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The Geospatial Canvas of Wind Energy Production: Assessing the Carrying Capacity in the Spanish Northwest

Rodrigo Arévalo-González | Victoria Ferrero | Estrella Alfaro-Saiz

Department of Biodiversity and Environmental Management, University of León, León, Spain

Correspondence: Estrella Alfaro-Saiz (estrella.alfaro@unileon.es)

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ABSTRACT

Large wind energy plants can significantly impact the environment if not managed properly. This study employs Geographic Information Systems (GIS) and spatial multi-criteria analysis (SMCA) to evaluate the carrying capacity of territories to host wind energy production. Carrying capacity, defined as a spatial category of suitability, is derived from the integrating multiple layers. The proposed approach incorporates 34 aptitude and 21 impact variables, addressing wind behavior, land use, and physical, natural, and historical-cultural characteristics. The aptitude variables were ranked by a panel of experts. This methodology was applied to regions in northwestern Spain to assess their capacity for hosting wind energy projects. Two carrying capacity maps were generated: one with absolute intervals and another with relative intervals. Positive carrying capacity, indicating a value above zero, varied between 0.00% and 43.85% of the area depending on the region. Strikingly, only 0.09% of the total area exhibited both optimal energy potential and maximum relative carrying capacity. The maps were compared to the binding zonings proposed by national and regional authorities, which were found to be slightly restrictive. Alarmingly, more than 50 wind turbines across eight projected wind energy plants have been authorized or are in the approval process for locations with negative carrying capacity under the new classification. This spatial approach offers a valuable tool for future territorial planning, ensuring a balance between energy production and environmental conservation. It provides a replicable framework for sustainable land management in regions facing similar challenges.

1 | Introduction

Energy production using fossil fuels leads to environmental degradation and high carbon emissions (Aydin et al. 2010; Latinopoulos and Kechagia 2015; Mentis et al. 2015; McKenna et al. 2022). In addition, fossil fuels are characterized by a low regeneration rate that drives to coal, oil, or natural gas depletion due to their high extraction rate (Höök and Tang 2013). In recent decades, renewable sources have been considered as an alternative approach to face current unprecedented energy demand. Wind energy is now the most important source of new power generating capacity in Europe and the United States (Sawin et al. 2016).

Wind energy can be produced in different ways, depending on its grade of distribution, size, and density in the space. A "large wind energy plant project" includes power generation and its sale to the electrical network. This excludes self-consumption installations

Brief informative title containing the major keywords: Decision support tool based on geographical information systems to assess the carrying capacity in the Spanish northwest to host renewable wind energy plants allowing sustainable land management and environmental protection.

Summary

To assess the carrying capacity to host wind energy production projects, a combined utilization of GIS and spatial multi-criteria analysis is proposed, integrating 34 aptitude and 21 impact variables regarding environmental conditions. It results in a promising decision support tool to guide future territorial ordering, avoiding impacts on the environment.

(MITERD 2020). Large wind energy plants can have significant negative impacts on the biotic, abiotic, human, and perceptual environments when located in erroneous places (San-Miguel et al. 2023; Terrón-Santos 2024). Previous studies have demonstrated renewable facilities, built without proper management that prioritize environmental values, generate environmental impacts, and have repercussions on the rural environment (composed of municipalities with a low population density) at the international (Rehbein et al. 2020; Jager et al. 2021), national (Serrano et al. 2020; Palacín et al. 2023), and regional levels (Díaz-Cuevas et al. 2017; Valera et al. 2022; Alfaro-Saiz et al. 2023; Bolonio et al. 2024).

At the European level, the installation of renewable energy generation plants is supported in order to achieve the energy-environmental objectives (Díaz-Cuevas 2018; Tsiropoulos et al. 2020; Alfaro-Saiz et al. 2023). On the other hand, none of the European environmental protection legislation establishes clear criteria to control the disposition of wind energy plants yet (Bouras et al. 2024). In Spain, in 2020 the national environmental Administration (Ministry for Ecological Transition and the Demographic Challenge, MITERD) proposed a zoning for the implementation of large wind renewable energy installations (MITERD 2020). In June 2022, some regional administrations (as e.g., Regional Government of Castilla y León, JCYL) also determined exclusion zoning for large wind farms in greater level of detail (Castilla y León 2022). Both proposals were based on generic environmental characteristics, just considering protected spaces but overlooking unique characteristics of local areas. Local areas present particular ecological connectivity, specific social demands, and threatened biodiversity without legal protection. Ignoring these facts leads to a deficit in environmental protection, which makes it impossible to guarantee projects do not impact negatively on the environment (Alfaro-Saiz et al. 2023). Although the MITERD zoning was initially presented as a merely indicative tool for companies, it obtained binding status with RDL 6/2022 (Spain 2022b), which made the procedures for renewable energy projects easier (Alfaro-Saiz et al. 2022, 2023). The surge in projects has sparked debates among researchers, NGOs, and citizen platforms (such as the Legal Fund for the Defense of the Cantabrian Mountains, FDJCC, and the Platform for the Future of the Central Mountain of Leon, PFMCL) that resulted in several manifestos and reports concerning wind management at the regional level in the Spanish northwest (FDJCC 2021a; Alfaro-Saiz et al. 2022, 2023).

Before the implementation of a wind energy plant there are some aspects that must be considered, such as the safety and health of inhabitants in the area or the natural and cultural assets. Those aspects can be considered through the integration of several layers, generating a new layer of spatial values or categories of suitability of the territory to host wind energy plants, called "carrying capacity." In some cases, their preservation is incompatible with a wind turbine installation, which constitutes an "excluding" scenario (meaning areas totally incompatible), given by a negative value of carrying capacity. In the remaining cases for which their installation would be possible, there would be a positive value of carrying capacity (Flórez-Gutiérrez 2021). To display the carrying capacity results in a more understandable way, areas with negative values of carrying capacity (i.e., lower than zero) can be grouped into an excluding carrying capacity interval, while those with positive values (i.e., equal to or greater than zero) can be grouped into several categorical intervals of non-excluding carrying capacity. Carrying capacity analysis allows territorial examination to determine how capable is to host a specific land use (Ruiz et al. 2023). The capacity level is based on cartographic layers that have values for each specific location. Thus, each position is defined by, firstly, the sum of the values for the variables that indicate the aptitude (excluding, neutral, or positive values) of that location for a particular land use and, secondly, those variables that have an impact (negative, neutral, or positive values) on that location for that use (Molina-Ruiz and Tudela-Serrano 2003; Gómez-Orea and Gómez-Villarino 2013; Espejel-García et al. 2015; Flórez-Gutiérrez 2021). Implantation of energy production facilities is plausible, thus, in areas of maximum values of positive aptitude and minimum of negative impact (Valera et al. 2022). It should be clarified that a negative impact value in an area can be counterbalanced by positive impact or aptitude values, while an excluding aptitude value means an infinitely negative value that cannot be counterbalanced.

> "*This study aims to develop an alternative approach to accommodate large wind energy plant projects with environmental criteria using Geographic Information Systems (GIS) tools.*"

This study aims to develop an alternative approach to accommodate large wind energy plant projects with environmental criteria using Geographic Information Systems (GIS) tools. GIS-based territorial studies are shaped as decision support systems for actual land use planning (Van-Haaren and Fthenakis 2011; Díaz-Cuevas et al. 2019) and allow the use of reliable tools to facilitate complex land use planning at multiple scales (Ramachandra and Shruthi 2005; Díaz-Cuevas et al. 2017). We applied our approach in the northwest area of Spain, in regions close to the Cantabrian Mountains (Los Ancares, El Bierzo, La Cabrera, and La Cepeda, in the province of León). According to predictions of biodiversity reduction due to climate change for 2071, these territories have the potential to comprise the greatest plant species richness in the whole national territory (Diéguez-Uribeondo et al. 2011; Jiménez-Alfaro et al. 2021). As of 3rd of July 2024, there are 11 large wind energy plants already installed in this area (FDJCC 2021b). In addition, there are six projected and authorized plants and another four projected and still in process. Finally, there are 15 projected wind energy plants that have been withdrawn or denied (FDJCC 2021b).

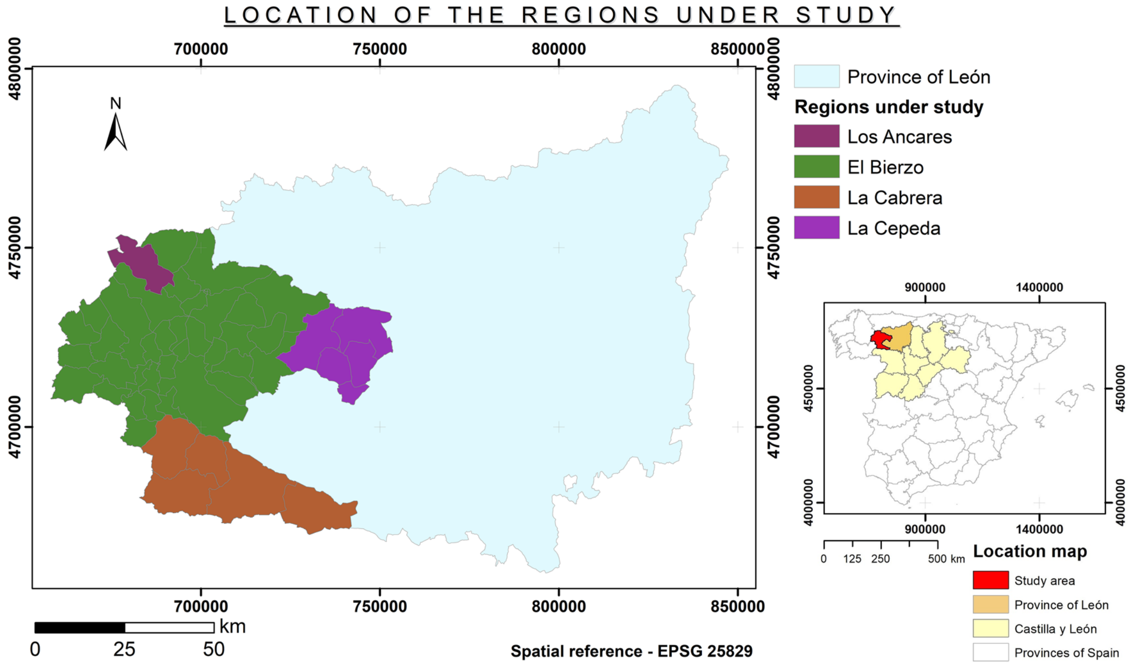

EXHIBIT 1 | Detail of the location of regions under study. [Color figures can be viewed at wileyonlinelibrary.com.]

The spatial approach here proposed aims to constitute an alternative method for a more sustainable planning of wind turbines, with strong focus on spatial planning for conservation and mitigation of environmental impacts.

2 | Materials and Methods

2.1 | Study Area

The selected area corresponded to the regions of Los Ancares, El Bierzo, La Cabrera, and La Cepeda (**Exhibit 1**), framed in the Spanish northwest and bordering the Cantabrian Mountains, internally to the province of León. All regions contain areas that belong to the National Natural Spaces Network (REN) or Natura 2000 Network except La Cepeda (JCYL 2023b). The studied area has more than 30 HIC (Habitats of Community Interest) of the Habitats Directive 92/43/EEC (MITERD 2023a). In Los Ancares, El Bierzo, and La Cabrera, wind gusts come predominantly from the west. There are 0.4% of calm days with a daily gust speed between 5 and 20 m/s (average 7.8 m/s) and an average daily speed of 1.8 m/s, according to numerical data from the Ponferrada station (El Bierzo) at 10 m above the ground, all of this in a similar way throughout the year. In La Cepeda, in addition to the westerly component, the northerly component also stands out.

2.2 | Cartographic Layers for GIS Analysis

Different aptitude and impact variables (defined as layers) were integrated in order to obtain the carrying capacity for each location in the map. The layers consisted, on the one hand, in base information to make the cartographic work possible and, on the other, in complementary information about wind power potential, position of projected wind turbines and wind zonings proposed by public Administrations (MITERD 2020; Castilla y León 2022). In detail, the set of layers consisted of:

1. Base layers, as (a) orthophotographs of the study area, (b) municipal and regional boundaries of the study area, and (c) the contour of the total study area.
2. Aptitude variables, mainly classified based on their relationship with (a) wind, (b) natural spaces and biodiversity, and (c) current land uses, historical-cultural enclaves and infrastructures. The 34 chosen aptitude variables are presented in **Exhibit 2**, indicating, for each one, the condition to be fulfilled to obtain the maximum, minimum, and excluding aptitude values. The variables were selected according to all possible aspects available in literature (see references in Appendices I, II, and VII) that applied to the study area. In relation to the ranges, they were adapted to the conditions of the area, to the sensitivity and importance associated with each variable, and to the degree of generalization in the spatial delimitation of the public available layers related to each variable. The aforementioned Appendices include extended information about particular reasons and references for any given condition and range.
3. Impact variables, referring to ecosystemically sensitive areas or existing infrastructures that determine the profitability of a power plant projection. The 21 chosen impact variables are presented in **Exhibit 3**, indicating for each one whether its impact value was negative or positive. The variables were selected as well with a literature review. See Appendix II for extended information, including the reason and references for the given impact type.
4. Complementary layers, including (a) a map of estimated power output at a hub height of 100 m, (b) the distribution of installed wind turbines and projected wind turbines, (c) MITERD (national Administration) Environmental Zoning

EXHIBIT 2 | Aptitude variables (n = 34) with the maximum, minimum, and exclusion threshold values. Variables are classified according to their relationship with: (a) wind (no. 1–5), (b) natural spaces and biodiversity (no. 6–18), and (c) current land uses, historical-cultural sites, and infrastructures (no. 19–34).

No.	Aptitude variable/layer	Condition for maximum aptitude value	Condition for minimum aptitude value	Condition for exclusion threshold
1	Distance to already installed wind turbines	>1200 m	200 m	Presence and buffer ≤200 m
2	Fraction of tree canopy cover in forest environments	<20%	80%	≥80%
3	Altitude	<1500 m	2000 m	≥2000 m
4	Slope	<3° (5%)	20° (36%)	≥20° (36%)
5	Average annual wind speed at hub height (100 m)	>7 m/s	3 m/s	≤3 m/s
6	Distance to singular trees	>300 m	50 m	Presence and buffer ≤50 m
7	Distance from critical conservation areas of the Cantabrian Capercaillie Recovery Plan	>100 m	0 m	Presence
8	Distance to Important Bird and Biodiversity Conservation Areas of Spain	>100 m	0 m	Presence
9	Distance to the Cantabrian Ecological Corridor	>1000 m	500 m	Presence and buffer ≤500 m
10	Presence of endangered and/or protected flora of Castilla y León	—	—	Presence on UTM grid
11	Distance to natural and artificial water bodies	>600 m	200 m	Presence and buffer ≤200 m
12	Distance to the National Network of Protected Natural Spaces	> 5000 m	1000 m	Presence and buffer ≤1000 m
13	Distance to the river network and the public water domain	>600 m	120 m	Presence and buffer ≤120 m
14	Distance to biosphere reserves	>5000 m	1000 m	Presence and buffer ≤1000 m
15	Distance to areas of high sensitivity in Cantabrian Capercaillie and Cantabrian brown bear recovery plans in Castilla y León regarding wind energy complexes	>100 m	0 m	Presence
16	Distance to SAC/SCI -Natura 2000 Network-	>5000 m	1000 m	Presence and buffer ≤ 1000 m
17	Distance to SPA -Natura 2000 Network-	>5000 m	1000 m	Presence and buffer ≤ 1000 m
18	Distance to Scheduled Wetland Areas	>600 m	400 m	Presence and buffer ≤ 400 m
19	Distance to arable areas in irrigated areas	>150 m	0 m	Presence
20	Distance to the road network	200–10,000 m	>10,000 m	Presence and buffer ≤200 m
21	Distance to archaeological sites	>600 m	200 m	Presence and buffer ≤200 m
22	Distance to cultural heritage sites	>600 m	150 m	Presence and buffer ≤150 m
23	Distance to UNESCO World Heritage Sites	>600 m	0 m	Presence
24	Distance to the pilgrims' routes to Santiago	>500 m	150 m	Presencia y buffer de ≤150 m
25	Distance to the center of medium-sized cities	> 5000 m	2500 m	Presence and buffer ≤2500 m
26	Presence of areas restricted by current regional and national legislation in relation to wind farms	—	—	Presence

(Continues)

EXHIBIT 2 | (Continued)

No.	Aptitude variable/layer	Condition for maximum aptitude value	Condition for minimum aptitude value	Condition for exclusion threshold
27	Distance to faults and tectonic contacts	>500 m	20 m	Presence and buffer ≤20 m
28	Distance to sites of geological interest	>100 m	0 m	Presence
29	Distance to railway lines	>500 m	200 m	Presence and buffer ≤200 m
30	Distance to the National Network of Nature Trails	>300 m	150 m	Presence and buffer ≤150 m
31	Distance to regional nature trails	>200 m	75 m	Presence and buffer ≤75 m
32	Presence of incompatible non-urban uses (watercourse, reservoir, mining, industrial, waste infrastructure, supply infrastructure, agricultural, and/or livestock facility, greenhouse, lake or pond, artificial water body, road, or rail network)	—	—	Presence
33	Distance to areas with incompatible urban, rural, and residential uses (inner city, urban expansion, urban green zone)	>3000 m	500 m	Presence and buffer ≤500 m
34	Distance to livestock trails	>200 m	75 m	Presence and buffer ≤75 m

of large wind turbines according to their environmental sensitivity, and (d) JCYL (regional Administration) Renewable Zoning of excluding wind energy zones.

The layers were processed following a step-by-step operational workflow (**Exhibit 4**) in order to allow the replicability of every step, as indicated in several studies (Díaz-Cuevas 2018; MITERD 2020; Zahedi et al. 2022; SEO/BirdLife 2023; Yildiz 2024).

2.3 | Obtaining and Processing the Layers

The base layers (orthophotographs, municipal, and regional boundaries and the contour of the total study area) were downloaded or digitalized from JCYL (2023b) -Raster, 25 × 25 cm-, JCYL (2023b) -Vectorial, polygon-, and JCYL (2023b) -Vectorial, polygon-, respectively.

The thematic cartographic data available for each of the variables or layers (aptitude, impact, and complementary) were downloaded or digitized. Download sources for aptitude and impact variables are detailed in Appendices I and II, respectively. Complementary layers sources were Global Wind Atlas (2023) -Raster, 250×250 m-, FDJCC (2021b) -Vector, point-, MITERD (2020) -Raster, 25×25 m-, and JCYL (2023b) -Vectorial, polygon-, for the map of power output, the distribution of wind turbines, the MITERD Zoning, and the JCYL Zoning, respectively. The coordinates were transformed to the Spatial Reference System (SRE) defined by the legal framework in Spain (Spain 2007), EPSG 25829, Datum: ETRS 1989, Projection: Transverse Mercator, Zone: 29. Then, each of the layers was cropped to the studied area. For the aptitude and impact raster layers as well as for all complementary layers, it was just done on the study surface whereas for the aptitude and impact vector layers, an extra 500 m radius buffer was added to prevent loss of information due to "edge effect." Four classes or intervals of carrying capacity (three positive or non-excluding and one negative or excluding) were defined for the final carrying capacity map with absolute positive classes (i.e., equidistant classes between the minimum and maximum potential values of positive carrying capacity). This criteria was used in order to simplify the understanding and symbology of a final map of carrying capacity, following Díaz-Cuevas et al. (2019).

2.4 | Elaboration of the Aptitude and Impact Matrices

For the elaboration of the aptitude matrix, the considered variables were ranked in order of importance. One of the multiple methodologies for ranking the degree of influence of those aptitude variables with not only excluding values was used (MITERD 2020). It consisted of a survey of experts consisting of 19 specialists at the national level who belong to associations and public bodies (Baban and Parry 2001; Belmonte et al. 2013), who filled a questionnaire giving a punctuation between 1 and 7 for each variable according to its lower or greater degree of influence by large wind energy plant projects. The variables with a greater mean value of influence were prioritized over the others.

Having already defined the conditions for the minimum and maximum aptitude values for each aptitude variable (Exhibit 2), the aptitude matrix (see Appendix III) was elaborated according to the hierarchical level of the variable in a proportional manner. This was made in a similar way to the fuzzy sets used in previous studies (Hansen 2005; Aydin et al. 2010; Latinopoulos and Kechagia 2015; Zahedi et al. 2022) and described in Adedeji et al. (2020), but discretizing the range of possible values. The maximum aptitude value was considered to be the number of influential variables in the matrix with non-excluding values (in

EXHIBIT 3 | Impact variables ($n = 21$) indicating the impact type.

No.	Impact variable/layer	Impact type (by value)
1	Presence of the projected area in view of the possible declaration of the Médulas-Teleno Geopark	Negative
2	Presence of SEO/BirdLife's sensitive bird areas related to wind energy plants	Negative
3	Presence of very important plant areas	Negative
4	Presence of the total scope of the Cantabrian brown bear and Cantabrian capercaillie recovery plans	Negative
5	Presence of hunting reserves associated with the presence of the Iberian wolf	Negative
6	Presence of visual catchments (visible territories) from key points of population centers and roads with a visual range of 10 km and taking an imaginary wind turbine height of 100 m above the surface of the digital elevation model and taking into account the viewing height of 1.70 m	Negative, neutral
7	Erosive state value	Negative, neutral
8	Presence of the IUCN Grand Ecological Connector	Negative
9	Presence of current and potential expansion habitat of the Cantabrian brown bear -*Ursus arctos pyrenaicus*-	Negative
10	Presence of current habitat, connectivity, and areas of potential expansion of the Cantabrian capercaillie -*Tetrao urogallus cantabricus*-	Negative
11	Presence of habitats of community interest (Habitats Directive 92/43/EEC)	Negative
12	Probability of landslides on slopes	Negative
13	Distance to mountain passes	Negative
14	Distance to the electricity grid	Negative, neutral, positive
15	Value of sensitivity of Gliding Birds of Castilla y León to wind installations	Negative, neutral
16	Value of sensitivity of Public Utility Mounts in Castilla y León with respect to wind energy installations	Negative
17	Wind speed considered by the international standard UNE-EN IEC 61400-1:2020	Positive
18	Presence of High Fire Hazard Zones	Negative
19	Presence of Birdlife Protection Zones against collision and electrocution on high-voltage power lines	Negative
20	Presence of important mammal areas in Spain	Negative
21	Presence of low or exceptional probability flood zones (Return Period T = 500 years)	Negative

this case 31, out of the 34 total aptitude variables), with one being the smallest positive value and zero being the neutrality value. The excluding value—that is, which refers to as impossible the use of the land for wind energy production—was represented by a value of $-\infty$ (Mentis et al. 2015). Once the order of importance of the aptitude variables was decided, neutral (i.e., zero) and positive increasing values of aptitude were given to each variable according to its hierarchical level.

The impact matrix (see Appendix IV) was constructed in an analogous way to the previous one without the hierarchical ranking. They were considered both, negative and positive impact values in addition to the value zero (neutrality), previously defined (Exhibit 3). The maximum impact value in absolute units (i.e., no sign) per variable was calculated considering the impact matrix with a level of influence comparable to that of the aptitude matrix (i.e., a maximum impact value is able to override a maximum aptitude value, following a criterion of "equivalent complementarity"). Therefore, the impact could influence at most three aptitude interval changes, assuming that one class change corresponds to a sum or subtraction of the maximum value of aptitude divided by the number of the carrying classes (four in total, the three non-excluding and the excluding one).

In the impact matrix, some variables related to the impact on biodiversity which referred to a space of potential presence of threatened species were considered, but were available in a low detailed spatial resolution of UTM 10×10 or 5×5 km grid squares (variables of Very Important Plant Areas and Areas of presence and potential expansion of the Cantabrian capercaillie and the Cantabrian brown bear). In the absence of precise data of any conservation plan or inventory with the identification, presence, and location of the species, the full UTM 10×10 or 5×5 km grid squares were considered as areas with maximum negative impact value in the impact matrix ("very high" category), according to the environmental precautionary principle (Sliz-Szkliniarz and Vogt 2011; Hansson 2020). However, variables with areas of potential presence in UTM 1×1 km grid squares were taken into account in the aptitude matrix with an excluding value for the full surface of presence, as they represent significantly more precise areas.

2.5 | GIS Operations to Obtain Carrying Capacity

Each of the aptitude and impact thematic layers were cartographically processed to match the values designated in the corresponding matrix for each variable. The multi-layer calculation work required the totality of the layers in matrix or raster format, so the aptitude and impact layers in vector format were converted to raster. A cell resolution of 50×50 m was defined, as this was the highest level of spatial resolution according to the limiting detail of all available raster layers. The symbology of each of the layers corresponding to each aptitude and impact variable was reclassified, and pixels took the aptitude and impact values assigned in each matrix for the variable.

All aptitude value layers were integrated into one by algebraic sum or linear combination operation without standardization (MITERD 2020). With this it was obtained a map of aptitude values. All impact value layers were also integrated, resulting in an impact value map. Finally, the aptitude and impact value maps were integrated, resulting in a map of carrying capacity values.

The symbology of the map was adapted to obtain a final carrying capacity map differentiated in four intervals or classes of absolute carrying capacity (High, Medium, Low, and Excluding). Absolute map was differentiated by equidistant classes between the minimum and maximum potential values of positive carrying capacity. To delimit the first three intervals, the maximum theoretical positive value for each cell of the map was divided in three equal parts, indicating High, Medium, and Low capacity. The negative interval (Excluding capacity) corresponded to all values smaller than zero.

Additionally, a final carrying capacity map was differentiated by relative classes following Jenks' method of natural cuts (Jenks 1967). For this, it was considered the maximum and minimum carrying capacity pixel values obtained and they were discretized three positive relative classes (Maximum, Intermediate, and Minimum) by minimizing the intra-class variance and maximizing the inter-class variance. A fourth negative capacity interval (Excluding capacity) corresponded to all values smaller than zero. The differences between the absolute and the relative approaches can be seen in **Exhibit 5**.

2.6 | Validation of the Carrying Capacity Map Given by Absolute Intervals

To validate the correctness of the cabinet results, some reference points in the field were tested. The required number of validation points was determined using binomial probability theory, Equation (1), which relates the expected accuracy of the validation sampling points, the allowable error, and the target confidence level.

$$N = \frac{Z^2 \cdot p \cdot q}{E^2} \tag{1}$$

where: N = minimum number of validation points required per class; p = expected accuracy of the validation sampling points for a class (%); $q = 100 - p$ (%); E = permissible error in classifying a class (%); $Z \approx 2$ (for a standard deviation of 1.96 with a two-sided 95% confidence interval for significance).

The spatial distribution of the validation points (representatives of the 50×50 m pixel area of the carrying capacity map) was carried out using simple random sampling throughout the territory. The authors conducted a field visit to each of these sites, and their absolute carrying capacity interval was determined under their technical criteria based on considered aptitude and impact variables.

A confusion matrix was then developed. The overall accuracy with 95% confidence intervals was obtained using the Adjusted Wald method.

2.7 | Complementary Analysis

The carrying capacity by absolute intervals of the territory was spatially described with the proportion of the area occupied by

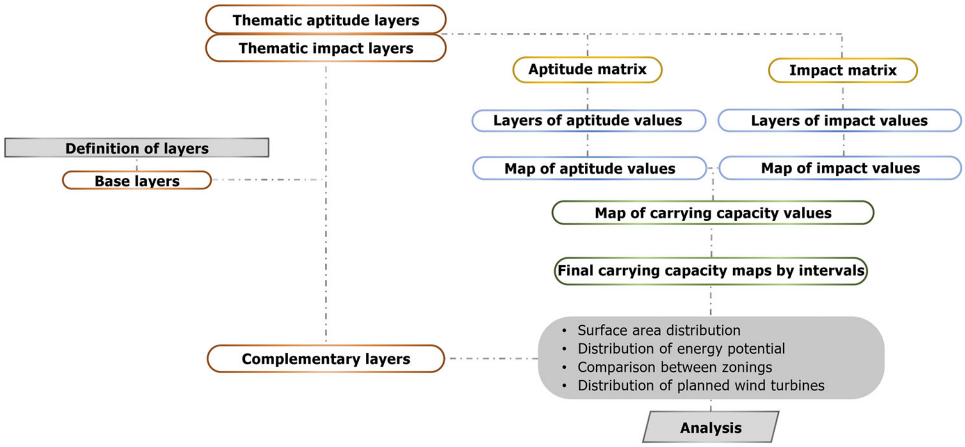

EXHIBIT 4 | Operational flow chart. [Color figures can be viewed at wileyonlinelibrary.com.]

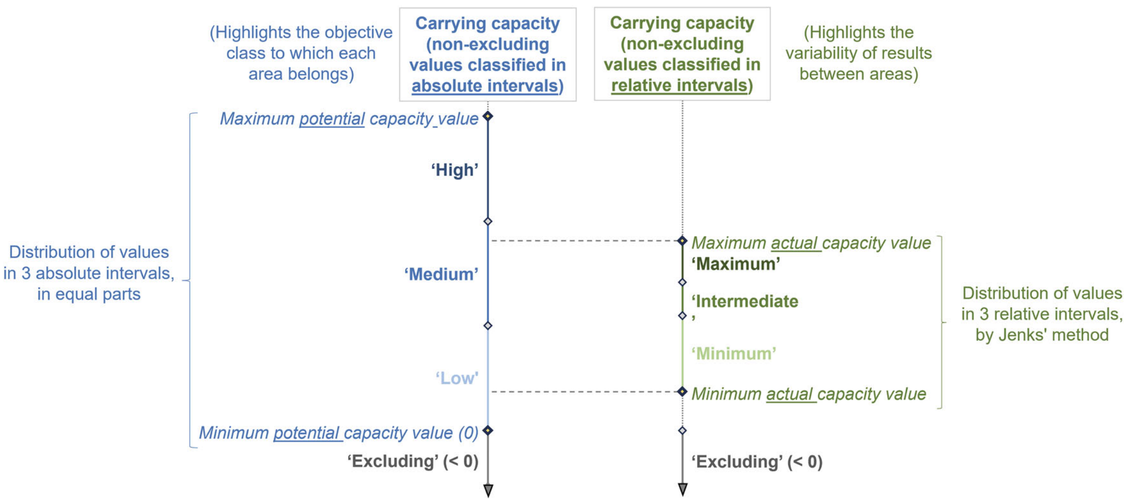

EXHIBIT 5 | Graphical differentiation of the determination of absolute and relative carrying capacity intervals. [Color figures can be viewed at wileyonlinelibrary.com.]

each interval in each region (Los Ancares, El Bierzo, La Cabrera, and La Cepeda) with respect to the total studied area. For the area of each region, the index (%) of positive or non-excluding carrying capacity area was also calculated as the portion of surface of the region with positive capacity.

Likewise, a map of the distribution of the potential value according to the carrying capacity value was obtained, crossing the results of the carrying capacity in relative classes (Maximum, Intermediate, Minimum, and Excluding) with the available data on estimated wind energy potential at a hub height of 100 m. Potential was grouped into three classes, considering it Insufficient (<200 W/m^2), Sufficient (200–400 W/m^2), or Optimal (>400 W/m^2), adapting criteria in Aymamí et al. (2011), Asadi et al. (2023), and Sari and Yalcin (2024).

A comparative mapping between the zonings of (a) this study, (b) the MITERD -national Administration- (MITERD 2020) and (c) the JCYL -regional Administration- (Castilla y León 2022) was carried out. It was also compared the area considered as excluding territory to host large wind energy plants by the three approaches.

Finally, the suitability of the layout of the projected wind turbines in the territory was studied according to their legal phase of projection. The locations of the projected wind turbines in the territory were mapped, differentiating them by the legal phase of projection (Authorised, In process, and Withdrawn due to an unfavorable Environmental Impact Statement or Denied due to a negative modification of the urban plan) and by the absolute carrying capacity class to which they belonged (High, Medium, Low, or Excluding). An interactive violin chart was created, focused on the non-excluding resulting carrying capacity values of each projected wind turbine, according to the legal phase of projection. Finally, the number of wind turbines located in areas assessed as Excluding was studied, per phase of projection and projected plant.

3 | Results

3.1 | Aptitude and Impact Matrices

The resulting aptitude matrix (see Appendix III) was composed of the positive, neutral, and negative excluding values given to a

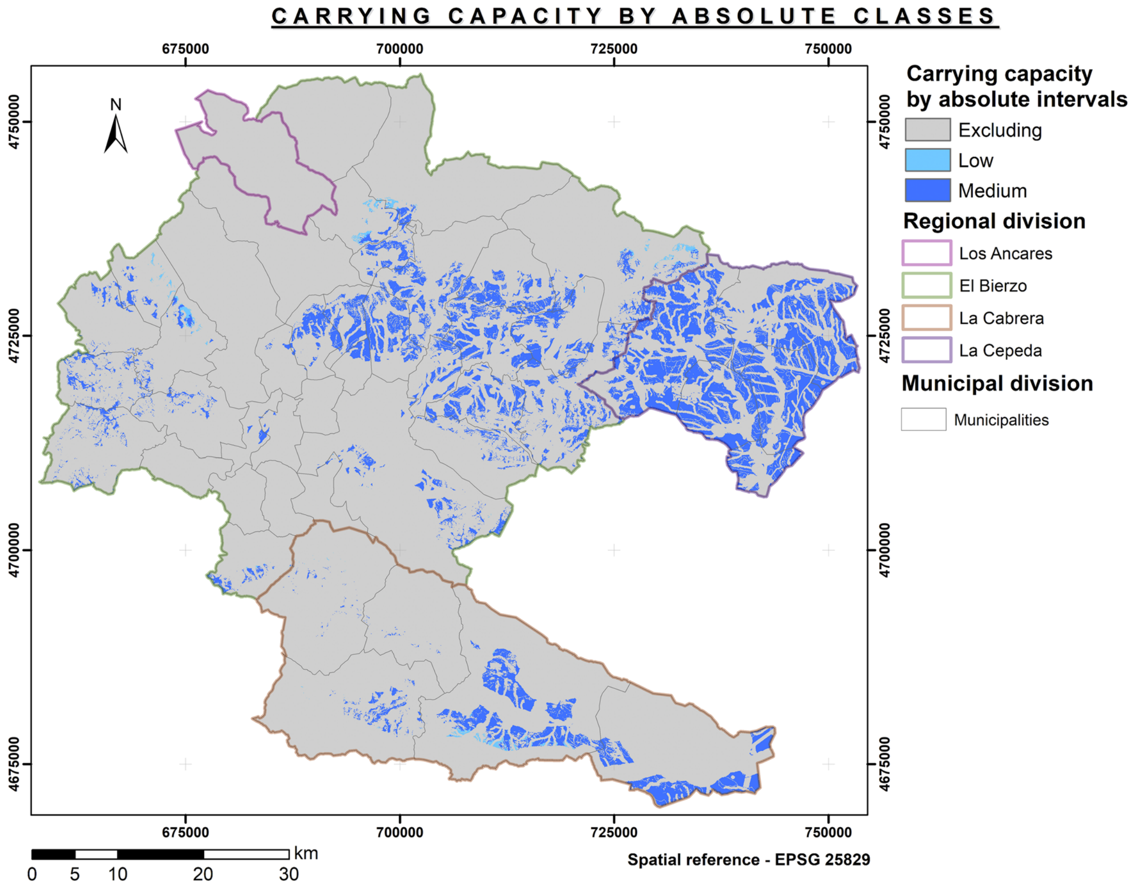

EXHIBIT 6 | Map of carrying capacity given by absolute intervals. The map categorizes the space in intervals that are equidistant between the minimum and maximum potential values of positive carrying capacity (0 and 874). It gives objective information on the level of capacity of a location to host large wind power projects considering just the resulting value of capacity and comparing it with the maximum value that is possible to achieve. [Color figures can be viewed at wileyonlinelibrary.com.]

total of 34 aptitude variables with spatial meaning in the studied area (Exhibit 2 and detailed information in Appendix I). Aptitude variables values had a close relation to explanatory conditions of the functioning of reality in the most concerning aspects (wind behavior and availability, natural spaces and biodiversity and current land uses, historical-cultural enclaves and infrastructures). For each variable, a range of values between the maximum and minimum aptitude value was given depending on the relation of the variable with a theoretical land use based on large wind power plants. Intermediate values between the maximum and the minimum were discretized depending on the hierarchical level of the variable, following the criteria of 19 specialists. For example, the variable in the highest hierarchical level, "Distance to the National Network of Protected Natural Spaces," presented a maximum aptitude value of +31 units when a condition of more than 5000 m of distance was fulfilled and a minimum value of $-\infty$ units when a condition of less than 1000 m of distance was presented for a singular location represented by a pixel of 50 × 50 m. Intermediate conditions, distributed in discrete intervals of distance, presented values between +30 and 0 units of aptitude. These values were given to this variable in order to guarantee ecosystem protection.

The resulting impact matrix (see Appendix IV) was composed of the positive, neutral and negative non-excluding values given to a total of 21 impact variables with spatial meaning in the studied area (Exhibit 3 and detailed information in Appendix II). Impact variables values followed a criteria of equivalent complementarity with respect to the aptitude variables. For each variable, the impact values were given depending on the relation of the variable with a theoretical land use based on large wind power plants. For example, the variable "Distance to the electricity grid," presented a negative, neutral, or positive impact value attending to an increase of the profitability of a new wind plant installation project but also to the optimum electricity transmission distance.

3.2 | Final Carrying Capacity Maps Given by Absolute and Relative Intervals

The final carrying capacity maps were generated, showing the resulting categories by absolute (Excluding, Low, and Medium carrying capacities) and relative classes (Excluding, Minimum, Intermediate, and Maximum carrying capacities), respectively (**Exhibits 6** and 7). The absolute map was differentiated by equidistant classes between the minimum and maximum potential values of positive carrying capacity (0 and 874). It provides information on the level of capacity of a location to host large wind power projects considering just the resulting value of capacity and comparing it with the maximum value possible to achieve, allowing to form a map with, for example, no "High" category if there is not any area with a value close to the maximum

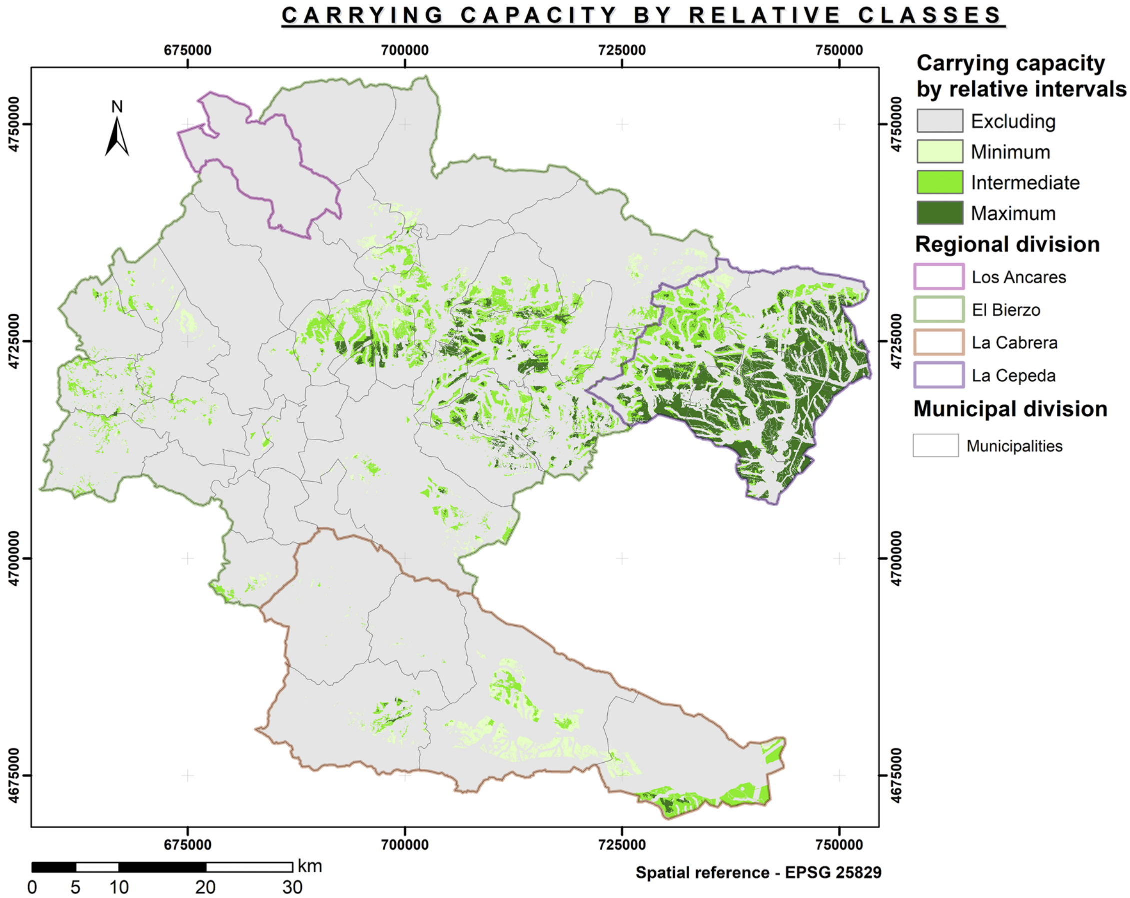

EXHIBIT 7 | Map of carrying capacity given by relative intervals. This map categorizes the space in intervals between the minimum and maximum actual obtained values of positive carrying capacity (211 and 485), minimizing the intra-class variance and maximizing the inter-class variance, allowing better differentiations of the capacity between locations. [Color figures can be viewed at wileyonlinelibrary.com.]

potential values of positive carrying capacity. However, relative map categorizes the space in the number of desired positive classes between the minimum and maximum obtained values of positive carrying capacity (211 and 485), minimizing the intra-class variance and maximizing the inter-class variance, thereby allowing better differentiation of the capacity between locations. Both maps, absolute and relative, share the spatial distribution of areas with excluding values (i.e., areas where land use for wind energy production is not feasible).

To validate the map of carrying capacity given by absolute intervals, four reference points per interval (N) were required (Equation 2).

$$N = \frac{2^2 \cdot 99 \cdot 1}{10^2} \approx 4 \qquad (2)$$

The confusion matrix (**Exhibit 8**) allowed to determine an overall accuracy with its following confidence intervals of 100.00% (78.40%–100.00%).

3.3 | Complementary Analysis Concerning Zoning

According to the distribution of the absolute classes of carrying capacity, 0.00% of the area corresponded to the High carrying capacity class, 12.18% to the Medium class, 0.28% to the Low class, and 87.54% to the Excluding class, of a total (100%) of 4293 km^2 (**Exhibit 9**). The Medium class was shared between the regions of El Bierzo (5.19%), La Cabrera (1.84%), and La Cepeda (5.15%). The Low class was shared between the regions of El Bierzo (0.19%) and La Cabrera (0.09%). The Excluding class was shared between the regions of Los Ancares (3.24%), El Bierzo (56.91%), La Cabrera (20.78%), and La Cepeda (6.62%).

The carrying capacity maps (both absolute and relative) presented an index of area with positive or non-excluding carrying capacity differentiated by region (calculated as the portion of surface of the region with positive capacity, that is [(surface with positive carrying capacity / total surface) * 100]), being 0.00% for Los Ancares, 8.64% for El Bierzo, 8.51% for La Cabrera, and 43.85% for La Cepeda.

The total studied area (in km^2 and %) according to its wind energy potential (at a hub height of 100 m) crossed with its classification by relative carrying capacity intervals (Maximum, Intermediate, Minimum, and Excluding) is shown in **Exhibit 10**. Energy potential was defined as Insufficient (< 200 W/m^2), Sufficient (200–400 W/m^2), or Optimal (>400 W/m^2). A territory of 557 km^2 (12.97% of a total surface of 4239 km^2) presented Optimal potential. Most of this territory was defined with Excluding capacity. Moreover, only 4 km^2 (0.09% of the total surface)

EXHIBIT 8 | Confusion matrix for the validation of the map of carrying capacity given by absolute intervals: Cabinet results (c) versus ground-truth reference data (r) for each interval.

	Excluding (r)	Low (r)	Medium (r)	High (r)	Total
Excluding (c)	**4**	0	0	0	4
Low (c)	0	**4**	0	0	4
Medium (c)	0	0	**4**	0	4
High (c)	0	0	0	**0**	0
Total	4	4	4	0	**12**

EXHIBIT 9 | Breakdown of land area (in km^2 and % with respect to a total area of 4293 km^2) by region according to its classification by absolute carrying capacity intervals. Absolute intervals differentiate three positive equidistant classes between the minimum and maximum potential values of positive carrying capacity (High, Medium, and Low). The Excluding class, which means areas totally incompatible to host the installation of a wind power plant is defined by negative values.

		Territory				
		Los Ancares	**El Bierzo**	**La Cabrera**	**La Cepeda**	**Total**
Absolute interval of carrying capacity	High	0 km^2 (0.00%)	0 km^2 (0.00%)	0 km^2 (0.00%)	0 km^2 (0.00%)	0 km^2 (0.00%)
	Medium	0 km^2 (0.00%)	223 km^2 (5.19%)	79 km^2 (1.84%)	221 km^2 (5.15%)	523 km^2 (12.18%)
	Low	0 km^2 (0.00%)	8 km^2 (0.19%)	4 km^2 (0.09%)	0 km^2 (0.00%)	12 km^2 (0.28%)
	Excluding	139 km^2 (3.24%)	2443 km^2 (56.91%)	892 km^2 (20.78%)	284 km^2 (6.62%)	3758 km^2 (87.54%)
	Total	139 km^2 (3.24%)	2675 km^2 (62.31%)	975 km^2 (22.71%)	504 km^2 (11.74%)	4293 km^2 (100%)

EXHIBIT 10 | Breakdown of land area (in km^2 and %) by energy potential (estimated at a hub height of 100 m) according to its classification by relative carrying capacity intervals. Energy potential is defined as Insufficient (≤200 W/m^2), Sufficient (200–400 W/m^2) or Optimal (<400 W/m^2). Relative intervals differentiate, by Jenks' method, three positive classes between the minimum and maximum real values of positive carrying capacity (Maximum, Intermediate, and Minimum) in addition to the class of negative capacity named as Excluding (meaning areas totally incompatible to host the installation of a wind power plant).

		Wind energy potential at a hub height of 100 m			
		≤200 W/m^2 (Insufficient)	**200–400 W/m^2 (Sufficient)**	**>400 W/m^2 (Optimal)**	**Total**
Relative interval of carrying capacity	Maximum	32 km^2 (0.75%)	156 km^2 (3.63%)	4 km^2 (0.09%)	192 km^2 (4.47%)
	Intermediate	109 km^2 (2.54%)	118 km^2 (2.75%)	15 km^2 (0.35%)	242 km^2 (5.64%)
	Minimum	42 km^2 (0.98%)	50 km^2 (1.16%)	9 km^2 (0.21%)	101 km^2 (2.35%)
	Excluding	1994 km^2 (46.45%)	1235 km^2 (28.77%)	529 km^2 (12.32%)	3758 km^2 (87.54%)
	Total	2177 km^2 (50.71%)	1559 km^2 (36.31%)	557 km^2 (12.97%)	4293 km^2 (100%)

presented Optimal potential with Maximum relative carrying capacity.

The area considered to be excluded from hosting large wind energy installations was different between the different available zonings. Comparing the excluding areas between the MITERD (national Administration) zoning, the JCYL (regional Administration) zoning, and the resulting zoning in this study, it was verified that this study excluded 2/3 of the part of the area that both of the Administrations did not exclude. That is to say, of a total area of 4293 km^2, MITERD, JCYL and this study, consider as excluding locations, respectively, 2479, 2530, and 3758 km^2. See Appendix V to notice the cartographic representation.

3.4 | Complementary Analysis Concerning the Assessment of Projected Wind Turbine Sites

The locations of the projected wind turbines in the territory are presented, showing a differentiated symbology according to (1) the legal phase of projection (authorized, in process, and withdrawn due to an unfavorable Environmental Impact Statement or denied due to a negative modification of the urban plan) and (2) the absolute carrying capacity class to which they belong. When looking at wind turbines projected in adequate locations, 29 of them are currently in authorized phase, 32 are in process of authorization, and 75 belong to wind power plants already withdrawn or denied. When looking at wind

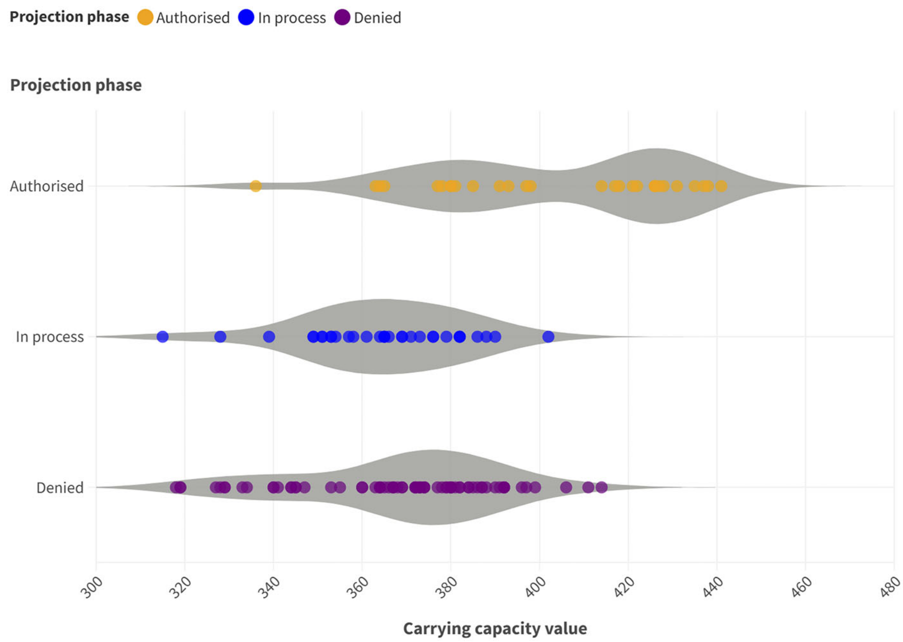

EXHIBIT 11 | Violin chart on the non-excluding real carrying capacity values (from 211 to 485) of the projected wind turbines, according to the legal phase of projection. Interactive graph broken down by wind turbine available at: https://public.flourish.studio/visualisation/17301678/. [Color figures can be viewed at wileyonlinelibrary.com.]

turbines projected in inadequate locations, the majority of the turbines that were designed to be located in Excluding areas, a total of 135, are actually withdrawn or denied. However, 12 wind turbines are currently in authorized phase but located in Excluding areas. Similarly, another 43 which are in process of authorization are also in areas defined as Excluding (see Appendix VI to observe the cartographic representation). The violin chart (**Exhibit 11**) graphically showed the density of projected wind turbines designed to be located at sites with one or the other positive (i.e., non-excluding) carrying capacity value, depending on the legal projection phase (authorized, in process, and withdrawn or denied). Turbines of projected wind power plants already authorized tend to be designed to locate in places with a higher positive capacity value than turbines of plants that are withdrawn or denied or that are in process of authorization yet.

4 | Discussion

4.1 | A GIS Territorial Planning Approach Focused on Environmental Conservation

In the last decade, Spain has developed strategies in favor of the installation of renewable energy plants, following the energy-environmental objectives pursued by the European Union (Díaz-Cuevas 2018; Tsiropoulos et al. 2020). However, it is still necessary to provide tools that help in the correct spatial planning of these plants, so that they minimally affect the fauna, flora, and habitat (Alfaro-Saiz et al. 2023).

A proper foresight on the specific conditions of local areas has been obviated in previous studies (e.g., Mentis et al. 2015; Cristea and Jocea 2016; MITERD 2020; Castilla y León 2022; Asadi et al. 2023; Yildiz 2024). Here, it is proposed to work with a forward-looking vision mainly focused on environmental values instead of wind energy potential, that is, assessing the land potential for agricultural uses, the expansion potential of resilient species typical of the environment, and the areas projected for declaration of future Geoparks. Certain environmental variables that are little known and not yet considered in previous researches, such as the connection between Natura 2000 Network areas, should be also considered, as in this study.

The approach taken is completely extrapolable to other enclaves with similar conflicts between consumption plus production and well-being plus environmental protection that require guiding tools for a solution based on sustainable land management, ensuring quality of life in rural areas, and the protection of natural values. The methodology is fully applicable to other regions as long as public layers are available, which in the case of some countries, including Spain, is guaranteed.

Previous articles tend to define the suitability of the territory to host wind energy plant projections based mainly on estimated wind power potential (Ramachandra and Shruthi 2005; Cristea and Jocea 2016; Yildiz 2024), meaning the producible energy in W/m^2 through the wind at a certain hub height. This study shifts the focus from an energy production and consumption vision to the conservation of rural quality life and natural values, considering that the biggest impacts on biodiversity are produced in areas with large numbers of turbines and high-power density (Morant et al. 2024). Thus, estimated wind power potential was not included as an aptitude or impact variable. However, data cross-checking is still of interest to check whether locations with great carrying capacity values also present great energy potential values. Therefore, when analyzing the estimated energy potential, it has been found that only 0.09% (4 km^2) of the entire studied area present an Optimal potential (>400 W/m^2) with Maximum relative carrying capacity. This opens the door to a new paradigm in wind plants planning, based on a balance between conservation and energy climate targets criteria and generated in advance of wind plant projection. Furthermore, it highlights the potential impact generated by all wind turbines installed in the last decades with criteria mainly focused on energy potential, such as in the Maestrazgo Wind Cluster, in Teruel (Spain). That impact could have been solved in a preventive way by spatial zoning that would have taken into account variables such as distributions of threatened biodiversity.

4.2 | Aptitude and Impact Matrices and Carrying Capacity Maps

In spatial multi-criteria approaches, there are different methods to adjudge hierarchical importances and values to aptitude and impact variables, as for example by one expert decision, by a survey to heterogeneous experts (Baban and Parry 2001), by pairwise comparison matrices with the criteria of one or more experts (Yousefi et al. 2024) or with machine learning based on previous available approaches (Bilgili et al. 2024). The method of surveying heterogeneous experts with knowledge of the local territory for the hierarchy of variables in the aptitude matrix was chosen over the other methodologies due to its practicality and following the criteria of one of the most pioneering and cited studies on the cartographic elaboration of guide maps for wind management (Baban and Parry 2001). Moreover, public participation in the development of management allows the contribution of actors with different specializations and interests (Belmonte et al. 2013).

Besides, the implementation of aptitude variables together with impact variables has been considered the best option to register a higher variability of spatial information (Gómez-Orea and Gómez-Villarino 2013; Espejel-García et al. 2015; Flórez-Gutiérrez 2021). The elaboration of the hierarchical aptitude and the impact matrices allows to translate its given value ranges into cartographic layers with spatial meaning. Such layers are integrable by simple algebraic addition, which simplifies and improves the process of multi-criteria integration of variables and avoids the use of fuzzy sets.

Previous studies generally considered only an aptitude matrix, and those that also considered an impact matrix, did not give it an equivalent importance to the aptitude matrix, resigning the impact matrix to a secondary plane and considering a maximum impact value subjectively and with no standardized way of calculation. In this study, the process of calculation of the maximum impact value per variable of the impact matrix has been presented as a novelty in spatial multi-criteria analysis. It has been assessed by following a criterion of equivalent complementarity with respect to the aptitude matrix.

The considered aptitude and impact variables in the study area highlight the presence and need of protection of at least 12 threatened or protected plant taxa sometimes present in unprotected natural spaces and without conservation plans and 9 taxa involving emblematic or threatened Iberian-Cantabrian fauna, as the Cantabrian capercaillie (*Tetrao urogallus cantabricus* Castroviejo), a bird mainly affected by human pressure.

For the first time, in mapping the zoning of renewable plants, the final carrying capacity map is not only differentiated by relative classes (e.g., Díaz-Cuevas 2018; MITERD 2020; Yildiz 2024), but also by absolute classes. Relative classes allow to differentiate the resulting positive values of carrying capacity between locations by minimizing the intra-class variance and maximizing the inter-class variance, but always refer to the bounded range of values between the minimum and the maximum achieved for the specific case in the area of study (Díaz-Cuevas 2018). On the contrary, absolute classes allow to know if a location reaches (or not) one or the other level of carrying capacity with respect to the full range between the minimum and the maximum possible positive capacity value (having considered the sum of all the variables of the aptitude and impact matrices).

> *“Accordingly, the final carrying capacity map differentiated by absolute classes shows that no area reaches the “High” carrying capacity class, so the analyzed territory may not be the most suitable for the projection of large wind farms.”*

Accordingly, the final carrying capacity map differentiated by absolute classes shows that no area reaches the “High” carrying capacity class, so the analyzed territory may not be the most suitable for the projection of large wind farms. The final carrying capacity maps prove that the classes of carrying capacity are distributed differentially across the territory, showing that the region of La Cepeda has the highest rate of area with positive carrying capacity (43.85%, compared to 0.00%, 8.64% and 8.61% in Los Ancares, El Bierzo, and La Cabrera, respectively). This is expected considering that La Cepeda is the only region that lacks any protected areas (Natural Spaces Network or Natura 2000 Network). This lack of conserved zones is somehow reflected in a lower relative environmental value compared to the rest of the regions, which exhibit higher levels of biodiversity for being intersection zones between oceanic, Mediterranean, and high mountain climates.

The results obtained in this work are of great interest for the territorial planning of wind energy production facilities in general, and points to specific pitfalls in the current planification of the studied regions. This work has been carried out with an awareness of the possible repercussions and controversy that the results may have on environmental, social, economic, and political interests. Therefore, despite the consideration of a large number of variables of interest at the local level, and with the aim of maximum objectivity and rigor, we assume that, due to the very nature of the subject, the methodology used to obtain the results will always be debatable and expandable. It is worth mentioning that GIS-based models might present some limitations. The quality of public data at source might be insufficient. In this case, it is suggested that more effort be put into collecting field data through sampling. However, as in this study, it is recommended to use quality data mainly from official sources. On the other hand, methodologies based on expert opinion may have potential biases. To reduce these biases, this study used a panel of experts from different specialities, bringing together disciplines from the natural, social, and economic environments.

There are criteria related to cumulative and/or synergistic effects (Serrano et al. 2020) not considered in this study. They are more complex to quantify or only addressable from a perspective focused on local particularities. It is the case of the balanced density of wind turbines per km^2, the existence of open and maintained forest roads, the presence of karst, the routing of the turbines, the location of other installations such as solar photovoltaic energy plants, the proximity and abundance of previously installed electricity transmission grids and even future climate change scenarios (Nogues et al. 2021).

As the impact on the territory increases when considering the synergistic effects between different renewable energy generation facilities, as well as their associated infrastructures (Serrano et al. 2020), future studies could focus on an analysis of the territory that is not limited to wind energy. It should also be considered other energy production technologies based on renewable sources in an integrated manner, such as solar energy (Spain 2022a).

4.3 | Comparison With Public Administration Zonings and Assessment of Projected Wind Turbine Sites

It can also be seen that the exclusion areas for MITERD (national Administration) and JCYL (regional Administration) follow very similar criteria, although the regional approach promised greater detail at local scales. When comparing the MITERD Sensitivity and JCYL Exclusion maps with the results in this work, most of the areas excluded by MITERD or JCYL are considered as excluding too. On the other hand, less than 1/3 of the area that MITERD (535 km^2/1814 km^2) or JCYL (535 km^2/1763 km^2) did not exclude are areas with sufficient carrying capacity to host large wind power plants following our criteria. The remaining 2/3 of the area that they did not consider as excluding, should not be considered for such purposes. There is a clear need to update the assessment methodology of the Administrations with the most recent techniques and knowledge to ensure more coherent and effective environmental management (Valera et al. 2022). Current zonings by Administration have been set using a limited number of variables. Moreover, some considered variables with apparent potential might not have much significance at present time. For example, the variable "zonal delimitation of management plans for threatened plant species," might be irrelevant in many cases, since most Spanish regions have no approved management plans for their threatened plant taxa at all. On the other hand, a good example of a misclassified area is the whole Ancares region (see differences between classifications in Appendix V).

> *"Focusing on projected plants still in the process of authorization or withdrawal, a total of 43 wind turbines in 5 projected plants are projected in areas that have been catalogued as Excluding in this study."*

Focusing on projected plants still in the process of authorization or withdrawal, a total of 43 wind turbines in 5 projected plants are projected in areas that have been catalogued as Excluding in this study. In the case of already authorized future plants, several wind turbines are projected in Excluding areas. This is the case of 9, 2, and 1 wind turbines belonging to the Trabadelo, Santa Cruz, and Veldedo plants, respectively, as the Environmental Impact Assessments elaborated in the process of authorization or withdrawal, sometimes present faults that minimize the notion of negative effects on the territory (Alfaro-Saiz et al. 2021), summing a total of 12 wrongly located wind turbines in three authorized projected plants. The environmental authorization process has proven useful in some cases, since turbines of projected wind power plants already authorized tend to have been designed to locate in places with a higher positive capacity value. However, it would be convenient to generate a standardized national manual focused on good practices when carrying out Environmental Impact Studies for renewable energy projects and setting minimum criteria such as a robust survey of endangered populations, which is not currently required.

5 | Conclusions

Large wind energy plants generate significant impacts on the environment when installed in the absence of adequate management. This work has made it possible to develop a highly interesting tool for guiding territorial planning and the development of wind energy production facilities, taking as a case study various regions of the Spanish northwest. The usefulness of the analysis of the territory through its carrying capacity through GIS tools and multi-criteria consideration (with 34 aptitude variables and 21 impact variables) has become evident to differentiate the suitability of the land to host large wind installations for energy production.

For the first time, a procedure to calculate the values of the variables in the impact matrix has been defined in order to respect a criteria of equivalent complementarity between aptitude and impact matrices. It has been also presented as a novelty the results of carrying capacity by absolute classes and not only through relative classes. The focus point has been moved as well from the power consumption vision to the conservation vision. When analyzing the estimated energy potential, it has been found that only 0.09% of the entire studied area present an Optimal potential (> 400 W/m^2) with Maximum relative carrying capacity.

This study includes the first results of land assessment for the implementation of large wind farms in the Spanish northwest, obtained by means of maps of absolute and relative carrying capacity. In this way, it will be useful as a decision support tool for the Administration and even for developers when selecting the best possible locations to project large wind energy plants according to demanding protection criteria centered on physical-natural variables. Furthermore, a comparison has been made with the zonings of public national and regional Administrations, demonstrating that these latter provide solutions that are insufficiently restrictive and limitedly useful for the local planning of wind energy plants. In fact, more than fifty wind turbines of eight projected wind energy plants are currently authorized or in process of authorization in areas with Excluding (i.e., negative) carrying capacity.

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Ethics Statement

The content has been ethically approved by the authors.

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

We confirm the presence of data in a public repository: https://github.com/rarevg00/Capacidad-de-acogida-al-oeste-de-Le-n-para-la-implantaci-n-de-e-licas/tree/main.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

APPENDIX I Aptitude variables (n = 34), indicating the layer type and the digital source. It also indicates the reason for their inclusion, their impact area, their condition to be fulfilled to obtain the maximum, minimum and exclusion threshold values, and the references supporting this data. Variables are classified according to their relationship with: (a) wind (no. 1 to 5), (b) natural spaces and biodiversity (no. 6 to 18) and (c) current land uses, historical-cultural sites and infrastructures (no. 19 to 34). APPENDIX II Impact variables (n = 21), indicating the layer type and the digital source. It also indicates the reason for their inclusion, their impact area, their impact type, and the references supporting this data. APPENDIX III Hierarchical aptitude matrix. It presents the range of conditions to be fulfilled for each variable to obtain each possible aptitude value. The range of conditions for each variable was discretized into the number of possible aptitude values, between the maximum and the minimum value. APPENDIX IV Non-hierarchical impact matrix. It presents the range of conditions to be fulfilled for each variable to obtain each possible impact value. APPENDIX V Visual comparison between zonings: A) Carrying capacity map by relative intervals from this study, B) Environmental sensitivity map (by relative intervals) from MITERD and C) Exclusion map from JCYL. APPENDIX VI Absolute carrying capacity class (Excluding and Medium) of each projected wind turbine in its different legal phases of projection (authorized, denied, and in process of authorization). APPENDIX VII References in Appendices I and II. **Supplementary Graphics:** tqem70158-supp-0002-SupMedia.png **Supplementary Graphics:** tqem70158-supp-0003-SupMedia.png