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European wind power value exhibits spatially heterogeneous declines as penetration rises

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European wind power value exhibits spatially heterogeneous declines as penetration rises

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Abstract

Wind power cannibalization, the decline in market value as wind penetration increases, is typically evaluated using national averages that can obscure strong spatial variation. Here we quantify spatiotemporal patterns of wind value across Europe by combining hourly ERA5-based wind-output potential at 0.25° resolution with hourly wholesale electricity prices at the bidding-zone level over 2015 to 2024. Average wind value factors decreased from 0.94 to 0.78 as wind generation shares rose from 10% to 19%, but this decline is spatially uneven. Resource-rich regions in northern Europe exhibit persistently low value factors (0.60-0.75) and sustained negative trends (-0.03 to -0.06 yr^{-1}) through 2024. Within bidding zones, high-wind areas show capture price anomalies of roughly -5 to -10 EUR/MWh relative to zonal means. These results indicate that efficient wind expansion requires coordinated spatial deployment, transmission investment and market designs that reflect regional integration conditions.

Main

Renewable energy expansion is pivotal to Europe's decarbonization strategy. Wind and solar reached a combined 30% share of European Union (EU) electricity generation in the first half of 2024, overtaking fossil fuels for the first time[1]. This growth reflects substantial investments in renewable capacity alongside efficiency improvements and continued cost reductions across EU member states[2,3]. However, while increased deployment has supported emission reductions, it has introduced fundamental challenges to electricity market functioning.

Central among these challenges is renewable energy cannibalization, whereby higher variable renewable output suppresses wholesale electricity prices during periods of abundant generation, reducing revenues for generators[4,5]. This erosion in market value is captured by the value factor, defined as the ratio of a generator's revenue per unit of output to the average market price. As penetration rises, value factors decline systematically, with both wind and solar experiencing significant drops at annual penetration levels of approximately 30% and 15%, respectively[6,7]. The transition from feed-in tariffs to market-based support schemes has amplified these effects by exposing renewable investments to wholesale price dynamics[8]. In Spain, the market remuneration of wind and solar power fell markedly between 2014 and 2020, with negative price effects becoming significantly stronger when wind generation exceeded around 40% of total electricity production[9]. Similarly, Italy experienced price decreases of €2.3/MWh for solar and €4.2/MWh for wind per additional GWh of hourly output[10], while Germany showed negative cross-impacts between wind and solar market values[11,12].

Cannibalization extends beyond national borders through interconnected European markets. German renewable generation has consistently lowered wholesale prices in France[13], and surplus generation in one country suppresses prices in adjacent markets[14]. Recent evidence from Nordic markets demonstrates that these effects intensify with increasing interconnection capacity and renewable penetration[15]. Despite these insights, existing literature relies predominantly on market-zone-level data, overlooking spatial heterogeneity within bidding zones. This gap becomes critical as transmission constraints shape how zonal prices and curtailment risks translate into heterogeneous revenues across locations with different wind-output profiles[16,17]. High-resolution modelling for Germany reveals pronounced spatial and technological dependencies, with increasing regional disparities in market values[18]. Modelling studies indicate that at around 30% penetration, the market value of wind declines by 20-50% due to cannibalization[19], and grid congestion in Germany increased by 35% between 2019 and 2021 while associated costs nearly doubled[20].

Here we address this gap by integrating ERA5-based gridded wind generation estimates with hourly market prices to quantify wind cannibalization across Europe from 2015 to 2024 at the bidding-zone level and below. We estimate wind power generation potential on 0.25° × 0.25° latitude-longitude grid using 100 m wind speeds and a representative turbine power curve, compute grid-cell capture prices and value factors to characterize spatial variation within and across bidding zones, and relate national wind generation shares to value factors to assess the link between deployment intensity and market value (Fig. S1).

Wind generation potential shows strong spatial heterogeneity

The spatial distribution of mean wind power output across Europe reveals pronounced regional heterogeneity, with grid-cell temporal-mean estimates ranging from below 200 kW in southern mountainous regions to above 1,200 kW in northern coastal areas (Fig. 1). ERA5 100 m wind speeds, converted using the Vestas V112 3.0 MW turbine power curve, indicate a pronounced north-to-south gradient with lower output toward southern latitudes. The analysis identifies continuous transnational high-potential corridors, most notably the North Sea belt where generation potential exceeds 1,000 kW across a zone spanning northern France, Belgium, the Netherlands, northern Germany and western Denmark. This cross-border wind potential extends from western Norway across northern Sweden and Finland, with similarly high potential in the Baltic states.

Comparison with existing wind farm locations (Fig. 1) reveals spatial mismatches between deployment patterns and resource optimization. Installations concentrate in moderate-resource central European regions while high-potential northern Scandinavian areas remain less utilized. Intra-country resource heterogeneity of production potential often exceeds between-country differences, with four-fold variations observed within individual nations. Germany exhibits this pattern clearly, ranging from northern coastal zones exceeding 1,000 kW to southern Bavaria below 400 kW, while France shows comparable variation between its Atlantic coast (800-1,000 kW) and central regions (200-400 kW).

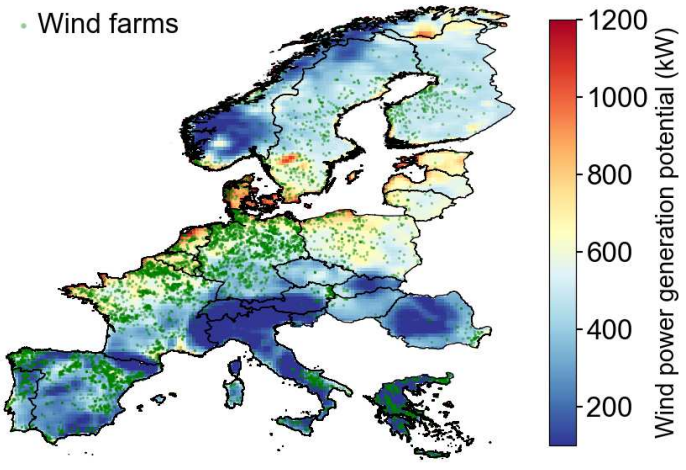


Fig. 1 | Mean annual wind power generation potential across Europe (2015-2024), derived from ERA5 100 m wind speeds and a representative turbine power curve. Green circles indicate existing wind farm locations[21].

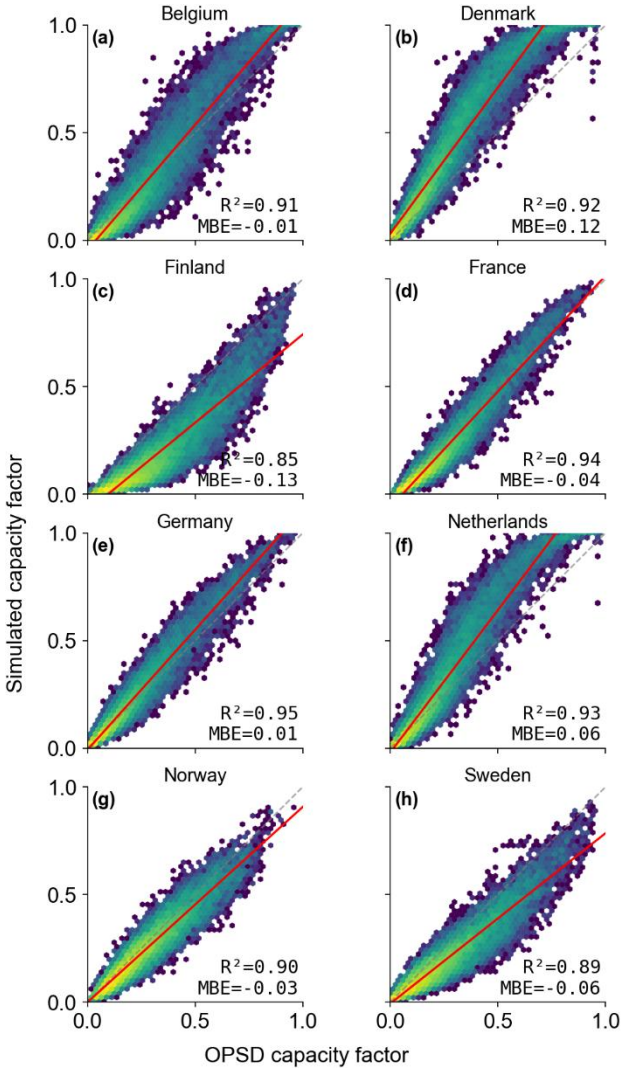


Fig. 2 | Validation of ERA5-based simulated wind capacity factors against observed data from the Open Power System Data (OPSD) platform for selected European countries over 2015-2019. Density scatter plots with the 1:1 line (black dashed) and performance metrics (R^2 and MBE).

The ERA5-based generation model was validated against observed wind power performance using national-level capacity factors from the Open Power System Data (OPSD) database for 2015-2019. The model demonstrates strong agreement across examined European countries, with coefficients of determination ranging from $0.85 \leq R^2 \leq 0.95$ (Fig. 2), reflecting the consistency of ERA5 wind speeds when combined with a standardized power-curve transformation. Across all countries, mean biases remain small ($-0.13 \leq \text{MBE} \leq 0.12$), indicating limited systematic deviation between simulated and observed capacity factors. The model is not intended to precisely match observed capacity factors at individual wind farms. Such precision is beyond the scope of the present framework, which operates at the grid-cell level rather than at specific

plant locations. Notably, the close agreement is obtained despite comparing grid-cell estimates at wind farm locations with national averages, rather than reproducing plant-level performance. The purpose of this comparison is therefore not validation at the level of wind farms, but to demonstrate that the metric captures large-scale patterns relevant for real-world wind deployment. These wind generation estimates thus provide a suitable basis for subsequent analyses of capture prices and value factors.

Capture prices reveal within-zone heterogeneity amplified by the energy crisis of 2021-2022

Wind power capture prices show strong spatiotemporal variation across European bidding zones from 2015-2024, with a major discontinuity during the European energy crisis 2022 (Fig. 3a). During 2015-2020, capture prices are relatively stable across most regions, typically 30 to 50 EUR/MWh, with lower values in Nordic markets (20-40 EUR/MWh) and higher values in parts of southern Europe (40-60 EUR/MWh). These patterns reflect persistent differences in generation mix, demand conditions and cross-border exchange. Figure 3b isolates local capture-price anomalies relative to each bidding-zone mean and highlights within-zone heterogeneity. During 2015-2020, anomaly maps show weak and spatially diffuse deviations, indicating limited within-zone dispersion under typical market conditions.

The energy crisis period (2021-2022) marks a sharp shift. Capture prices increase strongly across Europe, with 2022 reaching values above 200 EUR/MWh in many Central, Eastern and Southern bidding zones (Fig. 3a). At the same time, Fig. 3b shows larger and more spatially organized within-zone anomalies, implying greater sensitivity of wind revenues to local output timing relative to the zonal price signal during system stress. In several bidding zones, anomaly magnitudes reach approximately ±5 to ±10 EUR/MWh. During 2023-2024, northern Germany shows recurring negative coastal anomalies on the order of -5 to -10 EUR/MWh (Fig. 3b), while parts of Finland exhibit localized negative anomalies along the Ostrobothnian coast, generally below -10 EUR/MWh. Within-zone anomaly structures persist in several regions even as capture prices decline from their 2022 peaks (Fig. 3 a,b), indicating that within-zone dispersion does not fully return to pre-crisis conditions.

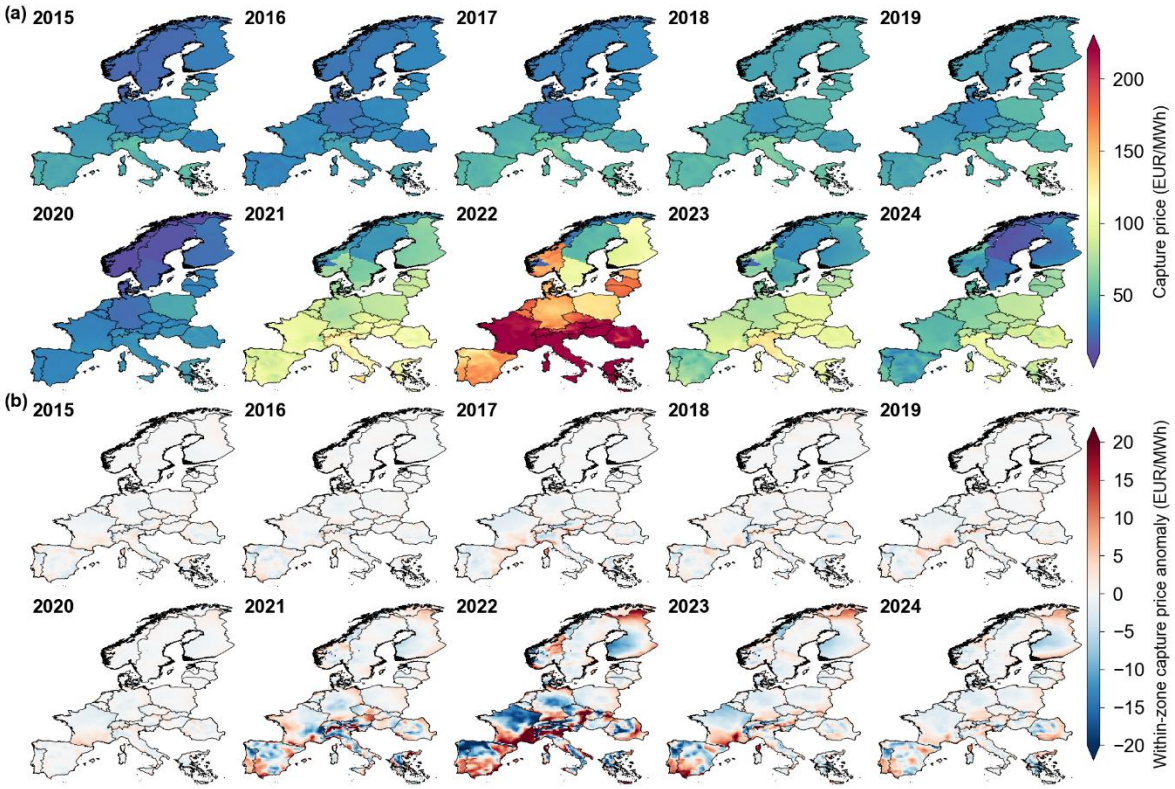


Fig. 3 | Spatial distribution of wind power capture prices across Europe from 2015 to2024. (a) Annual mean capture prices (EUR/MWh) by bidding zone. (b) Capture-price anomalies relative to the bidding-zone mean capture price (EUR/MWh). Anomalies reflect within-zone heterogeneity arising from spatial differences in wind-output timing under common zonal prices.

Value factors show systematic spatial divergence after 2020

Wind power value factors demonstrate systematic spatiotemporal evolution across European markets (Fig. 4). During the baseline period (2015-2020), most European regions maintained value factors between 0.9-1.1, indicating minimal cannibalization and limited price suppression during high wind generation periods. Nordic countries consistently recorded value factors above 1.0, while Central European markets exhibited stable values near unity. From 2021 onward, systematic value factor degradation became evident across multiple regions, with the most pronounced declines concentrated in the Nordic countries (Denmark, Sweden, Norway, Finland). Some regions in Sweden and Finland declined to value factors below 0.6 by 2024 (Fig. 4). Germany exhibited comparable patterns, particularly in northern regions where value factors decreased to the 0.5-0.7 range.

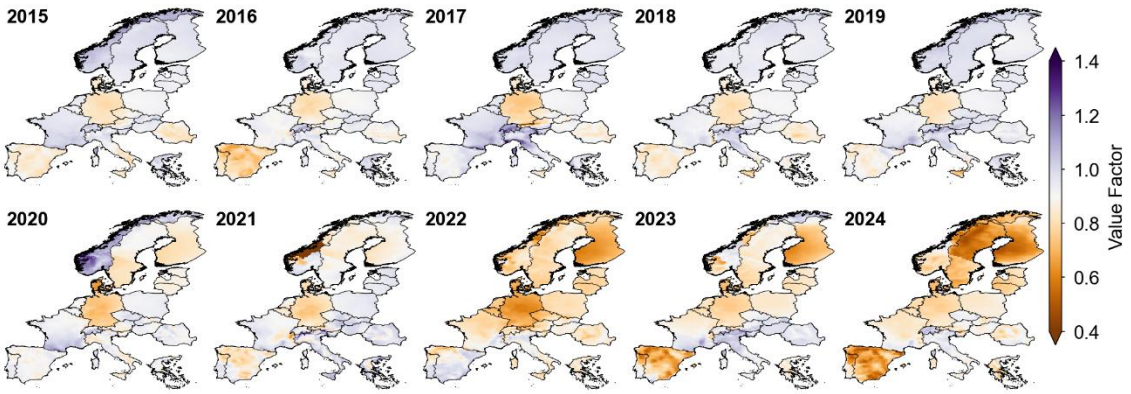


Fig. 4 | Spatiotemporal evolution of annual wind value factors across Europe (2015-2024).

Within-country heterogeneity exceeds between-country differences in several cases (Table 1). Sweden exhibits value factor ranges from 0.45 in SE1 (north) to 0.91 in SE3 (south-central) by 2024, representing a 40% intra-national variation. Finland shows similar patterns with western coastal regions below 0.49 and southeastern regions near 0.89. In contrast, Central European markets including Austria, Czech Republic, Slovakia and Hungary maintained relatively stable value factors, predominantly ranging between 0.8-1.0 throughout the study period. Southern European countries exhibited distinct patterns characterized by greater temporal stability; Spain and Portugal demonstrated modest declines, with most regions maintaining value factors above 0.8.

Table 1 | Within-country value factor heterogeneity in 2024 for selected countries. Values represent the minimum and maximum value factors observed across grid cells within each country, along with the range and coefficient of variation. For countries with multiple bidding zones (Sweden, Norway, Italy), reported extremes may reflect between-zone heterogeneity.

Country	Minimum VF	Maximum VF	Range	Coefficient of Variation
Finland	0.49 (Ostrobothnia)	0.89 (South)	0.40	0.14
Sweden	0.45 (SE_1)	0.91 (SE_3)	0.45	0.14
Norway	0.54 (NO_4)	0.96 (NO_3)	0.42	0.12
Italy	0.80 (IT_SARD)	1.03 (IT_NORD)	0.23	0.04
Germany	0.79 (North)	0.85 (South)	0.06	0.04

Wind penetration drives heterogeneous value erosion across countries

The trend analysis (Fig. 5) confirms widespread decline in wind power value factors over the full period, with strong regional contrasts in both magnitude and statistical significance. Negative trends dominate across Northern Europe, with typical decline rates of -0.03 to -0.06 yr^{-1},

and locally stronger trends approaching -0.08 yr^{-1} in parts of Scandinavia and northern Germany. Many of these trends are statistically significant ($p < 0.1$). Central and Southern European regions generally exhibit weaker negative trends, commonly between -0.01 and -0.03 yr^{-1}, with several areas showing trends close to zero. The relationship between annual wind generation share and wind power value factors across European countries over 2015-2024 reveals widespread cannibalization tendencies (Fig. 5). Most countries exhibit negative penetration sensitivities ($\beta_{WGS} < 0$; see Methods), indicating that higher wind generation shares are associated with lower relative market values. This relationship is strongest in the Netherlands, Belgium, Spain, Sweden, Norway and Finland, where wind penetration sensitivities typically range between -1.6 and -2.5. These magnitudes imply that a 1 percentage-point increase in wind share corresponds to a decline of roughly 1.6 to 2.5 percentage points in the value factor, consistent with pronounced cannibalization associated with stronger simultaneity effects and unfavorable wind-price covariance. Countries with more diversified generation portfolios tend to exhibit weaker relationships. Germany shows a modest wind penetration sensitivity ($\beta_{WGS} \approx$ -0.3), indicating only modest marginal value declines compared to more wind-concentrated systems. Several Central and Eastern European countries (for example, Czechia, Austria, Romania) display near-zero to positive β_{WGS} estimates, likely reflecting weak or statistically uncertain relationships over 2015-2024 rather than evidence of reverse cannibalization.

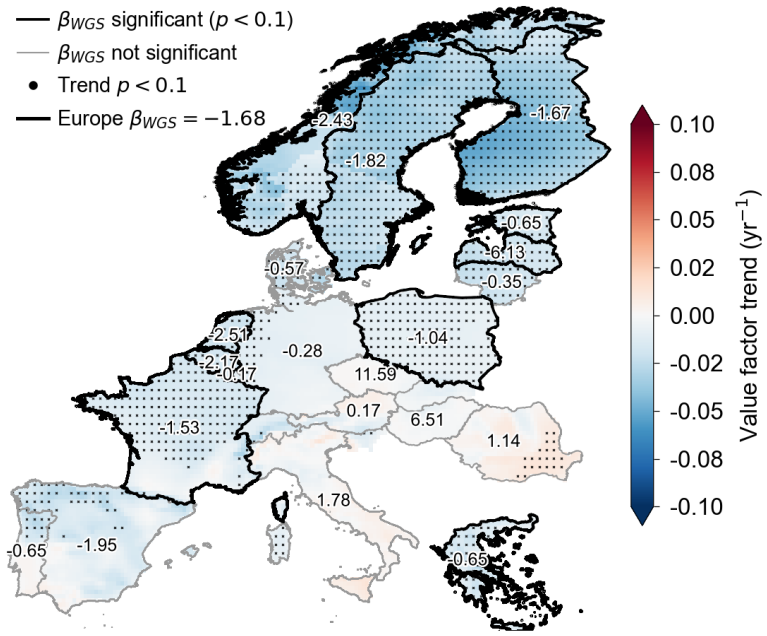


Fig. 5 | Spatial patterns of wind value factor trends and country-level β_{WGS} estimates across Europe (2015-2024). Colours show grid-cell trends in wind value factor (yr^{-1}); stippling indicates statistically significant trends ($p < 0.1$). Numbers showing wind penetration sensitivities

(β_{WGS}) averaged over countries. Country borders denote significant (black) and non-significant (grey) country mean β_{WGS} estimates.

The aggregated European statistics reinforce these findings (Table S1). Between 2015 and 2024, the average wind share increased from approximately 9.7% to over 18.5%. The Europe-wide value factor declined from 0.94 (2015) to 0.78 (2024), with the sharpest reduction occurring after 2020, coinciding with accelerated wind deployment and increasing price volatility. The decline in value factors persists even during years of elevated wholesale electricity prices (2021-2022), indicating that high price levels alone do not offset the relative revenue erosion associated with wind-output profiles. Post-crisis, this approximately 16 percentage-point reduction implies material revenue erosion.

Value factor degradation is spatially structured by resource concentration

The spatial relationship between wind generation potential and wind power value factors reveals a systematic geographic structure in cannibalization sensitivity (Fig. 6). The Pearson correlation map (Fig. 6a) indicates predominantly negative correlations in regions with high wind resource availability. This is most notable across the Nordic countries (Denmark, Sweden, Norway, and Finland), which exhibit correlations between -0.5 and -0.7, with resource sensitivities (β_{WP}; see Methods) reaching -0.3 to -0.5 (Fig. 6b), indicating that a 10% above-average wind power year is associated with a 3-5 percentage-point decline in value factor. Central European regions show weaker correlations (-0.25 to -0.40) and smaller regression coefficients (-0.1 to -0.4), while the Baltic states and Mediterranean regions approach zero or positive correlation with minimal resource sensitivity.

This inverse relationship between resource quality and economic value reveals that technical resource optimization has become decoupled from economic optimization under current market structures. Areas exceeding 1,000 kW mean annual generation, concentrated along the North Sea corridor, northern Scandinavia and Baltic coasts (Fig. 1), exhibit value factors predominantly below 0.70 by 2024, while regions below 600 kW maintain values above 0.85 (Fig. 4). The mechanism driving this pattern is the simultaneity of generation across spatially correlated wind resources: when geographically clustered wind farms produce concurrently during high wind events, they saturate local markets, creating price suppression when transfer capacity and flexibility are insufficient to absorb the surplus. Our capture-price analysis confirms this dynamic, with northern Swedish and Finnish zones showing capture-price anomalies of -5 to -

10 EUR/MWh relative to their bidding-zone means (Fig. 3b). This north-to-south gradient demonstrates that wind power value erosion is both temporally linked to increasing penetration and spatially structured by resource concentration patterns.

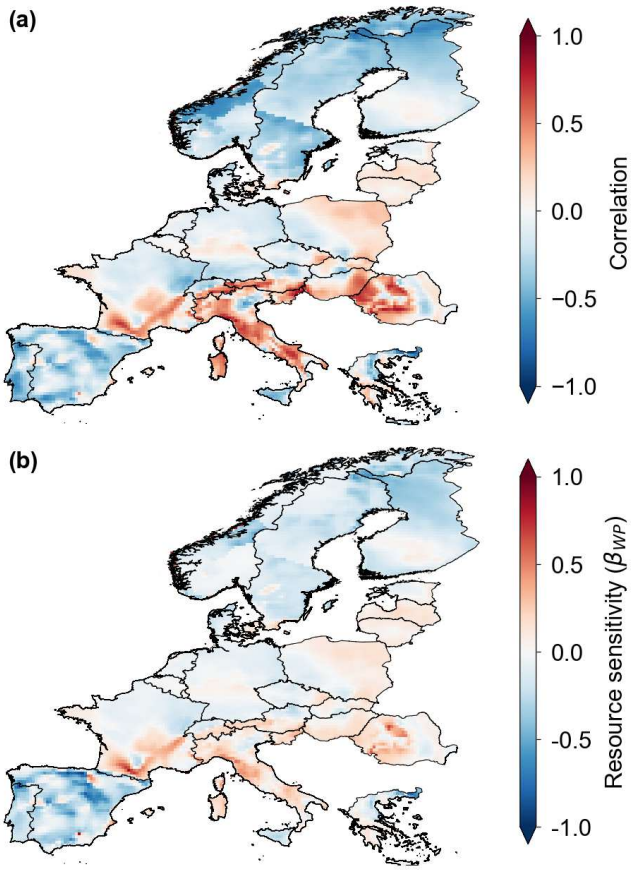


Fig. 6 | Spatial relationship between wind power value factors and wind generation potential across Europe over 2015 to 2024. (a) Pearson correlation between wind value factors and wind generation potential at each grid cell. (b) Resource sensitivity (β_{WP}): OLS regression slope of value factor with respect to normalized wind generation potential.

Discussion

This study presents the first high-resolution spatial analysis of wind power cannibalization across Europe, revealing pronounced intra-country heterogeneity that existing national and price-zonal assessments have obscured. Wind value factors declined from 0.94-0.78 over the study period, but this average masks within-country heterogeneity exceeding 40% in individual nations. Across the Nordic countries and the North Sea corridor, sites with the highest wind potential frequently exhibit lower value factors (typically 0.60 to 0.75), whereas many Central

European markets maintain value factors above 0.85 (Fig. 4). This inverse relationship indicates that wind-output profiles associated with resource-rich regions face stronger value erosion when wind penetration increases faster than system-integration improvements. Our spatially resolved analysis extends theoretical predictions[22] that value decline accelerates once wind penetration exceeds 30% of instantaneous demand, demonstrating that these effects manifest at sub-national scales where resource-rich regions exhibit stronger value erosion signals than suggested by national averages[18]. This scale mismatch helps explain why national-level assessments can understate cannibalization in deployment hotspots.

Three structural features emerge as key correlates of cannibalization severity. First, spatial concentration of wind-output potential increases simultaneity and strengthens wind-price covariance, consistent with the negative correlations ($-0.25 < r < -0.75$) observed across Northern Europe. Second, within-zone capture-price anomalies of approximately -5 to -10 EUR/MWh for high-potential areas relative to bidding-zone means are consistent with transmission-limited integration. Persistent north-to-south gradients in value factors within Sweden (0.45 in SE1 versus 0.91 in SE3) and Finland (western ~0.49 versus southern ~0.89) align with documented transmission bottlenecks between surplus northern zones and demand-concentrated southern regions[23]. Under perfect spatial arbitrage, such persistent within-zone patterns would not emerge. Capture-price anomaly patterns show systematic spatial structure within bidding zones (Fig. 3b), and the spatial correlation between high wind potential (Fig. 1) and low value factors (Fig. 4) strengthens over time, particularly in regions where transmission expansion has lagged generation growth[24]. Prior work quantifies the economic magnitude: relaxing congestion can increase renewable value by 13 to 31% in constrained markets[25], and transmission constraints create anticipatory effects where market participants adjust bidding strategies based on expected congestion, further depressing prices in export-limited regions[26,27]. Third, the continuation of negative value-factor trends (-0.03 to -0.06 yr^{-1}) in Nordic regions following the energy crisis suggests these dynamics persist through 2024 rather than reverting to pre-crisis conditions.

Central European markets demonstrate comparatively higher wind values, with the Czech Republic, Austria and Hungary exhibiting value factors that are consistently high (often ≥ 0.85) over the study period (Fig. 4). Diversified generation portfolios represent a plausible buffering mechanism: markets with substantial flexible resources (for example, hydropower and responsive gas capacity) may better accommodate wind variability and limit value erosion[27]. The

availability of pumped hydropower storage in Austria and Switzerland creates temporal arbitrage opportunities that moderate price impacts during high-renewable periods[28]. Our results are consistent with a meaningful portfolio effect: regions characterized by higher flexibility tend to exhibit higher value factors than comparably wind-rich regions dominated by less flexible generation[14,29]. The 2021 to 2022 energy crisis exposed vulnerabilities in renewable integration that were less visible under normal conditions[30,31]. Wind value factors declined across several regions in 2021 to 2022 even as annual-average electricity prices were elevated, illustrating that high average prices do not necessarily translate into higher wind capture values when volatility and timing mismatch increase[14,15]. The near-linear cannibalization behaviour observed before 2020 is consistent with systems retaining sufficient flexibility to accommodate increasing wind output without widespread nonlinear value collapse[32,33].

These patterns carry direct implications for market design and deployment strategy. The systematic within-zone capture-price differences are consistent with limitations of zonal pricing in conveying spatial scarcity and surplus conditions. Modelling suggests that nodal pricing reforms could improve investment efficiency by 10 to 25% in systems with network constraints by providing location-specific price signals[34]. The pronounced correlation between wind generation potential and value factor degradation indicates that resource quality alone provides insufficient guidance for deployment decisions, suggesting value in auction mechanisms that explicitly account for system integration costs[35]. Recent auction designs that include firm-delivery or flexibility requirements illustrate one such approach, potentially incentivizing developers to internalize integration costs through co-located storage or demand response[36]. Rapid wind deployment and spatial clustering may increase simultaneity effects in already value-depressed areas, while persistent expectations of low capture values can influence bidding and contracting behaviour in energy-only markets (where generators are remunerated solely for delivered energy, without separate capacity payments), potentially reinforcing low-price outcomes during surplus hours[37,38]. The fundamental relationships between resource concentration, spatial correlation and capture-value degradation are relevant beyond European electricity markets: US markets including Texas and California exhibit similar spatial resource clustering and network constraints, suggesting comparable cannibalization patterns may arise[6,25,39].

Several limitations warrant discussion. ERA5's 31 km resolution cannot resolve small-scale wind variations in complex terrain, particularly affecting Alpine, Pyrenean and Scandinavian mountain regions[40]. The single turbine specification overlooks technological diversity in operational fleets[2]. The absence of curtailment data means value factors may represent upper

bounds in transmission-constrained areas, with local analyses indicating profit-maximizing curtailment levels of 15 to 29% in high-penetration regions[41,42]. Dynamic modelling incorporating storage, demand response and sector coupling represents a critical next step, as our static framework cannot capture how flexibility resources reshape value patterns[43]. Climate change impacts on wind resources and spatial correlation also demand investigation, with ensemble climate projections suggesting 5 to 10% changes in wind availability by mid-century[44].

As European wind capacity expands through 2030, the spatial patterns documented here indicate growing tension between technical resource optimization and economic viability under current market frameworks. Our findings suggest renewable deployment strategies may benefit from evolving beyond capacity maximization toward system-integration optimization. Support mechanisms that account for regional integration capacity alongside resource quality could better align deployment incentives with realized system value. The high-resolution approach developed here provides a foundation for evidence-based assessment of where wind-output profiles experience stronger value erosion under zonal pricing. It also supports the prioritization of transmission, flexibility, and market-design interventions that better reflect regional integration conditions.

Methods

Data sources

Climate data

This study utilizes the fifth-generation ECMWF atmospheric reanalysis (ERA5), for characterizing wind resources across Europe. ERA5 provides a globally complete and consistent atmospheric dataset with a native horizontal resolution of approximately 31 km ($0.25^\circ \times 0.25^\circ$) and an hourly temporal resolution[45]. For this analysis, the key variable is wind speed 100 m above ground level, which is on average a typical hub height for modern onshore wind turbines ranging between 80 to 125 m[46,47]. The period of analysis for this study spans from January 1, 2015, to December 31, 2024. This timeframe is selected to align with periods of significant wind power expansion in Europe and the availability of comprehensive electricity market data. The choice of ERA5 is predicated on its status as one of the most advanced and widely used reanalysis datasets for meteorological and renewable energy applications, offering substantial improvements over previous generations of reanalysis. Despite its known limitations, such as

potential biases in complex terrain or underestimation of extreme wind speeds, its comprehensive spatiotemporal coverage and consistency make it uniquely suitable for a European assessment of wind generation potential[40].

Turbine power curve data

For simulations, we used the publicly available free sample power curve VESTAS V112-3000 kW (3 MW rated power, 112 m rotor diameter)[48], assumed hub height of 100 m to match ERA5 100 m wind data directly (Fig. S1).

European electricity market data

Hourly wholesale electricity price data for the European countries and bidding zones included in the analysis are primarily sourced from the ENTSO-E Transparency Platform[49]. This platform provides comprehensive, standardized data on electricity generation, residual load, transmission, and market prices across Europe. Figure 1 shows the European electricity bidding zones included in this study, for which hourly wholesale electricity price data are available from 2015 onwards. All price series were preprocessed to handle missing values (via linear interpolation) and standardized to a common time zone (UTC) to enable synchronized analysis across countries and bidding zones.

Validation data

National average capacity factors from the Open Power System Data (OPSD) platform[50], derived from ENTSO-E generation and installed capacity records for 2015-2019, were used to benchmark the generation model (see Validation section below).

Wind power generation model

Hourly wind power potential of a representative turbine

Hourly wind power potential at each grid cell was estimated as the output of a representative turbine by applying a turbine-specific power curve to ERA5 wind speeds at 100 m. The resulting time series represents site-specific production potential (per turbine) and is used to characterize spatial differences in wind-output timing under common zonal prices.

$$P_{(x,y,t)} = f\left(v_{(x,y,t)}; \mathcal{C}\right) \quad (1)$$

Where: $P_{x,y,t}$is the potential power output (kW) of a representative turbine at grid cell (x, y) and hour t. $v_{x,y,t}$is the 100 m wind speed (m/s) at the same location and time. $f$denotes linear interpolation on the turbine power curve; and $\mathcal{C}$ is the manufacturer-provided power curve of a

representative onshore wind turbine. This approach converts wind speeds into spatiotemporally resolved per-turbine wind-output potential, used here to evaluate how spatial differences in wind timing interact with zonal market prices.

Validation of wind power generation model

In the absence of wind farm-level production data, we validated the reanalysis-derived representative-turbine capacity factor potential against national average capacity factors from OPSD. Following established approaches[51,52], we computed hourly capacity factors from ERA5 wind speeds using a standard turbine model within each country to obtain a national mean hourly capacity factor time series:

$$CF\ (t) = \frac{\sum_{i=1}^{N} P_i(t)}{N \cdot P_{rated}} \quad (2)$$

where $P_{i,t}$ is the simulated per-turbine potential output (MW) at grid cell i and time t, $P_r = 3$ MW is rated power, and N is the number of grid cells within the country.

This reanalysis-based wind power modelling approach has been widely adopted and validated in previous studies, which demonstrate close agreement between simulated capacity factors and national averages derived from observed generation and installed capacity data[51,52]. Building on this established validation framework, our analysis follows the same methodology to ensure consistency with observed system-level wind power performance.

For validation, these simulated capacity factors were directly compared with the national average capacity factors published by OPSD, which are derived from ENTSO-E generation and installed capacity records. This benchmarking ensured consistency between reanalysis-based simulations and observed system-level performance.

Modelling cannibalization metrics

Wind power cannibalization is quantified using two complementary economic indicators: capture price (CP) and value factor (VF). These metrics provide both absolute and relative measures of wind power's market performance, enabling a comprehensive assessment of economic impacts across different market conditions and penetration levels.

CP is the generation-weighted average electricity price achieved by wind power[6,53,54]. It is calculated for each region (e.g., an ERA5 grid cell, a bidding zone) using the formula:

$$CP = \frac{\sum_t \text{Price}_t \cdot G_{\text{wind},t}}{\sum_t G_{\text{wind},t}} \quad (3)$$

where $G_{wind,t}$ is the modeled wind power generation in hour t, and $Price_t$ is the wholesale electricity price in hour t. The summation is over all hours in the considered period. To isolate spatial heterogeneity within bidding zones, we compute local anomalies of capture price relative to the corresponding bidding-zone mean.

VF is the ratio of the wind power capture price to the simple average (baseload) wholesale electricity price over the same period and region[5]. It provides a relative measure of wind power's market value:

$$VF = \frac{CP}{\frac{\sum_t \text{Price}_t}{N}} \quad (4)$$

N represents the number of price hours. A VF below (above) 1 indicates that wind power, on average, earns less (more) than the average market price.

These metrics are computed at the native ERA5 grid resolution to capture fine-scale spatial heterogeneity in wind resources and market conditions. Results are subsequently aggregated to relevant administrative boundaries and electricity market zones (bidding zones) for policy interpretation and cross-regional comparison.

Note that wholesale prices are observed at the bidding-zone level and are therefore uniform within each zone at a given hour. Consequently, any within-zone variation in capture price and value factor reflects spatial differences in wind output profiles and their covariance with the zonal price time series, not sub-zonal price variation.

The geographical scope of this study covers all countries interconnected within the European electricity grid for which ERA5 and market price data are available. The temporal scope covers the period 2015-2024, allowing for the analysis of the decadal trend in cannibalization effects.

Statistical methods

Our analysis combines a country-level assessment of value erosion with a grid cell assessment of spatial heterogeneity, so that national averages and within zone patterns are interpreted within a single framework. At the country level, we use observed wind generation shares to quantify how increasing wind penetration relates to wind value factors. At the grid cell level, we relate climate derived wind potential to value factors to identify spatial patterns consistent with resource concentration effects. This structure links the country level wind share analysis

with the grid cell wind potential analysis, enabling consistent interpretation of national trends and mapped spatial patterns.

Wind generation share (WGS) is derived from ENTSO-E data as the ratio of annual wind electricity generation to total electricity demand at the national level. To quantify the relationship between wind penetration and wind market value over time, we estimate country specific Ordinary Least Squares (OLS) regressions using annual time series:

$$VF_{c,t} = \alpha_c + \beta_{WGS} \cdot WGS_{c,t} + \varepsilon_{c,t} \quad (6)$$

where c denotes country and t denotes year. The slope coefficient β_{WGS}, hereafter termed wind penetration sensitivity, represents the change in value factor associated with a one percentage-point increase in national wind generation share. This specification allows comparison of heterogeneous cannibalization dynamics across national systems, which may differ due to flexibility, interconnection, and market design.

To examine spatial structure, we link wind value factors to climate derived wind power potential (WP) at the grid cell level. For each grid cell, we compute the Pearson correlation between annual value factors and annual wind potential:

$$r = corr(VF_t, WP_t) \quad (7)$$

where WP_t denotes annual wind potential. We map correlation coefficients to identify regions where wind resource availability and wind value co vary over the study period.

In addition, we estimate grid cell OLS regressions to quantify the sensitivity of value factors to wind potential:

$$VF_t = \alpha + \beta_{WP} \cdot \frac{WP_t}{\overline{WP}} + \varepsilon_t \quad (8)$$

The slope β_{WP}, hereafter termed resource sensitivity, represents the change in value factor per unit increase in normalized wind generation potential at each grid cell, $\bar{WP}$ is the multi-year mean wind potential at each grid cell. This identifies regions where higher wind potential systematically coincides with lower relative market value, which is consistent with spatial cannibalization.

Data availability

ERA5 reanalysis data are publicly available from the Copernicus Climate Data Store[55]. Hourly wholesale electricity price data were obtained from the ENTSO-E Transparency Platform[49]. Validation data were sourced from the Open Power System Data initiative. The Vestas V112 turbine power curve was obtained from The Wind Power[48]. Wind farm locations were obtained from the Global Energy Monitor[21]. Processed data are available via Zenodo[56].

Code availability

The code is currently available in an active development repository on GitHub (https://github.com/amna2123/wind-power-cannibalization) and will be archived in Zenodo upon acceptance of the manuscript.

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Author contributions

A.B.: conceptualization, data curation, formal analysis, methodology, validation, visualization, writing—original draft preparation. M.S.: methodology, writing—review and editing. B.M.: conceptualization, supervision, writing—review and editing. G.L.: writing—review and editing.

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