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Spatial Overlap Between Wind Power Licensing Areas and Potential Grazing Lands in Greece: A National Screening Assessment

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Abstract

Wind energy expansion constitutes a central component of Greece's energy transition. However, the spatial allocation of Wind Power Production Plants (WPPs) may coincide with potential grazing lands and Natura 2000 protected areas, creating potential land-use and conservation interfaces that require careful planning. This study provides a national-scale spatial screening assessment of the overlap between WPP licensing areas and potential grazing lands in Greece. Geospatial data from the Regulatory Authority for Energy (RAE), retrieved in February 2026, were intersected with CORINE Land Cover 2018 data using GIS-based vector analysis. Four alternative grazing-land classification scenarios were applied to account for uncertainty in the spatial definition of potential grazing lands. A spatial intersection was conducted between WPP licensing areas and Natura 2000 boundaries, followed by an assessment of potential grazing-land overlap within the resulting WPP-Natura 2000 areas. The results showed that, across the four scenarios, 65.89% to 70.34% of the total WPP polygon area overlapped potential grazing lands, while overlap within individual licensing stages ranged from 63.40% to 85.93%. Approximately 28.64% of the total WPP polygon area was located within Natura 2000 sites. Within these WPP-Natura 2000 areas, the proportion classified as potential grazing land ranged from 62.68% to 72.19% across the four scenarios. Regional analysis further revealed marked variation in overlap intensity among NUTS-2 regions, licensing stages, and grazing-land scenarios, with producer-certification areas generally showing the highest regional intensities. Although WPP licensing polygons do not represent the actual physical footprint of wind turbines and associated infrastructure, their substantial spatial coincidence with potential grazing lands highlights an important interface between renewable-energy development, livestock farming activities, and biodiversity conservation. The study provides a first-order national-scale screening assessment that can support integrated spatial planning, grazing management, biodiversity conservation, and environmental permitting in Greece.



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1. Introduction

Wind energy is a key component of the global transition towards low-carbon energy systems and plays an increasingly important role in climate change mitigation and energy-security strategies [1,2]. Greece has significantly expanded wind power deployment as

part of its broader energy transition [3]. Wind Power Production Plants (WPPs) are often developed in mountainous and semi-natural landscapes, where wind-energy potential may coincide spatially with areas of high ecological value and other land uses [4]. As renewable energy infrastructure expands, its spatial interaction with other land uses, ecosystems, and conservation priorities becomes increasingly relevant to sustainable spatial planning [4,5]. Although the direct physical footprint of wind-energy infrastructure is limited to turbines and associated facilities, the broader spatial areas associated with their projects' planning and licensing may encompass substantially larger landscapes [5]. These areas may encompass or spatially overlap with pastures and other grazing lands, which are important components of Mediterranean rural landscapes, supporting animal production, contributing to biodiversity conservation, and other ecosystem functions and services [6,7]. They may also overlap with Natura 2000 protected sites [4]. Consequently, the spatial interaction between wind-energy development and grazing landscapes represents a potentially important interface between renewable-energy production, livestock farming, land management, and biodiversity conservation.

International spatial assessments have highlighted how renewable energy development can interact with agricultural and natural land cover types and have emphasized the importance to direct future development toward lower conflict areas. Using a spatially explicit assessment across European countries, Kiesecker et al. [8] showed that future wind and solar development may affect substantial areas of agricultural and natural lands, and that the extent of potential land use conflict varies geographically and can be reduced through more spatially informed siting strategies. In parallel, comparative research in Spain and the Czech Republic has documented diverse forms of land use conflict associated with onshore wind development, including environmental protection, landscape values, property interests, and local communities [9]. These findings indicate that the interaction between wind energy development and existing land uses is a broader international planning issue.

Pastoral land and rangeland are particularly relevant to this emerging land use nexus. These land categories cover extensive areas globally and are increasingly being targeted for renewable energy development due to their substantial spatial extent and renewable-energy potential. The expansion of renewable-energy and other green transition projects is resulting in new interactions with pastoral lands. These interactions can lead to opportunities for coexistence and shared land use, but they also raise concerns about land access, pastoral rights, competition for resources, and livelihoods [10]. This distinction is particularly relevant when considering the potential interactions between the broader spatial extent of wind-power projects and pastoral land uses, as licensing or project areas may extend well beyond the physical footprint of the associated infrastructure [8].

Previous studies have investigated the environmental effects that are associated with wind energy development, although their findings remain inconclusive [11–17]. Wind-farm development and associated land-cover changes may affect soil organic carbon and may also be associated with broader physical, chemical, and biological changes in soils [11]. Similarly, changes in vegetation and land cover associated with wind power installations have been documented, with more pronounced changes generally observed in areas closer to the facilities [12]. However, the available evidence does not lead to clear and coherent conclusions. No significant effects of turbine presence on plant community structure, ecological indicators, or pasture quality were detected in a mountain region in Romania [13]. At the agricultural land level, no statistically significant negative effects of wind turbines on agricultural land values were detected, either on farms or in surrounding areas [14]. These contrasting findings indicate that the effects of wind energy infrastructure may be

highly context-dependent, varying with environmental conditions, spatial scale, and the type of impact considered.

Potential interactions between wind-energy development and grazing animals have also received attention. Studies conducted in Sweden reported changes in habitat use by semi-domesticated reindeer in relation to wind farms, with responses varying across spatial scales and phases of development [15]. Wind farm construction has also been associated with changes in migration routes and movement corridors of free ranging reindeer, including reduced use of corridors located close to development areas [16]. However, evidence from Norway suggests that responses may not necessarily involve generalized avoidance of wind power installations, although localized avoidance of associated infrastructure, particularly access roads, may occur during and after construction [17]. Such differing responses highlight the complexity of interactions between wind-energy infrastructure, grazing animals, and landscape use.

Importantly, most available research examining the interactions between grazing animals and wind energy infrastructure originates from northern European systems, particularly those involving semi-domesticated reindeer [15–17]. Evidence concerning livestock responses to wind energy development under Mediterranean grazing conditions remains comparatively limited. Mediterranean pastoral systems differ substantially from those in northern European in terms of vegetation heterogeneity, livestock species, grazing management practices, climatic conditions, and seasonal patterns of pasture use [6,18,19]. Such differences can shape livestock–vegetation interactions and ecosystem responses, limiting the direct transferability of findings from northern European pastoral systems to Mediterranean pastoral landscapes.

Greece represents a particularly relevant case for examining these spatial interactions due to its extensive deployment of onshore wind energy across mountainous and semi-natural landscapes and its high biodiversity value. Previous national-scale research has already highlighted the need to reconcile wind energy development with biodiversity conservation and Natura 2000 objectives through effective spatial planning [4]. These spatial considerations are also reflected in the environmental assessment and permitting framework governing the development of WPPs in Greece, which operates within an established legislative and regulatory framework. The foundations of the modern environmental protection framework were established through Law 1650/1986, while subsequent amendments, including Law 3010/2002, further developed environmental assessment and permitting procedures [20,21]. The framework was substantially revised through Law 4014/2011, which remains the central legislative instrument governing the environmental permitting of projects and activities in Greece [22]. Projects and activities are classified according to their potential environmental impacts, with Category A projects requiring the preparation of an Environmental Impact Assessment Study as part of the environmental permitting procedure [22].

The environmental permitting framework also includes specific provisions for projects and activities located within the Natura 2000 Network. Depending on the characteristics and category of the proposed project, a Special Ecological Assessment may be required as part of the environmental assessment procedure to evaluate potential effects on protected habitats and species, including, where relevant, potential cumulative effects in combination with other projects [22]. The requirements and documentation associated with environmental and ecological assessments are further specified through relevant ministerial decisions, including Decision 52983/1952/2013 for Category B projects and Decision 170225/2014 for Category A projects [23,24]. More recently, conservation objectives have been established for bird species in Special Protection Areas (SPAs) through Ministerial Decision No. YPEN/ΔΔΦΤΙΒ/50146/1786/10-05-2023 (Ministry of Environment and En-

ergy) and for natural habitat types and species of Community interest in Special Areas of Conservation (SACs) and Sites of Community Importance (SCIs) through Decision No. YPEN/ΔΔΦΠΒ/24776/985/22-03-2023 [25,26]. These regulatory developments reinforce the importance of considering renewable-energy development in relation to the conservation objectives of Natura 2000 sites within the national network.

Within the Greek context, grazing lands have both agricultural and ecological functions in Mediterranean landscapes [6,7,18,19]. The structure and use of grazing landscapes are influenced by grazing intensity, livestock movements, pasture abandonment, shrub encroachment, and broader processes of vegetation succession [27,28]. The delineation of grazing lands is itself complex because several land cover categories may be potentially associated with livestock farming activities. In Greece, methods for the preliminary identification of areas suitable for inclusion in Grazing Management Plans have considered multiple land cover categories rather than only areas explicitly classified as pastures [29]. This creates an important methodological issue for national-scale spatial assessments: estimates of overlap between wind energy development and grazing land may depend substantially on how potential grazing areas are defined.

This issue is also relevant to biodiversity conservation. According to the Priority Actions Framework (PAF) for the Natura 2000 Network in Greece for the 2021–2027 Multiannual Financial Framework, several grassland habitat types reported under Article 17 of the Habitats Directive for the 2013–2018 reporting period were assessed as having an unfavorable conservation status, while others were reported as having either unknown or favorable status [30]. Among the principal pressures affecting these habitats are intensive grazing or overgrazing and, conversely, the abandonment of traditional pasture management, including the cessation of grazing or mowing [30]. Conservation measures identified for these habitats include the promotion of extensive grazing, facilitation of livestock movement, regulation of grazing intensity and distribution, management of shrub encroachment and vegetation succession, and other habitat restoration interventions [30]. Consequently, spatial changes that potentially influence the accessibility, use, or management of grazing areas may also have implications for the conservation of semi-natural grassland habitats.

Despite the expansion of wind energy development in Greece and the importance of grazing landscapes, the spatial interaction between WPP licensing areas and potential grazing lands has not been systematically quantified at the national scale. Furthermore, the sensitivity of such estimates to alternative definitions of potential grazing land remains insufficiently explored. A national-scale spatial assessment can provide an important first step before more detailed questions concerning ecological effects or livestock responses are addressed. Mapping where WPP licensing areas and potential livestock farming activities coincide can help highlight landscapes in which more detailed environmental, ecological, or livestock-management assessments may be particularly relevant.

The present study therefore provides a national-scale GIS-based assessment of the spatial relationships between WPP licensing areas, potential grazing lands, and Natura 2000 sites in Greece. By integrating WPP licensing data with CORINE Land Cover, Natura 2000 boundaries, and administrative regions, the study generates derived spatial evidence on the extent and spatial distribution of these overlaps at both national and regional scales. The analysis also examines the sensitivity of the results to four alternative land-cover-based definitions of potential grazing land and distinguishes among three WPP licensing stages. Rather than estimating ecological impacts at the turbine scale, livestock responses, or direct land use changes, the study is explicitly designed as a first order spatial screening assessment that identifies areas of potential spatial interaction that may require further investigation.

Specifically, the study aims to: (i) quantify the spatial extent of WPP licensing areas according to licensing stage; (ii) estimate their overlap with potential grazing lands; (iii) assess the sensitivity of overlap estimates to four alternative grazing land classification scenarios; (iv) quantify the proportion of WPP licensing areas located within Natura 2000 sites; and (v) discuss the implications of these spatial patterns for renewable-energy planning, grazing management, biodiversity conservation, and environmental permitting.

2. Materials and Methods

2.1. Study Area and Data Sources

The study encompassed the entire territory of Greece. A national-scale approach was adopted to provide a comprehensive assessment of the spatial relationships among wind-energy licensing areas, potential grazing lands, and Natura 2000 sites.

Land-cover data were derived from the CORINE Land Cover (CLC) 2018 dataset, version 2020_20u1, produced within the Copernicus Land Monitoring Service and coordinated by the European Environment Agency (EEA) [31]. CLC provides a standardized, hierarchical land-cover classification that supports consistent national-scale spatial analysis [31]. Spatial data for Wind Power Production Plants (WPPs) were obtained from the publicly accessible RAE Geospatial Map (Geoportal) [32]. The dataset was accessed in February 2026 and includes projects classified as Category A under the Greek environmental permitting framework. Consequently, the analysis excluded smaller WPP projects falling outside Category A.

Three categories representing different stages of project development were analyzed: (i) projects with an operating license; (ii) projects with an installation license; and (iii) projects holding a producer certification, representing an earlier stage of the development and licensing process. The dataset included 435 operating license projects, 125 installation license projects, and 1137 producer certification projects. These categories were analyzed separately because they represent distinct stages of project development and differ substantially in their overall spatial extent.

Spatial boundaries of Natura 2000 sites were obtained from the officially available shapefile provided by the Ministry of Environment and Energy [33] at the time of the analysis.

2.2. Potential Grazing-Land Scenarios

The spatial delineation of grazing land is not straightforward because areas used or potentially suitable for grazing may correspond to several CORINE land cover categories. Based on land cover categories considered relevant to Grazing Management Plans and on previous approaches to the preliminary identification of potential grazing areas in Greece [29], four alternative classification scenarios were developed.

- Scenario A included the following CORINE land cover classes: 231 (Pastures), 321 (Natural grasslands), 322 (Moors and heathland), 323 (Sclerophyllous vegetation), 324 (Transitional woodland-shrub), 331 (Beaches, dunes, sands), and 332 (Bare rocks).
- Scenario B included all classes incorporated in Scenario A together with classes 242 (Complex cultivation patterns) and 243 (Land principally occupied by agriculture, with significant areas of natural vegetation).
- Scenario C included the classes incorporated in Scenario A, excluding classes 331 (Beaches, dunes, sands) and 332 (Bare rocks).
- Scenario D included the classes incorporated in Scenario C together with classes 242 (Complex cultivation patterns) and 243 (Land principally occupied by agriculture, with significant areas of natural vegetation).

The four scenarios represent alternative interpretations of which CORINE land cover classes may reasonably be considered potential grazing lands (Table 1). Rather than

selecting a single definition as the preferred representation of potential grazing land, all four scenarios were retained for the sensitivity analysis. This approach enabled us to assess whether the estimated spatial overlap patterns remained consistent across alternative definitions of potential grazing lands.

Table 1. CORINE land-cover classes included in the four alternative potential grazing-land classification scenarios.

CORINE Code	Land-Cover Category	Scenario A	Scenario B	Scenario C	Scenario D
231	Pastures	✓	✓	✓	✓
242	Complex cultivation patterns	–	✓	–	✓
243	Land principally occupied by agriculture, with significant areas of natural vegetation	–	✓	–	✓
321	Natural grasslands	✓	✓	✓	✓
322	Moors and heathland	✓	✓	✓	✓
323	Sclerophyllous vegetation	✓	✓	✓	✓
324	Transitional woodland-shrub	✓	✓	✓	✓
331	Beaches, dunes, sands	✓	✓	–	–
332	Bare rocks	✓	✓	–	–

The inclusion of CORINE categories in the four scenarios does not imply that all areas within these CORINE classes are actively grazed; rather, they form part of the alternative land-cover-based definitions used to represent potential grazing land at the national scale.

2.3. GIS Spatial Analysis

Spatial analyses and thematic mapping were conducted using ArcGIS Pro 3.4.3 [34]. All spatial layers were processed using the Greek National Coordinate Reference System (EGSA87). Vector-based overlay and intersection operations were used to quantify the spatial relationships among WPP licensing areas, CORINE land cover classes, Natura 2000 sites, and the administrative regions of Greece (Figure 1). To evaluate potential spatial overlap among WPP polygons, the polygons were dissolved separately for each licensing stage. The resulting total areas matched the total calculated from the original polygons, indicating that no spatial overlap among WPP polygons occurred across the three licensing-stage datasets. Additionally, our checks for duplicate features in the WPP datasets found no duplicates. No geometry-repair operation was applied, as no geometry-related errors were encountered during processing.

For the grazing land analysis, CORINE Land Cover 2018 classes included in each of the four potential grazing land scenarios were selected separately and extracted as spatial layers. WPP licensing polygons were subsequently intersected with the selected CORINE classes for each scenario. For each WPP licensing stage and grazing land scenario, the intersecting area was calculated in hectares, and the percentage of overlap was calculated relative to the total area of WPP polygons within the respective licensing stage. The WPP dataset included polygons with a minimum area of approximately 500 m². No additional minimum-area threshold was applied to the spatial intersection results, and small intersection polygons were retained in the analysis.

For the Natura 2000 analysis, the Natura 2000 polygons were dissolved before the spatial intersection with the WPP licensing polygons. For each licensing stage, both the absolute intersecting area and the percentage of the total WPP polygon area located within Natura 2000 sites were calculated. The resulting WPP-Natura 2000 overlap areas were subsequently intersected with the four potential grazing land scenarios to quantify the three-way spatial overlap among WPP licensing areas, Natura 2000 sites, and potential grazing land.

To examine the regional distribution of overlap, the three WPP licensing-stage datasets were combined and intersected with the administrative boundaries of the thirteen NUTS-2 regions of Greece. The resulting polygons were recalculated in hectares and aggregated by licensing stage and region. An overlap intensity index was then calculated for each licensing stage, region, and grazing-land scenario as the percentage of the total grazing-land area within the region that overlapped the corresponding WPP licensing-stage polygons.

$$\text{Overlap Intensity}_{s,r,c} (\%) = (\text{Grazing land area}_{r,c} \text{ overlapped by licensing stages} / \text{Total grazing land area of region}_{r,c}) \times 100$$

where s denotes the WPP licensing stage, r the NUTS-2 region, and c the grazing-land classification scenario.

The resulting values were used to characterize regional variation in overlap intensity and to produce heatmaps.

The WPP polygons provided by the licensing authority represent broader licensing or reservation areas and do not directly correspond to the actual physical footprint occupied by wind turbines and related infrastructure. Therefore, the results of the spatial analysis should be interpreted as an assessment of the spatial coincidence and potential spatial pressure between the licensing areas and the examined land cover or protected-area categories, rather than as a measure of direct land occupation or ecological impact.

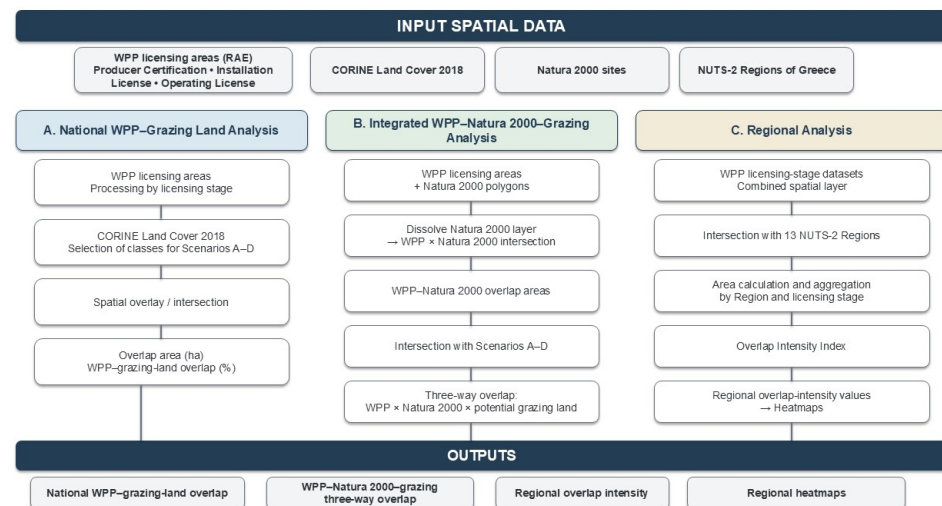


Figure 1. GIS workflow for the national-scale assessment of WPP-grazing-land overlap, the integrated WPP-Natura 2000-grazing analysis, and the regional overlap intensity assessment.

2.4. Sensitivity and Descriptive Analysis

The analysis was based on descriptive comparisons of spatial overlap among three stages of WPP licensing, four potential grazing-land classification scenarios, and thirteen NUTS-2 administrative regions in Greece. No inferential statistical testing was applied. The four alternative potential grazing-land scenarios were used as a sensitivity analysis to assess the extent to which estimates of WPP-grazing land overlap depended on the definition of potential grazing land. The range of overlap estimates across the four scenarios was examined to determine whether the main national-scale spatial patterns remained consistent under alternative grazing-land definitions. At the regional level, overlap intensity values were descriptively summarized across licensing stages and scenarios to characterize spatial variation in the distribution of WPP-grazing land overlap.

3. Results

3.1. Spatial Extent of WPP Licensing Areas

The total area represented by WPP polygons differed substantially among the different licensing stages. Producer certification areas covered by far the largest spatial extent (131,064.32 ha), followed by operating-license areas (22,265.80 ha) and installation-license areas (8100.45 ha). In total, the combined spatial extent of the three licensing categories was 161,430.57 ha. This value is the sum of the spatial extents from the three licensing stage datasets, with each WPP project assigned to a single licensing stage. Notably, producer certification polygons accounted for approximately 81.19% of this combined spatial extent and therefore exerted a substantial influence on the combined national results. This reflects the substantially larger spatial extent represented at this earlier stage of the licensing process. The combined values should therefore be interpreted in the context of the different spatial extent and development stage of the three licensing categories, rather than as a measure of the area occupied by operational wind-energy infrastructure (Figures 2–4).



Figure 2. Spatial distribution of WPP areas in Greece according to operating license.



Figure 3. Spatial distribution of WPP areas in Greece according to installation license.

3.2. Spatial Overlap with Potential Grazing Lands

Substantial proportions of WPP licensing areas overlapped land cover classes potentially associated with grazing across all four classification scenarios. Overlap was consistently highest for installation license areas and lowest for producer certification areas, while operating license areas showed intermediate values. The range of overlap estimates was particularly high for installation license areas, whereas producer-certification areas showed consistently lower percentages across all scenarios. Detailed results for each licensing stage and classification scenario are presented in Table 2.

Table 2. Total area (ha) and percentage (%) of potential grazing land within the three WPP licensing categories under the four classification scenarios.

Licensing Stage	Total Area (ha)	Scenario A (ha/%)	Scenario B (ha/%)	Scenario C (ha/%)	Scenario D (ha/%)
Operating license	22,265.80	16,657.46/74.81	17,309.66/77.74	16,609.55/74.60	17,261.75/77.53
Installation license	8100.45	6849.81/84.56	6960.80/85.93	6665.72/82.29	6776.71/83.66
Producer certification	131,064.32	83,217.00/63.49	89,291.45/68.13	83,089.69/63.40	89,164.18/68.03
Total	161,430.57	106,724.26/66.11	113,561.90/70.34	106,364.96/65.89	113,202.64/70.12



Figure 4. Spatial distribution of WPP areas in Greece according to producer certification.

For context, the total extent of potential grazing land was also calculated for each classification scenario. Potential grazing land covered 4,891,730 ha (37.95%), 7,082,695 ha (54.95%), 4,530,719 ha (35.15%), and 7,038,255 ha (54.60%) of the terrestrial area of Greece under Scenarios A–D, respectively. These values provide a national baseline for interpreting the overlap estimates between WPP and potential grazing land.

3.3. Sensitivity of Spatial Overlap to Grazing-Land Definition

The estimated national overlap varied according to the land cover classes included in the definition of potential grazing land. Across all WPP categories combined, Scenario B produced the highest estimate, with 70.34% of the total WPP polygon area classified as potential grazing land. Scenario C produced the lowest estimate (65.89%), whereas Scenario D yielded a nearly identical estimate (70.12%). Scenario A resulted in an intermediate overlap of 66.11%. The absolute difference between the highest and lowest national estimates was therefore approximately 4.45 percentage points.

Total WPP–grazing land overlap ranged from 65.89% to 70.34%, indicating substantial spatial coincidence between the national WPP polygon area and potential grazing land under all four scenarios. The pattern was particularly pronounced for WPPs with operating

and installation licenses. Even under Scenario C, which produced the lowest national estimate, approximately three quarters of the operating license areas (74.60%) and more than four fifths of the installation license areas (82.29%) overlapped potential grazing lands. Detailed overlap results for the individual CORINE Land Cover classes across the four grazing land scenarios are provided in Supplementary Table S1.

The sensitivity analysis provides an indication of the extent to which overlap estimates depend on assumptions regarding grazing land classification, while showing that the main national-scale pattern remained consistent across the alternative scenarios (Figure 5).

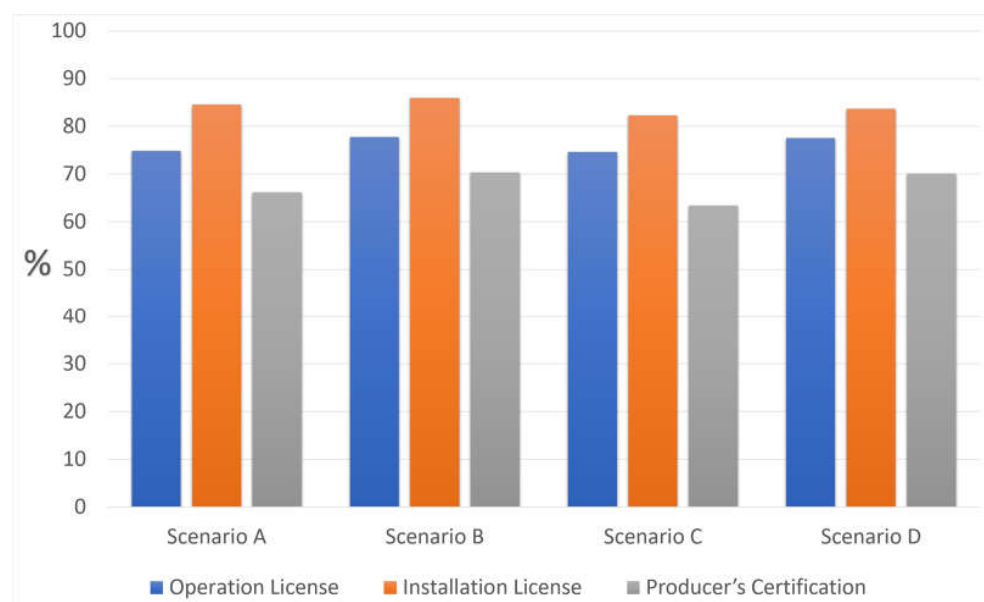


Figure 5. Percentage of WPP polygon area overlapping potential grazing lands according to licensing stage and pasture classification scenario.

3.4. Spatial Overlap with Natura 2000 Sites

A substantial proportion of WPP licensing areas was located within the Natura 2000 Network. The extent of overlap varied among licensing stages, with producer-certification areas showing the highest proportion of their total area located within Natura 2000 sites, followed by operating-license areas, whereas installation license areas showed the lowest proportion. Overall, 28.64% of the total WPP polygon area was located within Natura 2000 sites (Table 3, Figure 6), while Natura 2000 sites accounted for 27.59% of the terrestrial area of Greece.

Table 3. Spatial overlap of WPP licensing areas with Natura 2000 sites and potential grazing land under the four classification scenarios.

Licensing Stage	WPP Area Within Natura 2000 (ha/% of WPP Area)	Scenario A (ha/% of WPP–Natura Overlap)	Scenario B (ha/% of WPP–Natura Overlap)	Scenario C (ha/% of WPP–Natura Overlap)	Scenario D (ha/% of WPP–Natura Overlap)
Operating license	5319.60/ 23.89	4108.41/77.23	4222.63/79.38	3344.39/62.87	4185.05/78.67
Installation license	1278.31/ 15.78	1061.71/83.05	1080.67/84.54	844.12/ 66.03	896.61/70.14
Producer certification	39,637.05/30.24	27,213.31/68.65	28,071.96/70.82	24,793.58/62.55	28,006.17/70.66
Total	46,234.96/28.64	32,383.44/70.04	33,375.26/72.19	28,982.09/62.68	33,087.83/71.56

Percentages in the first column represent the proportion of each WPP licensing stage located within Natura 2000 sites. Percentages reported for Scenarios A–D represent the proportion of the respective WPP–Natura 2000 overlap additionally classified as potential grazing land under each grazing-land classification scenario.



Figure 6. Spatial distribution of WPP licensing areas in relation to Natura 2000 sites in Greece.

3.5. Integrated Spatial Pattern

The integrated spatial analysis revealed substantial three-way spatial overlap among WPP licensing areas, potential grazing lands, and the Natura 2000 Network. Overall, 28.64% of the total WPP polygon area was situated within Natura 2000 sites. Within this WPP-Natura 2000 overlap, the proportion additionally classified as potential grazing land varied among the four scenarios, ranging from 62.68% under Scenario C to 72.19% under Scenario B. Scenarios A and D produced similarly high estimates of 70.04% and 71.56%, respectively (Table 3). These results indicate that a substantial proportion of the WPP areas located within Natura 2000 sites also coincided spatially with areas classified as potential grazing land, although the magnitude of this three-way overlap varied depending on the grazing land classification scenario.

3.6. Regional Overlap Intensity and Spatial Patterns

The regional analysis revealed clear spatial variation in overlap intensity across the three WPP licensing stages and the four grazing land classification scenarios (see Supplementary Table S2 and Supplementary Figure S1). The total area of potential grazing land also varied substantially among the NUTS-2 regions and across the four classifica-

tion scenarios, providing the spatial basis for the calculation of regional overlap intensity (Supplementary Table S2). Overall, producer certification areas exhibited the highest regional overlap intensities, followed by areas with operating license and installation license. Within producer certification areas, the highest intensity was recorded in the North Aegean region under Scenario A (3.87%), while Sterea Ellada showed the highest values under Scenarios B–D, reaching 2.88–3.65%. For operating license areas, Sterea Ellada consistently showed the highest overlap intensity across all four scenarios, ranging from 0.88% to 1.12%. Installation license areas generally exhibited lower overlap intensities, with the highest values recorded in Central Macedonia under Scenarios A and C (0.43% and 0.38%, respectively). In contrast, Sterea Ellada showed the highest values under Scenarios B and D (0.31% and 0.30%, respectively). Despite differences among scenarios, the heatmaps showed broadly consistent spatial patterns, indicating that the national-scale overlap was spatially concentrated in specific NUTS-2 regions rather than being evenly distributed across Greece.

4. Discussion

The results demonstrate substantial spatial coincidence between wind energy licensing areas and potential grazing lands in Greece. Even under the most restrictive of the four grazing land scenarios, a large proportion of the WPP polygon area intersected land cover classes potentially associated with livestock farming. The pattern was particularly evident for WPPs during the operating and installation stages, with estimated spatial overlap ranging from approximately 75% to 86%, depending on the definition of potential grazing lands. These findings are important because areas used for livestock farming constitute an important component of Mediterranean semi-natural landscapes. Livestock grazing can provide both agricultural and ecological benefits by maintaining open habitats, regulating vegetation succession, and contributing to landscape heterogeneity [6,7,18,19]. Previous studies indicate that the effects of wind energy development on landscape components do not lead to clear and coherent conclusions. Changes in soil and vegetation have been reported in some studies [11,12], whereas other research has identified limited changes in plant community characteristics associated with wind energy infrastructure [13]. Similarly, no statistically significant negative effects of wind turbines on agricultural land values were identified in the study by Sampson et al. [14]. The available evidence therefore does not support a simple assumption that wind energy development necessarily produces uniform negative effects on grazing landscapes. Rather, potential effects appear to be context-dependent and influenced by specific environmental conditions, spatial scales, and management characteristics. The present analysis contributes to this broader discussion from a different perspective. Rather than quantifying ecological impacts, livestock responses, or direct land use conversion, it identifies the spatial contexts in which wind energy licensing areas and potential livestock farming activities coincide and where more detailed environmental, ecological, or livestock management assessments may therefore be particularly relevant.

The use of four alternative potential grazing land scenarios represents an important component of the analysis because grazing areas cannot be delineated unambiguously using a single CORINE land cover class. Land cover categories considered relevant to Grazing Management Plans include natural grasslands and other semi-natural vegetation types, while agricultural mosaics and areas containing substantial proportions of natural vegetation may also represent areas potentially suitable for livestock grazing [29]. Consequently, estimates based on a single definition of potential grazing land may be sensitive to the classification criteria adopted. The relatively limited variation among the four scenarios indicates that the overall national-scale pattern of spatial overlap between WPP

licensing areas and potential grazing land was broadly consistent, despite differences in the land cover classes included in the respective definitions. At the same time, the variation among scenarios indicates that the magnitude of the estimated overlap remains sensitive to how potential grazing land is delineated. Therefore, the sensitivity analysis supports the interpretation of the four scenarios as alternative land cover-based proxies, rather than as definitive representations of actual grazing activity. It should be noted that producer certification polygons account for the largest share of the total WPP spatial extent. As a result, the combined national estimates are substantially influenced by this earlier licensing stage and should be interpreted alongside the stage-specific results.

A critical consideration in interpreting these findings is the distinction between WPP licensing polygons and the actual physical footprint of wind energy infrastructure. The areas represented in the spatial dataset used in this study correspond to broader licensing or project areas and therefore do not directly represent the area physically occupied by wind turbines and associated infrastructure. The distinction between the broader spatial extent of a wind energy project and the area directly affected by its infrastructure has also been emphasized in previous studies [5,35]. Recent work from Greece has further demonstrated the importance of considering both the spatial extent and intensity of wind energy development when assessing its relationship with licensing and protected areas [36]. Turbine foundations, access roads, substations, transmission infrastructure, and other associated facilities occupy only a part of the broader project area [5,35]. Consequently, the high percentages of overlap reported in this study cannot be interpreted as equivalent percentages of grazing land converted to wind energy infrastructure. The analysis therefore identifies spatial coincidence and potential areas of interaction rather than direct land occupation, land use conversion, or ecological impact. Potential implications for livestock movement, access to grazing areas, or pasture management practices remain possible but were not evaluated in the present study and require project-level assessment. Evidence from Greece further demonstrates that wind energy development can involve land take associated not only with turbine installations but also with the construction and widening of access roads [37]. Licensing polygons can therefore provide a useful basis for national-scale spatial screening but should not replace project-specific assessments based on the actual footprint and location of individual infrastructure components.

The regional analysis indicated that the overlap at the national scale was not spatially uniform across Greece. Producer certification areas generally exhibited higher regional overlap intensities than operating and installation license areas, although the magnitude and spatial distribution of overlap varied among regions and grazing land scenarios. The heatmaps nevertheless revealed broadly consistent spatial patterns across the scenarios, indicating that the spatial coincidence between WPP licensing areas and potential grazing land was concentrated in specific NUTS-2 regions rather than being evenly distributed across the country. Because the regional metric is based on the area of potential grazing land within each region, it should be interpreted as an overlap intensity measure rather than as a measure of absolute WPP density or livestock pressure.

The integrated analysis further demonstrated that WPP licensing areas, potential grazing land, and Natura 2000 sites can spatially coincide within the same areas. This three-way spatial relationship highlights locations where renewable energy licensing, potential grazing land, and biodiversity-conservation considerations intersect. However, the analysis does not determine whether such co-occurrence corresponds to ecological or management conflict, since the grazing classification is based on land cover and the WPP polygons do not represent the physical footprint of infrastructure. Therefore, the three-way overlap should be interpreted as a screening indicator identifying locations where a more detailed project and site level assessment may provide additional information.

The potential effects of wind energy development on grazing animals remain insufficiently understood, particularly under Mediterranean conditions. Although previous studies examined the responses of semi-domesticated reindeer to wind-energy development in northern European environments, reporting changes in migration routes, movement corridors, habitat use, and spatial distribution during different phases of project development [15–17], the extent to which these findings can be applied to Mediterranean livestock remains uncertain. More broadly, recent literature has highlighted the limited and fragmented evidence concerning the potential effects of renewable-energy infrastructure on extensively managed livestock [38]. These findings indicate that animal responses cannot necessarily be interpreted as simple or uniform avoidance of wind-energy infrastructure. Instead, responses may vary according to the phase of development, infrastructure characteristics, animal species, livestock management practices, and broader landscape conditions. Grazing sheep, goats and cattle raised under Mediterranean conditions differ substantially from semi-domesticated free ranging reindeer in terms of body size, grazing behavior, movement patterns, human supervision, management practices, and patterns of pasture use [6,18,19]. Therefore, the limited availability of research specifically examining livestock responses to wind-energy development under Mediterranean grazing conditions represents an important knowledge gap [38]. The substantial spatial coincidence identified in the present study highlights the need for targeted field-based research in landscapes where potential grazing areas and operating wind-energy infrastructure coexist. Future studies could examine livestock distribution, movement patterns, habitat use, grazing behavior and other relevant indicators in relation to wind-energy infrastructure and associated facilities. Such information could contribute to a better understanding of potential interactions between renewable-energy development and livestock management and could provide useful evidence for the preparation and implementation of Grazing Management Plans.

The finding that approximately 28.64% of the total WPP polygon area overlaps Natura 2000 sites introduces an additional conservation dimension to the spatial patterns identified in this study. According to the Greek Priority Actions Framework (PAF) for the Natura 2000 Network for the 2021–2027 period, several grassland habitat types were reported as having unfavorable or unknown conservation status during the Article 17 reporting period for 2013–2018, while others were assessed as having a favorable status [30]. Importantly, both excessive grazing and the abandonment of grazing may constitute pressures on grassland ecosystems. The principal pressures identified for these habitats include intensive grazing or overgrazing and, conversely, the abandonment of traditional pasture management through the cessation of grazing or mowing [30]. Management interventions identified for maintaining or restoring favorable conservation status include the promotion of extensive grazing, regulation of grazing intensity and distribution, management of vegetation succession and shrub encroachment, and other habitat-specific restoration measures [30,39]. These considerations illustrate why the interaction between renewable energy planning and grazing management cannot be reduced to a simple question of whether WPP infrastructure directly removes pasture area. In some protected areas, the continuation of appropriately managed grazing is itself an important component of habitat management and conservation. Consequently, changes in livestock accessibility, movement, or grazing management could be relevant considerations in some contexts, although such effects were not assessed in the present study. This qualification is particularly important when interpreting the spatial coincidence identified here: overlap between WPP licensing areas, potential grazing lands, and Natura 2000 sites does not demonstrate ecological impact, but it identifies spatial contexts in which more detailed assessment of infrastructure development, grazing management, landscape configuration, and site-specific conservation objectives may be warranted. More broadly, previous research on renewable energy

infrastructure within Natura 2000 sites has highlighted the importance of considering not only direct land occupation but also the spatial configuration and potential fragmentation of affected landscapes [38,40]. Although the nature and magnitude of such effects may vary according to the type, scale, and configuration of the infrastructure involved, this broader spatial perspective may also be relevant when assessing wind energy development in protected landscapes.

The Greek environmental permitting framework already provides mechanisms for assessing the project-specific effects of WPP development. Environmental Impact Assessment Studies evaluate the likely environmental consequences of Category A projects and identify appropriate mitigation measures and alternatives [22,24]. For developments that may affect Natura 2000 sites, Special Ecological Assessments provide an additional framework for evaluating potential effects on protected habitats and species [22,24]. These mechanisms remain essential and cannot be replaced by national-scale GIS screening. However, the present analysis demonstrates the potential value of an additional, broader spatial planning perspective. Project-level assessments are inherently focused on individual developments, whereas national or regional-scale screening can identify broader patterns of spatial coincidence and landscapes where multiple land use and conservation objectives intersect. A screening framework integrating WPP licensing data, potential grazing lands, Natura 2000 sites, and additional environmental or agricultural information could therefore help identify areas requiring particular attention before more detailed project-level assessment. Such an approach may also be useful for examining cumulative spatial patterns where multiple WPP developments occur within the same grazing landscape or protected area. This broader perspective may become increasingly relevant in landscapes affected by simultaneous changes in grazing management and broader processes of pasture abandonment or vegetation succession [27,28,30]. The objective should not be to interpret spatial overlap automatically as evidence of environmental conflict. Rather, national-scale screening can identify potential planning interfaces where renewable energy objectives, grazing management, and biodiversity conservation should be considered jointly.

Several limitations of the present analysis should be explicitly acknowledged. First, WPP licensing polygons do not represent the actual footprint of wind energy infrastructure [41,42]; therefore, the estimated spatial overlap should not be interpreted as direct land use conversion. Second, the RAE dataset used in the present analysis includes only Category A projects. Consequently, smaller projects falling outside this category were not included, and the total spatial extent of wind energy development, as well as the estimated spatial overlap with potential grazing lands and Natura 2000 sites, may therefore be underestimated. Third, potential grazing lands were identified using CORINE Land Cover 2018. Although CORINE provides consistent and standardized national coverage, its thematic and spatial resolution cannot capture detailed local variation in grazing intensity, pasture quality, seasonal patterns of pasture use, or livestock distribution. There is also a temporal mismatch between the CORINE Land Cover 2018 dataset and the WPP data retrieved in February 2026. Consequently, the analysis assumes that the 2018 land cover classification provides a sufficiently representative description of land cover conditions at the time of the WPP assessment. No independent contemporary land cover dataset was used to validate this assumption. Fourth, areas classified as potential grazing lands are not necessarily actively grazed. Conversely, some locally important grazing resources may not be adequately represented by the land cover categories included in the present classification scenarios. The four scenarios should therefore be interpreted as alternative land-cover-based proxies for potential grazing land rather than as direct maps of actual grazing activity. Fifth, the present analysis identifies spatial coincidence but does not assess causal environmental effects. It does not quantify potential impacts on soil, vegetation,

habitat condition, livestock behavior, livestock productivity, or biodiversity. Finally, the analysis reflects the spatial status of WPP data retrieved in February 2026. Wind energy licensing is a dynamic process, and both the spatial distribution and licensing status of projects may change over time.

Future research should therefore combine national-scale spatial screening with detailed project-level information on the actual location and footprint of turbines, access roads, substations, transmission infrastructure, and other associated facilities [41–43]. The integration of grazing animal capital data, stocking rate, seasonal pasture use, habitat condition, and landscape configuration could enable a more comprehensive assessment of potential interactions between renewable energy development and pastoral systems. Particularly important would be field-based research examining the grazing behavior and spatial use of sheep, goats, and cattle in the vicinity of operating wind energy infrastructure under Mediterranean conditions. Such studies could determine whether the spatial coincidence identified in the present analysis is associated with measurable changes in livestock movement, grazing distribution, habitat use, or pasture utilization.

5. Conclusions

This national-scale assessment demonstrates a substantial spatial coincidence between WPP licensing areas and potential grazing lands in Greece. Depending on the definition of potential grazing land, between 65.89% and 70.34% of the total WPP polygon area overlapped land cover classes included in the four grazing land scenarios. The overlap was particularly high for projects that are at the operating and installation stages, while approximately 28.64% of the total WPP polygon area was located within Natura 2000 sites. These spatial patterns may be relevant to the consideration of livestock farming activities alongside biodiversity and conservation objectives in renewable energy spatial planning; however, such environmental or livestock management implications were not directly assessed in the present study. National-scale GIS screening can complement project-level environmental assessment by identifying areas where more detailed investigation may be warranted. Future research combining actual infrastructure footprints with information on grazing intensity, livestock distribution, and animal behavior could help determine whether the spatial patterns identified here translate into measurable ecological or livestock management effects.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su182010287/s1>, Table S1: Spatial overlap between WPP licensing areas and individual CORINE Land Cover classes under the four potential grazing land scenarios; Table S2: Regional overlap intensity of WPP licensing areas with potential grazing lands under the four classification scenarios; Figure S1: Regional overlap intensity of WPP licensing areas with potential grazing lands under the four classification scenarios. Numbers indicate WPP licensing stages: 1 = Producer certification; 2 = Installation license; 3 = Operating license.

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Abbreviations

The following abbreviations are used in this manuscript:

WPPs	Wind Power Production Plants
RAE	Regulatory Authority for Energy
SPAs	Special Protection Areas
SACs	Special Areas of Conservation
SCIs	Sites of Community Importance
PAF	Priority Actions Framework
CLC	CORINE Land Cover
EEA	European Environment Agency
EGSA87	Greek National Coordinate Reference System

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