Spatial Determinants of Onshore Wind Energy Deployment: A Grid-Level Spatial Econometric Analysis of Aragón region (Spain) – EXTENDED ABSTRACT

1. Introduction

The rapid expansion of renewable energy constitutes a central pillar of the European Union's decarbonization strategy. Among renewable technologies, onshore wind energy has played a particularly prominent role in achieving climate and energy targets. However, the spatial deployment of wind power infrastructure is far from neutral: it generates territorial transformations, redistributes economic opportunities and environmental burdens, and raises concerns about spatial equity and regional justice. Understanding the determinants that explain why wind energy installations are located in some areas and not others is therefore essential for informed and territorially balanced energy planning.

This paper investigates the spatial determinants of onshore wind energy deployment in Aragón, a predominantly rural NUTS-2 region in northeastern Spain. Aragón stands out as one of the European regions with the highest installed wind capacity, making it an ideal case study to explore the territorial dynamics of large-scale renewable energy expansion. Despite its leadership in wind energy production, the internal spatial logic governing the distribution of wind farms across the region remains insufficiently examined.

The central research question guiding this study is: What factors determine the location of onshore wind farms within Aragón? We assess the relative importance of natural resource endowment, economic conditions, technical and infrastructural characteristics, and spatial interdependencies in shaping wind farm siting decisions.

2. Literature Background and Motivation

Existing literature on renewable energy siting highlights the importance of wind resource availability, grid access, land-use regulations, and socio-economic factors. Traditional approaches often rely on administrative units (e.g., municipalities or provinces) as the spatial unit of analysis (García-Riazuelo et al, 2025; Damette and Del Lo, 2022; Balta-Ozkan et al 2021). However, such aggregation may introduce bias due to the Modifiable Areal Unit Problem (MAUP), potentially distorting the identification of location determinants.

Moreover, wind energy deployment frequently exhibits spatial clustering. The presence of one wind farm may increase the probability of subsequent installations nearby due to shared infrastructure, accumulated technical knowledge, path dependency, and regulatory or social acceptance dynamics. Neglecting these spatial interdependencies may lead to biased and inconsistent estimations.

This study contributes to literature in two keyways. First, it addresses MAUP by conducting the analysis at a fine grid-cell level rather than using large administrative areas. Second, it explicitly incorporates spatial dependence through spatial econometric modeling, thereby providing a more rigorous framework for analyzing renewable energy location patterns.

3. Data and Spatial Framework

To overcome aggregation bias, the empirical analysis is conducted at the grid level, dividing Aragón into homogeneous spatial cells. This fine-scale spatial resolution allows for a more accurate representation of local characteristics and reduces distortions associated with arbitrary administrative boundaries. Specifically, we work with 46,896 grids, each measuring 1 square kilometer.

The dependent variable captures the presence (or intensity) of onshore wind installations within each grid cell. Independent variables are constructed using multiple data sources, including:

- Regional statistical databases,
- Geographic Information Systems (GIS),
- Spatial datasets on infrastructure and topography,
- Wind resource maps.

The explanatory variables are grouped into three main categories:

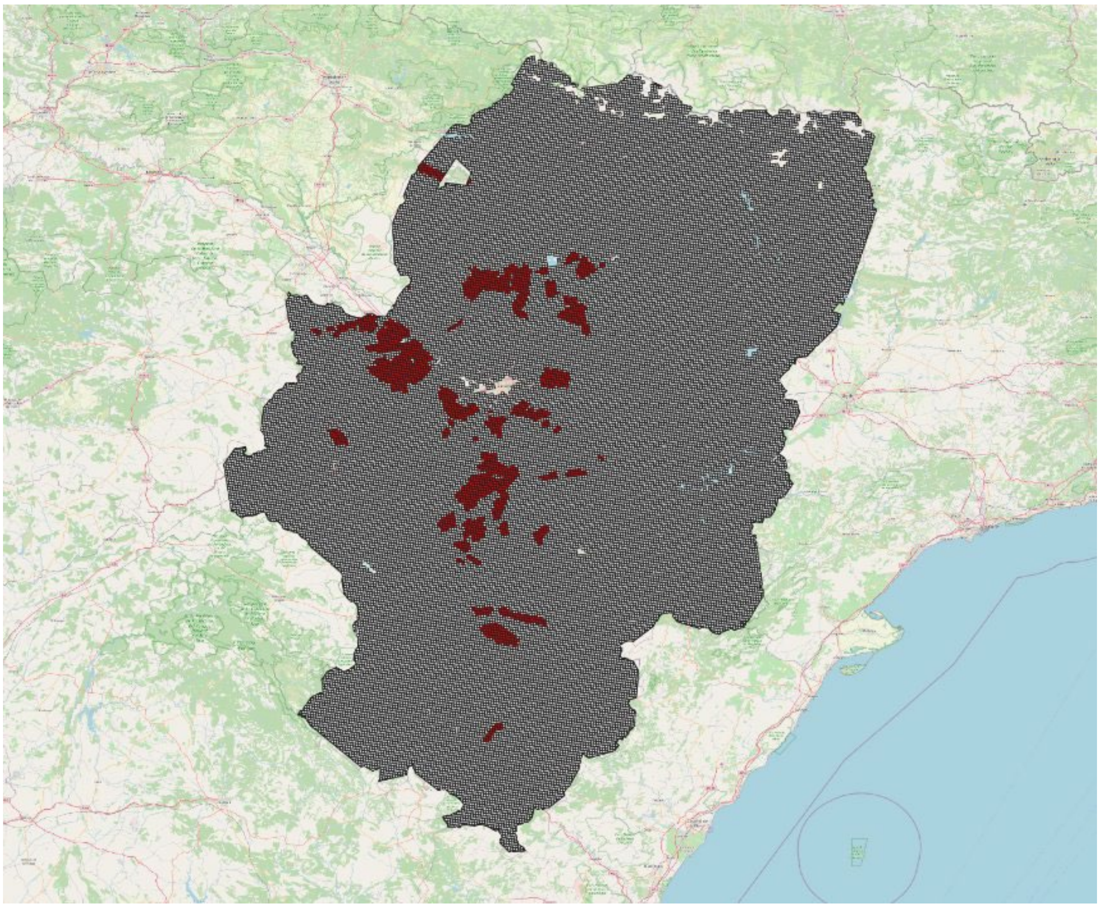
1. **Natural resource factors**: wind speed potential and topographic characteristics.
2. **Technical and infrastructural factors**: proximity to transmission lines, accessibility, and terrain suitability.
3. **Economic and territorial factors**: indicators reflect economic structure, land availability, and regional characteristics.

Table 1. Description of variables.

Variable	Description	Expected sign
Power	Installed capacity of wind energy in MW.	Dependent variable
Wind	Wind power density	+
roughness	Terrain roughness index	-
population20	Population living in a buffer of 20km.	-
Population10	Population living in a buffer of 10km.	-
population5	Population living in a buffer of 5km.	-
substation	distance in km to the nearest substation	+
powerline	distance in km to the nearest powerline	+
mun	municipality	
county	county	
income	municipality income pc	+
Zonification	Environmental sensitiviy indicator (MITECO)	-

This multi-source approach allows for a comprehensive assessment of both physical suitability and socio-economic attractiveness.

Figure 1. Grids for Aragon and wind installation.



4. Methodology: Spatial Econometric Modeling

Preliminary exploratory spatial data analysis reveals significant spatial clustering in wind farm locations. Global and local spatial autocorrelation statistics indicate that wind energy installations are not randomly distributed but instead form spatial agglomerations.

To account for this spatial dependence, we estimate spatial econometric models, including spatial lag and spatial error specifications. These models incorporate a spatial weights matrix that captures neighborhood relationships between grid cells.

The spatial lag model tests whether the presence of wind installations in neighboring cells increases the likelihood of installation in each location, consistent with agglomeration and spillover effects. The spatial error model accounts for unobserved spatially correlated factors.

By explicitly modeling spatial interactions, the analysis avoids biased coefficient estimates and provides insights into the role of spatial externalities in renewable energy deployment.

The methodological contribution of this paper lies in the combination of:

- A fine-resolution grid-based spatial framework,
- Integration of GIS-derived variables,
- Explicit treatment of spatial autocorrelation through econometric techniques.

This approach advances empirical strategies in the study of renewable energy geography.

5. Results

The results confirm the existence of a strong spatial agglomeration process. The spatial autoregressive parameter is positive and statistically significant, indicating that wind installations tend to cluster geographically. The presence of wind farms in neighboring cells significantly increases the probability of new installations, suggesting path dependency and infrastructure-sharing mechanisms.

Wind resource availability emerges as an important and statistically significant determinant. Areas with higher average wind potential are more likely to host wind farms. However, wind availability alone does not fully explain the observed spatial pattern.

Technical and infrastructural variables also play a decisive role. Proximity to electricity transmission infrastructure significantly increases the likelihood of wind deployment, reflecting the importance of grid access in investment decisions.

Economic and territorial factors further contribute to explaining location patterns. Certain rural areas exhibit higher probabilities of wind development, possibly reflecting land-use compatibility and lower opportunity costs.

Importantly, some areas with high wind potential remain underutilized, indicating that non-resource-related constraints influence sitting decisions. These findings demonstrate that wind resource endowment is a necessary but not sufficient condition for wind energy deployment.

6. Discussion

The evidence highlights the multi-dimensional nature of wind farm location decisions. The spatial clustering effect suggests that renewable energy expansion follows cumulative and path-dependent dynamics rather than purely resource-driven logic.

From a methodological perspective, ignoring spatial dependence would underestimate the role of agglomeration forces and potentially distribute effects to other explanatory variables. Similarly, using large administrative units could mask significant local heterogeneity.

The grid-based spatial econometric framework adopted here reveals that renewable energy transitions are territorially uneven processes shaped by physical geography, infrastructure networks, economic structure, and spatial spillovers.

7. Policy Implications and Territorial Justice

Understanding the determinants of wind energy deployment is crucial for spatial planning and policy design. As renewable energy targets accelerate, ensuring that deployment patterns are territorially balanced becomes increasingly important.

The strong agglomeration pattern identified in Aragón suggests that wind energy expansion may concentrate in specific corridors, potentially intensifying territorial inequalities. Policymakers must therefore consider not only resource efficiency but also spatial equity.

By identifying the factors that drive wind farm location decisions, this study provides evidence that can inform:

- Regional land-use planning,
- Infrastructure investment strategies,
- Renewable energy zoning policies,
- Mechanisms to promote territorially just energy transitions.

A spatially informed policy approach can help distribute both the benefits and burdens of renewable energy more equitably across rural territories.

8. Conclusion

This paper analyzes the determinants of onshore wind energy deployment in Aragón using a fine-scale grid-based spatial econometric approach. The findings confirm that wind resource availability is a key driver but not the sole determinant of wind farm location. Infrastructure accessibility, economic conditions, and spatial spillovers significantly shape deployment patterns.

The main contribution of the study is methodology. By overcoming the Modifiable Areal Unit Problem and explicitly modeling spatial dependence, the paper provides a robust empirical framework for studying renewable energy siting decisions.

As Europe advances toward climate neutrality, understanding the territorial logic of renewable energy expansion is essential. Spatially rigorous analyses such as the one presented here can support more effective, efficient, and territorially just energy planning strategies.

References

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