

# Addressing acceleration areas for renewable energy development in the European Union (EU): A case study of mainland Portugal

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## ABSTRACT

The urgent need to accelerate the energy transition in the European Union has made spatial planning a key tool for effective and equitable deployment of renewable energy. Directive (EU) 2023/2413 requires Member States to designate “renewable acceleration areas” where renewable projects can be rapidly implemented with minimal environmental impact. However, the methodological basis for identifying such areas remains underdeveloped and uneven across countries. This paper proposes a methodological framework for identifying areas for wind energy implementation in mainland Portugal, with implications for other EU countries. Results show that, under the most restrictive scenario, wind energy development is incompatible or highly inadvisable in 95 % of the territory. Still, land remains available for installing 11,513 turbines, equating to 23,026 MW (assuming 2 MW per turbine). A less conservative interpretation of slope restrictions would allow for the installation of 1194 additional turbines. These findings highlight that particular attention should be paid to technical criteria, such as slope, in the same way that environmental protection and population-related factors are critically reviewed. It also emphasizes the need to assess “incompatible” areas more critically, categorizing them by the type and number of constraints. Proximity to energy demand is highlighted as a key factor for enhancing self-sufficiency and reducing externalities. Finally, it is recommended that suitability weightings be delegated to local planners, fostering flexibility and local empowerment with the involvement of experts familiar with the territory to be planned. This approach promotes balanced and flexible renewable energy zoning to the implementation of EU renewable energy targets and planning mandates.

## 1. Introduction

The transition to renewable energy across the EU-27 -the 27 Member States of the European Union -is a central interest of the European Green Deal and the EU's strategy for climate neutrality by 2050. This shift responds to pressing challenges: climate change mitigation, fossil fuel dependency, and concerns over energy security and price volatility. Increasing the share of renewables is expected to reduce emissions, promote economic development, generate employment, and stabilize energy costs.

In this context, the REPowerEU Plan (2022) (European Union, 2022), aims to accelerate the clean energy transition in response to geopolitical and energy market disruptions, notably the war in Ukraine. One of its

key measures is the simplification of administrative procedures for renewable energy deployment. Permitting processes for renewable energy projects vary considerably across EU Member States, often involving multiple layers of governance, complex environmental assessments, and lengthy consultation procedures. These administrative hurdles have become one of the main bottlenecks for renewable energy deployment. To accelerate the implementation of renewable energy facilities, Directive (EU) 2023/2413 (European Parliament of the Council, 2023) establishes a legal framework for the designation of “renewable acceleration areas”, defined as zones suitable for the rapid deployment of renewable energy with minimal environmental impact. This measure provides a strategic pathway to streamline permitting procedures by pre-selecting areas where projects are expected to have

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low environmental impact and face fewer regulatory obstacles, thereby enhancing legal certainty and investor confidence. Article 15 mandates that Member States designate such areas by February 2026, using available data and prioritizing artificial or degraded land, while excluding environmentally sensitive areas.

EU countries are progressing at different paces. Italy adopted the “Aree Idonee” Decree ([Ministero dell’Ambiente e della Sicurezza Energetica, 2024](#)), establishing mandatory criteria for defining suitable and unsuitable areas, with regional authorities responsible for implementation. Additionally, the “Agriculture Decree” regulates renewable energy on farmland, balancing energy production with agricultural protection. Spain launched in 2020 the Environmental Zoning Tool for Renewable Energies ([Ministry for the Ecological Transition and the Demographic Challenge, 2020](#)) which evaluates environmental sensitivity to guide the placement of solar and wind projects. Portugal lacks an official zoning tool but has advanced through technical studies. [Simões et al. \(2023\)](#) conducted a national analysis identifying low-sensitivity areas for potential “Go-To Areas” under Directive 2023/2413.

Despite ongoing efforts, Member States continue to face significant challenges: overlapping land uses, data limitations, and administrative burdens complicate zoning. A harmonized yet flexible approach is essential to ensure efficient, equitable, and context-sensitive renewable energy planning.

Spain’s model is centralized and advisory, focused on environmental factors. Italy’s is legally binding and integrates socio-economic and infrastructural considerations, with regional implementation. [Simões et al. \(2023\)](#) approach for Portugal, despite the commendable progress achieved through this initial zoning initiative, several noteworthy issues merit attention and further discussion:

- The resulting zones considered the same criteria for wind and solar energy even though the impacts of these two types of energy are very different. Also, the analyses emphasized that the suitability of the remaining zones has not been assessed, treating all zones as equally suitable.
- Existing installations were not considered, making it difficult to assess the actual remaining developable area.
- Large-scale projects eliminated areas smaller than 100 ha from consideration. Therefore, a comprehensive understanding of available remaining area is essential for effective planning. It would be necessary to know how much area remains available.
- Although the energy transition involves bringing production closer to consumption, in line with ensuring energy self-sufficiency, this criterion has not been incorporated into the analysis.
- The examination of the analysis of “Go-To Areas” for wind and solar deployment, the study generates four scenarios based on applied constraints. In Scenario 1, wind and solar activities are considered incompatible across 88 % of the Portuguese surface. This percentage increases to 90 % in Scenario 2, and further to 95 % and 97 % in Scenarios 3 and 4, respectively. Therefore, a detailed analysis of the areas considered incompatible must be incorporated.

These results highlight the urgent need to refine and expand current zoning methodologies in line with Directive 2023/2413. In particular, Article 15.3 of the Directive calls for the use of all appropriate data and tools to identify areas where renewable energy deployment would not cause significant environmental harm which implies both exclusion and suitability analyses, informed by technical and socio-territorial considerations.

The objective of this study is to develop a comprehensive methodological framework to guide the identification of renewable energy areas based not only on environmental criteria, using the case of Portugal to illustrate its practical application. This framework, which encompasses both methodological and conceptual components, will be demonstrated through its application to wind energy deployment in Portugal. The proposed case is expected to enhance understanding of the identification of potential areas for renewable energy, generating new knowledge that goes beyond the boundaries of the case itself and paves the way for a more equitable and efficient designation of renewable energy areas across Member States.

## 2. Literature review. Addressing the identification of potential areas for renewable energy

The identification of optimal locations for renewable energy deployment has been a growing concern since the early 21st century. [Krewitt and Nitsch \(2003\)](#), were among the first to highlight the territorial planning challenges posed by renewable energy development. Since then, numerous studies have proposed methodologies to delineate suitable areas, particularly for wind and solar farms.

[Díaz-Cuevas et al. \(2025\)](#) analysed some of these studies, alongside other works ([Höfer et al., 2016](#); [Díaz-Cuevas et al., 2018](#); [Yushchenko et al., 2018](#); [Romero-Ramos et al., 2023](#), among others), emphasizing the role of Geographic Information Systems (GIS) and Multicriteria Decision Methods (MCDM) in spatial energy planning. These methodologies involve the delineation of exclusion zones based on environmental and technical considerations. Subsequently, the remaining areas are assessed according to suitability factors, which are often prioritized through the assignment of specific weights, followed by a analysis in which these factors are aggregated into a composite suitability index.

A key observation is the variability of criteria across studies. The number of exclusion criteria employed varies significantly depending on the study area, data availability, and territorial specificity ([Díaz-Cuevas et al., 2025](#)). For instance, for solar energy 28 criteria were considered in the case of Iran ([Hafeznia et al., 2017](#)), whereas only six are applied in Tanzania ([Aly et al., 2017](#)), and some studies use as few as three ([Romero-Ramos et al., 2023](#)).

On the other hand, access to updated information on existing wind and solar power plants in study areas is often not included in analyses due to the unavailability of such geospatial data. However, having access to this information would enable the exclusion of already occupied areas and the assessment of potential synergistic effects. A common issue in many studies is the reliability of geospatial data, which frequently exhibit heterogeneous formats, differing coordinate systems, and limited documentation regarding spatial resolution or reference systems ([Elkadeem et al., 2022](#)). Harmonizing coordinate systems using available GIS tools and adopting common standards such as the INSPIRE Directive would help overcome these limitations. Nevertheless, few studies perform adequate quality control or implement methodological enhancements such as sensitivity analysis, cross-validation with real infrastructure data, or regular updates of spatial datasets—despite their potential to significantly improve the robustness and reliability of results.

Restrictions applied to exclusion criteria are often derived from previous studies conducted in different territorial contexts, rather than being defined by the legal framework of the study area ([Díaz-Cuevas et al., 2018](#)). In some cases, the buffer distances used are adopted from prior studies and applied in new contexts without a consensus on their

suitability concerning technical aspects such as wind speed or solar radiation. For instance, [Watson and Hudson \(2015\)](#) adopted restrictions for wind farms based on distances used in the United Kingdom 14 years earlier ([Díaz-Cuevas et al., 2025](#)).

Regarding the analysis of the suitability of the remaining land, suitability factors also vary according to the study area. For instance, [Höfer et al. \(2016\)](#) considered nine suitability factors, whereas other studies, such as that by [Nasehi et al. \(2016\)](#), used 11. The selection of these factors is generally based on previous studies and expert opinions. However, as with exclusion criteria, some studies derived their factors selection from literature review ([Tahri et al., 2015](#)). Notably, none of these studies incorporate electricity demand as a suitability factor, despite its potential to guide renewable energy sitting toward areas of higher consumption and to promote energy self-sufficiency.

Once the factors are selected, they are normalized and spatially represented. After normalization, the factors are weighted. One of the most used techniques for this task is the Analytic Hierarchy Process (AHP), as this method is particularly useful when dealing with criteria of different nature, such as technical, economic, and environmental factors. This method, proposed by [Saaty \(1980, 1989\)](#), is widely used in such studies. However, as stated in [Díaz-Cuevas et al. \(2025\)](#), one of the main criticisms is the ambiguous way the relative weights of the criteria are derived and whether the criteria ratings are consistent ([Höfer et al., 2016](#)). There are cases where the authors themselves determine the weights ([Latinopoulos and Kechagia, 2015](#); [Romero-Ramos et al., 2023](#)) or rely on weights established for these criteria in other studies, as seen with [Bimenyimana et al. \(2024\)](#), who use the same weights for all ECOWAS countries, which does not help minimize biases and does not ensure that the weights reflect local realities, despite varying preferences.

In all analyses conducted, the presence of wind and solar resources in sufficient quantity and quality receives the highest weighting. However, for areas with abundant solar or wind resources, the distance to transmission lines may be considered a more important factor ([Díaz-Cuevas et al., 2025](#)). [Yushchenko et al. \(2018\)](#), assumed in one of their scenarios that the general level of solar irradiance in West Africa is adequate for solar power production and suggest that the focus should be on minimizing potential investment costs, represented by limiting the distance to electricity grid lines (for lower connection costs) and major roads (for lower accessibility costs). The weights assigned to each factor vary considerably across studies. For example, [Aly et al. \(2017\)](#) assigned a high weight to solar resources (irradiance) at 69.6 %, followed by accessibility at 22.9 %, and distance to population centers at 7.5 % for photovoltaic plant siting. In contrast, [Al Garni and Awasthi \(2017\)](#) weighted solar resources (irradiance and temperature) at 0.587 and terrain slope at 0.159.

Due to these differences and considering the scale of the study area, [Díaz-Cuevas et al. \(2021\)](#) decided to leave factor weighting to the planning and management bodies of each specific area (e.g., provinces, municipalities) and for future, more detailed analyses ([Díaz-Cuevas et al., 2025](#)). Accordingly, the aim of that study was only to identify suitable areas, highlighting those with greater potential for renewable energy, which can be further analysed using different methodologies and criteria. This underscores the need for a multiscale analysis.

All these methodological divergences can be explained by contextual factors—legal, political, economic, and territorial—that shape zoning strategies. Countries with strong centralized planning may adopt national tools, while decentralized systems delegate analysis to regional or local levels. The availability and openness of spatial data, public

acceptance, infrastructure maturity, and administrative capacity also play a key role in shaping methodological choices.

Therefore, the definition/identification of compatible areas for the installation of renewable energy plants becomes one of the key challenges, where the analysis of these experiences highlights how, without a well-defined theoretical structure, these tools may be misunderstood or misused, potentially leading to suboptimal planning decisions. It is thus essential to establish a robust theoretical framework that facilitates a more effective and beneficial use of these technologies in spatial planning. Without this, tools risk being inconsistently applied or misunderstood, leading to suboptimal planning outcomes. This review highlights both the opportunities and limitations of current practices and supports the design of context-sensitive, evidence-based methodologies for zoning renewable energy development.

### 3. Study area, material and methods

#### 3.1. Study area

Portugal is situated on the Iberian Peninsula in southwestern Europe, covering approximately an area of 92,230 km<sup>2</sup>. In 2020, the country achieved historically low energy dependence, reaching 67.4 %, although this was influenced by factors such as the pandemic's impact on energy consumption. The National Energy and Climate Plan ([Ministério do Ambiente e da Ação Climática, 2024](#)) aims to reduce energy dependence to 65 % by 2030.

In terms of electricity consumption ([Fig. 1](#)), the areas of highest consumption are located on the central-northern coast (with intensity in Oporto, Lisbon and Setúbal) and in the Algarve (where the annual peak occurs in summer, unlike the other regions of highest consumption, because this area is known as a sun and beach area). Also, Portuguese industry is historically concentrated, with five districts identified as the main centers of industrial consumption: Braga, Porto, Aveiro, Lisbon and Setúbal ([Amaro, 1991](#)).

According to [Simões and Estanqueiro \(2003\)](#), areas with high wind potential are often found in remote regions with low energy consumption, limiting the injection of wind energy into the grid (Plano de Desenvolvimento e investimento da Rede Nacional de Transporte, 2022–2031, Reguladora dos Serviços Energéticos -ERSE-, 2021). Surprisingly, some of the municipalities with the highest electricity consumption per inhabitant are identified as "Go-To Areas" by [Simões et al. \(2023\)](#), ([Figs. 1 and 2](#)).

The country hosts 2906 wind turbines with a total installed capacity of 5602 MW connected to the grid. Districts like Viseu, Coimbra, and Vila Real lead in installed wind power capacity, collectively representing 46 % of the total capacity in Portugal ([Fig. 2](#)).

Concerning "Go-To Areas" defined by [Simões et al. \(2023\)](#), wind and solar activity are a priori to be incompatible in approximately 88 % of the Portuguese surface in scenario 1, 90 % in scenario 2, and 95 % and 97 % of the incompatible surface in scenarios 3 and 4, respectively ([Table 1](#)).

Further analysis of territorial distribution of installed wind turbines in relation to the proposed "Go-To Areas" for wind and solar deployment, Scenario 1 revealed that 356 wind turbines are already situated in these areas. Scenario 2 shows 252 wind turbines, Scenario 3 has 171 wind turbines, and Scenario 4 has 115 wind turbines. This distribution highlights the need for careful consideration of existing installations when planning for future projects.

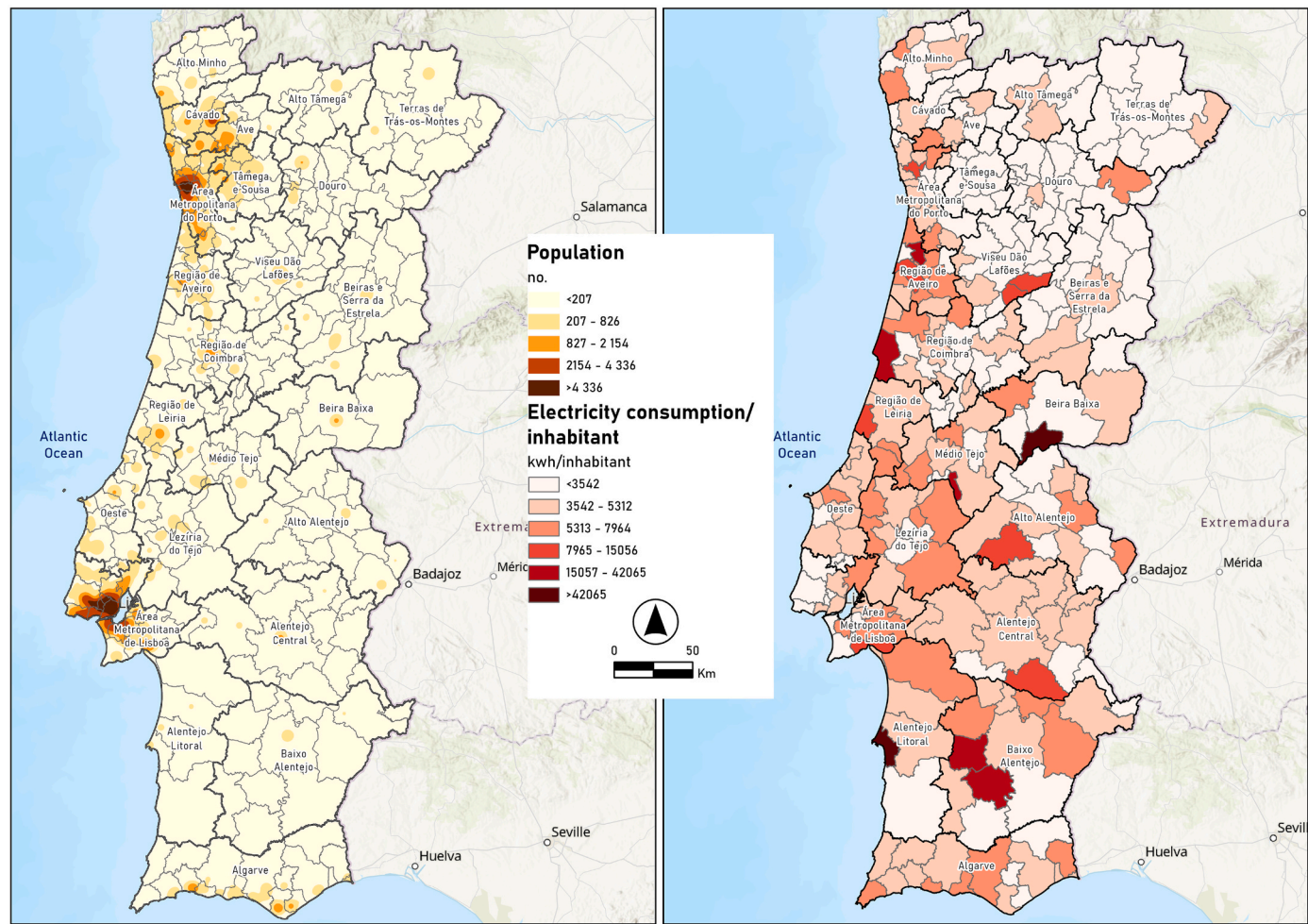


**Fig. 1.** Population and electricity energy consumption (KWh) per inhabitant in Mainland Portugal (2021).  
Fuente: Own elaboration based on population data and the Directorate-General for Energy and Geology<sup>1,1</sup>

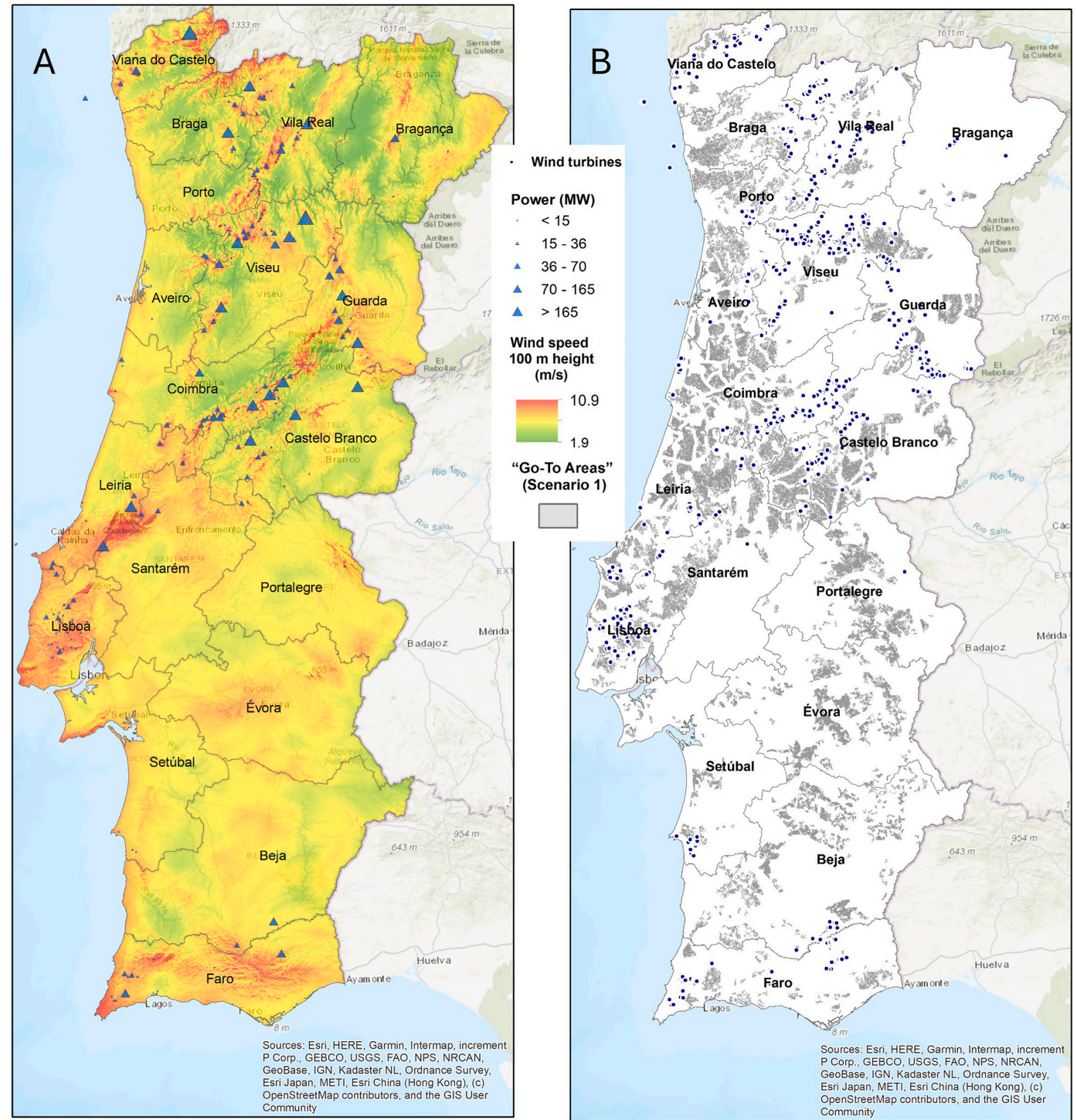


Fig. 2. Wind energy plants and wind speed in Mainland Portugal (Fig. 2a) and “Go-To Areas” (Scenario 1) and wind turbines (Fig. 2b). Source: Author’s own work based on Simões et al. (2023) and The Wind Atlas

### 3.2. Material and methods

To address potential for wind energy deployment, spatial data must be collected and processed for integration into a Geographic Information System (GIS). Data availability is essential for accurate territorial assessment and most EU countries progress extensive geographic datasets that meet the quality standards established by the INSPIRE Directive (European Parliament and Council, 2007).

In Portugal, there are several bodies responsible for producing and distributing socio-demographic and environmental information at the

national level. Table 2 lists the main organisations consulted, including the Directorate-General for Territorial Planning, the national public body responsible for spatial and urban planning policies and the Instituto de Conservação da Natureza ou das Flores, a Portuguese state body whose purpose is to contribute to the revaluation and conservation of aspects related to nature and biodiversity in Portugal.

For wind-energy resources, the wind speed grid with 50 m resolution (for a turbine height of 100 m) was based on results published by the Global Wind Atlas 3.0, a free, web-based application developed, owned, and operated by the Technical University of Denmark (DTU). The Global

**Table 1**  
Compatible areas (km<sup>2</sup>/% ) following scenarios.

|                                                                                                                                | Area               |      |
|--------------------------------------------------------------------------------------------------------------------------------|--------------------|------|
|                                                                                                                                | (Km <sup>2</sup> ) | (%)  |
| Scenario 1                                                                                                                     | 10,350             | 11.2 |
| Scenario 2 (Scenario 1 & mineral resource protection areas)                                                                    | 8977               | 9.7  |
| Scenario 3 (Scenario 2 & removing areas from mainland Portugal aquifer systems, removing 500m buffer in residential buildings) | 4162.02            | 4.5  |
| Scenario 4 (Scenario 3 & withdrawing National Agricultural Reserve and National Ecological Reserve areas)                      | 2652.20            | 2.9  |

Source: Author's own work based on [Simões et al. \(2023\)](#).

**Table 2**  
Criteria and Restrictions applied.

| Criteria                                                                                                                                                                                                       | Restriction applied                                                                                                                   | Source                                                                                                                                                            |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Built-up areas (continuous and dispersed)                                                                                                                                                                      | Continuous <500 m                                                                                                                     | Carta de Uso e Ocupação do Solo - 2018                                                                                                                            |
| Other uses: tourism facilities (hotels, golf courses, etc.), leisure facilities, sports facilities, agricultural facilities, parks and gardens, salt pans, commercial facilities ...                           | Scattered; Rural villages and buildings <250 m ( <a href="#">Watson and Hudson, 2015</a> ; <a href="#">Díaz-Cuevas et al., 2018</a> ) | Directorate-General for Territorial Planning                                                                                                                      |
| Road network & Rail network                                                                                                                                                                                    | Incompatible + buffer 250 m                                                                                                           | Infraestruturas de Portugal, S. A.                                                                                                                                |
| Aerodromes, Airports                                                                                                                                                                                           | Incompatible + buffer 250 m                                                                                                           | Agência Portuguesa do Ambiente (APA)                                                                                                                              |
| Rivers, water public domain, lagoons, wetlands, zones with significant potential flood risk, rivers, bathing waters                                                                                            | Incompatible + buffer 250 m                                                                                                           | Agência Portuguesa do Ambiente (APA)                                                                                                                              |
| Natural areas, protected landscapes, environmental protected areas                                                                                                                                             | Incompatible Buffer 150 m. ( <a href="#">Simões et al., 2023</a> ).                                                                   | Instituto da Conservação da Natureza e das Florestas                                                                                                              |
| Forested areas, Biogenetic resources, Ecological corridors & Public interest tree                                                                                                                              | Incompatible. ( <a href="#">Simões et al., 2023</a> ). Buffer <250 m, <a href="#">Yue and Wang (2006)</a>                             | Endogenous Energies of Portugal (E2P) ( <a href="http://e2p.inegi.up.pt/">http://e2p.inegi.up.pt/</a> )                                                           |
| Areas already occupied by any renewable energy facility                                                                                                                                                        | <250 m wind turbines ( <a href="#">Díaz-Cuevas et al., 2018, 2019</a> )                                                               | Portuguese Environment Agency (APA)                                                                                                                               |
| Beaches and Coastline Programs, Albufeiras                                                                                                                                                                     | Incompatible ( <a href="#">Simões et al., 2023</a> )                                                                                  | Portuguese Environment Agency (APA)                                                                                                                               |
| Cork oak agroforestry; Holm oak agroforestry; Stone pine agroforestry; Cork oak and holm oak agroforestry; Cork oak forests; Holm oak forests; Other oak forests; Other deciduous forests; Stone pine forests. | Incompatible ( <a href="#">Simões et al., 2023</a> )                                                                                  | Directorate-General for Territorial Planning                                                                                                                      |
| Classified cultural heritage, Archaeological heritage ...                                                                                                                                                      | Not in those areas Archaeological heritage (+ buffer of 150 according to <a href="#">Simões et al., 2023</a> )                        | Direção-Geral de Património Cultural (DGPC)                                                                                                                       |
| National Reserves (REN)                                                                                                                                                                                        | Not in zones 1 and 1 and 2                                                                                                            | Linking Landscape, Environment, Agriculture and Food (LEAF) – <a href="http://epic-webgis-portugal.isa.ulisboa.pt">http://epic-webgis-portugal.isa.ulisboa.pt</a> |
| DEM/Slope <20 %.                                                                                                                                                                                               | Not in areas ( <a href="#">Simões et al., 2023</a> )                                                                                  | <a href="#">Gonçalves and Pinhal (n. d.)</a>                                                                                                                      |

Source: Author's own work

Wind Atlas is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP) ([Technical University of Denmark & World Bank, 2023](#)).

Slope data were derived from the Digital Elevation Model (DEM), obtained by the Shuttle Radar Topography Mission using SAR Interferometry, with an approximate resolution of 30 m, between latitudes 60S and 60N. The data were collected by [Gonçalves & André Pinhal.<sup>2</sup>](#)

The coordinate system used was the European Terrestrial Reference System for continental Portugal 1989 (ETRS89), projected in (EPSG:3763). All collected data has been transformed and projected to this reference system and the resolution of the model is 100 m.

Particular attention was paid to the processes of spatial data collection, management and processing of spatial data (e.g., reprojection/transformation, conversion to raster/vector, incorporation in a spatial database) of the shapefiles, gjson, raster files or spatial tables representative of each criterion. The ArcGIS 10.3 software was used because of its extensive spatial analysis capabilities.

The methodological approach involved constructing a GIS-based locational model, following a two-step sequence.

- Step 1. Development of a locational sub-model to identify areas where the construction of wind energy plants is incompatible. Criteria and constraints were mapped, and a final exclusion map was generated in which each 100 × 100 m cell receives a value corresponding to the number of criteria it fails to meet. These criteria aim to safeguard cultural and natural heritage while ensuring energy efficiency, thereby promoting the economic and spatial efficiency of energy infrastructure.

The exclusion criteria outlined in [Table 2](#), were based on local planning and legislation, as documented in [Simões et al. \(2023\)](#). When legal thresholds were unavailable, values were adopted from scientific literature, particularly from studies with similar spatial resolution and geographic scope. In the case of infrastructure (e.g., airports, railways, and roads), the heterogeneity of exclusion distances found in the literature led us to adopt a precautionary and technically grounded approach: areas were considered incompatible if located within the infrastructure footprint or within a 250 m buffer. This distance is justified not only on environmental and planning grounds, but also for safety reasons assuring that wind turbine blades remain at a safe distance from roads and transport corridors. This same restriction was applied to water bodies, in line with common practice in spatial planning and environmental protection.

All criteria and constraints were spatially mapped and reclassified (using the Reclassify tool in the Spatial Analyst module of ArcGIS). Incompatible areas were assigned a value of 1 and compatible areas a value of 0. This binary classification allowed the subsequent use of raster algebra to sum the individual constraint layers using the Raster Calculator tool, resulting in a final map in which each cell indicates the number of exclusion criteria it violates.

- Step 2. Evaluation of areas where wind activity is compatible.

Once compatibility areas have been identified, these will be evaluated according to their suitability level prioritizing into.

- 1) Areas with highest presence of wind resource in sufficient quality and quantity. For this purpose, although the Atlas of Wind Power Potential in Portugal elaborated by [Costa and Estanqueiro \(2006\)](#), which measures the wind potential in number of equivalent hours of operation, was used in the study by [Simões et al. \(2023\)](#). For this study, data were not available at the level of detail and format required. For this reason, wind speed data will be collected from The Wind Atlas which has been reclassified into three levels of suitability (low, high, and very high).

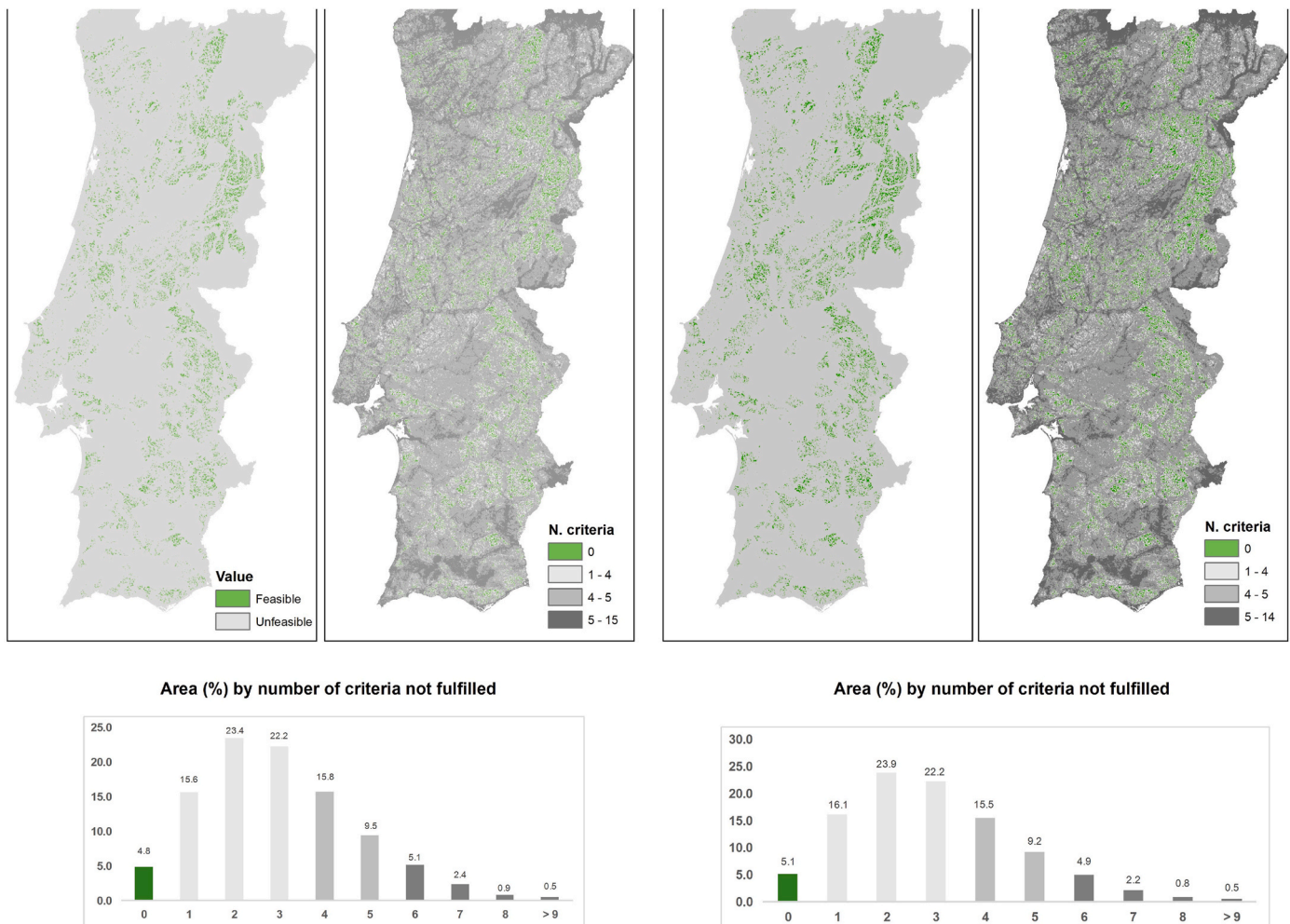


**Fig. 3.** Incompatible areas and n° unfulfilled criteria in Scenario 1 (slope >20 %) (A–B) and in Scenario 2 (slope >26.44 %) (C–D). Source: Author's own work

2) Municipalities with the highest electricity consumption per inhabitant have been reclassified into three levels of suitability (low, high, and very high). This aligns with the principle of energy self-sufficiency, would avoid negative externalities in areas with lower electricity consumption, and would reduce the impacts associated with the need to build new lines and infrastructure to bring energy closer to consumption centers.

Once the maps representative of the reclassified suitability based on wind consumption and wind speed were obtained, were combined with the incompatibility map (reclassified between 0 and 1), using the combine option in ArcGIS, as described in Díaz-Cuevas et al. (2019). The combine tool, developed by ESRI and integrated into ARCGIS, enables the consolidation of multiple rasters in a manner that assigns a single output value to each distinct combination of input values.

Finally, the percentage of surface area with high or very high potential for wind energy implementation will be calculated for each municipality.

## 4. Results

### 4.1. Incompatible areas

Fig. 3 shows the areas of Portuguese territory where, based on the criteria analysed, wind energy activity is incompatible or highly inadvisable. Several aspects must be highlighted.

In approximately 95 % territory, wind energy units are incompatible or highly inadvisable while a total of 4260 km<sup>2</sup>, needs to be analysed in depth to assess the suitability of wind energy activity there (Fig. 3).

Although 4260 km<sup>2</sup> might seem a priori a very small area of territory, however, following the work of Díaz-Cuevas et al. (2018), and taking into account that the space between turbines should be three times the rotor diameter (Yue and Wang, 2006; Tegou et al., 2010) for 2 MW wind turbines (114 m rotor), this implies a radius of 342 m around each turbine or, in other words, 367,442 m<sup>2</sup> (0.37 km<sup>2</sup>). Therefore, there would still be land available for the installation of 11,513 turbines, that would amount to 23,026 MW at an average of 2 MW per turbine.

Most of the territory where wind energy activity is a priori or highly incompatible, 15.6 %, is so because it fails to meet one criterion (of the criteria analysed), so these are the territories which, in the absence of a sufficient surface area with high or very high suitability, would merit study. Territories where five or more criteria are not met should be discarded from the analysis.

On the other hand, regarding the wind turbines already installed, the overlap of these with the layer of number criteria allows to identify if any of them do not fulfil some of the criteria analysed. For this purpose, the model has been recalculated, discarding the criterion of areas incompatible with wind activity due to installed wind turbines. A total of 2606 wind turbines do not fulfil some of the criteria analysed (Fig. 3 – A–B).

An analysis of the unfulfilled criteria reveals that 606 existing wind turbines do not comply with the slope criterion, highlighting that it is

**Table 3**  
Statistics values for slope criteria.

| RI   | Q1    | Q3    | OUTLIERS         | Average  |
|------|-------|-------|------------------|----------|
| 7.54 | 22.38 | 29.93 | <11.07 & > 41.24 | 26.44 %. |

Source: Author's own work

both feasible and economically viable to install wind turbines in areas with slopes exceeding 20 % (a criterion included in the generated model, derived from Simões et al., 2023). By examining wind turbines located in areas with slopes greater than 20 % and excluding outliers from the analysis (calculated using Equations (1) and (2)), the average slope value in these areas is 26.44 % (Table 3). This new finding will be incorporated into the recalibration of the previous model. It is hypothesized that the presence of wind turbines in these areas, despite not meeting the slope restriction, demonstrates their economic viability. The results reveal that 5.3 % of the territory falls within this consideration. In this revised scenario (Fig. 3 – C-D), a priori compatibility with wind farms is estimated at 5.1 % of the territory (equivalent to 4702 km<sup>2</sup>), which would accommodate 1194 new turbines. This equates to a total new capacity of 25,414 MW, assuming an average turbine capacity of 2 MW. In addition, it should be noted that the maximum number of unfulfilled criteria in this model has decreased from 15 to 14.

$$A = Q1 - 1.5RI \quad (\text{Eq.1})$$

$$A = Q3 + 1.5RI \quad (\text{Eq.2})$$

Where Q1 is the value of first quartil; Q3 is the value of third quartil; and

RI is the interquartile range.

#### 4.2. Analysing compatible areas

Once the areas where wind energy activity is highly inadvisable were obtained, the compatible areas were analysed according to wind resource and electricity consumption per inhabitant. These values have been reclassified between 1 and 3 (low, medium, high).

To evaluate wind resource suitability (Fig. 4A), the study first established the lowest suitability range by examining the wind speed values at locations with existing wind turbines. The minimum average wind speed value for installed turbines in the study area was determined as 4.9 m/s. The remaining intervals, medium and high, were defined through tertiles, resulting in suitability intervals categorized as Low (<4.9 m/s), Medium (4.9 < 6.0 m/s), and High (6.0 ≤ 15.8 m/s). Simultaneously, electricity consumption per inhabitant (Fig. 4B) was assessed using tertiles to establish suitability intervals: Low (≤ 3202 kWh/inhabitant), Medium (3202 < 4525 kWh/inhabitant), and High (4525–83,563 kWh/inhabitant). The suitability maps generated from these criteria were then combined with the map indicating compatible/incompatible areas using the COMBINE tool de ESRI.

This integration was intended to highlight areas for prioritized analysis at more detailed scales, particularly those classified as “high” in Fig. 4C. This strategic approach ensures a nuanced understanding of areas with favourable wind resources and high electricity consumption, facilitating targeted analysis and decision-making in subsequent planning and implementation phases.

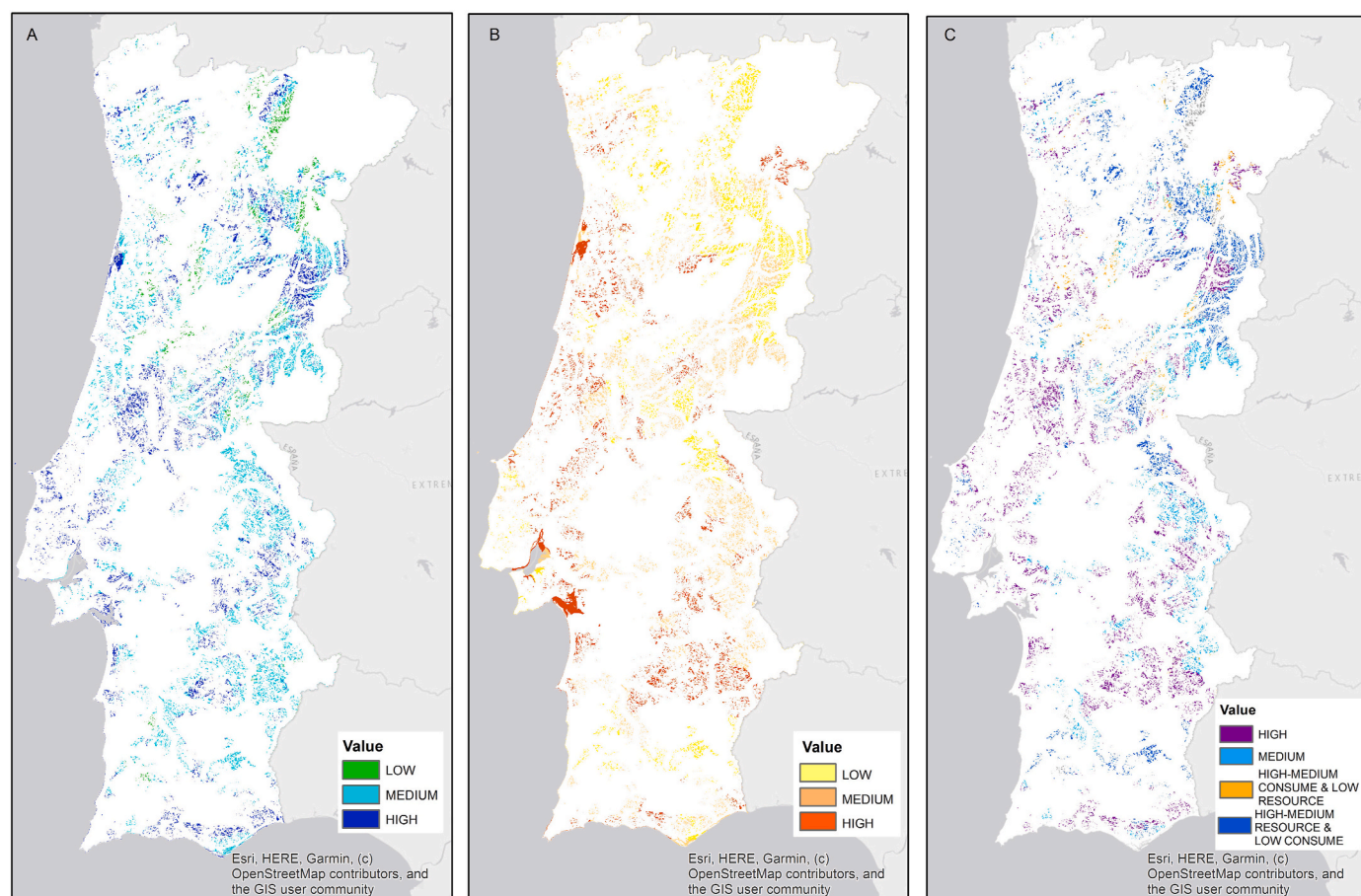


**Fig. 4.** Compatible areas classified according to wind speed values (A), electricity consumption per inhabitant (B) and combination of both with compatible and incompatible zones (C).

Source: Author's own work

## 5. Discussion and policy implications

The European Union's renewable energy targets for 2030 and 2050 have driven a significant increase in wind and solar installations, enabling the EU-27 to meet its 2020 objectives and more than double its wind energy capacity since 2010 (Eurostat, 2023; Márquez-Sobrino et al., 2023). However, this rapid deployment has exposed major challenges in spatial planning and site designation. Directive (EU) 2023/2413 responds to these challenges by requiring Member States to designate "renewable acceleration areas" by 2026.

This study, focused on mainland Portugal, proposes a methodological framework to further elaborate designation and identifies key analytical dimensions that Member States should consider. Several essential challenges emerged from the application of this framework:

**Definition of criteria, model validation, and scenario design** - Establishing appropriate exclusion criteria is critical. These criteria often encompass protected areas, bodies of water, and minimum required distances from heritage sites. However, the identification of compatible areas should go beyond environmental constraints and incorporate social, economic, and cultural factors, contributing to more inclusive and context-sensitive spatial planning.

In many cases, specific restrictions are not clearly defined by national legislation, which often leads to the adoption of values from other contexts, particularly in relation to technical criteria that have traditionally guided exclusion analyses. This practice can result in inconsistencies, as observed in Portugal with the slope criterion. Similarly, improvements in turbine foundations and construction techniques have expanded the feasibility of installations on steeper slopes. In addition, the development of larger turbines with higher hub heights and larger rotor diameters—have significantly improved performance under lower wind speed conditions. As a result, areas previously considered marginal due to suboptimal wind speeds or steeper slopes may now be viable for energy production.

In line with these considerations, the reliability of the model was assessed through a cross-validation exercise: the model was reconstructed excluding the constraint related to existing wind turbines, and the results were compared to actual turbine locations. Of the 2906 wind turbines installed in mainland Portugal, 2606 are in areas classified as incompatible. Nearly two-thirds of these cases are mainly due to their proximity (less than 250 m) to roads, railway lines, or water bodies.

These findings suggest that exclusion thresholds should not be treated as static parameters, but rather as flexible guidelines that must be periodically revised to reflect evolving technical capabilities and adapted to empirical evidence and local contexts. This reinforces the importance of developing multiple scenarios that account for political, legal, and territorial specificities, avoiding the unnecessary dismissal of potentially suitable areas and ensuring more context-sensitive and effective spatial planning.

Following Díaz-Cuevas et al. (2017), at least two scenarios should be analysed: one reflecting current legal constraints, and another more restrictive scenario based on the precautionary principle (European Union, 2012). In Portugal, the absence of regulatory thresholds for infrastructure such as roads and railways led to the application of a generic 250 m buffer. This, combined with the exclusion analysis, enabled the development of a less restrictive slope-based scenario. This approach aligns with Article 15.3 of Directive 2413, which calls for the use of all appropriate tools and data—including GIS analytical capabilities—to prevent significant environmental impacts.

**Data limitations and the need for multiscale analysis** - One of the main barriers identified is restricted access to critical spatial data, such as the national electricity transmission network. Although such data exist, they are not always publicly accessible due to security concerns. Likewise, variables such as migratory corridors, visual impact, or social acceptance are difficult to map and highly dynamic, requiring local-scale assessments.

To address these challenges, the creation of joint European

databases, improved data transparency, and strengthened collaboration between authorities and researchers are recommended. National-scale analyses should be understood as preliminary screening to identify viable areas and exclude clearly unsuitable ones, but not as definitive planning tools. This first filter facilitates deeper, regionally adapted studies and accelerates decision-making processes. In fact, Elkadeem et al. (2022:20) emphasize that "the availability of a recent and authoritative dataset at a more detailed geospatial scale could lead to a more robust interpretation." The methodology presented here serves as a valuable resource for planners and decision-makers, helping to identify areas that require more detailed analysis, particularly considering the EU's commitments to renewable energy.

The existence of these data and planning gaps has practical consequences for energy transition strategies. For instance, insufficient access to infrastructure data (such as grid connection points) or the use of overly rigid exclusion criteria at national scales can lead to the misidentification of suitable areas or to the rejection of sites that, under local conditions, may be viable. This not only risks hindering renewable deployment but may also result in spatially unbalanced planning, reduced public acceptance, or increased implementation costs due to poorly aligned infrastructure. Therefore, bridging these gaps is essential to support timely, context-sensitive, and socially legitimate energy planning. Addressing them through integrated databases, empirical validation of criteria, and coordination across scales will increase the accuracy and usability of zoning methodologies and make them more impactful in real-world decision-making contexts.

**Suitability factors and the need for local expertise** - Suitability factors are weighted differently across studies, and no consensus exists on which variables should be prioritized. Given these divergences and the national scale of the present study, it is proposed that the prioritization of criteria and factors be delegated to local planning bodies (e.g., municipalities, provinces), where contextual and technical knowledge can be integrated into decision-making. This approach enhances governance and decision-making by recognizing that each specific territory should determine its own priorities based on local values and constraints (Díaz Cuevas et al., 2017). This multiscale approach reinforces the guiding nature of the methodological framework: it does not determine final locations but rather identifies priority areas for more detailed analysis and refined planning.

Acceleration zones must complement - but not replace - environmental and social impact assessments at the sub-regional or local level. These are essential for addressing issues that cannot be captured nationally, such as cumulative impacts, social acceptance, or landscape perception. Moreover, resource availability (wind or solar) should not be the sole priority criterion, especially when technical conditions are adequate across the territory (Haddad et al., 2021). Proximity to infrastructure and demand centers must also be considered (Elkadeem et al., 2022; Díaz-Cuevas et al., 2021), further reinforcing the importance of expert knowledge and multiscale approaches.

**Territorial inequality and diversification of resources** - This research reveals that meeting all exclusion criteria is not sufficient to achieve energy transition objectives, given the unequal territorial distribution of wind potential. This poses a challenge for high-consumption territories. The following strategies are proposed.

- Assess alternative renewable sources (e.g., solar, biomass) in areas where wind is not viable; This conceptual framework can also be applied to other renewable energy sources - such as solar or biomass - in areas where wind energy is not viable, where specific criteria and constraints are carefully considered.
- Prioritize artificial or degraded lands in line with Directive 2413.
- Promote energy efficiency and demand reduction policies.

In addition, exploring areas initially deemed incompatible but with high wind potential and local demand may be a viable strategy through more detailed, localized assessments.

A fair and balanced zoning framework should be developed, integrating both technical and socioeconomic criteria, and aligning production with consumption. Prioritizing large-scale projects in high-consumption areas - as suggested in this study - supports energy self-sufficiency and a more equitable distribution of impacts. This approach helps avoid placing the burden of renewable energy development on low-consumption regions, a dynamic some scholars describe as “energy colonialism” (Valqueresma et al., 2024; Contreras and Matarán Ruíz, 2023; Dunlap, 2023). In any case, these criteria also contribute to minimizing evacuation infrastructures and the need to reinforce the electricity grid, thus reducing impacts and optimising the use of resources.

In Portugal, municipal-level electricity consumption data enable the application of this approach. However, further analysis is still needed to define strategies tailored to industrial-scale projects, self-consumption schemes, and community energy initiatives.

The methodology proposed here represents a necessary first step in supporting EU Member States in the effective, equitable, and territorially adapted identification of renewable areas. The multiscale approach — combining exclusion analysis, scenario development, and demand-proximity criteria — provides a foundation for more just, resilient, and technically sound spatial planning.

Furthermore, this framework can be adapted to other renewable technologies, such as solar or hybrid systems, provided that their specific criteria and constraints are carefully considered. In a context marked by climate urgency and territorial complexity, advancing towards data-driven, locally informed, and participatory energy planning is essential to achieving a truly sustainable energy transition.

## 6. Conclusions

This study proposes a robust conceptual framework to guide the application of Geographic Information Systems (GIS) in the identification of renewable energy areas, aiming to support a more equitable, efficient, and sustainable energy transition —especially in the current context of acceleration zone designation by EU Member States.

The proposed methodology integrates exclusion analysis, scenario development, critical reassessment of initially incompatible areas, interdisciplinary criteria, and spatial alignment between energy generation and consumption, allowing for flexible, context-sensitive application tailored to the specificities of each Member State.

One of the key findings highlights the limitations of analyses conducted solely at the national scale, which should be complemented by more detailed regional and local studies to ensure social and territorial legitimacy and governance. In this regard, the integration of wind resource data with municipal electricity consumption has proven useful for identifying areas with high energy demand, promoting self-sufficiency and a more equitable distribution of impacts, and thus helping to avoid dynamics of “energy colonialism.”

In the case of Portugal, the model showed that 95 % of the territory would be excluded under highly restrictive criteria, underscoring the need to revise exclusion thresholds—such as slope—based on technological advancements and local conditions.

The study emphasizes the importance of data-driven, participatory, and territorially informed energy planning. The methodology is transferable to other EU countries and renewable technologies and aligns with Directive (EU) 2023/2413 and the European Green Deal. It thus contributes to the development of more just, resilient, and technically sound renewable energy planning.

## CRediT authorship contribution statement

**Pilar Díaz-Cuevas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Belén Pérez-Pérez:** Writing – review & editing, Writing – original draft,

Visualization, Supervision, Methodology, Conceptualization. **Hélder Silva Lopes:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Paula Ferreira:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors declare no conflict of interest

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## Data availability

Data will be made available on request.

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