms, access roads, electrical works, etc.); WPS $\geq$ 2015 Area = area for projects commissioned from 2015 onwards, which are subject to the one-to-one reforestation works obligation; Net Equivalent Area = Total Area − WPS $\geq$ 2015 Area, except for the cases of "Artificial habitats" and "Semi-natural habitats" which do not fall in the legal provision for reforestation (in these cases Net Equivalent Area is equal to the Total Area).

MAES Level 2	Corine Land Cover Level 2	Corine Land Cover Level 3	Total Area (ha)	WPS $\geq$ 2015 Area (ha)	Net Equivalent Area (ha)
Artificial habitats					
Urban ecosystems	Urban fabric	112: Discontinuous urban fabric	1.12	1.03	1.12
	Industrial, commercial and transport units	121: Industrial or commercial units	15.93	0.00	15.93
	Industrial, commercial and transport units	122: Road and rail networks and associated land	0.10	0.10	0.10
	Mine, dump and construction sites	131: Mineral extraction sites	0.05	0.00	0.05
	Mine, dump and construction sites	132: Dump sites	0.05	0.00	0.05
Subtotal			17.25	1.12	17.25
Semi-natural habitats					
Cropland	Arable land	211: Non-irrigated arable land	1.45	1.11	1.45
	Permanent crops	223: Olive groves	2.97	2.30	2.97
	Heterogeneous agricultural areas	242: Complex cultivation patterns	2.25	0.14	2.25
	Heterogeneous agricultural areas	243: Land principally occupied by agriculture, with significant areas of natural vegetation	14.65	9.22	14.65

Table 4. *Cont.*

MAES Level 2	Corine Land Cover Level 2	Corine Land Cover Level 3	Total Area (ha)	WPS ≥ 2015 Area (ha)	Net Equivalent Area (ha)
	Subtotal		21.33	12.77	21.33
		Natural habitats			
Grassland	Pastures	231: Pastures	2.69	1.28	1.40
Grassland	Scrub and/or herbaceous vegetation associations	321: Natural grasslands	177.34	169.42	7.92
Forest	Forests	311: Broad-leaved forest	2.71	2.61	0.10
Forest	Forests	312: Coniferous forest	23.59	12.31	11.28
Forest	Forests	313: Mixed forest	13.56	4.80	8.77
Forest	Scrub and/or herbaceous vegetation associations	324: Transitional woodland-shrub	28.45	22.26	6.19
Heathland and shrub	Scrub and/or herbaceous vegetation associations	322: Moors and heathland	14.98	9.98	5.00
Heathland and shrub	Scrub and/or herbaceous vegetation associations	323: Sclerophyllous vegetation	117.60	58.92	58.67
Sparcely vegetated land	Open spaces with little or no vegetation	332: Bare rocks	21.79	21.79	0.00
Sparcely vegetated land	Open spaces with little or no vegetation	333: Sparsely vegetated areas	18.77	9.81	8.97
	Subtotal		421.48	313.19	108.29
Total		19 Land Cover Types	460.06	327.08	146.87

Within the forested classes, CLC "312: Coniferous forest" represents the largest forest type (23.59 ha; 5.13%). It is noted that this class includes a sizeable polygon erroneously mapped as coniferous forest, despite being treeless prior to WPS installation, indicating a mapping artifact.

Projects permitted or commissioned from 2015 onward—following the enforcement of Law 4280/2014 (GG A' 159/2014) [36] in August 2014—are legally required to reforest an area of forest land equal to that occupied by WPS works, or to implement equivalent forest management or engineering measures. Accordingly, the effective present-day land take should be interpreted using the values reported in the "Net Equivalent Area" column of Table 4.

The percentage of the total occupied area per Land Cover type and MAES Type is illustrated in Figure 5.

3.3. Footprint in Protected Areas

Using a GIS overlay of the digitized WPS footprints with the boundaries of the Natura 2000 network, we conducted an indicative assessment of the protected-area index for the projects under study. We found that 63.87 ha fall within Natura 2000, corresponding to 13.9% of the total area of the digitized subset.

Within these 63.87 ha, 44.6% lie in Special Protection Areas (SPAs) and 85.0% in Special Areas of Conservation/Sites of Community Importance (SACs/SCIs); 29.5% of the area overlaps both designations (see Figure 6).

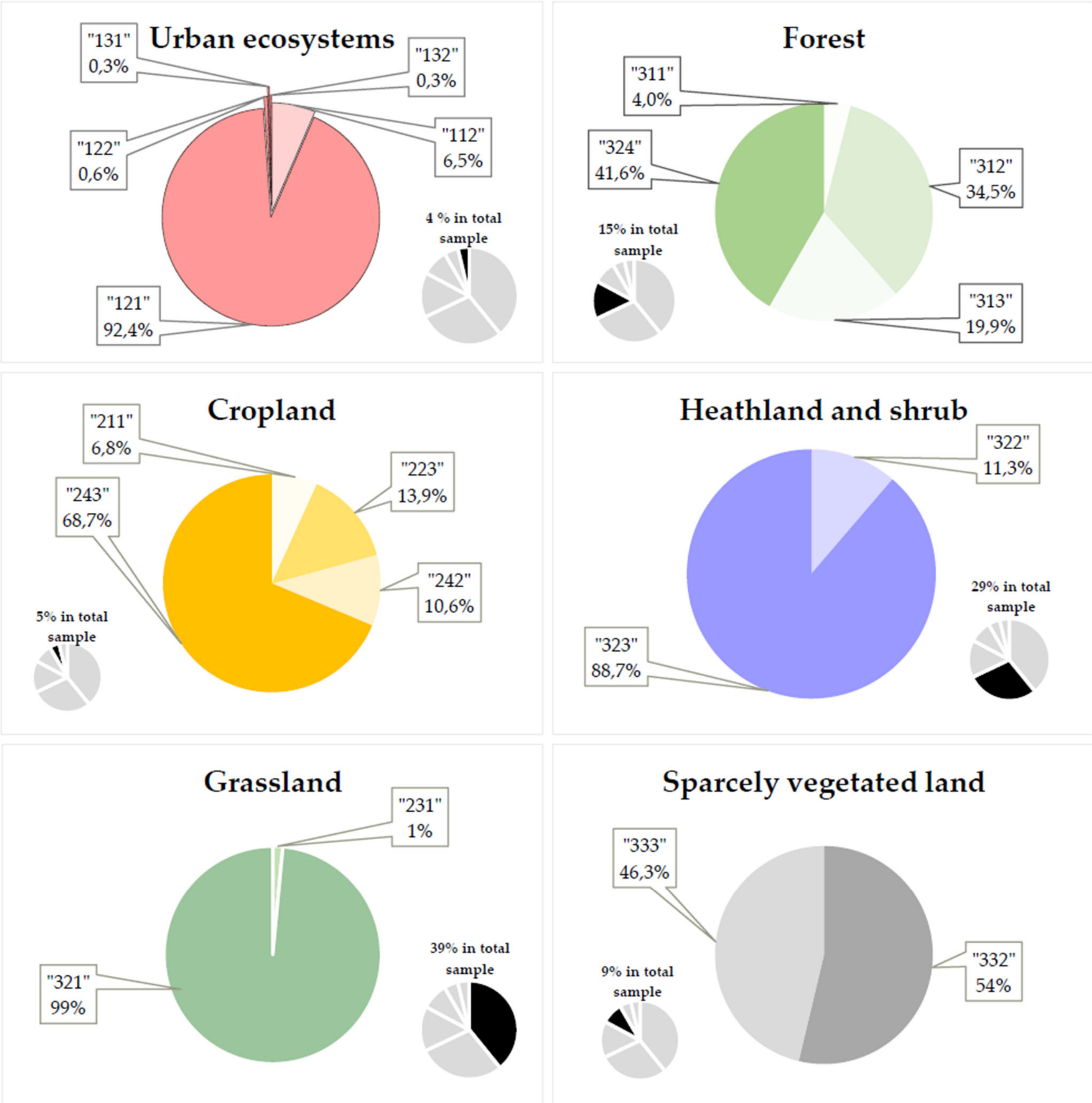

Figure 5. Percentage of the total occupied area per Land Cover Type and MAES Type (Level 2). Note: The Corine Land Cover Level 3 classification codes are used (see Table 4).

For SAC-pSCI locations where habitat-type mapping was available, we performed an additional overlay using terrestrial habitat polygons. This analysis shows that (Table 5) the largest share of occupied area corresponds to habitat types 4090 and 6170 (Annex I, Directive 92/43/EEC), followed by the nationally interest habitat type 5340 [43].

No interventions were found in priority habitats, which was expected, since they constitute an exclusion zone for wind development, according to the Greek Spatial Planning Framework for RES [26].

In our spatial analysis for the Natura 2000 network associated with the examined WPS, we did not include landscape and visual impacts, species-level ecological impacts, habitat condition, biodiversity indicators, or social and socio-economic effects. These components are assessed in detail within the project-specific environmental licensing studies for each installation and were therefore not incorporated into the present spatial analysis.

Figure 6. Natura 2000 network sites in Greece (GR) associated with the investigated WPS footprints. The sites depicted are: SPA GR2220006 “Kefalonia: Ainos, Agia Dynati kai Kalon Oros”, SAC-pSCI GR2320007 “Oros Panachaiko-Syragkes Panagopoulas”, SPA GR2320010 “Ori Barmpas, Klokos, Farangi Selinounta” and SAC GR1210001 “Oros Vermio”.

Table 5. Total area by habitat type for the relevant Natura 2000 sites.

Habitat Type	Description	Total Area (ha)	Percentage%
6170 [1]	Alpine and subalpine calcareous grasslands	15.68	0.38%
62A0 [1]	Eastern sub-Mediterranean dry grasslands (*Scorzoneratalia villosae*)	1.66	0.11%
4090 [1]	Endemic oro-Mediterranean heaths with gorse	20.06	0.48%
5210 [1]	Arborescent matorral with *Juniperus* spp.	4.17	0.22%
53402	Garrigues of the Eastern Mediterranean	1.75	0.36%
92C0 [1]	*Platanus orientalis and Liquidambar orientalis* woods (*Platanion orientalis*)	0.02	0.03%
934A [2]	Greek forests of *Prinos*	0.05	0.00%
951B [2]	Greek fir forests (*Abies cephalonica*)	1.78	0.07%

Note.[1] = Annex I of Council Directive 92/43/EEC; [2] = Habitat of national interest.

3.4. Comparison with Lignite Mines

Using the digitization method described above, the total disturbed area of the three largest lignite mines in Greece was estimated at approximately 16,750 ha, equivalent to 0.13% of the national land surface (Table 6).

Table 6. Estimated disturbed area of the three largest lignite mines in Greece.

Lignite Mines	Expropriation Zone (km^2)	Disturbed Area (km^2)
Amyntaio	63.44	36.5
Ptolemaida	149.6	103
Megalopoli	56.6	28
Total	**269.64**	**167.5**

The environmental and public health impacts of lignite mining—consistently documented as severe—are incommensurable with those associated with wind power development [52]. For instance, health-related concerns occasionally raised for wind turbines, such as low-frequency noise as infrasound, have not been shown to cause adverse effects at exposure levels encountered near operational wind farms [53–55]. By contrast, lignite extraction entails extensive and often irreversible land disturbance, while the direct land footprint of wind energy is orders of magnitude lower for comparable levels of electricity production.

Applying the average land coverage of 0.33 ha/MW to the onshore wind deployment targets of Greece's National Energy and Climate Plan (NECP) for 2030 and 2050 indicates that merely 0.02% and 0.03% of the country's territory, respectively, would be occupied by wind infrastructure [56]. In comparison, lignite mining has already transformed 0.13% of the national territory—nearly four times the projected land take of wind energy even under the 2050 scenario, illustrated in Figure 7. In practice, the difference may be even greater when repowering of older WPS is considered (see Section 4.4).

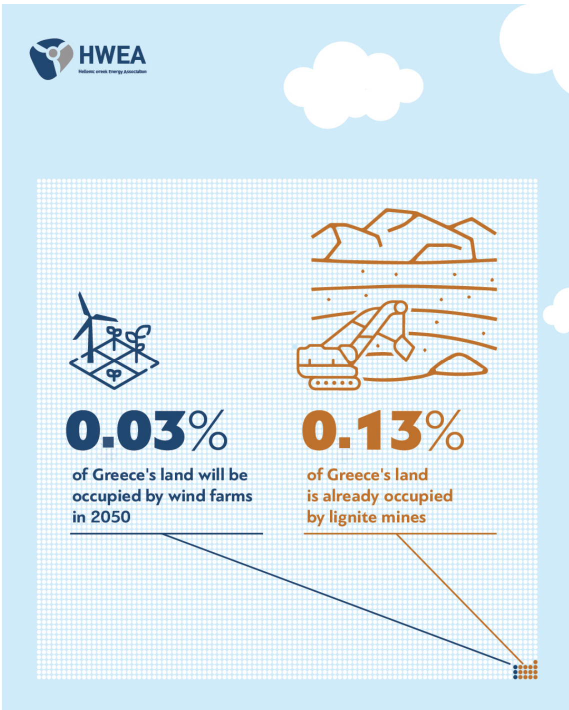

Figure 7. Comparison of land currently occupied by lignite mines in Greece and the projected land requirements for meeting Greece's 2050 targets.

4. Discussion

4.1. Comparison with Other Studies

Research on the land occupation of wind energy infrastructure has expanded significantly over the last two decades, with studies employing a range of methods and geographical scales. A key distinction across the literature lies in whether the "land take" is defined as the *direct physical footprint* of infrastructure (roads, turbine pads, substations, crane pads, etc.) or as the *total project area*, which also includes the spacing between turbines. The latter approach has been shown to substantially overestimate land occupation, since the inter-turbine space is typically left available for other land uses (e.g., grazing, agriculture, forestry, beekeeping).

In 2009, Fthenakis and Kim [24] performed a cross-technology life-cycle review of land-use metrics across coal, gas, nuclear, hydro, PV, wind and biomass. For onshore wind, they estimated direct land transformation using the total array-spacing area rather than digitized turbine footprints, reporting 6.5–19 km^2/TWh (equivalently expressed as m^2/MWh) for specific USA and European cases. They explicitly note that only 1–10% of the wind farm's area is physically occupied by infrastructure (pads, roads), while the remainder remains available for other uses.

One of the earliest systematic analyses was provided in 2009 by Denholm et al. [11], who examined 161 USA wind projects (>25 GW), constructed after 2000 with capacities above 20 MW, using permitting documentation and Environmental Impact Statements. They reported an average *direct footprint* of 0.3 $\pm$ 0.3 ha/MW (permanent) plus 0.7 $\pm$ 0.6 ha/MW (temporary), amounting to approximately 1.0 $\pm$ 0.7 ha/MW of disturbed land. By contrast, the total project area yielded a much higher average of 34.5 $\pm$ 22.4 ha/MW. Importantly, they highlighted the limitations of using "total project area" as an indicator of land take, since this metric often reflects lease or spacing requirements rather than true disturbance.

Diffendorfer and Compton [13] in 2014 conducted the first large-scale study to *digitize* the actual disturbed surfaces of wind facilities, moving beyond previous approaches that relied on permitting documents or generalized assumptions of total project area [11]. Their dataset included 39 operational wind power facilities in the USA, comprising 3257.05 MW of installed capacity and 1926 turbines. By using high-resolution aerial imagery and GIS digitization, they were able to capture the precise surface disturbance (roads, pads, substations) instead of inferring land use from turbine spacing or lease boundaries. They reported an average land transformation of 0.93 $\pm$ 0.12 ha/MW, with strong variation across landscapes: forested sites and rugged topographies showed the highest values—up to ~4.3 ha/MW, which the authors explicitly note as an extreme outlier and which is far from values found in our study—while tilled and flat areas required the least land. This methodological innovation established a new benchmark for empirical assessments of wind energy land occupation.

A follow-up by Diffendorfer et al. [50] extended this dataset to examine landscape fragmentation across the same 39 facilities. They found that new projects reduced undeveloped land by only 1.8% within 1 km buffers, but increased indices of landscape pattern by 50–140%. Importantly, they highlighted that reuse of existing roads substantially lowered new disturbance, whereas greenfield road construction was the main driver of habitat loss.

Trainor et al. [25] synthesized land-use intensities across power technologies and expressed them as km^2/TWh/yr. For onshore wind, they relied on Denholm et al. [11] for empirical per-MW land take estimates and converted these to energy-normalized units using a representative 33% capacity factor. They reported 1.3 km^2/TWh for the direct (actual) footprint (roads, pads, substations) and 126.9 km^2/TWh for the landscape impact (total/spacing), noting that only ~3% of a plant's area is physically occupied by infrastructure while the remainder reflects turbine spacing. Importantly, they also stressed a key advantage of renewables: wind and solar can continue producing on the same sites year after year without expanding cumulative land requirements, unlike fuel-based systems that must continually appropriate new land for extraction and supply.

At the national scale in the USA, Harrison-Atlas et al. [10] analyzed 1089 operational wind plants totaling 106.7 GW. To make areas comparable across the fleet, they constructed a uniform footprint for each plant by drawing a convex-hull polygon around turbine locations, applying a standardized buffer of 300 m, and then merging overlapping polygons. Using this method, they reported a national average capacity density of 4.3 MW/km^2—or 23.3 ha/MW, to be compared with the metrics reported in other studies—and showed that ~96 to 99% of each footprint is non-infrastructure, reinforcing that only a very small fraction constitutes actual disturbance.

Miller and Keith [48] analyzed the USA onshore fleet (~430 operational plants totaling ~45.4 GW in 2016) and computed a plant "area" from turbine layouts by constructing Voronoi polygons around each turbine in an equal-area projection. They then estimated each plant's area as the median Voronoi polygon area multiplied by the turbine count, with an eight-rotor-diameter buffer included for comparison. This yielded a spacing-based total envelope rather than actual disturbed land. Using this method, the corrigendum reported an installed capacity density of 2.8 MW/km^2 (≈35.7 ha/MW), a value used for cross-study comparisons of total and spacing land intensity.

In Europe, detailed empirical assessments have been conducted more recently. Kati et al. [49] digitized artificial surfaces and road networks for 90 operational wind farms in Greece (2002–2020, ~1.2 GW). They reported an average of 7729 ± 5245 m^2/MW (0.773 ha/MW) of new artificial land cover, equivalent to 3.53 ± 2.39 m^2/MWh, with road construction dominating land occupation. New roads averaged 148 ± 256 m/MW and road widening 174 ± 259 m/MW.

In a regional case study for Thrace (NE Greece), Damianidis et al. [57] mapped the actual disturbed surfaces of wind projects by photo-interpreting 1996 orthophotos against 2021 imagery to delineate turbine pads, ancillary works, and new or widened access roads tied to each project. They identified 36 projects (694.7 MW in total) with 332 wind turbines (including 55 in licensed but not-yet-built parks) and quantified an actual footprint of 0.26 ha/MW (the authors note the road estimate is conservative because cut slopes were not included).

Balotari-Chiebáo and Byholm [20] analyzed 42 operational wind farms (513 turbines) in Ostrobothnia, Finland. To ensure comparability, they delineated the total project "envelope" from municipal project boundaries (using a 533 m buffer around individual turbines where boundaries were unavailable) and quantified the actual disturbed area by buffering turbine pads (39 m radius) and roads (6 m) prior to rasterization. On this basis, infrastructure occupied only 1.4–6.0% of each project area, corresponding on average to 23 ha/MW for the total project area versus 0.6 ha/MW for the directly disturbed footprint, reinforcing that only a small fraction of the siting envelope is truly transformed.

In Sweden, Svensson et al. [21] mapped how onshore wind projects intersect with land cover, ownership, and formal protection regimes, showing a strong concentration in forest-dominated landscapes and frequent proximity to protected areas. Although they do not report per-MW land-take metrics, their results underscore a core principle of impact assessment: the ecological value of a site matters more than the raw extend of land take—i.e., land occupation alone is not a reliable metric for evaluating a project's environmental impacts.

The European Academy of Wind Energy [22] has highlighted the specific challenges of siting wind projects in mountainous or "complex terrain." While not providing ha/MW values, the report emphasizes that increased road construction and site preparation in such environments raises direct land take relative to flat, agricultural settings.

Observation-based siting densities from Austria and Denmark [23]—computed by assigning operational turbines to a 1 km × 1 km grid and averaging capacity per occupied cell—are 4.79 MW/km^2 for Austria (≈20.9 ha/MW) and 1.76 MW/km^2 for Denmark (≈56.8 ha/MW). The underlying datasets comprise 2295.5 MW in Austria (1071 sites; data as of 2015) and 3881.7 MW in Denmark (4393 sites; data as of 2017). These figures do not measure either the *actual disturbed area* or the *total plant footprint*; rather, they indicate how much capacity tends to fit within broader landscapes under observed siting patterns (i.e., a total/spacing context, not actual land take). The higher Austrian value reflects concentrated deployment in a few suitable lowland and agricultural zones, whereas Denmark's mean is pulled down by many older, small turbines and a more diffuse onshore build-out. Imposing a minimum cell-density threshold (>0.6 MW km^{-2}) accordingly raises the Danish average to ~2.75 MW/km^2.

Ioannidis and Koutsoyiannis [12] synthesized published studies and, for land-use accounting, adopted "total land use"—i.e., turbine spacing/lease area—as the primary indicator of landscape impact, explicitly counting inter-turbine space in addition to infrastructure. Building chiefly on Denholm et al. [11] values, they reported 340,000 m^2/MW for onshore wind and converted this to 176,000 m^2/GWh via assumed capacity factors. They also combined this framing with large-scale visibility (ZTV) material and "visual dominance" rings to compare technologies, ultimately ranking wind above solar PV and hydropower in land use and visibility. In this respect, treating spacing as "used" land inflates wind's footprint relative to studies that measure only the actually disturbed surfaces, while spacing typically remains multifunctional (e.g., grazing, forestry).

By contrast, Jacobson et al. [14] treated a wind project's "footprint" as essentially just the sealed base of each turbine—"primarily the area of the tower and of exposed cement above the ground surface"—and, in practice, they counted foundations only. Accordingly, they parameterized onshore wind with a footprint of 3.22 m^2/MW (or 0.000322 ha/MW) and a spacing requirement of 0.051 km^2/MW (~5.1 ha/MW; installed power density 19.8 MW/km^2). In this case, the footprint excludes access roads, crane pads, and substations and consequently underestimates direct land take.

Taken together, the reviewed literature converges on several robust findings. First, empirical studies that quantify actual physical disturbance through digitization of infrastructure or permitting documentation consistently place the mean actual land transformation for onshore wind between 0.26 and 0.93 ha/MW [11,13,20,58]. Our results—based on project documentation and high-resolution mapping for a nationwide Greek sample of 129 WPS—yield a capacity-weighted mean of 0.33 ha/MW, situating our study toward the lower end of the internationally reported range.

For Greece, when benchmarked against the Thrace case (0.26 ha/MW) [57] and our nationwide, capacity-weighted mean (0.33 ha/MW), the Kati et al. [49] estimate of 0.773 ha/MW appears unexpectedly high—about three times the value reported by Damianidis et al. [57] and more than double our value. This discrepancy likely reflects differences in definitional and digitization choices (e.g., how "artificial surfaces" and road widths are delineated or attributed to each project), highlighting the need for careful harmonization across studies. Our estimates are further supported by energy-normalized metrics (1.58 m^2/MWh), which fall well within the range reported by studies converting empirical per-MW values to output-based indicators [25].

In contrast, studies relying on total project area or spacing-based envelopes [10,12,48] report land-use intensities that are orders of magnitude larger, but these metrics primarily reflect siting density or lease geometry rather than actual land transformation. Overall, the comparison demonstrates that when harmonized definitions are applied, the present study is fully consistent with the international literature and reinforces the conclusion that only a small fraction (≈1–4%) of wind farm siting envelopes is subject to direct physical disturbance, with terrain and infrastructure design—rather than turbine spacing—being the dominant drivers of variation (Table 7).

Table 7. Comparison of the present study with data from other studies.

Study	Country	Sample	Method (What Was Measured)	Metric	Reported Values
Current study	Greece	129 wind projects; 2605.5 MW 1245 turbines	Actual footprint (pads, roads, electrical works, etc.) derived from as-built documentation and digitization of high-res imagery	ha/MW m^2/MWh	0.33 ± 0.14 ha/MW 1.58 ± 0.56 m^2/MWh (sample of 950.0 MW)
Fthenakis and Kim [24]	USA, Europe	Different layouts (arrays of turbines) in USA, Denmark, Germany	Literature synthesis (total/spacing area calculated using array-spacing layouts; excludes Actual disturbance)	km^2/TWh	6.5–19 km^2/TWh (equivalent to 6.5–19 m^2/MWh)
Denholm et al. [11]	USA	161 wind projects (>25 GW; >20 MW each; post-2000)	Permitting documentation and Environmental Impact Statement; actual Land (permanent and temporary) and total project area	ha/MW	Permanent: 0.3 ± 0.3 ha/MW; Temporary: 0.7 ± 0.6 ha/MW; Direct total: ≈1.0 ± 0.7 ha/MW; Total area: 34.5 ± 22.4 ha/MW
Diffendorfer & Compton [13]	USA	39 operational facilities; 3257.05 MW; 1926 turbines	High-resolution aerial imagery + GIS digitization of roads, pads, substations; landscape variations; actual Land	ha/MW	0.93 ± 0.12 ha/MW
Diffendorfer et al. [50]	USA	39 operational facilities; 3257.05 MW; 1926 turbines	Fragmentation analysis within 1-km buffers; reuse of existing roads; habitat loss in greenfield	Relative change (%)	Undeveloped land −1.8% by new projects; Landscape indices: +50–140%; reuse of existing roads lowers new disturbance
Trainor et al. [25]	USA	161 wind projects (>25 GW; >20 MW each; post-2000)	Use a representative 33% capacity factor to convert empirical per-MW land take to per-MWh	km^2/TWh	1.3 km^2/TWh actual footprint; 126.9 km^2/TWh total-spacing context
Harrison-Atlas et al. [10]	USA	1089 operational plants; 106.7 GW	Uniform project footprints (convex hull polygon around turbines + 300 m buffer; overlaps merged)	MW/km^2; ha/MW; %	Capacity density: 4.3 MW/km^2 (≈23.3 ha/MW); Non-infrastructure share: ~96–99%
Miller and Keith [48]	USA	~430 operational plants; ~45.4 GW (2016)	Plant area from turbine layouts (Voronoi method; 8D buffer comparison; total and spacing	MW/km^2; ha/MW	Installed capacity density: 2.8 MW/km^2 (≈35.7 ha/MW); (power density reported but not used here)
Kati et al. [49]	Greece	90 operational wind farms (~1.2 GW; 2002–2020)	Satellite digitization of artificial surfaces + new/widened roads; actual Land	m^2/MW; m^2/MWh;	Artificial surfaces: 7729 ± 5245 m^2/MW (=0.773 ha/MW); Energy-normalized: 3.53 ± 2.39 m^2/MWh;
Damianidis et al. [57]	Greece (Thrace)	36 projects; 332 turbines (incl. 55 licensed not-built); 694.7 MW total	Satellite digitization (pads, new/widened roads; accompanying works; actual land)	ha/MW	Actual footprint: 0.26 ha/MW; note: road estimate is conservative (cut slopes excluded)
Balotari-Chiebáo & Byholm [20]	Finland (Ostrobothnia)	42 operational wind farms; 513 turbines	Total: municipal project boundaries (+533 m where needed); actual: 39 m pad buffers and 6 m road buffers; rasterized; both actual and total reported	ha/MW; %	Total: 23 ha/MW; Actual: 0.6 ha/MW; infrastructure 1.4–6.0% of project area
Nitsch et al. [23]	Austria and Denmark	Austria: 1071 sites; 2295.5 MW. Denmark: 4393 sites; 3881.7 MW	Observation based siting density (1 × 1 km grid; total land)	MW/km^2; ha/MW	Austria: 4.79 MW/km^2 (≈20.9 ha/MW); Denmark: 1.76 MW/km^2 (≈56.8 ha/MW)
Ioannidis & Koutsoyiannis [12]	Review (international literature)	—	Literature synthesis (emphasizing total/spacing; counting inter-turbine space; excluding actual disturbance)	m^2/MW; m^2/GWh	Wind Total: 340,000 m^2/MW; ~176,000 m^2/GWh (via assumed capacity factor)
Jacobson et al. [14]	Global (143 countries; Scenario-based)	—	Scenario assumptions (sealed-base footprint; multi-purpose spacing; actual (narrow) and total)	m^2/MW; km^2/MW; MW/km^2; %	Footprint: 3.22 m^2/MW (≈0.000322 ha/MW); Spacing: 0.051 km^2/MW (≈5.1 ha/MW); Installed density: 19.8 MW/km^2; global land: 0.17% footprint + 0.48% spacing

Notes: Parenthetical conversions (e.g., MW/km^2 → ha/MW) are unit conversions added to improve comparability across actual and total metrics.

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4.2. What Does Such a Land Occupation Index Really Mean?

A single figure of land occupation (e.g., ha/MW) reveals very little about the breadth and significance of environmental impacts—especially when it is not supported by site-specific, evidence-based reasoning regarding the "significant" effects on biodiversity, in light of the ecological characteristics of the location.

Impacts depend on the type of infrastructure (e.g., an unsealed forest road used for wind-farm access is not equivalent to an asphalted, access-controlled roadway, even if both cover the same area) and on local context (geomorphology, habitats, species, and landscape connectivity).

As such, the index alone is not an appropriate basis for "go or non-go" decisions in project permitting. If land occupation is treated as a cost, the argument must be embedded in a cost–benefit analysis, i.e., one that considers alternatives, including the "no-project alternative", and explicitly compares the land requirements of all available energy technologies (conventional and renewable).

Any such analysis should also account for offsetting and restoration measures. Particularly in Greece, wind projects are legally required to finance and deliver reforestation or equivalent forest management and engineering works on areas equal to those occupied, as designated by the Forest Service [36]. These actions are in addition to on-site restoration of the altered footprint and may occur in areas unrelated to the wind-farm site. They should therefore be included when assessing the net environmental balance of a project. For comparability with published figures, the per-MW and per-MWh land-take values reported in the present study do not subtract such reforested areas.

Further, wind-farm infrastructure can also yield co-benefits that a bare land-take index ignores: access roads are designed under forest law specifications and can support wildfire response, rural safety, and forest management, and they also facilitate mountain cattle-breeding, beekeeping, and other livelihoods important for sustaining small upland communities.

Moreover, according to Greece's RES Spatial Planning framework [26], areas of high ecological value (e.g., cores of national parks, priority habitats, strict protection zones) are excluded from wind energy deployment, meaning that the effective "cost" is smaller than often implied.

Another notable characteristic of Greece is the clear correlation between wind resource and elevation [17]. Placing projects in high-wind mountainous areas produces more energy with fewer turbines, lowering consumer costs. For these reasons, cross-country comparisons of land take per MW with nations that possess extensive lowland wind resources—and far fewer land-use conflicts in plains and low hills—are methodologically difficult to conduct.

Lastly, although visual impact and stakeholder opposition are important for siting decisions and may indirectly influence project layout—for example by leading to fewer turbines, a smaller footprint, or even relocation—they do not themselves constitute physical land disturbance and therefore should not be included in land-take estimations.

4.3. Land Usage of Various Energy Sources

Having quantified the actual land occupation of wind energy, it is useful to place these results in the broader context of land-use intensity across energy sources. When comparing land occupation across energy sources, it is essential to distinguish between the direct physical footprint of infrastructure (e.g., turbine pads, substations, crane pads, access roads) and the total project area, which includes inter-turbine spacing.

For wind energy, including the entire spacing area is not appropriate, since the land between turbines remains available for multiple simultaneous uses such as grazing, agriculture, and beekeeping. This distinction is crucial for robust comparisons, as secondary data sources sometimes misrepresent wind's land use by incorporating spacing areas [12], thereby inflating reported values far beyond the actual physical footprint.

The most comprehensive quantitative dataset to date is the Land-Use Intensity of Electricity (LUIE) compiled by Lovering et al. [9]. This work reports median annual land-use intensities spanning four orders of magnitude, from nuclear at 7.1 ha/TWh up to dedicated biomass at 58,000 ha/TWh. Wind energy is reported in two categories: "Wind-" (footprint), which reflects only direct infrastructure, and "Wind+" (spacing), which includes inter-turbine land. Only the former constitutes true direct land occupation. On this basis, wind's actual footprint is among the lowest of all renewable options (~130 ha/TWh). Ground-mounted PV typically requires ~2000 ha/TWh per year, while natural gas ~410 ha/TWh, coal ~1000 ha/TWh per year, and hydropower shows highly variable land requirements depending on reservoir configuration (LUIE Median 650 ha/TWh or LUIE Mean 15,000 ha/TWh) [9].

Complementary evidence from Our World in Data [58] broadly aligns with these findings, although their reported values for wind are upwardly biased when spacing is included. Taken together, the international literature consistently positions wind—measured by direct footprint—among the least land-intensive energy sources, second only to nuclear in the LUIE database. By contrast, coal, natural gas, hydro (in many cases), and biomass exhibit substantially higher land-use intensities.

In direct comparisons between wind and photovoltaic energy, empirical assessments indicate that onshore wind entails lower land requirements than ground-mounted photovoltaic systems when land use is defined by actual physical occupation rather than spacing assumptions [59].

This comparison is particularly important considering current global energy trends. Coal and natural gas together still generate more than 60% of global electricity [4], despite their well-documented and severe environmental and health impacts. Transitioning to renewables is therefore critical not only for decarbonization but also for reducing pressures on land. Within the renewable portfolio, wind energy stands out as a technology that combines low direct land occupation with the ability to maintain multifunctional landscapes, making it one of the most sustainable options for large-scale power production.

Finally, our findings are consistent with this literature. When we compared actual wind-farm footprints with those of lignite mining, we found that existing lignite mines already occupy nearly the quadruple area that onshore wind will occupy by 2050 under the national RES targets.

4.4. Repowering Wind Farms: Reusing Land, Reducing Footprint

The Land-Use Intensity of electricity generation (LUI_E) was calculated above on an annual basis for each WPS. However, if total electricity production is accumulated over the entire life-cycle of a WPS—typically 20–25 years—important insights emerge. Wind energy, like all renewable sources, can reuse the same land area every year, and therefore no additional cumulative land is required, unlike fossil fuel-based systems that demand new land extraction and fuel supply each year [25].

In this context, it is meaningful to examine the repowering of aging wind energy projects, which provides a long-term pathway to minimize land-use pressures. The observed pattern of replacing many older turbines with fewer units delivering higher generation is a direct consequence of technological progress in wind energy, including larger rotor diameters and substantially increased capacity factors. By replacing outdated turbines with fewer, higher-capacity machines on existing sites, the operational lifetime of a wind farm can be extended for two or more decades without requiring additional land take. The Malpica case in Spain [60]—where 69 old turbines were replaced by 7 new ones—clearly illustrate this technological shift, resulting in a smaller number of turbines achieving higher total electricity output.

Beyond Spain's Malpica, other repowering projects in the United Kingdom (Delabole wind farm) [61] and Denmark (Nørrekær Enge case) [62] exhibit the same pattern: fewer turbines delivering higher generation. Although explicit land-take data were not reported, such large reductions in turbine number within unchanged boundaries imply lower actual land take per MWh.

In Greece, there is also a representative example of the benefits of repowering. Over the past decade, PPC Renewables has dismantled 105 older wind turbines across ten Aegean islands and Crete, replacing them with 24 new machines of equivalent total capacity but much higher efficiency. The repowering project included the complete removal of old turbine foundations and the restoration of unused land surfaces. For instance, at a decommissioned WPS located in eastern Crete, 20 small wind turbines were replaced by only 2 modern units, while all unused platforms were restored and seeded (see Presentation S4).

By the end of 2025, approx. 755 wind turbines (~577 MW) older than 20 years remained in operation in Greece [34]. As most of these are located in areas of high wind potential, they are expected to be gradually replaced by fewer, more productive turbines, further reducing the effective land footprint and extending the productive use of the same sites for several additional decades.

Such processes reinforce the conclusion that, when assessed over their full operational and repowering lifetime, wind farms achieve among the lowest cumulative land-use intensities (m^2/MWh) of all electricity generation technologies.

4.5. Good Practices for Minimizing the Land Footprint of Wind Energy Projects

As demonstrated in the present study, the land footprint of wind energy facilities is relatively limited, particularly when compared to conventional power generation systems. Nevertheless, the ongoing energy transition toward a decarbonized mix requires the deployment of many wind farms and other renewable energy installations in the coming years. This creates increasing pressure on land resources and necessitates the implementation of practices that minimize permanent land occupation and associated environmental disturbance.

In this context, a range of design and construction practices can be adopted to further reduce land transformation:

1. Shared Interconnection Infrastructure: Wind projects developed in the same geographical area can benefit from common interconnection infrastructure, such as substations and overhead high-voltage transmission lines. This practice is already applied in Greece. The Independent Power Transmission Operator (IPTO) considers all renewable energy projects within a region—including both wind and photovoltaic (PV) plants—when issuing a binding Grid Connection Offer (bGCO), often encouraging shared infrastructure. In addition to reducing overall land use, this approach facilitates the assessment of cumulative environmental impacts by the relevant permitting authorities.
2. Shared Access Roads: For adjacent wind farms, particularly those located along the same ridgeline, it is recommended that developers share primary access roads. This is especially important in Greece, where rugged terrain results in more extensive interventions for primary access roads compared to the internal connection roads between turbines. Consolidating access infrastructure not only reduces land take but also lowers construction costs and environmental impacts. Such a policy recommendation could be effectively implemented through coordination by local forest authorities, which collect and review permit applications for wind projects within a given area, as well as through guidance from central government bodies (e.g., the Ministry of

Environment), including the issuance of standardized technical circulars specifying road design and construction requirements.

3. Use of Specialized Blade-Transport Vehicles: The ongoing technological evolution toward higher-capacity wind turbines (≥4 MW), characterized by increasing rotor diameters and blades exceeding 70 m in length, presents structural logistical challenges for transportation—especially through mountainous terrain or narrow village roads. In such cases, the use of specialized transport systems such as "blade lifters", which can elevate blades up to 60 degrees, significantly reduces the need for extensive road widening where sharp turns occur. This practice can substantially limit land disturbance along access routes.
4. Custom-Designed Erection Platforms: The installation of a large wind turbine typically requires hardstands and temporary storage areas for components such as tower sections, the nacelle, and blades. However, these temporary storage areas are primarily needed during the erection phase, whereas during operation a substantially smaller area is sufficient. On sites with steep slopes—where excavation requirements are significant—it can be advantageous to design reduced-footprint erection platforms, provided that safety and logistics permit it. In this approach, turbine components are delivered and installed sequentially, minimizing the need for large storage areas. Tower sections are lifted and installed first, followed by the nacelle and blades, allowing the platform to remain compact while still supporting crane operations.

Beyond measures aimed at minimizing physical land transformation, good practice in wind energy deployment also requires targeted mitigation of impacts on nearby human settlements and wildlife. Such measures include appropriate setback distances from dwellings, careful micro-siting to reduce visual dominance, pre-construction ecological surveys, avoidance of sensitive habitats, seasonal construction restrictions, and post-construction monitoring to adapt operational practices if needed. Wind projects are typically developed in sparsely populated and weakly forested areas—common in Greece due to strong wind potential in mountainous and semi-arid regions—though final siting ultimately depends on wind resource availability and must balance energy yield, land take, and environmental sensitivity.

4.6. Compensatory Measures Mandated by Legislation in Greece

The land coverage value determined in the present study, beyond the specifics of the applied methodology, should be considered an upper-bound estimate, due to legal provisions in Greece that require the implementation of compensatory measures for each wind energy project.

First, it is important to note that the vast majority of wind farms in Greece are located on land legally classified as "forest land" [26]. Under Greek forestry legislation [63], the term "forest land" does not exclusively refer to areas densely covered with tall trees but also includes grasslands, areas with sparse low vegetation or even virtually unvegetated terrain (e.g., rocky mountain crests). The latter categories constitute the typical landscape for most wind farm locations in Greece, with few exceptions.

In this context, on top of the environmental terms applied to every wind project, Greek forestry legislation imposes the following compensatory measures for projects sited on forest land [36]:

1. Land-Use Fee: A fee is calculated based on the area of intervention and paid by the project developer to the Green Fund. This amount is earmarked exclusively for reforestation activities and cannot be used for other purposes.
2. Mandatory Reforestation: Since 2014 (see Sections 3.2 and 4.2 above), each new wind project is also required to undertake reforestation of an area affected by past wildfires,

equivalent in size to the area disturbed by the project's infrastructure (e.g., turbine platforms, roads, etc.), as stated in the project's permits. If no such burned area is available nearby, the project developer can either implement equivalent forest management and engineering works elsewhere—based on cost equivalence determined by the competent forestry authority—or, alternatively, transfer the corresponding amount to the Green Fund. These reforestation works are a compensatory measure, in addition to the restorations inside the wind farm site (planting of cuts and embankments), which are executed separately. Examples of implemented reforestation-related works include forest road maintenance, recreation parks, fire prevention works such as firebreaks, and pruning of areas with thick vegetation (e.g., see Presentation S4).

These legal requirements make clear that the direct land footprint reported in this study likely overestimates the net spatial impact of wind energy infrastructure, since the above compensatory actions partially offset the disturbed area. However, quantifying this offset was not feasible within the scope of the present study, since the specifics vary on a case-by-case basis and would require extensive data collection for each project individually.

5. Conclusions

We examined the land occupation of wind energy projects in a country with predominantly complex terrain—Greece. The mean Land-Use Intensity values (in ha per MW and ha per MWh) we found based on primary project-level documentation lie at the lower end of the ranges reported in recent studies from the USA and Europe.

Regarding land-cover categories, we found that wind turbines in Greece are generally installed in areas of low vegetation and avoid mature forest habitats, which play an important role in carbon storage [20]. In addition, legislation in force since 2014 requires reforestation of an area equal to the total footprint of a WPS, which contributes to a positive environmental balance.

With respect to ecological sensitivity, instruments such as the national RES spatial planning framework and the Habitats Directive (92/43/EEC) ensure that no interventions occur within priority habitats, strict nature reserves, or other areas of high protection value for biodiversity [26].

Based on the data collected, larger turbines (capacity > 3 MW) are associated with smaller land occupation per MW. This likely reflects the fact that, for a given plant capacity, fewer turbines, and thus fewer new access roads and ancillary platforms, are required. Further work should explore more than two turbine-size classes (beyond the ≤3 MW vs. >3 MW split) and assess correlations with turbine geometry (e.g., rotor diameter).

When compared with other conventional and renewable technologies, onshore wind exhibits one of the smallest land footprints. Even so, there remains room for further reduction by applying good practices such as shared interconnection and access infrastructure among neighboring projects and by deploying logistics and design solutions tailored to large turbines (e.g., blade-lifters for transport, site-specific hardstand design).

Recent efforts to assemble harmonized, open global datasets of wind and solar infrastructure underscore that consistent spatial definitions and metadata are essential for making land-use metrics (ha/MW, m^2/MWh) comparable across studies and regions [64]. Nonetheless, standardization must be coupled with data quality; accordingly, we made a concerted effort in this study to minimize reliance on OSM-derived proxies and to maximize accuracy.

The present sample is nationally representative and spatial information on roads, pads, substations, and ancillary works was compiled through substantial effort by integrating data from multiple sources. Nevertheless, spatial heterogeneity and regional variability such as differences in terrain, vegetation cover, planning regimes, and land-use constraints may influence land-use intensity values and limit the direct transferability of the results to other geographic contexts. Future research would benefit from the establishment of centralized, publicly accessible spatial datasets by the relevant authorities, which would enable regular updates as wind deployment expands and facilitate comparisons across regions with differing terrain, land cover, and planning constraints. In addition, temporal variations in land-use intensity across the project life-cycle—particularly between construction, operation, and repowering phases—warrant further investigation, especially in the context of ongoing technological evolution toward fewer, higher-capacity turbines delivering higher generation.

Land requirements linked to the manufacturing of turbines and electrical equipment fall outside the scope of this work; in any case, these upstream activities are shared across multiple industrial sectors and are expected to contribute only marginally to the overall land footprint compared with on-site infrastructure.

Finally, the total area (spacing) of a WPS is not a reliable metric of land coverage: it is ambiguous to delineate, weak in accuracy, inconsistent across regions and, most importantly, does not reflect the actual human disturbance. Equally important, repowering offers an additional long-term benefit: by replacing outdated turbines with fewer, more efficient ones on the same sites, wind farms can continue operating for several more decades without new land take, thereby further reducing the lifetime land-use intensity of wind energy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land15020344/s1. Presentation S1: Examples by illustration of digitized areas from WPS where polygons of different entities represent the boundaries of occupied land. Presentation S2: Examples of Corine Land Cover Types from the digitized WPS subset. Presentation S3: Examples by illustration of repowered WPS, wind turbine foundations dismantling and former occupied land restoration. Presentation S4: Examples by illustration of implemented forest management and engineering works such as forest road maintenance, firebreak and pruning of areas with thick vegetation.

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Abbreviations

The following abbreviations (in alphabetical order below) are used in this manuscript:

bGCO	Binding Grid Connection Offer
CAD	Computer-Aided Design
CLC	Corine Land Cover
DEM	Digital Elevation Model
DNV	Det Norske Veritas
EEA	European Environmental Agency
EEC	European Economic Community
ERDF	European Regional Development Fund
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems
GLO-30	Global Digital Elevation Model 30 m Resolution instance
GWA	Global Wind Atlas
HWEA	Hellenic Wind Energy Association
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPTO	Independent Power Transmission Operator
LUIE	Land-Use Intensity per Electricity generated each year
LUIP	Land-Use Intensity per installed capacity
MAES	Mapping and Assessment of Ecosystems and their Services
MEE	Ministry of Environment and Energy (Greece)
NECP	National Energy and Climate Plan
PV	Photovoltaic
RES	Renewable Energy Sources
SACs	Special Areas of Conservation
SCIs	Sites of Community Importance
SPAs	Special Protection Areas
WPS	Wind Power Stations
WTG	Wind Turbine Generator

References

1. FAO. FAOSTAT. 2019. Available online: https://www.fao.org/faostat/en/#home (accessed on 23 September 2025).
2. Smil, V. *Energy and Civilization: A History*; MIT Press: Cambridge, MA, USA, 2017.
3. DNV. *Energy Transition Outlook 2024: A Global and Regional Forecast to 2050*; DNV: Høvik, Norway, 2024.
4. Ember. *Global Electricity Mid-Year Insights 2025*; Ember: London, UK, 2025; Available online: https://ember-energy.org/latest-insights/global-electricity-mid-year-insights-2025/ (accessed on 7 October 2025).
5. IPBES. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services*; Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., et al., Eds.; IPBES Secretariat: Bonn, Germany, 2019. [CrossRef]
6. Hooke, R.L.; Martín Duque, J.F. Land transformation by humans: A review. *GSA Today* **2012**, *22*, 4–10. [CrossRef]
7. Kennedy, C.M.; Oakleaf, J.R.; Theobald, D.M.; Baruch-Mordo, S.; Kiesecker, J. Managing the middle: A shift in conservation priorities based on the global human modification gradient. *Glob. Change Biol.* **2019**, *25*, 811–826. [CrossRef]
8. Smil, V. *Grand Transitions: How the Modern World Was Made*; Oxford University Press: Oxford, UK, 2021.
9. Lovering, J.; Swain, M.; Blomqvist, L.; Hernandez, R.R. Land-use intensity of electricity production and tomorrow's energy landscape. *PLoS ONE* **2022**, *17*, e0270155. [CrossRef]
10. Harrison-Atlas, D.; Lopez, A.; Lantz, E. Dynamic land use implications of rapidly expanding and evolving wind power deployment. *Environ. Res. Lett.* **2022**, *17*, 044064. [CrossRef]
11. Denholm, P.; Hand, M.; Jackson, M.; Ong, S. Land-Use Requirements of Modern Wind Power Plants in the United States. NREL/TP-6A2-45834; National Renewable Energy Laboratory: Golden, CO, USA, 2009.
12. Ioannidis, R.; Koutsoyiannis, D. A review of land use, visibility and public perception of renewable energy in the context of landscape impact. *Appl. Energy* **2020**, *276*, 115367. [CrossRef]
13. Diffendorfer, J.E.; Compton, R.W. Land cover and topography affect the land transformation caused by wind facilities. *PLoS ONE* **2014**, *9*, e88914. [CrossRef] [PubMed]

14. Jacobson, M.Z.; Delucchi, M.A.; Cameron, M.A.; Coughlin, S.J.; Hay, C.A.; Manogaran, I.P.; Shu, Y.; von Krauland, A.-K. Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. *One Earth* **2019**, *1*, 449–463. [CrossRef]
15. Mongird, K.; Bracken, C.; Burleyson, C.D.; Oikonomou, K.; Ou, Y.; Rice, J.S.; Thurber, T.; Voisin, N. More Land Is Needed for Solar and Wind Infrastructure under Existing Siting Constraints. *Commun. Earth Environ.* **2025**, *6*, 112. [CrossRef]
16. Xu, K.; Zhu, H.; Zhang, S.; Wang, M.; Li, W.; Zhou, W.; Li, S.; Shi, Z.; Chang, J. Land Use Impacts the Environmental Benefits of Wind Energy Farms in China. *Commun. Earth Environ.* **2025**, *6*, 133. [CrossRef]
17. HWEA—Hellenic Wind Energy Association. Workshop: "Wind Energy Within the Institutional Framework for Biodiversity Protection" (Videos, Photos & Presentations), 16 March 2023. Presentation of Papastamatiou P. (In Greek) Available online: https://eletaen.gr/imerida-eletaen-viopoikilotita/ (accessed on 6 October 2025).
18. Davis, N.N.; Badger, J.; Hahmann, A.N.; Hansen, B.O.; Mortensen, N.G.; Kelly, M.; Larsén, X.G.; Olsen, B.T.; Floors, R.; Lizcano, G.; et al. The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. *Bull. Am. Meteorol. Soc.* **2023**, *104*, E1507–E1525. [CrossRef]
19. ['Capacity Factor Layers for Greek Regions'] Obtained from the Global Wind Atlas Version 4.0, a Free, Web-Based Application Developed, Owned, and Operated by the Technical University of Denmark (DTU). The Global Wind Atlas Version 4.0 is Released in Partnership with the World Bank Group, Utilizing Data Provided by Vortex, with Funding from the Energy Sector Management Assistance Program (ESMAP). For Additional Information. Available online: https://globalwindatlas.info (accessed on 5 September 2025).
20. Balotari-Chiebáo, F.; Byholm, P. Quantifying land impacts of wind energy: A regional-scale assessment in Finland. *Environ. Dev. Sustain.* **2024**, *26*. [CrossRef]
21. Svensson, J.; Neumann, W.; Bjärstig, T.; Thellbro, C. Wind power distribution across subalpine, boreal, and temperate landscapes. *Ecol. Soc.* **2023**, *28*, 18. [CrossRef]
22. Clifton, A.; Barber, S.; Stökl, A.; Frank, H.; Karlsson, T. Research challenges and needs for the deployment of wind energy in hilly and mountainous regions. *Wind Energy Sci.* **2022**, *7*, 2231–2254. [CrossRef]
23. Nitsch, F.; Turkovska, O.; Schmidt, J. Observation-based estimates of land availability for wind power: A case study for Czechia. *Energy Sustain. Soc.* **2019**, *9*, 47. [CrossRef]
24. Fthenakis, V.; Kim, H.C. Land use and electricity generation: A life-cycle analysis. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1465–1474. [CrossRef]
25. Trainor, A.M.; McDonald, R.I.; Fargione, J. Energy sprawl is the largest driver of land use change in the United States. *PLoS ONE* **2016**, *11*, e0162269. [CrossRef]
26. Hellenic Republic. Special Spatial Planning Framework for Renewable Energy Sources. Government Gazette B′ 2464/03.12. 2008. Available online: https://ypen.gov.gr/wp-content/uploads/2020/11/FEK2464B_2008_RES.pdf (accessed on 23 January 2026).
27. ADEME (Agence de la transition écologique). *Les Français et l'éolien: Résultats du Sondage Harris Interactive*; ADEME: Paris, France, 2021; Available online: https://www.ademe.fr/presse/communique-national/sondage-harris-interactive-les-francais-et-leolien/ (accessed on 13 February 2026).
28. Fachagentur Wind und Solar. *Umfrage zur Akzeptanz der Windenergie an Land—Ergebnisse Herbst 2022*; Fachagentur Wind und Solar: Berlin, Germany, 2022; Available online: https://www.fachagentur-wind-solar.de/fileadmin/Veroeffentlichungen/Wind/Akzeptanz/FA_Wind_Umfrageergebnisse_Herbst_2022.pdf (accessed on 13 February 2026).
29. Department for Energy Security and Net Zero (DESNZ). *Public Attitudes Tracker: Renewable Energy (Spring 2024, UK)*; UK Government: London, UK, 2024. Available online: https://www.gov.uk/government/statistics/desnz-public-attitudes-tracker-spring-2024 (accessed on 13 February 2026).
30. Skiniti, G.; Daras, T.; Tsoutsos, T. Analysis of the Community Acceptance Factors for Potential Wind Energy Projects in Greece. *Sustainability* **2022**, *14*, 16009. [CrossRef]
31. Analysis Metron. *Public Opinion Survey on Environmental Issues and Renewable Energy for WWF Greece*; Metron Analysis: Athens, Greece, 2019.
32. Foundation for Economic and Industrial Research (IOBE). *Public Opinion Attitudes towards the Green Transition and Renewable Energy Sources in Greece*; IOBE: Athens, Greece, 2024.
33. Korozi, O.; Vagiona, D.G. Environmental Impact Assessment of Onshore Wind Farms in the Region of Central Greece Using a Modified RIAM Method. *J. Environ. Earth Sci.* **2024**, *6*, 1. [CrossRef]
34. HWEA—Hellenic Wind Energy Association. *The Map of Operational Wind Farms*; Hellenic Wind Energy Association: Athens, Greece, 2026; Available online: https://arcg.is/0ayPKK0 (accessed on 23 January 2026).
35. RAE. Geospatial Map for Energy Units and Requests from the Regulatory Authority for Energy. Available online: https://geo.rae.gr (accessed on 8 October 2025).

36. Hellenic Republic. Law 4280/2014—Environmental Upgrading and Private Urban Development. Government Gazette A' 159/08.08. 2014. Available online: https://www.kodiko.gr/nomothesia/document/91406/nomos-4280-2014 (accessed on 23 January 2026).
37. Copernicus. Copernicus Digital Elevation Model (DEM) GLO-30. Available online: https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM (accessed on 23 September 2025).
38. Copernicus. CORINE Land Cover 2012 (Vector/Raster 100 m), Europe, v2020. Available online: https://land.copernicus.eu/en/products/corine-land-cover/clc-2012#download(accessed on 10 October 2025).
39. Copernicus. CORINE Land Cover 2018 (Vector/Raster 100 m), Europe, v2020. Available online: https://land.copernicus.eu/en/products/corine-land-cover/clc2018#download (accessed on 10 October 2025).
40. European Environment Agency (EEA). Ecosystem coverage in Europe. Available online: https://www.eea.europa.eu/en/analysis/indicators/ecosystem-coverage-in-europe (accessed on 10 October 2025).
41. European Environment Agency (EEA). Natura 2000 Database. November 2022. v.32. Available online: https://www.eea.europa.eu/data-and-maps/data/natura-14/natura-2000-spatial-data (accessed on 10 February 2025).
42. Ministry of the Environment and Energy (MEE). Prioritised Action Framework (PAF) for Natura 2000 in Greece, Pursuad to Article 8 of Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Flora and Fauna (The Habitats Directive) for the Multiannual Financial Framework Period 2021–2027. Available online: https://ypen.gov.gr/wp-content/uploads/2024/03/Prioritised-Action-Framework-PAF-for-Natura-2000-for-the-Multiannual-Financing-Period-2021-2027.pdf (accessed on 10 October 2025).
43. Ministry of the Environment and Energy (MEE). Boundaries (Vector Data) of the Terrestrial Habitat Types Within Natura 2000 Sites of Greece. Available online: https://ypen.gov.gr/perivallon/viopoikilotita/diktyo-natura-2000/ (accessed on 10 February 2025).
44. Hellenic Republic. Law 4872/2021—Just Development Transition, Regulation of Specific Issues Related to Decarbonization (Lignite Phase-Out), and Other Urgent Provisions. Government Gazette A' 247/10.12. 2021. Available online: https://www.kodiko.gr/nomothesia/document/763747/nomos-4872-2021 (accessed on 23 January 2026).
45. PPC. Strategic Environmental Assessment for Special Spatial Planning for Megalopolis De-Lignitization Core Zone. November 2023. Available online: https://ypen.gov.gr/stratigiki-meletis-perivallontikon-epiptoseon-s-m-p-e-tou-eidikou-poleodomikou-schediou-e-p-s-tou-pyrina-zonis-apolignitopoiisis-z-ap-megalopolis/ (accessed on 23 September 2025).
46. PPC. Strategic Environmental Assessment for Special Spatial Planning for Ptolemaida De-Lignitization Core Zone. November 2023. Available online: https://ypen.gov.gr/dimosiopoiisi-tis-stratigikis-meletis-perivallontikon-epiptoseon-sbe-tou-eidikou-poleodomikou-schediou-e-p-s-zonis-apolignitopoiisis-z-ap-ptolemaidas/ (accessed on 23 September 2025).
47. PPC. Strategic Environmental Assessment for Special Spatial Planning for Amyntaio, Kleidi, Achlada De-Lignitization Core Zone. November 2023. Available online: https://ypen.gov.gr/stratigiki-meletis-perivallontikon-epiptoseon-s-m-p-e-tou-eidikou-poleodomikou-schediou-e-p-s-ton-pyrinon-zonis-apolignitopoiisis-z-ap-amyntaiou-kleidiou-achladas/ (accessed on 23 September 2025).
48. Miller, L.M.; Keith, D.W. Observation-based solar and wind power capacity factors and power densities. *Environ. Res. Lett.* **2018**, *13*, 104008. [CrossRef]
49. Kati, V.; Kassara, C.; Panagos, P.; Tampouratzi, L.; Gotsis, D.; Tzortzakaki, O.; Petridou, M.; Psaralexi, M.; Sidiropoulos, L.; Vasilakis, D.; et al. The overlooked threat of land take from wind energy infrastructures: Quantification, drivers and policy gaps. *J. Environ. Manag.* **2023**, *348*, 119340. [CrossRef]
50. Diffendorfer, J.E.; Dorning, M.A.; Keen, J.R.; Kramer, L.A.; Taylor, R.V. Geographic context affects the landscape change and fragmentation caused by wind energy facilities. *PeerJ* **2019**, *7*, e7129. [CrossRef]
51. May, R.; Jackson, C.R.; Middel, H.; Stokke, B.G.; Verones, F. Life-cycle impacts of wind energy development on bird diversity in Norway. *Environ. Impact Assess. Rev.* **2021**, *90*, 106635. [CrossRef]
52. Vasilakopoulos, A.; Karanasiou, A.; Eleftheriadis, K.; Diapouli, E.; Florou, K.; Manousakas, M.-I.; Bairachtari, K.; Vratolis, S.; Bougiatioti, A.; Grivas, G. Cardiovascular Impacts of Air Pollution in a Coal-Burning Region: A Decade of Hospital Data from Western Macedonia, Greece. *Atmosphere* **2025**, *16*, 1397. [CrossRef]
53. LUBW (Landesanstalt für Umwelt Baden-Württemberg). *Tieffrequente Geräusche inkl. Infraschall von Windkraftanlagen und anderen Quellen*; LUBW: Karlsruhe, Germany, 2016; Available online: https://pudi.lubw.de/detailseite/-/publication/84558 (accessed on 3 November 2025).
54. National Health and Medical Research Council (NHMRC). *NHMRC Statement: Evidence on Wind Farms and Human Health*; NHMRC: Canberra, Australia, 2015. Available online: https://www.nhmrc.gov.au/health-advice/environmental-health/wind-farms (accessed on 3 November 2025).
55. Technology Research Center VTT Oy; University of Helsinki; Finnish Institute of Occupational Health; National Institute for Health and Welfare. *Infrasound and Health of Wind Turbines*; Finnish Government Analysis, Assessment and Research Activities: Helsinki, Finland, 2020; Available online: https://tietokayttoon.fi/julkaisu?pubid=34903 (accessed on 3 November 2025).

56. Hellenic Republic. Greece's National Energy and Climate Plan (NECP). Government Gazette B' 6983/31.12. 2024. Available online: https://ypen.gov.gr/energeia/esek/ (accessed on 23 January 2026).
57. Damianidis, C.; Kapsalis, E.; Korakis, G.; Xystrakis, F. *Χαρτογράφηση–φωτοερμηνεία των αλλαγών χρήσεων/κάλυψης γης ως επίπτωση της εγκατάστασης ΑΣΠΗΕ (υπαρχόντων και μελλοντικών) στη Θράκη [Mapping–Photointerpretation of Land-Use/Cover Changes Due to the Installation of Wind Power Plants (Existing and Prospective) in Thrace]; Thrace Biodiversity Protection Society: Dadia–Soufli, Greece, 2022; p. 31, (In Greek). Available online: https://workdrive.zohopublic.eu/external/488eed0d07c9f284b2e256eb79c983f0762c6a552d94a35f2f7a244d16c94304 (accessed on 5 September 2025).*
58. *Ritchie, H. How does the land use of different electricity sources compare? Our World in Data 2022. Available online: https://ourworldindata.org/land-use-per-energy-source (accessed on 23 September 2025).*
59. *Cogato, A.; Pezzuolo, A.; Marinello, F. Soil Footprint and Land Use Change of Photovoltaic and Wind Power Plants: An Italian Case Study.* Land **2023**, 12, *1822. [CrossRef]*
60. *Villena-Ruiz, R.; Ramírez, F.J.; Honrubia-Escribano, A.; Gómez-Lázaro, E. A techno-economic analysis of a real wind farm repowering experience: The* Malpica *case.* Energy Convers. Manag. ***2018***, 172, *182–199. [CrossRef]*
61. *IRENA.* Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019.*
62. *Borch, K.; Kirkegaard, J.K.; Nyborg, S. Three wind farm developments, three different planning difficulties: Cases from Denmark.* Energies ***2023***, 16, *4662. [CrossRef]*
63. *Hellenic Republic. Law 998/1979—On the Protection of Forests and Forest Lands of the Country. Government Gazette A' 289/29.12. 1979. Available online: https://www.dtklawfirm.gr/wp-content/uploads/2019/01/998.1979.pdf (accessed on 23 January 2026).*
64. *Dunnett, S.; Sorichetta, A.; Taylor, G.; Eigenbrod, F. Harmonised global datasets of wind and solar farm locations and power.* Sci. Data ***2020***, *7, 130. [CrossRef]*