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Wind energy and protected areas on islands: Scaling, spatial intensity, inequality, and licensing outcomes across an archipelago

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ABSTRACT

Islands are increasingly positioned at the forefront of renewable energy transitions. They host high biodiversity, limited land availability, and growing wind-energy development, creating structural tensions between decarbonization and conservation. Yet the spatial distribution of renewable energy infrastructure across island systems remains poorly quantified. This study provides a distribution-sensitive assessment of terrestrial wind-energy development across Greek islands by examining scaling relationships, spatial intensity, inequality, spatial clustering, and licensing outcomes. We distinguish between absolute deployment metrics (installed capacity and total project footprint) and relative spatial intensity (normalized by island area). Quantile regression characterizes heterogeneous scaling relationships, while Lorenz curves and Gini coefficients quantify inequality in wind-energy pressure. Installation-level models evaluate how overlap with Natura 2000 protected areas relates to licensing outcomes. Wind capacity increases with island area, but scaling differs across the deployment distribution, with larger islands disproportionately defining the upper deployment frontier. Wind potential constrains deployment at the lower and upper tails but does not explain median patterns. Total project footprint declines with increasing Natura coverage, whereas footprint intensity rises, indicating spatial compression as infrastructure becomes concentrated within the remaining non-protected land. Inequality metrics reveal strong concentration of wind-energy pressure, and spatial autocorrelation analyses indicate significant geographic clustering of deployment intensity. Natura overlap was associated with licensing outcomes in unadjusted models, but was not a significant predictor after accounting for application year and project footprint. The findings demonstrate that wind energy projects in islands are shaped by conservation coverage and distributional dynamics alongside resource availability. More broadly, they show that where wind-energy development is concentrated may be as important as how much is installed, highlighting the value of spatial intensity, inequality, and distributional metrics for revealing conservation pressures overlooked by aggregate capacity alone. Incorporating these indicators into Environmental Impact Assessment and Strategic Environmental Assessment can improve cumulative, archipelago-scale planning in conservation-sensitive contexts.

1. Introduction

The accelerating climate and biodiversity crises are increasingly intertwined through land-use change, infrastructure expansion, and energy transitions. Global assessments consistently identify land-use change as the primary driver of biodiversity decline, while climate change amplifies and interacts with these pressures (IPBES, 2019; WWF, 2022). Islands occupy a particularly sensitive position within this nexus. Although they cover a small fraction of the Earth's surface, they host a disproportionate share of global biodiversity and ecosystem services, while simultaneously exhibiting heightened vulnerability to climatic variability, land-use pressures, and socio-economic shocks (Moustakas et al., 2025; Vogiatzakis et al., 2023). Their limited land area, ecological distinctiveness, and dependence on natural capital make them especially susceptible to cumulative environmental impacts (Morello-Frosch et al., 2011; Burris and Canter, 1997).

In parallel, islands have become central to renewable energy transitions and policy experimentation. Due to high electricity costs,

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abundant wind and solar resources, and isolated grid structures, particularly in Mediterranean and Greek island systems, they are frequently described as "testbeds" for achieving high or even 100% renewable energy penetration. Recent reviews of renewable energy pathways on islands emphasize wind and solar photovoltaics as dominant technologies, while noting that spatial constraints and land availability are often insufficiently incorporated into system modelling (e.g., Meschede et al., 2022). Technical studies further highlight the challenges of integrating variable renewables into isolated grids, including frequency stability, curtailment risks, and the need for storage or flexible demand (e.g., Wang et al., 2013; Ochoa-Correa et al., 2025). However, these contributions largely focus on techno-economic feasibility and system performance rather than on the spatial distribution of infrastructure and its interaction with conservation.

Wind energy expansion is central to European decarbonization strategies and to achieving Sustainable Development Goals related to clean energy and climate action (Borchardt et al., 2022). At the same time, renewable energy deployment entails land transformation, infrastructure development, and potential biodiversity trade-offs. This paradox—mitigating climate change through technologies that may simultaneously intensify biodiversity loss—has been described as a biodiversity–climate policy conflict or "green–green dilemma" (Kati et al., 2021; Moustakas et al., 2023). Wind farms contribute to habitat fragmentation, land take, and impacts on species populations and habitats, particularly in ecologically valuable or protected landscapes (Kati et al., 2021; Moustakas et al., 2023; Vlami et al., 2020a). In biodiversity hotspots such as Greece, where Natura 2000 sites cover a substantial proportion of terrestrial territory and wind development is legally permitted within protected areas, the potential for spatial conflict is particularly pronounced (Moustakas et al., 2023).

Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) are designed to mediate such trade-offs through project-level evaluation, cumulative impact consideration, and Appropriate Assessment under the Habitats Directive. However, critiques of current practice highlight limitations in capturing cumulative, synergistic, and distributional effects, particularly in spatially constrained systems (Moustakas et al., 2025; Vogiatzakis et al., 2023). While numerous studies assess site-level ecological impacts of wind energy, and others examine large-scale spatial planning scenarios to reduce biodiversity conflicts, less attention has been given to how renewable infrastructure is distributed across bounded island systems and how conservation coverage reshapes this distribution.

Recent research on island ecosystem services emphasizes that climate change impacts are often modulated more strongly by land-use change and other anthropogenic drivers than by climatic variables alone (Moustakas et al., 2025). Moreover, stakeholder-based analyses indicate that land use and renewable energy infrastructure are perceived as major pressures interacting with climate change in island contexts (Moustakas et al., 2026). These findings suggest that renewable energy expansion should not be assessed solely in terms of installed capacity or mean spatial effects, but within a broader land use–climate–conservation nexus framework. Yet empirical quantification of how conservation regimes interact with infrastructure deployment across entire archipelagos remains limited.

This study investigates the spatial distribution, intensity, inequality, and licensing outcomes of terrestrial wind energy deployment across Greek islands, with particular emphasis on interactions between wind infrastructure and Natura 2000 coverage. Specifically, the analysis addresses four related questions: (i) how wind-energy development is distributed across islands in terms of project footprint and installed capacity, (ii) how Natura 2000 coverage is associated with the level and spatial distribution of this deployment, (iii) to what extent wind energy pressure is concentrated rather than evenly distributed across islands, and (iv) how Natura-overlapping area relates to licensing outcomes at the installation level. To address these questions, we distinguish between absolute deployment (total capacity and footprint) and relative spatial intensity (normalized by island area), and employ quantile regression and ordinary least squares models to characterize both heterogeneous and mean relationships. In addition, we apply Lorenz curves and Gini coefficients to quantify inequality in wind energy pressure across the archipelago, and spatial autocorrelation analyses to evaluate the geographic clustering of deployment patterns. In this context, inequality refers to the uneven distribution of wind energy pressure across islands.

This study contributes to literature examining interactions among land use, climate change, conservation, and renewable energy deployment by adopting a distributional perspective on renewable energy deployment in bounded island systems. While existing work has largely focused on aggregate capacity, site-level impacts, or system performance, this analysis examines how development is allocated across space and how conservation coverage relates to that allocation. By combining installation-level and island-level analyses, the paper provides empirical evidence on how Natura 2000 coverage relates to the spatial organization, intensity, distribution, and licensing outcomes of wind energy deployment across an archipelago. From an impact assessment perspective, the results are relevant for understanding how EIA and SEA frameworks may account for cumulative, intensity-based, spatial, and distributional pressures beyond aggregate installed capacity.

2. Methods

2.1. Study system and data

This study examines the spatial distribution, intensity, and inequality of terrestrial wind energy development across Greek islands, with particular emphasis on interactions between wind infrastructure and Natura 2000 protected areas. Greek islands represent bounded spatial systems characterized by finite land availability, ecological sensitivity, and, in many cases, high conservation significance. These characteristics make them a suitable empirical setting for evaluating how renewable energy deployment interacts with spatial protection regimes and whether conservation coverage is associated with differences in the magnitude, spatial distribution, or intensity of infrastructure deployment.

The island inventory was obtained from Santi et al. (2024) and expanded to include all Greek islands represented in the spatial database. The final inventory comprised 871 islands, of which 105 contained at least one recorded wind-energy project and 766 contained no recorded wind-energy projects. Retaining islands without wind development allowed assessment of the full distribution of wind-energy pressure across the archipelago, including zero-development islands (Fig. 1).

Spatial data on wind-energy installations were obtained from the online geoinformation map (https://geo.rae.gr/) of the Regulatory Authority for Energy, Waste and Water (RAAEY). Information on licensing status was used to classify installations into three categories: approved/intermediate, operating, and rejected/terminated. Installation footprints were provided as georeferenced polygons and were spatially intersected with island boundaries and terrestrial Natura 2000 sites to compute overlap metrics. In this study, wind footprint refers to the area of project polygons represented in the RAAEY database and should therefore be interpreted as a licensed/project-area proxy rather than a direct measure of physically disturbed land. All spatial processing was performed in QGIS v. 3.44.7 (QGIS Development Team, 2026) using the Greek Geodetic Reference System 1987 (GGR87) and completed prior to statistical modelling.

The database contained 3831 unique wind-energy project identifiers. For licensing analyses, projects were represented by 3837 project-record observations, reflecting cases where the same project appeared in more than one licensing record. These records were classified as approved/intermediate ($n = 3011$), operating ($n = 193$), and rejected/terminated ($n = 633$).

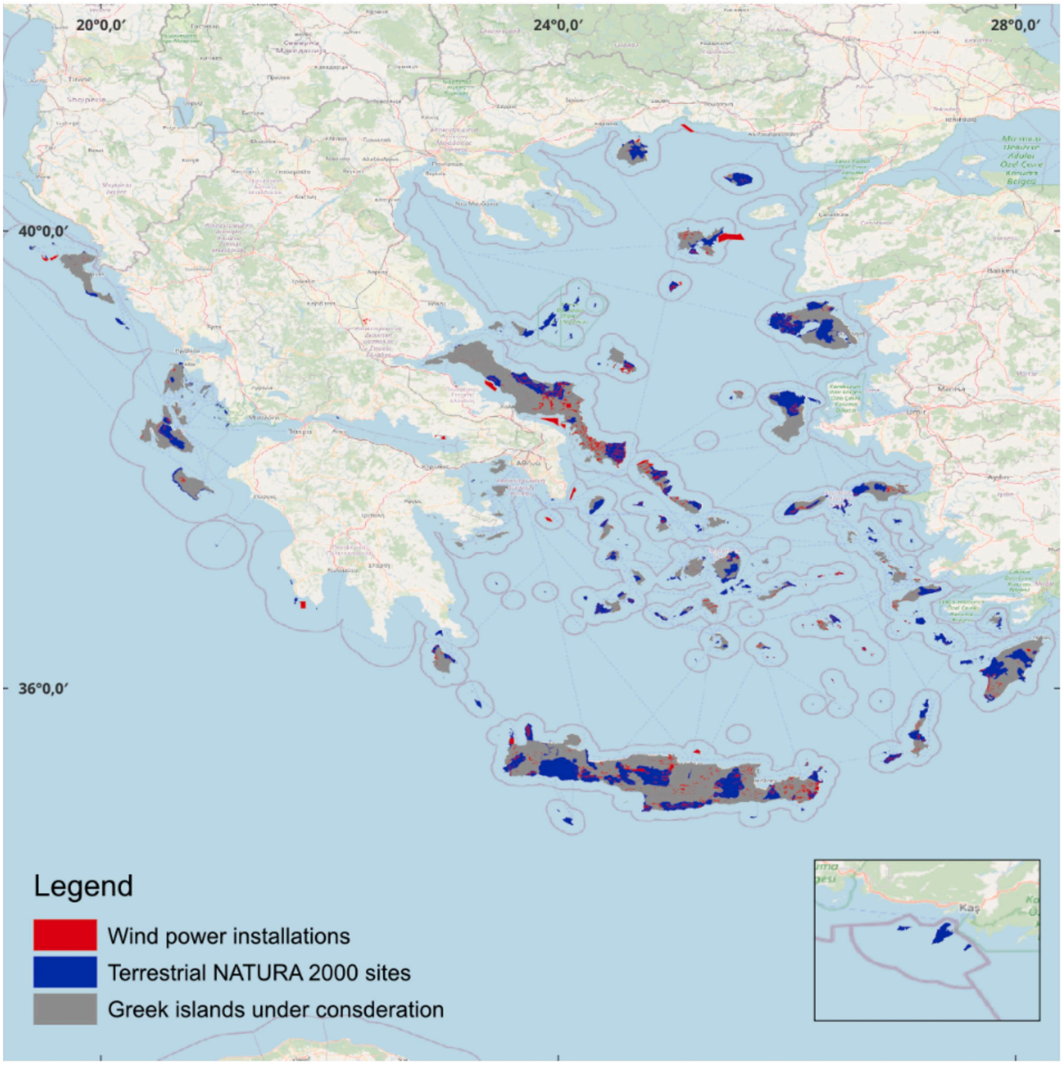


Fig. 1. Greek islands under consideration, terrestrial NATURA2000 sites and wind power installations. Embedded map: island Kastelorizo.

Data on wind energy potential, expressed as wind power density (W m^{-2}) at 100 m altitude, were obtained from the Global Wind Atlas (Davis et al., 2023). A raster file with 0.0025 × 0.0025 degree resolution was used to compute island-level statistics (mean, minimum, and maximum wind potential) using zonal statistics in QGIS. All variables deployed in the analysis are summarized in Table 1.

Table 1
Dataset structure and raw variables used in the analysis. Island area, Natura 2000 coverage, and wind potential were available for all 871 islands. Installed capacity and wind footprint were available only for the 105 islands containing recorded wind-energy projects.

Component / variable	Unit	n
Greek island inventory	islands	871
Islands with recorded wind-energy projects	islands	105
Islands without recorded wind-energy projects	islands	766
Unique wind-energy project identifiers	projects	3831
Licensing/project records	records	3837
Approved/intermediate	records	3011
Operating	records	193
Rejected/terminated	records	633
Island area	km^2	871
Natura 2000 coverage	% island area	871
Wind potential	W m^{-2}	871
Installed capacity	MW	105
Wind footprint	ha	105

Analyses were conducted at two levels. At the island level, wind deployment was aggregated to quantify total installed capacity and project footprint. At the installation level, Natura-overlapping area was calculated for each project to assess licensing-related patterns. The analysis combines descriptive, regression-based, and distributional statistical approaches to examine both average relationships and heterogeneity across islands. For spatial analyses, each island was represented by its geographic centroid. Island centroid coordinates were used to construct spatial-neighbourhood matrices, evaluate spatial autocorrelation, and visualize the geographic distribution of deployment indicators.

2.2. Data preprocessing

The dataset is structured at the polygon level, allowing multiple spatial units per installation, multiple installations per island, and multiple licensing states over time.

Let i index polygons, j installations, and k islands. Each installation may consist of multiple polygons, and each island may host multiple installations.

The spatial footprint of each polygon is measured as its area (in hectares), denoted A_{ij}. To account for skewness, the dependent variable is defined as:

$$y_{ij} = \log(A_{ij})$$

when multiple records exist for the same installation across time, only the most recent observation is retained to avoid double counting across licensing stages. Log-transformation is applied to reduce skewness and improve comparability across observations (Box and Cox, 1964).

2.3. Natura 2000 overlap metrics

Spatial overlays between wind-energy project polygons and the Natura 2000 network were used to derive measures of conservation coverage at both the island and installation levels. At the island level, Natura 2000 coverage was calculated as the proportion of island area designated as protected. At the installation level, Natura overlap was calculated as the total area (ha) of project polygons intersecting Natura 2000 sites.

When multiple records existed for the same installation across licensing stages, only the most recent observation was retained to avoid double counting. Natura-overlapping area was subsequently used in licensing analyses, whereas island-level Natura 2000 coverage was used in analyses of deployment intensity, footprint, installed capacity, and spatial distribution across islands.

2.4. Island-level aggregation

In contrast to the installation-level analysis, no exclusion based on Natura variation is applied at the island level (I.e. all licensing applications and their current latest status are included). Installations fully inside, fully outside, or partially overlapping protected areas are retained in order to capture the full distribution of wind energy pressure across islands.

Total wind energy footprint is defined as:

$$F_k = \sum_{i,j \in k} A_{ij}$$

Total installed capacity is defined as:

$$P_k = \sum_{j \in k} C_j$$

where $C_j$denotes the installed capacity of installation j.

To ensure comparability across islands of different sizes, both measures are normalized by island area S_k:

$$\text{Footprint intensity}_k = \frac{F_k}{S_k}, \text{Power intensity}_k = \frac{P_k}{S_k}$$

Islands without recorded wind-energy projects were assigned zero values for installed capacity, footprint area, power intensity, and footprint intensity. These islands were retained in archipelago-scale analyses of concentration, inequality, and spatial autocorrelation in order to characterize the full distribution of wind-energy pressure across Greek islands.

Island area, Natura 2000 coverage, and wind potential were available for all 871 islands. Analyses of concentration, inequality, and spatial autocorrelation therefore used the complete island inventory. In contrast, regression analyses examining relationships between deployment metrics and island characteristics were conducted using the 105 islands containing recorded wind-energy projects, because installed capacity and footprint variables were only defined for islands with wind-energy development. Consequently, regression analyses should be interpreted as conditional on islands with recorded wind-energy development rather than as models of wind-development occurrence across all islands.

2.5. Distribution across licensing categories

Installations are classified into licensing categories (approved, operating, and rejected) based on their recorded status. For each installation, Natura overlap is measured as the total area of polygons located within protected zones.

Differences across licensing categories are examined using distributional comparisons. To assess whether Natura overlap differs across licensing categories, non-parametric statistical tests are employed. A Kruskal–Wallis test is used to evaluate overall differences across groups (Kruskal and Wallis, 1952), followed by pairwise Mann–Whitney tests with multiple-testing correction (Mann and Whitney, 1947). These tests assess statistical differences without imposing distributional (normality) assumptions.

2.6. Installation-level licensing model

To examine how Natura 2000 overlap relates to licensing outcomes, we estimate a multinomial logit model at the installation level (McFadden, 1974). Licensing status is treated as a categorical outcome with three states: Approved (baseline), Operating, and Rejected.

For each installation j, Natura overlap is defined as the total area (ha) of project polygons intersecting Natura 2000 sites. To account for skewness, overlap is log-transformed as $\log(O_j + 1)$.

The model takes the form:

$$P(\text{Status}_j = k) = f(\log(O_j + 1), \log(S_j), N_j, W_j)$$

where:

- $O_j$is Natura-overlapping area (ha),
- $S_j$is island area,
- $N_j$is Natura coverage at the island level,
- $W_j$is wind potential.

Predicted probabilities are computed across the observed range of Natura overlap, holding other covariates at their mean values. Uncertainty is quantified using bootstrap resampling (Efron and Tibshirani, 1993), from which 95% confidence intervals are derived.

To account for temporal differences among project cohorts, an additional multinomial model included application year as a covariate. Predicted probabilities from both unadjusted and year-adjusted models were compared to evaluate whether associations between Natura overlap and licensing outcomes persisted after accounting for project timing. As an additional robustness analysis, a further multinomial logit model was fitted including total project footprint as an additional predictor, together with application year, island area, island-level Natura 2000 coverage, and wind potential. This model evaluated whether associations between Natura-overlapping area and licensing outcomes persisted after accounting for project size and the other covariates. Odds ratios were reported for both Natura-overlapping area and project footprint, while the remaining variables were included as adjustment covariates.

2.7. Quantile and ordinary least squares regression analyses

To examine how relationships between island characteristics and wind-energy deployment vary across the distribution of outcomes, quantile regression models were estimated:

$$Q\tau(\text{Yk}|\text{Xk}) = \alpha\tau + \beta\tau\text{Xk}$$

where Yk denotes the outcome variable, Xk the predictor variable, and $\tau \in (0,1)$ indexes the quantile.

Quantile regression was estimated using standard linear programming methods (Koenker and Bassett, 1978), allowing inference across multiple points of the conditional distribution rather than focusing solely on the mean. Models were fitted at $\tau = 0.10$, 0.25, 0.50, 0.75, and 0.90 to evaluate whether associations varied between low-, intermediate-, and high-deployment islands. Quantile regressions were used to examine relationships between (i) installed capacity and island area, (ii) installed capacity and wind potential, (iii) total footprint area and

Natura 2000 coverage, and (iv) footprint intensity and Natura 2000 coverage. Coefficient estimates and 95% confidence intervals were evaluated across quantiles to assess the robustness of observed patterns and determine whether relationships differed substantially across the deployment distribution. As a denominator-sensitivity analysis, footprint intensity was also recalculated using non-Natura island area, defined as island area minus Natura 2000 area, and the corresponding quantile regression was repeated.

To complement the quantile analyses, ordinary least squares (OLS) models were fitted to estimate mean relationships between island characteristics and deployment metrics. Separate models were fitted for total installed capacity, total footprint area, power intensity, and footprint intensity, using island area and Natura 2000 coverage as predictor variables. Regression coefficients and 95% confidence intervals were estimated using HC3 (Heteroskedasticity-Consistent Covariance Matrix Estimator Type 3) standard errors. HC3 estimators were selected because they provide robust inference under heteroskedasticity and perform well in datasets containing potentially influential observations. For graphical comparison across response variables, coefficients were standardized prior to visualization. Sensitivity analyses were conducted for the OLS models to evaluate whether estimated relationships were dependent on individual islands. In addition to the primary models, leave-one-island-out analyses were performed by sequentially excluding each island and refitting the models.

2.8. Inequality measurement

To quantify the spatial distribution of wind energy development across islands, inequality is measured using the Gini coefficient applied to normalized intensity measures (Gini, 1912).

Two variables are considered:

- footprint intensity F_k/S_k
- power intensity P_k/S_k

In this context, inequality refers to the uneven distribution of wind energy pressure across islands.

The Gini coefficient is defined as:

$$G = \frac{1}{2n^2\mu}\sum_{k=1}^{n}\sum_{l=1}^{n}|z_k - z_l|$$

where $z_k$denotes the variable of interest, $n$is the number of islands, and $\mu$is its mean.

Lorenz curves were used to visualize inequality in footprint intensity and power intensity, with bootstrapped confidence intervals used to characterize uncertainty (van der Vaart, 1998; Efron and Tibshirani, 1993). As a sensitivity analysis, leave-one-island-out procedures were applied by sequentially excluding each island and recalculating Gini coefficients. This analysis was used to evaluate whether estimated concentration patterns were dependent on individual islands.

2.9. Spatial autocorrelation

Spatial autocorrelation was evaluated using Global Moran's I (Moran, 1950), which quantifies the degree to which neighbouring observations exhibit similar values. For an observed variable x, Moran's I is defined as:

$$I = \frac{n}{W}\frac{\sum_i\sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2}$$

where $n$is the number of islands, $x_i$and $x_j$are observed values for islands $i$and j, $\bar{x}$is the sample mean, w_{ij}denotes elements of the spatial weights matrix, and $W = \sum_i\sum_j w_{ij}$. Positive values indicate spatial clustering of similar values, negative values indicate spatial dispersion, and values near zero indicate spatial randomness.

Island centroid coordinates were used to construct k-nearest-neighbour spatial weights matrices, with $k = 4$, $k = 6$, and $k = 8$ employed to assess sensitivity to neighbourhood definition. Moran's I was calculated separately for wind-power intensity and wind-footprint intensity. Statistical significance was assessed using permutation tests with 999 random permutations of the observed data (Legendre and Legendre, 2012).

To complement the global spatial statistics, deployment intensity maps were generated using island centroid coordinates to visualize the geographic distribution of wind-energy pressure and identify potential hotspot regions across the Greek archipelago.

3. Results

3.1. Scaling of wind capacity with island size

Wind capacity increased with island area across the deployment distribution (Fig. 2a; Table 2). Positive relationships were observed at all quantiles, with coefficients becoming progressively stronger towards the upper tail of the distribution. For example, estimated slopes increased from lower quantiles to τ = 0.75 (β = 0.228, 95% CI: 0.084–0.373), τ = 0.90 (β = 0.254, 95% CI: 0.101–0.407), and τ = 0.95 (β = 0.258, 95% CI: 0.083–0.433). This indicates that larger islands disproportionately define the upper deployment frontier. The divergence among quantiles demonstrates heterogeneous development trajectories among islands of similar size and suggests that geography constrains maximum feasible deployment without fully determining realized capacity.

3.2. Scaling of wind capacity with wind potential

Wind capacity exhibited a generally weak association with mean wind power density across islands (Fig. 2b; Table 2). Although some quantiles displayed positive relationships, particularly at lower and upper portions of the deployment distribution, effect sizes were small. For example, the τ = 0.10 quantile exhibited a positive slope (β = 0.0045, 95% CI: 0.0001–0.0089), whereas the median relationship remained weak. Substantial vertical dispersion in installed capacity at similar wind power densities indicates that resource availability alone does not determine realized deployment.

3.3. Natura coverage and absolute wind footprint

Total wind footprint declined with increasing Natura coverage across much of the deployment distribution (Fig. 2c; Table 2). Negative coefficients were observed at the median (β = −1.845, 95% CI: −3.209 to −0.481), upper quartile (β = −2.048, 95% CI: −3.234 to −0.862), and τ = 0.90 quantile (β = −1.585, 95% CI: −2.782 to −0.388). These results indicate that islands with greater protected-area coverage generally hosted smaller absolute wind-development footprints. However, upper quantiles remained comparatively less steep, indicating that islands with high conservation coverage may still host substantial infrastructure at the upper bound of the distribution.

As a denominator-sensitivity analysis, footprint intensity was recalculated using non-Natura island area rather than total island area. The positive association between Natura 2000 coverage and footprint intensity remained evident and was statistically significant across all evaluated quantiles (Table 2). This indicates that the spatial-compression pattern was robust to the choice of denominator.

3.4. Natura coverage and footprint intensity

When normalized by island area, wind-footprint intensity increased

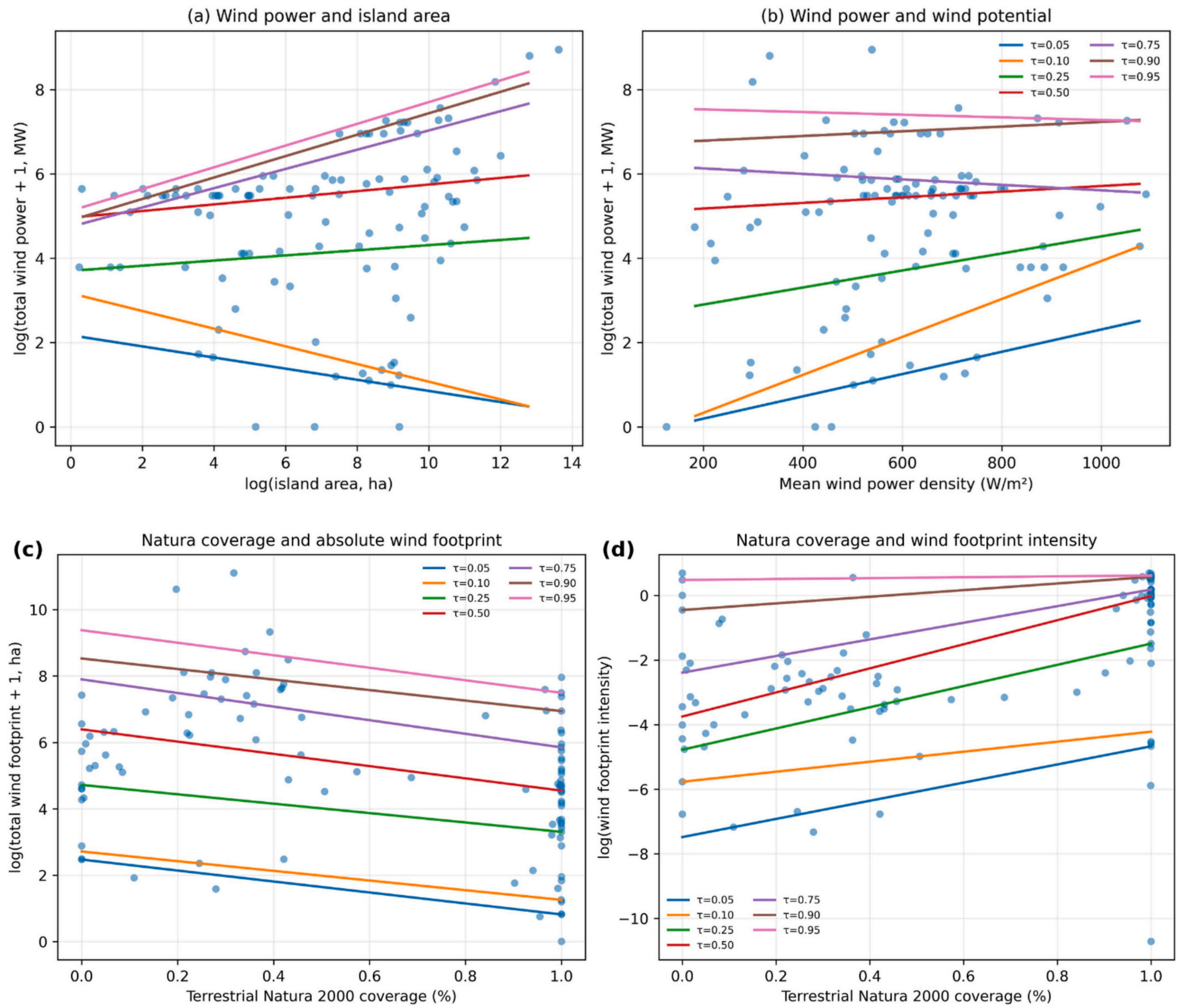


Fig. 2. Quantile-regression relationships between island characteristics and wind-energy deployment. (a) Scaling of wind capacity with island size. Log–log scatterplot of total installed wind capacity versus island area with quantile regression lines (τ = 0.05–0.95). (b) Scaling of wind capacity with wind potential. Log total installed wind capacity versus mean wind power density (W m^{-2}) across Greek islands, with quantile regression lines (τ = 0.05–0.95). (c) Scaling of wind-energy footprint with Natura 2000 coverage. Log total wind-energy footprint area versus proportion of island area designated as Natura 2000, with quantile regression lines (τ = 0.05–0.95). (d) Relationship between wind-footprint intensity and Natura 2000 coverage. Log wind-footprint intensity versus proportion of island area designated as Natura 2000, with quantile regression lines (τ = 0.05–0.95).

with Natura 2000 coverage across much of the deployment distribution (Fig. 2d; Table 2). Positive relationships were observed across intermediate and upper portions of the distribution, with particularly strong effects at τ = 0.25 (β = 3.284, 95% CI: 1.974–4.593), τ = 0.50 (β = 3.725, 95% CI: 2.971–4.480), and τ = 0.75 (β = 2.572, 95% CI: 1.666–3.477). Lower quantiles exhibited greater uncertainty, while relationships weakened towards the extreme upper tail of the distribution.

This pattern contrasts with the decline observed for absolute footprint (Section 3.3), indicating that islands with greater protected-area coverage generally hosted smaller absolute wind-development footprints but higher deployment intensity relative to island area. The divergence between absolute footprint and footprint intensity suggests that Natura coverage is associated with differences in the spatial concentration of development rather than uniformly lower levels of deployment. This pattern is consistent with a spatial-compression interpretation, whereby wind infrastructure becomes concentrated within a smaller proportion of available land as protected-area coverage increases.

3.5. *Inequality in wind-energy deployment*

Wind-energy deployment was highly unevenly distributed across islands (Fig. 3). Footprint intensity exhibited substantial concentration (Gini = 0.606, 95% CI: 0.539–0.665), whereas power intensity was even more concentrated (Gini = 0.906, 95% CI: 0.821–0.937). In both cases, Lorenz curves deviated markedly from the line of equality, indicating that a relatively small subset of islands accounted for a disproportionately large share of deployment intensity.

The degree of concentration was more pronounced for power intensity than for footprint intensity, suggesting that energy production is more unevenly distributed than spatial footprint. Bootstrap confidence intervals confirmed the robustness of these patterns. Overall, wind-

Table 2
Quantile-regression coefficients describing relationships between island characteristics and wind-energy deployment metrics across the deployment distribution. Coefficients are shown with 95% confidence intervals. Significant coefficients ($p < 0.05$) are shown in bold. Island area was log-transformed prior to analysis. Wind potential was expressed as mean wind power density ($W\ m^{-2}$). Natura 2000 coverage was expressed as the proportion of island area designated as Natura 2000. The final row presents a robustness analysis in which footprint intensity was recalculated using only non-Natura island area (island area − Natura 2000 area) as the denominator. The positive relationship between Natura 2000 coverage and footprint intensity remained evident across the deployment distribution, indicating that the spatial-compression pattern is robust to the choice of denominator.

Figure	Response variable	Predictor	τ = 0.10	τ = 0.25	τ = 0.50	τ = 0.75	τ = 0.90
Fig. 2a	Installed capacity	Island area	−0.210 (−0.422 to 0.003)	0.061 (−0.122 to 0.244)	0.079 (−0.046 to 0.203)	**0.228 (0.084 to 0.373)**	**0.254 (0.101 to 0.407)**
Fig. 2b	Installed capacity	Wind potential	**0.0045 (0.0001 to 0.0089)**	0.0020 (−0.0027 to 0.0068)	0.0007 (−0.0015 to 0.0029)	−0.0006 (−0.0023 to 0.0010)	0.0006 (−0.0027 to 0.0038)
Fig. 2c	Total footprint area	Natura 2000 coverage	−1.457 (−3.879 to 0.965)	−1.414 (−3.124 to 0.297)	**−1.845 (−3.209 to − 0.481)**	**−2.048 (−3.234 to − 0.862)**	**−1.585 (−2.782 to − 0.388)**
Fig. 2d	Footprint intensity (total island area)	Natura 2000 coverage	1.549 (−1.710 to 4.808)	**3.284 (1.974 to 4.593)**	**3.725 (2.971 to 4.480)**	**2.572 (1.666 to 3.477)**	1.026 (−0.054 to 2.107)
Robustness	Footprint intensity (non-Natura island area)	Natura 2000 coverage	**7.426 (5.683 to 9.168)**	**6.397 (4.805 to 7.988)**	**9.436 (7.479 to 11.394)**	**9.671 (7.428 to 11.913)**	**8.134 (5.151 to 11.118)**

energy pressure was concentrated within a limited subset of islands rather than being evenly distributed across the archipelago. Leave-one-island-out sensitivity analyses indicated that inequality estimates were not driven by a single island; the largest absolute change in Gini was 0.004 for footprint intensity and 0.032 for power intensity.

3.6. Licensing outcomes and Natura overlap

Unadjusted boxplots (Fig. 4a) showed systematic differences in Natura-overlapping area across licensing statuses. A Kruskal–Wallis test confirmed that these differences were statistically significant (H = 364.7, df = 2, $p < 0.001$). Post-hoc pairwise Mann–Whitney tests indicated that approved/intermediate projects differed significantly from both operating and rejected/terminated projects (p < 0.001 in both comparisons), whereas no statistically significant difference was observed between operating and rejected/terminated projects.

The multinomial model provided a clearer interpretation of these patterns (Fig. 4b; Table 3). In the unadjusted analysis, Natura overlap was positively associated with both operating and rejected/terminated outcomes relative to approved/intermediate projects. For example, the odds of rejection/termination increased with Natura overlap (OR = 2.26, 95% CI: 2.08–2.45), as did the odds of reaching operating status (OR = 1.97, 95% CI: 1.75–2.22).

However, these relationships largely disappeared after including application year in the model (Fig. 4c; Table 3). In the year-adjusted analysis, Natura-overlapping area was no longer a significant predictor of either operating or rejected/terminated outcomes, indicating that temporal differences among project cohorts explained much of the apparent association observed in the unadjusted model. A further robustness model additionally included total project footprint together with island area, Natura 2000 coverage, and wind potential. In this model, Natura-overlapping area remained non-significant for both operating and rejected/terminated outcomes, whereas project footprint was significantly associated with licensing outcome (Table 3).

3.7. Mean effects across deployment metrics

Ordinary least squares models broadly supported the patterns observed in the quantile regressions (Fig. 5; Table 4). Island area was positively associated with absolute deployment metrics, including total footprint area (β = 0.609, $p < 0.001$) and total installed capacity (β = 0.295, p < 0.001), but negatively associated with deployment intensity metrics. In particular, footprint intensity (β = −0.084, p < 0.001) and power intensity (β = −0.278, p < 0.001) both declined with increasing island area.

Natura 2000 coverage exhibited weaker and less consistent effects. A positive association was observed for total installed capacity (β = 1.570, $p = 0.018$), whereas effects on footprint area, footprint intensity, and power intensity were not statistically significant (Table 4). Robust regression and island-exclusion sensitivity analyses produced qualitatively similar effects for island area, indicating that the negative association between island size and deployment intensity was not driven by a small number of islands.

Ordinary least squares (OLS) coefficients (±95% HC3 confidence intervals) describing associations between island characteristics and wind-energy deployment metrics. Left panel shows effects of Natura 2000 coverage; right panel shows effects of island area. Deployment metrics include total installed capacity, total footprint area, power intensity, and footprint intensity.

3.8. Spatial clustering of wind-energy pressure

Spatial autocorrelation analyses revealed contrasting patterns between footprint intensity and power intensity (Fig. 6; Table 5). Footprint intensity exhibited significant positive spatial autocorrelation across all neighbourhood definitions examined, with Moran's I ranging from 0.281

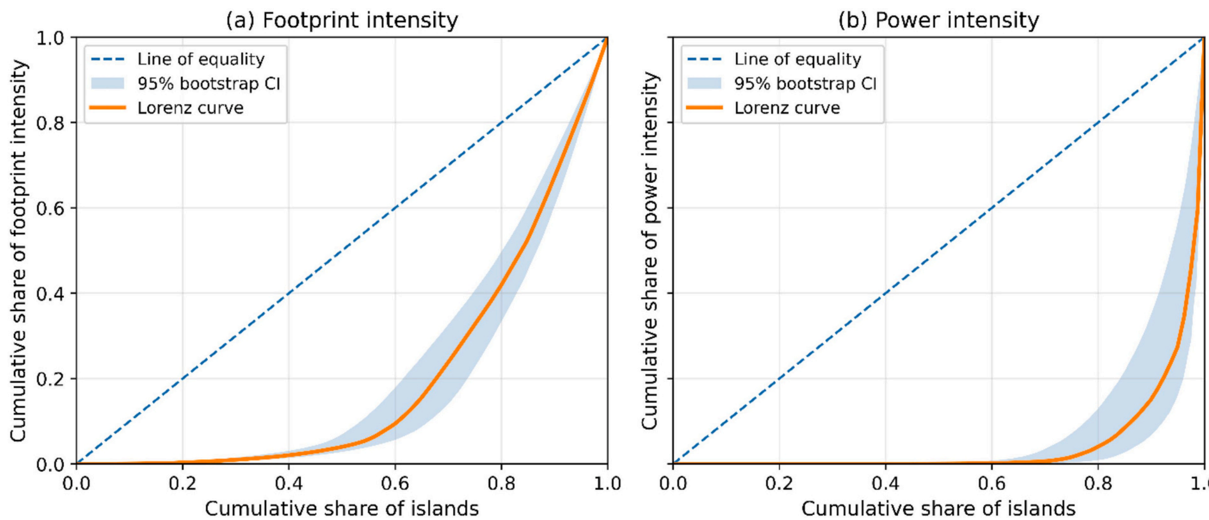


Fig. 3. Inequality in wind-energy pressure across Greek islands. Lorenz curves for (a) wind-footprint intensity and (b) wind-power intensity. The diagonal represents perfect equality. Shaded areas indicate 95% bootstrap confidence intervals.

to 0.415 (all $p = 0.001$). Clustering remained evident after log-transformation of the response variable.

In contrast, raw power intensity exhibited weak and non-significant spatial autocorrelation (Moran's $I = 0.022$–0.045; $p > 0.05$). However, log-transformed power intensity displayed significant positive spatial autocorrelation (Moran's $I = 0.258$–0.362; $p = 0.001$), indicating that spatial clustering became apparent after reducing the influence of extreme values. Spatial maps further showed that hotspots of wind-power intensity and wind-footprint intensity did not completely coincide geographically (Fig. 6b–c).

4. Discussion

4.1. Scaling dynamics in bounded island systems

This study provides a distribution-sensitive assessment of wind energy deployment across a bounded island system by combining scaling relationships, spatial intensity metrics, inequality of distribution measures, and licensing outcomes within a single archipelago-wide framework. This integrated perspective allows simultaneous examination of how geographic constraints, conservation coverage, and regulatory processes shape both the level and distribution of wind energy projects.

Wind capacity increases with island area, yet this relationship is not uniform across the distribution. Upper quantiles exhibit substantially steeper scaling than lower quantiles, indicating that larger islands disproportionately define the upper deployment frontier. This heterogeneity suggests that geographic size constrains maximum feasible development but does not deterministically predict realized capacity. Socio-economic, regulatory, planning, and grid-related factors mediate how spatial potential translates into infrastructure outcomes.

Island-level analyses incorporating wind potential further clarify this pattern. Wind resource availability exhibits positive associations with installed capacity at lower and upper quantiles, indicating that wind potential constrains deployment among low-capacity islands and contributes to shaping the upper-envelope frontier. However, the median relationship is weak, and substantial dispersion persists among islands with similar wind densities. This suggests that wind potential is a necessary but insufficient determinant of deployment. Spatial structure, regulatory frameworks, and conservation coverage mediate how resource endowment translates into realized wind energy development.

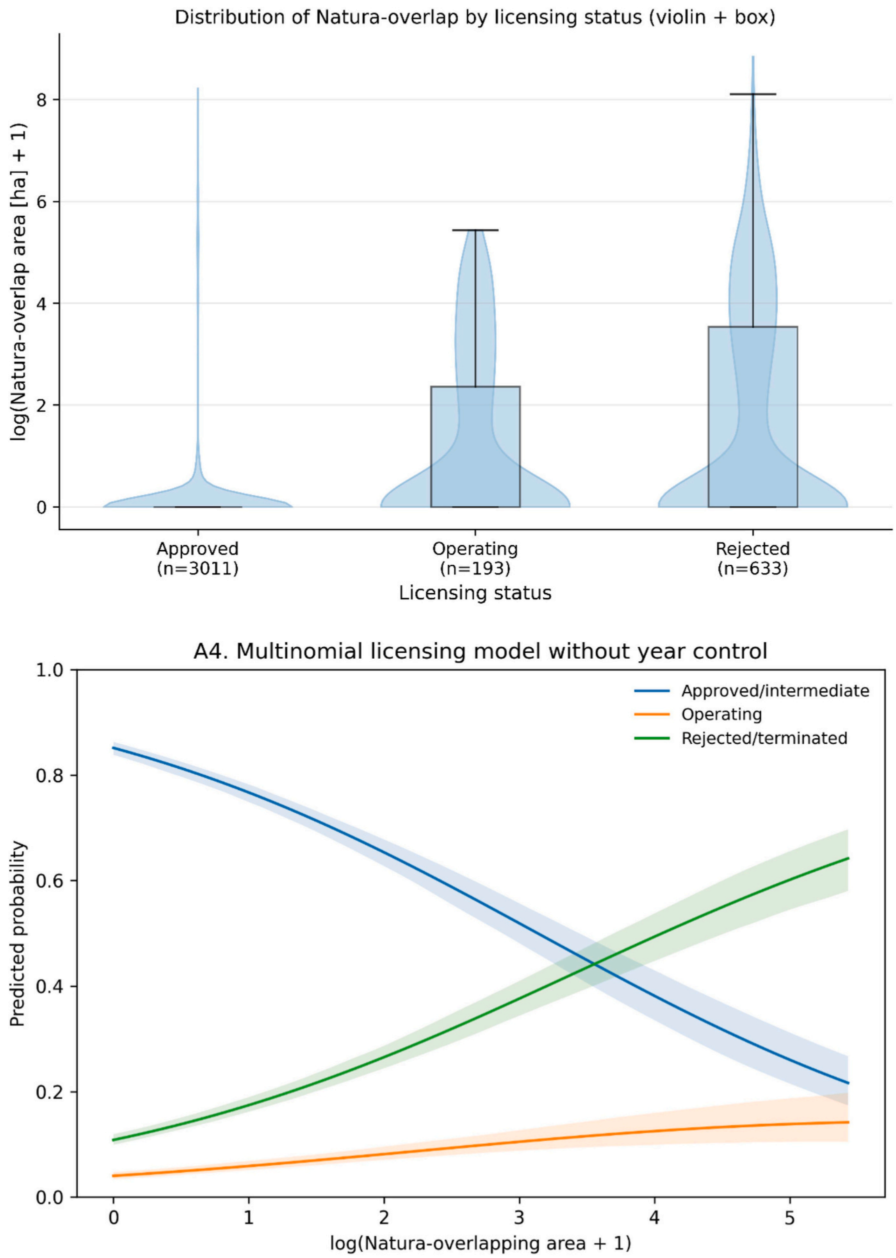
In island renewable energy research, much attention has been devoted to achieving high or 100% renewable penetration in isolated grids. Reviews emphasize that islands function as “testbeds” for renewable transitions due to high electricity costs and strong resource availability (Meschede et al., 2022; Ochoa-Correa et al., 2025). However, these studies primarily address techno-economic feasibility, storage requirements, and grid stability constraints rather than spatial deployment patterns. Our results indicate that even when resource availability scales with area, infrastructure deployment follows heterogeneous trajectories across islands. This divergence suggests that structural constraints, such as grid capacity, interconnection, planning frameworks, and local socio-political dynamics, interact with geography to shape realized capacity.

In bounded island systems, scaling relationships acquire particular significance. Unlike continental regions, islands cannot externalize land-use pressures to adjacent territories. All infrastructure development occurs within fixed spatial limits. Consequently, distributional divergence across quantiles reveals differences in how islands allocate limited land resources between conservation, infrastructure, and other uses. Such heterogeneity would be obscured by mean-based analyses and underscores the importance of distribution-sensitive methods in environmental impact assessment. Quantile regression allows identification of upper-envelope constraints and lower-bound variability, providing a more nuanced understanding of infrastructure scaling under spatial limits. While the analysis controls for key structural variables, unobserved or harder to quantify factors such as grid connectivity, local opposition, or planning regimes may also contribute to the observed heterogeneity.

4.2. Natura coverage and spatial compression

Absolute wind footprint declines as Natura 2000 coverage increases, suggesting that conservation designation is associated with a moderating effect on total infrastructure extent. However, when footprint is normalized by island area, wind footprint intensity increases sharply at high levels of conservation coverage. This divergence indicates that while protected areas may reduce absolute deployment, they may simultaneously be associated with spatial compression, as infrastructure becomes concentrated within the smaller fraction of land remaining outside protected zones. Alternative mechanisms, including island-specific planning, infrastructure, and connectivity constraints, may also contribute to the observed pattern. Importantly, this pattern remained unchanged when footprint intensity was recalculated using non-Natura island area rather than total island area, indicating that the observed spatial-compression pattern was robust to denominator choice.

Island renewable energy studies increasingly acknowledge land



a

b

Fig. 4. Licensing status, Natura 2000 overlap and temporal adjustment.
(a) Distribution of Natura-overlapping area among approved/intermediate, operating, and rejected/terminated wind-energy projects. (b) Predicted licensing probabilities from a multinomial model relating licensing outcomes to Natura-overlapping area. (c) Predicted licensing probabilities from a multinomial model including application year as a covariate. Shaded areas indicate 95% confidence intervals.

constraints in scenario modelling (Meschede et al., 2022), yet rarely quantify how conservation coverage redistributes deployment intensity across bounded territories. In spatially finite systems, exclusion in one portion of land necessarily redistributes pressure elsewhere. The compression dynamics observed here are consistent with this structural mechanism and are consistent with broader spatial assessment approaches that emphasize cumulative effects and impact distribution in renewable energy planning (Ferguson et al., 2025). Rather than functioning solely as exclusion zones, protected areas may reshape infrastructure concentration patterns.

Similar tensions between renewable energy deployment and protected-area conservation have been identified in Greece, where spatial planning approaches propose prioritizing already fragmented landscapes outside Natura 2000 sites (Kati et al., 2021). Similar patterns of tension between conservation priorities and land-use pressures have also been documented in Mediterranean island systems (Troumbis et al., 2018; Vlami et al., 2020a). However, even such approaches may generate intensified infrastructure clustering within non-protected areas when land availability is constrained. The present results add a distributional and intensity-based dimension to this debate by demonstrating that conservation coverage can alter relative pressure even when absolute footprint declines.

For impact assessment practice, this distinction is critical. Project-level evaluation often emphasizes direct overlap with protected areas. Yet if conservation is associated with spatial compression elsewhere, cumulative effects such as fragmentation, edge expansion, and

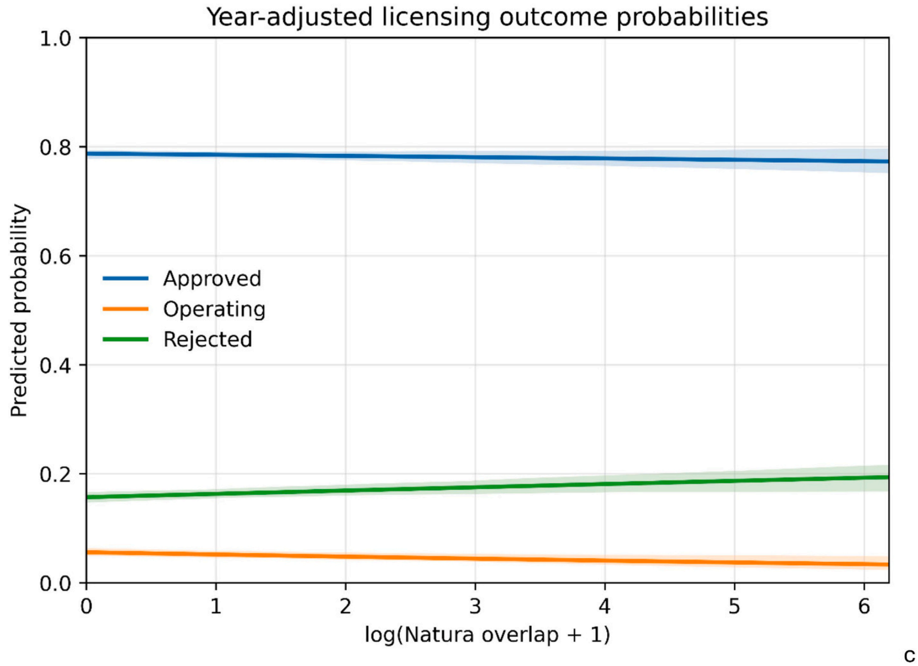


Fig. 4. (*continued*).

Table 3
Multinomial logistic regression results relating Natura 2000 overlap to licensing outcomes. Approved/intermediate projects were used as the reference category. Odds ratios (OR) are reported with 95% confidence intervals (CI). Natura-overlapping area was log-transformed.

Model	Outcome comparison	Predictor	OR	95% CI	*p*-value
Unadjusted	Operating vs approved/intermediate	Natura-overlapping area	**1.97**	1.75–2.22	**<0.001**
	Rejected/terminated vs approved/intermediate	Natura-overlapping area	**2.26**	2.08–2.45	**<0.001**
Year-adjusted	Operating vs approved/intermediate	Natura-overlapping area	0.90	0.77–1.05	0.191
	Rejected/terminated vs approved/intermediate	Natura-overlapping area	1.07	0.97–1.19	0.174
Year + project footprint + covariates (robustness)	Operating vs approved/intermediate	Natura-overlapping area	1.07	0.93–1.24	0.341
		Project footprint	**0.589**	**0.479–0.724**	**<0.001**
	Rejected/terminated vs approved/intermediate	Natura-overlapping area	0.92	0.85–1.01	0.072
		Project footprint	**1.333**	**1.209–1.470**	**<0.001**

The year-adjusted model included application year as a covariate. The robustness model additionally included total project footprint, application year, island area, Natura 2000 coverage, and wind potential. Odds ratios are presented only for Natura-overlapping area and project footprint; the remaining covariates were included as adjustment variables.

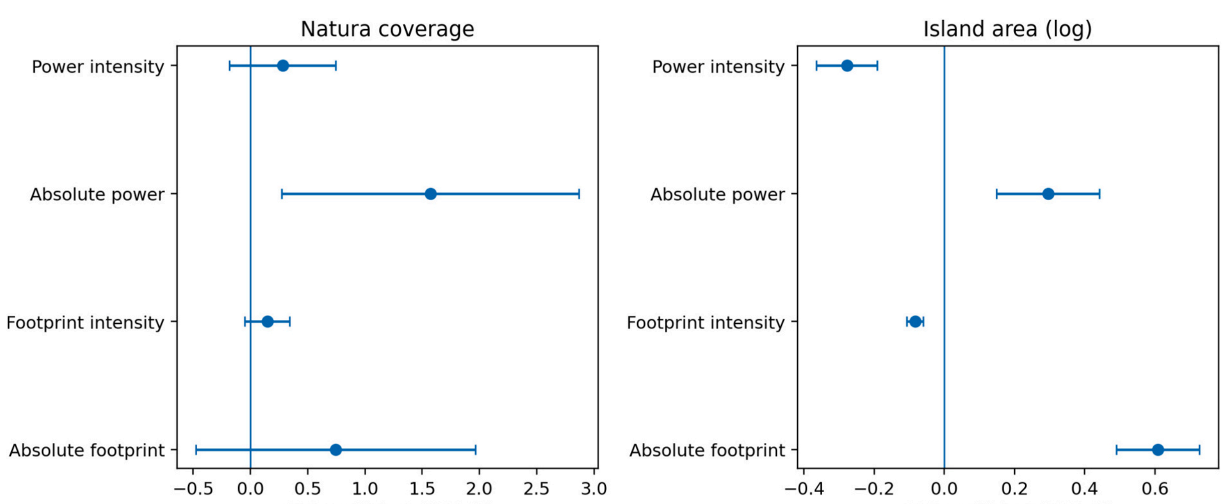


Fig. 5. Standardized effects of island area and Natura 2000 coverage on wind-energy deployment metrics.

landscape homogenization may intensify outside protected zones. Strategic Environmental Assessment should therefore incorporate

Table 4
Ordinary least squares (OLS) models describing associations between island characteristics and wind-energy deployment metrics. Confidence intervals were calculated using heteroskedasticity-consistent (HC3) standard errors. Significant effects ($p < 0.05$) are shown in bold.

Dependent variable	Independent variable	Coefficient	95% CI	p-value
Total footprint area	Island area	**0.609**	0.490 to 0.727	<0.001
Total footprint area	Natura 2000 coverage	0.744	−0.474 to 1.962	0.231
Footprint intensity	Island area	**−0.084**	−0.107 to −0.060	<0.001
Footprint intensity	Natura 2000 coverage	0.148	−0.048 to 0.345	0.138
Total installed capacity	Island area	**0.295**	0.149 to 0.442	<0.001
Total installed capacity	Natura 2000 coverage	**1.570**	0.271 to 2.869	0.018
Power intensity	Island area	**−0.278**	−0.364 to −0.191	<0.001
Power intensity	Natura 2000 coverage	0.282	−0.181 to 0.746	0.233

Notes: Island area was log-transformed prior to analysis. Natura 2000 coverage was expressed as the proportion of island area designated as Natura 2000. Separate OLS models were fitted for each deployment metric.

intensity-based and distributional metrics to capture redistribution effects that are not visible in aggregate capacity statistics.

4.3. Unequal distribution of wind energy pressure

Lorenz curves and Gini coefficients reveal substantial inequality in wind energy pressure across islands. A minority of islands bear a disproportionate share of footprint and power intensity. Such concentration patterns raise questions of spatial equity and burden-sharing in renewable energy transitions, particularly in bounded island systems where land availability is inherently limited. Leave-one-island-out sensitivity analyses indicated that inequality estimates were not dependent on any single island, supporting the robustness of the observed concentration patterns.

Island systems are tightly coupled socio-ecological units where ecosystem services, provisioning, regulating, and cultural, directly underpin livelihoods and identity (Vogiatzakis et al., 2023; Moustakas et al., 2025). Concentrated infrastructure pressure may therefore have implications for tourism-dependent landscapes, habitat continuity, and ecosystem service provision. Stakeholder-based analyses indicate that renewable energy infrastructure is frequently perceived as intertwined with broader land-use and climate pressures in island contexts (Moustakas et al., 2026; Vlami et al., 2020b). Uneven distribution of wind deployment may reinforce such perceptions of localized environmental burden, particularly where infrastructure development is concentrated on a relatively small number of islands.

In contrast, much of the island energy literature emphasizes system reliability, curtailment reduction, and cost optimization (Wang et al., 2013; Ochoa-Correa et al., 2025), with limited attention to spatial inequality metrics. By introducing Lorenz curves and Gini coefficients into renewable energy assessment at the archipelago scale, this study highlights the value of integrating distributional analysis into island energy governance. Inequality indicators can complement techno-economic metrics and inform more transparent and equitable allocation strategies across islands while taking into account differences in infrastructure capacity and environmental constraints. Such concentration may also have implications for legitimacy and social acceptance of renewable energy transitions, particularly where perceived burdens are unevenly distributed (Wolsink, 2013; Peterson et al., 2015; Vagiona, 2019; Morello-Frosch et al., 2011).

4.4. Licensing patterns

Installation-level analyses show that projects with larger Natura-overlapping areas are disproportionately represented among both rejected and operating installations relative to projects that are approved but not yet operating. Licensing status does not represent a single linear trajectory, with rejection representing one branch and operation following approval representing another. This pattern indicates differentiated sorting across outcomes rather than a simple progression. However, after accounting for application year, the association between Natura overlap and licensing outcome largely disappeared, indicating that temporal differences among project cohorts explain much of the apparent relationship observed in the unadjusted analyses. Licensing categories represent observed states rather than complete project lifecycles and may therefore reflect timing differences in addition to regulatory outcomes.

While our analysis is correlational, the results suggest that licensing outcomes are shaped by broader temporal and regulatory contexts rather than conservation overlap alone. Under Greek legislation, projects proposed within Natura 2000 areas are subject to additional environmental assessment requirements, implying that overlap with protected areas may trigger increased scrutiny without necessarily determining the final licensing outcome. This interpretation is consistent with recent evidence that wind energy project outcomes are not always clearly separated on environmental grounds, reflecting multidimensional assessment processes and decision thresholds (Karamanlidis and de Gabriel Hernando, 2025).

The disappearance of the Natura-overlap effect following temporal adjustment suggests that projects currently classified as approved but not operating may differ systematically in age from projects that have either reached operation or been rejected. Such differences may reflect delays associated with financing, grid connectivity, permitting, or implementation rather than conservation considerations alone. This interpretation is consistent with recent evidence that environmental assessment processes can influence renewable energy project outcomes while interacting with broader institutional and planning factors (Park et al., 2025; Larsen et al., 2018; Burris and Canter, 1997).

Previous work has documented tensions between wind energy expansion and conservation planning objectives in Mediterranean biodiversity hotspots (Kati et al., 2021; Moustakas et al., 2023). However, few studies have quantitatively examined how protected-area intersection relates to differentiated licensing outcomes at the installation level. The present findings suggest that Natura overlap is associated with licensing outcomes in unadjusted analyses, but not after accounting for application year or in the additional robustness model including project footprint. At the same time, the observed increase in footprint intensity with conservation coverage suggests that while protected-area designation may influence the spatial distribution of development, it does not necessarily reduce development pressure uniformly across islands.

From an impact assessment and policy perspective, these results highlight the importance of transparency in how conservation criteria are operationalized during licensing of renewable energy projects. They also highlight that distributional analyses should be considered alongside socio-economic and environmental assessments when evaluating renewable energy transitions at the archipelago scale. Clearer articulation of mitigation requirements, cumulative impact considerations, and decision-making criteria may enhance consistency and legitimacy in renewable energy planning within conservation-sensitive island systems.

4.5. Policy implications for island energy transitions

The results suggest that renewable energy policy and governance in island contexts should move beyond absolute capacity targets and incorporate intensity-based and distributional indicators. While this

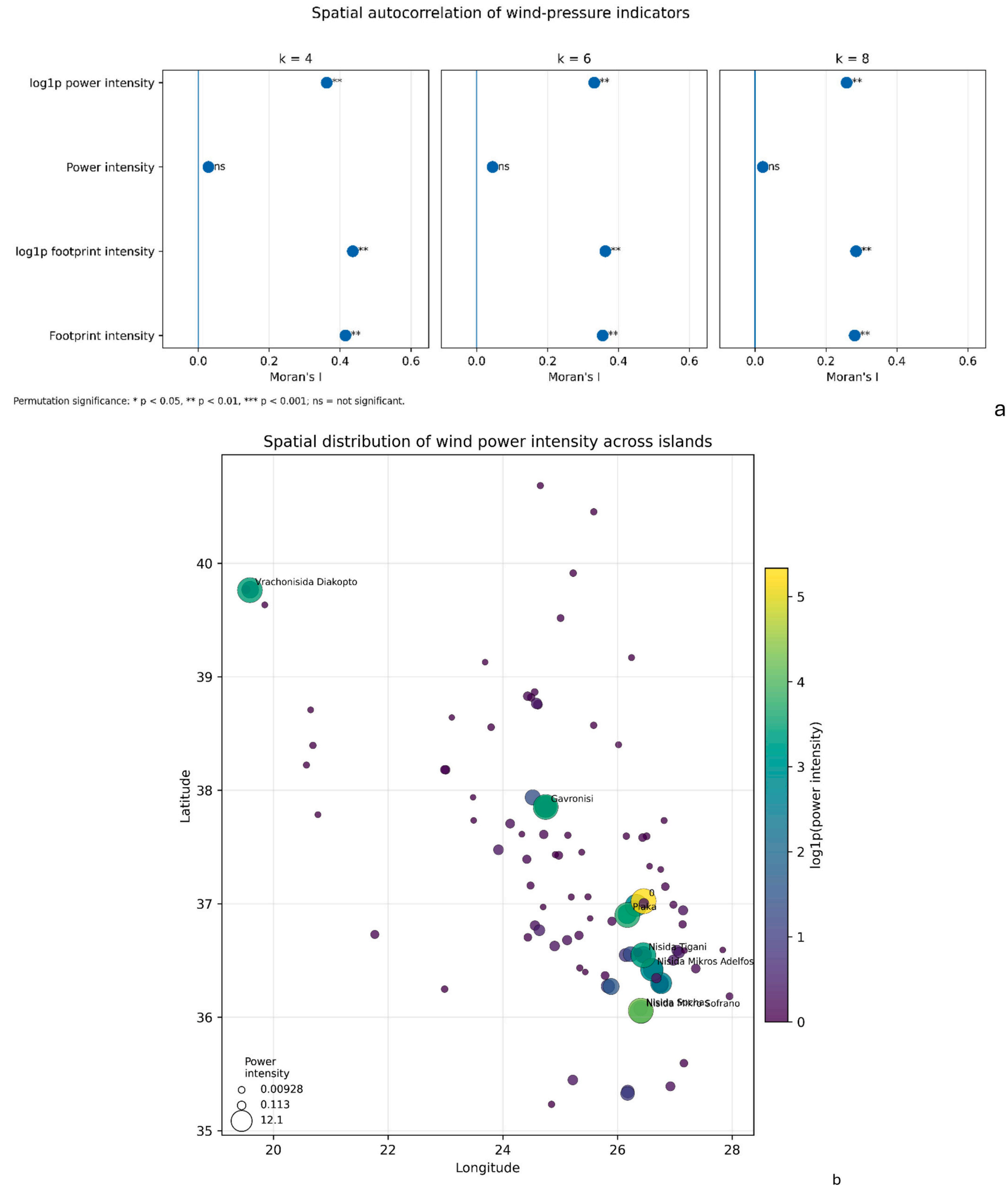


Fig. 6. Spatial structure of wind-energy pressure across Greek islands.
(a) Global Moran's I statistics for power intensity and footprint intensity under alternative nearest-neighbour spatial weighting schemes (k = 4, 6, and 8). (b) Spatial distribution of wind-power intensity across islands. Symbol size and colour are proportional to power intensity. (c) Spatial distribution of wind-footprint intensity across islands. Symbol size and colour are proportional to footprint intensity.

study focuses on Greek islands, the underlying mechanisms, limited land availability, conservation constraints, and spatially bounded systems,

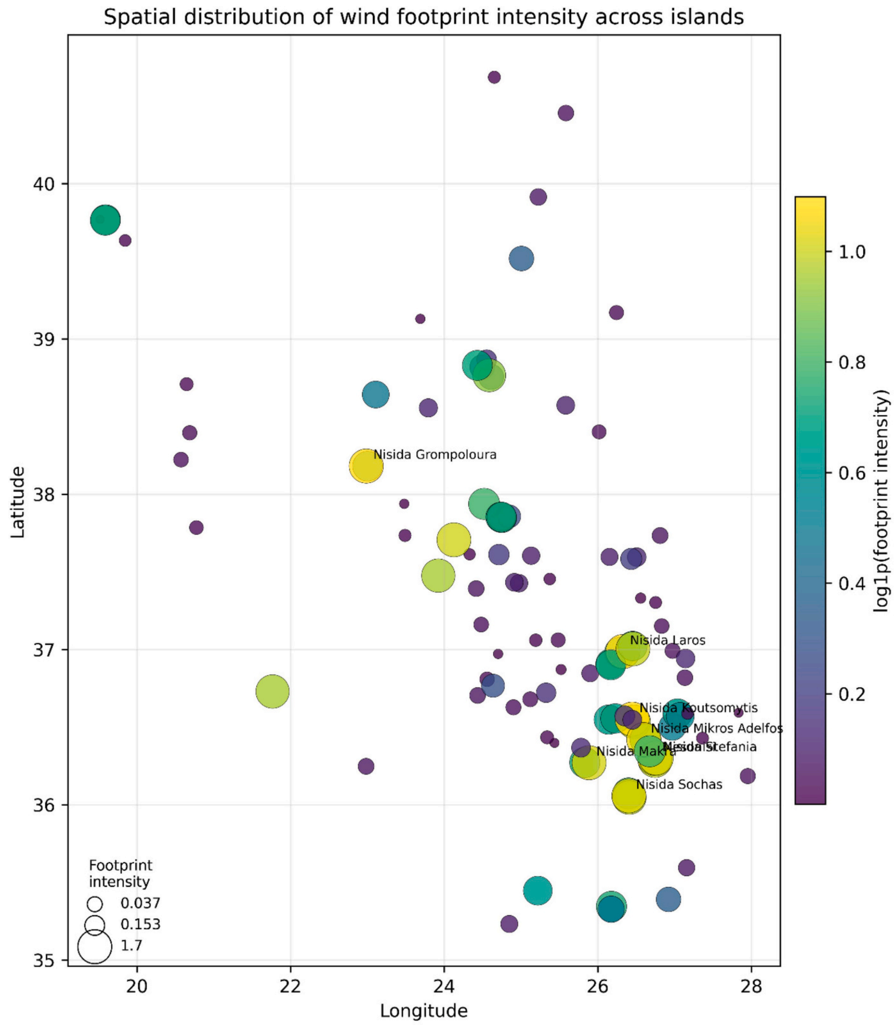


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Fig. 6. (*continued*).

Table 5
Global Moran's I statistics describing spatial autocorrelation in wind-energy deployment metrics across Greek islands. Spatial neighbourhoods were defined using k-nearest-neighbour weights (k = 4, 6, and 8). Statistical significance was assessed using permutation tests.

Variable	k-nearest neighbours	Moran's I	p-value
Footprint intensity	4	0.415	0.001
Footprint intensity	6	0.355	0.001
Footprint intensity	8	0.281	0.001
log(Footprint intensity +1)	4	0.436	0.001
log(Footprint intensity +1)	6	0.363	0.001
log(Footprint intensity +1)	8	0.285	0.001
Power intensity	4	0.028	0.493
Power intensity	6	0.045	0.083
Power intensity	8	0.022	0.525
log(Power intensity +1)	4	0.362	0.001
log(Power intensity +1)	6	0.331	0.001
log(Power intensity +1)	8	0.258	0.001

are common across many island contexts. Many island transition pathways emphasize achieving high renewable penetration and resolving grid stability challenges (Meschede et al., 2022; Ochoa-Correa et al., 2025). However, spatial allocation and conservation interactions represent equally critical dimensions of sustainability (Tsoutsos et al., 2019), and require coordinated cumulative impact assessment across planning levels (Dibo et al., 2025). Although wind potential remains a fundamental structural driver of siting decisions, the results indicate that wind potential does not automatically translate into proportional deployment. Distributional and conservation dynamics shape outcomes alongside economic incentives.

Monitoring frameworks that include footprint intensity and inequality metrics would better capture spatial compression and concentration effects. Previous work (Papadopoulos, 2020; Panagiotidou et al., 2016) has pointed to spatial inequalities in wind farm development in the Dodecanese Islands. Integrating such metrics into planning would enable identification of islands approaching disproportionate infrastructure burdens and support adaptive allocation strategies. This could be operationalized through Strategic Environmental Assessment indicators that track island-level intensity thresholds or cumulative distribution metrics across planning cycles.

Strategic Environmental Assessment should incorporate cumulative distributional analysis at the archipelago scale rather than treating islands solely independently, as impacts may otherwise remain obscured. Because islands are bounded systems, redistribution effects cannot be spatially externalized, and planning decisions on one island may have comparative implications for others within the same region. Although islands are analyzed as discrete spatial units, they are embedded within shared regulatory and energy systems, which may introduce interdependencies not fully captured in island-level models.

Spatial planning approaches that prioritize already fragmented or lower ecological value landscapes remain relevant (Kati et al., 2021). Yet even these approaches should be evaluated for their implications on relative intensity and clustering under conservation constraints. Furthermore, given evidence that land-use change modulates climate impacts more strongly than climatic variables alone in island ecosystem service studies (Moustakas et al., 2025), renewable energy transitions should be embedded within broader land-use governance frameworks rather than addressed as isolated sectoral objectives.

4.6. Contribution and broader implications

This study advances renewable energy impact assessment in island systems in three principal ways. First, by employing quantile regression and inequality metrics, it introduces a distribution-sensitive analytical framework that captures heterogeneity and concentration patterns obscured by mean-based approaches commonly used in energy system modelling. As much of the island energy literature emphasizes system reliability, curtailment reduction, and cost optimization (Wang et al., 2013; Ochoa-Correa et al., 2025), this work highlights the value of spatial inequality metrics for understanding how wind energy development is distributed across bounded island systems.

Second, the study provides empirical evidence that conservation coverage is associated with spatial-compression dynamics, whereby absolute project footprint declines while footprint intensity increases within the remaining available land. This pattern remained robust when footprint intensity was normalized by non-Natura island area. This finding highlights the importance of considering both absolute and relative measures of development pressure when evaluating renewable-energy transitions in spatially constrained environments.

Third, the study links renewable-energy deployment patterns, conservation regimes, and distributional outcomes at the archipelago scale. Rather than framing renewable-energy development and conservation objectives as inherently conflicting, the results suggest that their interaction is mediated by spatial allocation, regulatory implementation, and land-use structure.

Several limitations should be acknowledged. The analyses do not incorporate species-level biodiversity data, grid connectivity, economic feasibility, or socio-political drivers that may influence siting decisions and licensing outcomes. Consequently, the mechanisms underlying observed deployment patterns cannot be fully resolved. Future research integrating ecological, infrastructural, and governance variables could provide a more comprehensive understanding of renewable-energy allocation across island systems.

While island renewable energy research has predominantly focused on technical feasibility, grid integration, and economic optimization (Meschede et al., 2022; Ochoa-Correa et al., 2025), the present findings emphasize spatial distribution, conservation interactions, and inequality as complementary dimensions of sustainability assessment. More broadly, the results suggest that renewable-energy planning in island systems would benefit from incorporating cumulative, distributional, and archipelago-scale perspectives alongside conventional capacity-based metrics.

Declaration of competing interest

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

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT in order to proofread and edit the text. After using this tool/service, the authors reviewed and manually edited the content as needed and take full responsibility for the content of the published article.

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Data availability

All data are publicly available

References

Borchardt, S., Barbero, V.G., Buscaglia, D., Maroni, M., Marelli, L., 2022. Mapping EU policies with the 2030 agenda and SDGs. European Commission. https://doi.org/10.2760/110687.
Box, G.E.P., Cox, D.R., 1964. An analysis of transformations. J. R. Stat. Soc. Ser. B 26, 211–252.
Burris, R.K., Canter, L.W., 1997. Cumulative impacts are not properly addressed in environmental assessments. Environ. Impact Assess. Rev. 17, 5–18.
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., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O.J., Potter van Loon, A., Fox, R., Parvanyan, T., Krohn Hansen, S.B., Heathfield, D., Onninen, M., Drummond, R., 2023. The global wind atlas: a high-resolution dataset of climatologies and associated web-based application. Bull. Am. Meteorol. Soc. 104, E1507–E1525.
Dibo, A.P.A., Siqueira-Gay, J., Duarte, C.G., Turra, A., Sánchez, L.E., 2025. Guiding elements for strengthening cumulative impact assessment regulations for offshore wind energy. Environ. Manag. 75, 3025–3043. https://doi.org/10.1007/s00267-025-02282-3.
Efron, B., Tibshirani, R.J., 1993. An Introduction to the Bootstrap. Chapman & Hall, New York.
Ferguson, M.C., Williams, K.A., Goodale, M.W., Adams, E.M., Knaga, P., Kingdon, K., Avery-Gomm, S., 2025. A flexible framework for species-based regional cumulative effects assessments to support offshore wind energy planning and management. Environ. Impact Assess. Rev. 114, 107912. https://doi.org/10.1016/j.eiar.2025.107912.
Gini, C., 1912. Variabilità e mutabilità: Contributo allo studio delle distribuzioni e delle relazioni statistiche. Tipografia di P. Cuppini, Bologna.
IPBES, 2019. Global Assessment Report on Biodiversity and Ecosystem Services.
Karamanlidis, A.A., de Gabriel Hernando, M., 2025. Unsound renewable energy source development threatens an umbrella species in a Mediterranean biodiversity hotspot. J. Environ. Manag. 395, 127794. https://doi.org/10.1016/j.jenvman.2025.127794.
Kati, V., Kassara, C., Vrontisi, Z., Moustakas, A., 2021. The biodiversity–wind energy–land use nexus in a global biodiversity hotspot. Sci. Total Environ. 768, 144471.
Koenker, R., Bassett, G., 1978. Regression quantiles. Econometrica 46, 33–50.
Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47, 583–621.
Larsen, S.V., Hansen, A.M., Nielsen, H.N., 2018. The role of EIA in conflicts over renewable energy policies. Energy Policy 115, 43–53.
Legendre, P., Legendre, L., 2012. Numerical Ecology, 3rd English ed. Elsevier.
Mann, H.B., Whitney, D.R., 1947. On a test of whether one of two random variables is stochastically larger. Ann. Math. Stat. 18, 50–60.
McFadden, D., 1974. Conditional logit analysis of qualitative choice behavior. In: Frontiers in Econometrics. Academic Press, New York.
Meschede, H., Holzapfel, P., Kadelbach, F., Hesselbach, J., 2022. A review of 100% renewable energy scenarios on islands. WIREs Energy Environ. 11, e450.
Moran, P.A.P., 1950. Notes on continuous stochastic phenomena. Biometrika 37, 17–23.
Morello-Frosch, R., Zuk, M., Jerrett, M., Shamasunder, B., Kyle, A.D., 2011. Understanding cumulative impacts. Health Aff. 30, 879–887.
Moustakas, A., Georgiakakis, P., Kret, E., Kapsalis, E., 2023. Wind turbine power and land cover effects on bat deaths. Sci. Total Environ. 892, 164536.
Moustakas, A., Zittis, G., Vogiatzakis, I.N., et al., 2025. Climate, land use and other drivers' impacts on island ecosystem services. Sci. Total Environ. 973, 179147.
Moustakas, A., Christoforidi, I., Zittis, G., et al., 2026. The land use–climate–biodiversity nexus in the perceptions of European island stakeholders. Environ. Impact Assess. Rev. 117, 108199.
Ochoa-Correa, D., et al., 2025. Pathways to 100% renewable energy in island systems. Technologies 13, 180.
Panagiotidou, M., Xydis, G., Koroneos, C., 2016. Spatial inequalities and wind farm development. Environments 3, 18.
Papadopoulos, A.M., 2020. Renewable energies in small insular systems. Renew. Energy 149, 103–114.

Park, J., Kim, S., Lee, J., 2025. Evaluating the effectiveness of environmental impact assessment review for onshore wind projects. Environ. Impact Assess. Rev. 102, 107228.
Peterson, T.R., Stephens, J.C., Wilson, E.J., 2015. Public perception of low-carbon energy technologies. Energy Res. Soc. Sci. 8, 27–40.
QGIS Development Team, 2026. QGIS Geographic Information System. Open Source Geospatial Foundation.
Santi, F., Testolin, R., Zannini, P., Di Musciano, M., Micci, V., Ricci, L., Guarino, R., Bacchetta, G., Fernández-Palacios, J.M., Fois, M., Kougioumoutzis, K., Kunt, K.B., Lucchi, F., Médail, F., Nikolić, T., Otto, R., Pasta, S., Panitsa, M., Proios, K., Sfenthourakis, S., Simaiakis, S.M., Tranne, C.A., Triantis, K.A., Chiarucci, A., 2024. MEDIS-A comprehensive spatial database on Mediterranean islands for biogeographical and evolutionary research. Glob. Ecol. Biogeogr. 33, e13855.
Tsoutsos, T., Tsitoura, I., Kokologos, D., 2019. Sustainable energy planning for islands. Front. Energy Res. 7, 16.
Vagiona, D.G., 2019. Wind energy development in Greece. Energies 12, 631.
van der Vaart, A.W., 1998. Asymptotic Statistics. Cambridge University Press.
Vlami, V., Kokkoris, I.P., Zogaris, S., Kehayias, G., Dimopoulos, P., 2020a. Cultural ecosystem services in Natura 2000 network. Land 10, 4.
Vlami, V., Danek, J., Zogaris, S., Gallou, E., Kokkoris, I.P., Kehayias, G., Dimopoulos, P., 2020b. Residents' views on landscape and ecosystem services during a wind farm proposal. Sustainability 12, 2442.
Vogiatzakis, I.N., Balzan, M.V., Drakou, E.G., et al., 2023. Enhancing small–medium islands resilience. Res. Ideas Outcomes 9, e116061.
Wang, Y., Silva, V., Lopez-Botet-Zulueta, M., 2013. High wind penetration in isolated systems. IEEE Trans. Power Syst. 28, 2412–2420.
Wolsink, M., 2013. Social acceptance of renewable energy. Renew. Sust. Energ. Rev. 16, 822–835.
WWF, 2022. Living Planet Report 2022. WWF International.