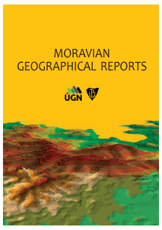

MORAVIAN GEOGRAPHICAL REPORTS

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journal homepage: **www.geonika.cz/mgr.html**

doi: **https://doi.org/10.2478/mgr-2025-0015**

Addressing wind turbines obsolescence and waste estimation: A geographical approach to decision-making

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Abstract

The imminent end-of-life of many installed wind turbines, combined with the need to meet the renewable energy targets set by the EU, presents critical challenges, such as assessing the obsolescence of installations and quantifying resulting waste. This study develops and applies a streamlined and transferable methodology to address these challenges, using the region of Andalusia (southern Spain) as a case study. The results indicate that, depending on assumed lifespans (20, 25 or 30 years), 90.87%, 25.29% or 9.97% of wind turbines in Andalusia will become obsolescence by 2030, and that nearly all installations are expected to cease operations by 2050. This article also maps turbines distribution, estimates waste generation and compares environmentally sensitive areas suitable for wind farms with those already occupied, aiming to assist in informed decision-making by stakeholders. An estimated 464,284 tonnes of waste will be generated, of which 63,742 tonnes correspond to rotor components. The proposed methodology offers a replicable approach for quantifying and managing turbine lifespan and associated waste generation, supporting informed decision-making processes and adaptability to other territorial contexts. Overall, the results underscore the urgency of incorporating obsolescence, waste generation and territorial sensitivity into energy planning to advance toward a just, and environmentally responsible transition.

Keywords: Wind energy planning, wind turbines, end-of-life, obsolescence, waste, spatial distribution

Article history: Received 1 December 2024, Accepted 16 June 2025, Published 30 September 2025

1. Introduction

Wind energy has experienced rapid growth in Europe over the past two decades, aligning with the EU's 2030 and 2050 targets (European Commission, EC, 2023a). This shift has led to a significant expansion of wind power installations, with the EU-27's installed capacity reaching 188,370.76 MW in 2020 – double the 78,989.18 MW recorded in 2010 (Eurostat, 2023). While wind farms are often considered to have a lower environmental impact compared to conventional energy sources – mainly due to reduced greenhouse gas (GHG) emissions and lower resource consumption (Sarkodie & Adams, 2018; Al-Mulali et al., 2016; Dogan & Seker, 2016) – they also generate several concerns. These include habitat fragmentation and impacts on wildlife (Balotari-Chiebáo & Byholm, 2024; Moustakas et al., 2023), land-use conflicts (Frantál et al., 2023; Díaz-Cuevas et al., 2016; Frolova et al., 2014), and acoustic and visual disturbances (Darabi et al., 2022).

A major challenge is the end-of-life management of wind farms, with options including lifetime extension, repowering, decommissioning, or abandonment (Windemer, 2019; Serri et al., 2018; Ziegler et al., 2018). Any of the options affects land use and energy transition planning, highlighting the need for strategies for land use and generated waste management. In Europe, the growing need for estimate obsolescence and waste has become increasingly critical as the EU accelerates its renewable energy transition.

The end-of-life management of wind turbines generally falls under the responsibility of the wind farm owner whether a private company, cooperative, or public entity and varies across countries (WindEurope, 2020a). While countries such as Germany, Denmark, France, Italy, and the Netherlands have established specific regulations, Spain addresses this issue solely through the Environmental Impact Assessment and general European waste legislation (Frolova et al., 2025; Márquez-Sobrino, 2024; WindEurope, 2020a). In some cases, national regulations require financial guarantees to cover decommissioning and recycling costs; for instance, Denmark mandates a minimum bank guarantee of €80 million per offshore wind farm (van der Meulen et al., 2020). Although organizations such as WindEurope advocate for a common European regulatory framework, a shared standard among Member States has yet to be implemented (WindEurope, 2020b).

In Spain, which currently has approximately 70.5 GW of installed renewable capacity (REE, 2025), The National Integrated Energy and Climate Plan (NICEP) 2023–2030 (MITECO, 2023a) outline a significant increase (160GW) from the 113 GW initally projected en NIECP 2021–2030 (MITECO, 2021). However, many of the sites with the highest wind speed are already occupied by aging turbines reaching the end of its useful life (De Simón-Martín et al., 2019), posing challenges for new installations and land-use optimization. Additionally, although general estimates of

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wind energy waste exist, more precise data about this quantity of waste, using more concrete methods and specific data on the volume of rotor waste (which includes the blades) remain unavailable, as well as spatial maps illustrating waste density from wind installations in Spain, are still lacking. Bridging this gap is crucial for informed decision-making and ensuring the sustainable development of wind energy.

Analyzing the obsolescence of the installed wind turbines in any given territory is essential for strategic decision-making. Wind energy obsolescence refers to the condition in which wind turbines reach the end of their operational lifespan, becoming inefficient, obsolete, or non-functional due to technological, economic, regulatory, environmental, or structural factors. This study focuses on obsolescence caused by infrastructure aging, although other contributing factors, such as increasing maintenance costs, changes in energy policies, or land-use conflicts, are also relevant. Assessing the volume and geographical distribution of wind energy waste, along with the territorial constraints of existing wind farms, is fundamental for planning viable alternatives for aging infrastructure.

The objective of this study is to take a first step toward addressing this gap by acquiring critical data for Andalusia, a region in southern Spain. Andalusia has experienced a steady expansion of installed wind power capacity since the 1990s. As a growing number of wind farms in the region approach the end of their operational lifespan, this study assesses total waste generation, particularly from the rotor, which includes the blades, as it is among the difficult-to-recycle components (Martini & Xydis, 2023; Jani et al., 2022).

To achieve this overarching objective, the study addresses the following research question: How many wind turbines in Andalusia are approaching the end of their operational life, what volume of waste is expected to be generated, and what are the expected territorial implications?

To respond to this question, the study proposes the following specific aims:

- Assess the level of wind energy obsolescence caused by infrastructure aging in the Andalusian region.
- Quantify and analyze the waste generated by wind turbines and rotor (including blades) in Andalusia, considering waste density and spatial distribution.
- Analyze territorial compatibility for the implementation of wind farms, considering the environmental sensitivity of the territory under study.

2. Theoretical background

2.1 Challenges at the end of the operational life of wind energy installations: Repowering, decommissioning, abandonment, or lifetime extension

Four options are possible for wind energy facilities that cease operation: Repowering, Decommissioning, Abandonment or Lifetime Extension. Although repowering is recognized as a viable strategy in some countries (Lacal-Arántegui et al., 2020; Fuchs et al., 2020), it faces significant technical, economic, regulatory, environmental, and social barriers in others, with the latter being the most prominent (Frolova et al., 2025). In Spain, interest in repowering remains limited, particularly for wind farms that have already amortized their investment (De Simón-Martín et al., 2022).

Repowering initiatives contributes to more sustainable wind energy model, but it can also lead to a reduction in effective capacity as observe in Germany (Unnewehr et al., 2021; Grau et al., 2021). This decline is primarily due to stricter land-use regulations and social acceptance issues that limit the installation of larger turbines. Additionally, repowering projects involve significant modifications such as new access routes, increased turbine heights, larger rotor diameters, and higher blade speeds, all of which have environmental and technical implications (Huso et al., 2021; Jefferson, 2018; Smallwood, 2017). Despite these challenges, repowering offers multiple benefits. It can reduce environmental impacts by optimizing land use, decreasing the number of turbines required, and improving wind resource efficiency (Szumilas-Kowalczyk et al., 2020; De Simón-Martín et al., 2019; Serri et al., 2018).

Decommissioning presents similar challenges, particularly due to the large volume of waste generated by end-of-life wind installations. Reliable data on the magnitude of this issue is essential for informed decision-making, yet studies remain scarce, and the sector still lacks the capacity to anticipate and effectively manage wind energy obsolescence. The calculation of potential installed capacity loss and the spatial distribution of these impacts remains underexplored, and it may constitute an additional issue.

Conversely, abandonment, while the least desirable option, often results from legal, technical, economic, or environmental constraints (Frolova et al., 2025; Ragheb, 2020; Conaway, 2017; Ortegon et al., 2013). In such cases, addressing the loss of installed power, waste management, and land reversibility becomes crucial. However, the return of land to its initial conditions is nearly impossible, influenced by the type of concession contract and the site's environmental, territorial, and social sensitivities (Windemer & Cowell, 2021; Windemer, 2019). In Spain, the case of Montaña Mina wind farm in the Canary Islands illustrates the consequences of abandonment. Operational since 1992, the wind farm was shut down in 2014 following the bankruptcy of its managing company and has remained inactive since 2017. The turbines are now damaged and obsolete, with no decommissioning efforts undertaken due to high costs and lack of accountability from local authorities (Gobiernocanarias, 2024; Lancelotdigital, 2023).

Another alternative to repowering is extending the lifespan of existing wind turbines. The standard operational lifespan of a wind turbine is typically 20 to 25 years, as defined by the UNE-EN IEC 61400-1 Standard (International Electrotechnical Commission, 2005). However, technological advancements have enabled newer models to operate for up to 30 years (Delaney et al., 2023). While life extension may delay waste generation, it comes at the cost of reduced energy efficiency and increased maintenance requirements (Liu & Barlow, 2017).

2.2 Wind turbines waste and obsolescence: Policy gaps and sustainability challenges

The decommissioning of wind turbines in Europe is expected to generate large volumes of waste, with estimates ranging from 50 kt in 2022 (Liu & Barlow, 2017) to 100 kt by 2050 (Albers et al., 2009; Lichtenegger et al., 2020), highlighting the use of fiberglass-reinforced plastics in turbine blades, which are particularly difficult to recycle (Liu & Barlow, 2017). Addressing this challenge requires not only quantifying the waste but also analyzing its spatial distribution using tools such as density maps. Wind turbine obsolescence also entails territorial impacts related to land use, infrastructure planning, and local dynamics (WindEurope, 2020a), particularly in areas with a high concentration of aging turbines (Andersen et al., 2016). Although between 85% and 90% of wind turbine components are recyclable (WindEurope, 2020a), blades remain the main challenge, as current recycling technologies are underdeveloped, lack standardization, and are often underutilized (Jani et al., 2022; Jiménez et al., 2022; Cooperman et al., 2021).

In Spain, it is estimated that approximately 10 kt of wind turbine waste will be generated annually by 2030, highlighting the urgency of the issue (IIDMA, 2023). Aging infrastructure further exacerbates the situation: 86% of wind turbines are at least 10 years old (De Simón-Martín et al., 2019), 12% were over 20 years old in 2022, and this figure is projected to rise to 36% by 2025 (MITECO, 2022). Additionally, by 2025, 8% of the installed wind power capacity will exceed 25 years, anticipating a wave of decommissioning or repowering. Currently, blades are generally disposed of in landfills (Eldiario,2020), although this practice is already banned in countries such as Germany (WindEurope, 2020a).

The regulations governing waste management in the EU and Spain establish the obligation to comply with polluter-pays principle and extended producer responsibility, but there is no clear evidence that these principles are being translated into concrete measures for the management of wind farms at the end of their lifespan in Spain. In theory, wind farm owners and/or manufacturers should bear the costs and logistics of decommissioning and recycling. However, Spain's implementation of this directive lacks sector-specific legislation, and each wind farm must address waste disposal within its initial Environmental Impact Assessment (EIA), approved at the time of project authorization. Regional governments are responsible for projects under 50 MW and the national government oversees larger-scale installations. In both cases, the lack of standardized financial guarantees, sector-specific policies, and effective enforcement mechanisms has resulted in significant governance gaps.

Regarding blade waste management, Spain has well-established regulation for hazardous waste, yet no specific policies address the composite materials that form wind turbine blades, which consist of a mixture of resins and carbon or glass fiber (Revilla-Cuesta et al., 2023). In contrast, other EU-27 countries have made greater strides in regulating the disposal and recycling of wind energy infrastructure (Frolova et al., 2025). A major oversight in current regulations is the lack of enforcement mechanisms for the end-of-life phase of wind farms. This hinders effective decommissioning practices, increasing the risk of environmental mismanagement and economic burdens for public administrations (Márquez-Sobrino, 2024). These gaps could shift the operational and financial burden of decommissioning and waste management onto national or regional authorities, particularly when companies dissolve or transfer aging assets. However, it should not be forgotten that there is the legal precept of the ultimate responsibility of the producer to whom the final management of the waste generated could be inferred if the companies awarded the contract do not take care of it.

Improving waste estimation and obsolescence mapping enables the identification of high-risk regions and the implementation of targeted management strategies. This supports policy frameworks based on circular economy principles and ensures that wind energy expansion becomes more environmentally sustainable in the long term. The study proposes practical measures to address wind turbine obsolescence and enhance the resilience of the wind energy sector.

3. Data and methods

3.1 Study area: Spatial distribution, governance and challenges of wind energy in Andalusia

With approximately 87,600 km^2 of territory and a population of 8.5 million inhabitants, Andalusia has been committed to renewable energy development for decades. This commitment has led to an 8.7% increase in energy self-sufficiency between 2011 and 2021, with renewables accounting for 98.9% of domestic electricity production in 2021, representing 23.3% of final energy consumption that same year (Andalusian Energy Agency, AAE, 2022). In 2022, the region had 3,535.5 MW of installed wind power across 157 wind farms, many of which are approaching the end of their lifespan.

The wind farms in Andalusia are concentrated in 64 municipalities, mainly in Cádiz, Tarifa, and Jerez de la Frontera, and are predominantly located in small municipalities with fewer than 5,000 inhabitants, where energy consumption is low. Wind farms mainly concentrated in Cádiz (38.79% of total installed capacity), followed by Málaga (17.59%), Almería (13.92%), Huelva (12.45%), Granada (11.10%) and Sevilla (5.72%). Meanwhile, Córdoba has no wind power installations, and Jaén has a marginal presence (0.41%). The provinces with the highest installed capacity benefit from favourable wind conditions, especially in coastal areas and elevated terrains (Fig. 1), have the highest wind speed. Cádiz stands out as its location between the Atlantic and the Mediterranean, which ensures strong and consistent winds, making it the epicenter of wind energy in Andalusia. Additionally,

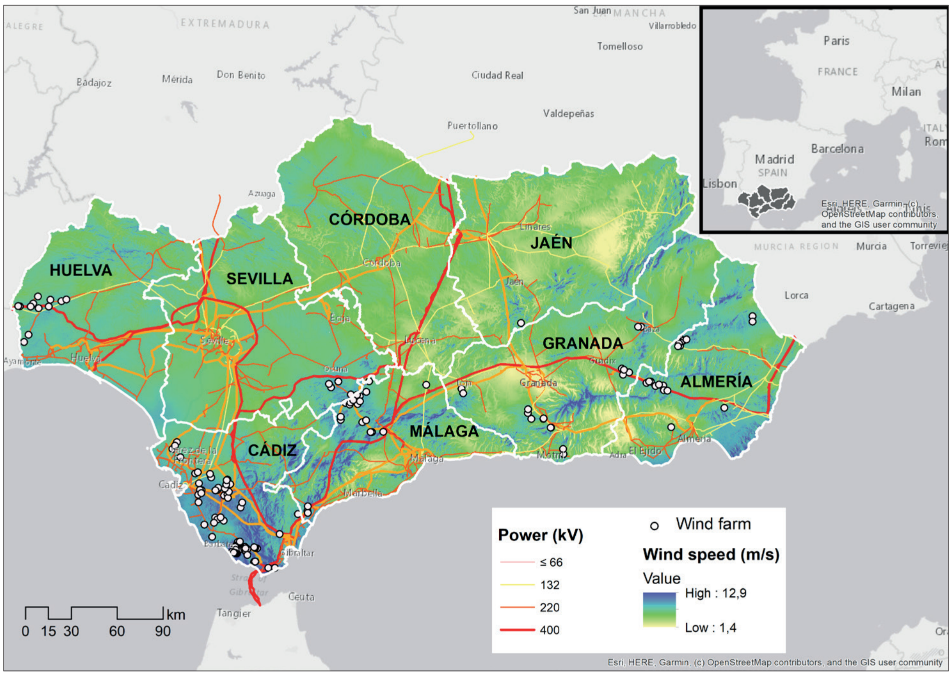

Fig. 1: Wind farms, wind speed (at 100 m height) and electricity grid in Andalusia
Source: Authors' elaboration

farmlands and mountainous landscapes have been identified as the primary hosts of wind turbines and installed capacity (Pérez-Pérez et al., 2024; Díaz-Cuevas et al., 2016).

Many wind farms have been sited in low-density rural areas with minimal local energy consumption (Pérez-Pérez et al., 2024), leading to land occupation, industrialization and/or transformation of rural landscapes (Barral et al., 2019; Poggi et al., 2018; Frolova & Pérez, 2008). Despite the theoretical promotion of distributed generation, ownership remains concentrated in the hands of large corporations. This reinforces a model in which low-consumption regions bear the territorial impacts and other negative externalities of wind energy production, while supplying energy to areas with higher demand.

The disconnection between energy production and consumption (Pérez-Pérez et al., 2024; Díaz, 2013) is one of the main issues with Spain's centralized wind energy model. Electricity generated by wind farms fed into the national grid and traded on the wholesale market, without ensuring direct benefits for local communities beyond limited fiscal compensation. Most of the economic returns remain in the hands of large corporations, many of which are headquartered outside Andalusia. This dynamic shows that, in practice, Spain's renewable energy rollout has not fostered a decentralized model but rather has reinforced a system based on large-scale projects (Nowakoski & Loomis, 2023), in which rural areas are subordinated to the energy needs of distant urban centers.

The wind energy sector in Spain is predominantly controlled by major national and international corporations. According to data from the Spanish Wind Energy Association (AEE, 2023), 57% of the installed wind power capacity in 2022 was held by just four companies: Iberdrola, Acciona Energía, Enel Green Power, and EDPR, with the first two being Spanish firms. This high degree of corporate concentration has sparked debates about territorial equity and the need for a more decentralized energy transition, one in which local communities play a more active role in energy production and in the distribution of its benefits.

This top-down approach has also diminished local communities control over key aspects such as infrastructure siting, revenue distribution, and long-term management. Several scholars describe this dynamic as a form of infrastructural colonization or colonial extractivism, with adverse impacts on rural communities, ecosystems, and territorial sovereignty (Contreras & Matarán, 2023; Normann, 2021; Batel & Devine-Wright, 2017).

In Andalusia, as in the rest of Spain, the management of wind farms at the end of their operational phase depends on the provisions established in their Environmental Impact Assessment (EIA), approved prior to the execution of each project. Unlike in other countries, these EIAs generally do not require the existence of a financial guarantee to ensure the proper management of waste generated by the facility at the end of its useful life. Hence, it becomes necessary to establish financial guarantee mechanisms to prevent the possibility that some concessionary companies may evade their responsibilities by dissolving or transferring ageing assets to weaker entities.

3.2 Methodology and sources of data

The methodology employed to achieve the stated objectives has been based on the implementation of four phases (Fig. 2):

- First phase: Based on the most recent aerial orthophotography available at the time of this study (IECA, 2022), the location of each wind turbine, originally compiled by Díaz (2013) and later updated by Díaz-Cuevas et al. (2016) and Pérez-Pérez et al. (2024), was supplemented with additional information regarding the year of installation, total mass, and rotor mass. Data on total and rotor mass was available for 93.35% of the turbines (1,902 units). This information was retrieved from TheWindPower.com and es.wind-turbine-models.com, two comprehensive databases offering detailed technical specifications and raw statistics on wind energy infrastructure. In cases where total mass values varied depending on tower height, calculations were made using the average tower height to ensure consistency.
- Second phase: Based on the installation years of wind turbines in the region and considering their useful life, which fluctuates between the 20 years (International Electrotechnical Commission, 2005), 25 years (Majewski et al., 2022; Jiménez et al., 2022) and 30 years (Delaney et al., 2023), the obsolescence level of wind power was calculated. Given the significance of the 2030 and 2050 horizons in European energy policy, these differences in operational lifetime were considered to calculate wind power obsolescence for these crucial years. This analysis facilitated the determination of the obsolescence degree for all wind farms in Andalusia and, consequently, the projected losses in installed wind power.
- Third phase: The foreseeable amount of waste from wind turbines installed in Andalusia was estimated in 2020. Based

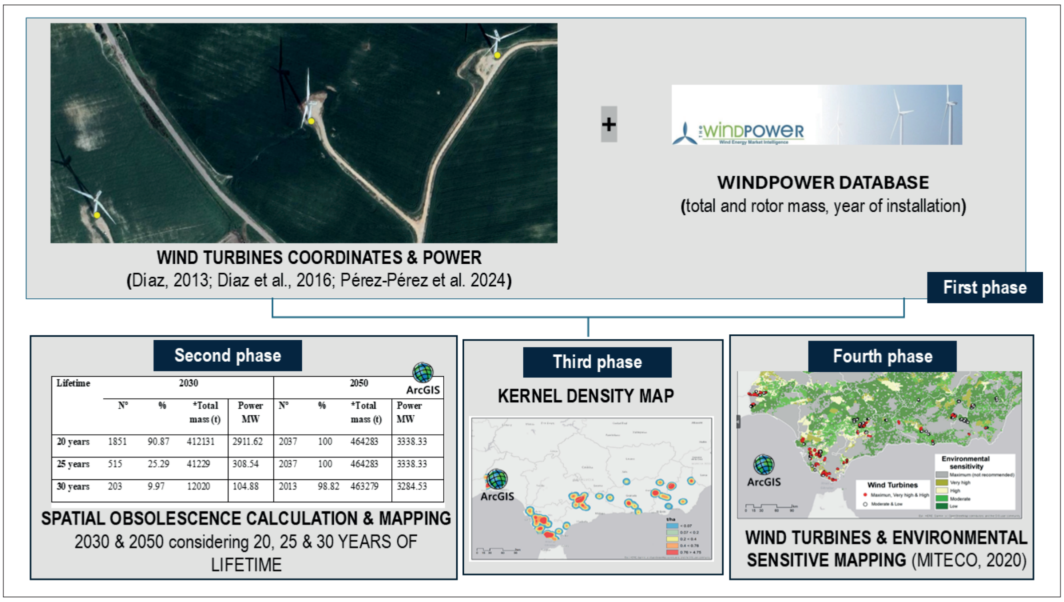

Fig. 2: Methodology scheme
Source: Authors' conceptualization

on the geolocation of the turbines and associated thematic information (total weight and rotor weight), their territorial distribution was analyzed using a Kernel density map. For this purpose, the Kernel Density function included in ESRI's ArcGIS software was employed. Conceptually, this function fits a uniform curved surface over each point, with the surface value being highest at the point location and decreasing with distance, reaching zero at the specified search radius. The function (Eq. 1) is based on the quartic kernel described by Silverman (1986), and the search radius was estimated using Silverman's rule of thumb for bandwidth selection, adapted to a two-dimensional context:

$$Density = \frac{1}{(radius)^2} \sum_{i=1}^{n} [\frac{3}{n} \cdot pob\ i \left(1 - (\frac{dist\ i}{radius})^2\right)^2]$$

where $i = 1, \ldots, n$. They are the entry points. Only include points in the sum if they are within the radius distance of the location (x,y); pob_i is the value of the population field of the point i, and $dist_i$ is the distance between the point i and the ubication (x,y).

The total mass of each wind turbine was assigned as the population field, determining its weight within the analysis. Given that the average power per turbine installed in Andalusia is 1.7 MW, and that the recommended spacing between turbines should be three times the rotor diameter – 342 meters for 2 MW turbines with a 114 meter rotor – this distance was used as the cell size for the analysis (Tegou et al., 2010; Yue et al., 2006). Subsequently, a territorial distribution analysis of wind turbine waste was conducted, measuring the estimated amount of waste per hectare and per inhabitant at the municipal level. The objective was to contextualize and identify municipalities likely to face the highest burden in terms of end-of-life waste management. For this purpose, municipal boundary data from the Andalusian Reference Database (IECA, 2023) were used.

- Fourth phase: The spatial and thematic information of wind turbines installed in Andalusia has been related to the zoning map of environmental sensitivity for wind energy in Spain, prepared by MITECO (2023b). This map characterizes the Spanish territory in five categories from highest to lowest degree of sensitivity: Maximum; Very high; High; Moderate; Low. The insights gained from this study hold potential significance in formulating comprehensive planning and management strategies for informed decision-making regarding the decommissioning of these energy infrastructures across short, medium, and long-term horizons.

4. Results

4.1 Degree of obsolescence in 2030 and 2050 scenarios

Table 1 and Figure 3 depict projections for the 2030 scenario. Considering 20-year lifespan for wind turbines and date when they were installed, most of these turbines (90.87%) will have reached the end of their operational lifespan by 2030. This would result in a substantial power loss of 2,911.62 MW, albeit with 9.13% of turbines still operational. Alternatively, if the useful life were extended to 25 years, approximately a quarter of wind farms (25.29%) would reach the end of their useful life by 2030. This would result in a power loss of 308.54 MW. Finally, contemplating an extension of the useful life to 30 years, most wind farms would remain operational by 2030, with only 9.97% ceasing operations during this period, leading to a loss of power totalling 104.88 MW. All of this would result in a loss of 2,911.62 MW, 308.54 MW or 104.88 MW respectively.

For the 2050 scenario, considering a lifespan of 20 or 25 years, all the wind turbines currently installed would have become obsolete, and 98.82% if we consider a lifespan of 30 years for the wind turbines currently installed. This would represent a significant loss of installed wind power.

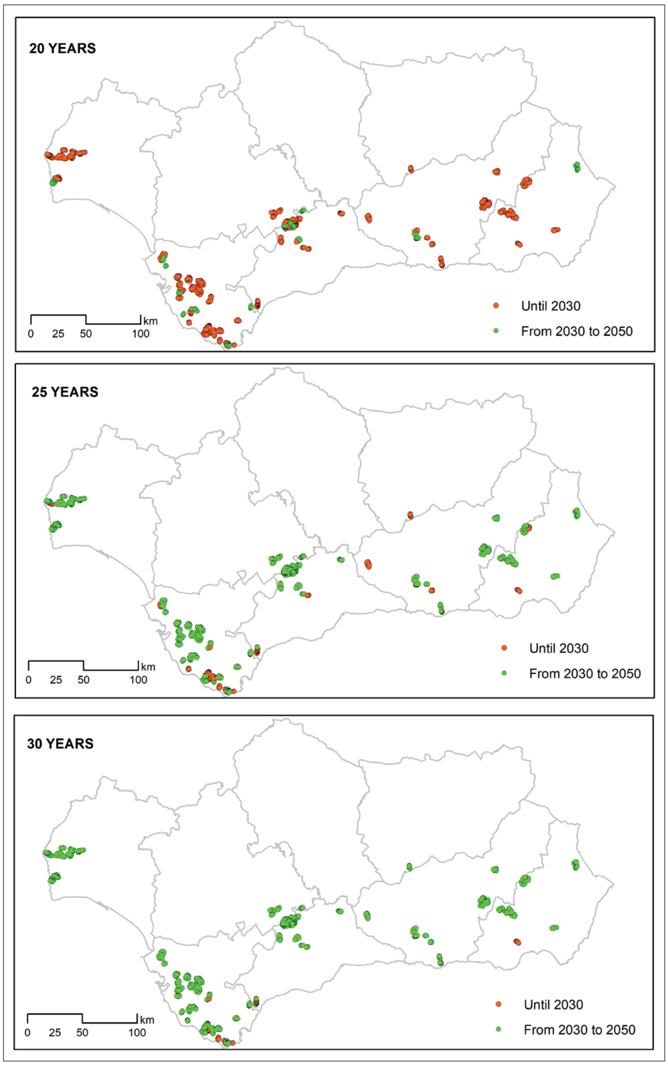

Fig. 3: Obsolescence degree of wind energy installations of Andalusia in 2030 and 2050
Source: Authors' elaboration

Lifetime	2030				2050			
	Number	%	*Total mass (t)	Power (MW)	Number	%	*Total mass (t)	Power (MW)
20 years	1,851	90.87	412,131	2,911.62	2037	100.00	464,283	3,338.33
25 years	515	25.29	41,229	308.54	2037	100.00	464,283	3,338.33
30 years	203	9.97	12,020	104.88	2013	98.82	463,279	3,284.53

Tab. 1: Obsolescence degree in wind turbines in Andalusia, over their estimated useful lives
*Notes: *Mass values obtained from a sample of 93.3% of wind turbines*
Source: Authors' calculations

Figure 3 presents the spatial distribution of wind turbines in Andalusia according to their obsolescence. Thus, considering a 20 year useful life, 1,851 of the 2,037 turbines would have reached the end of their operational lifespan in 2030, and by 2050, none of the currently installed turbines would be functional. If a 25 year lifespan is assumed, 515 turbines would be obsolete by 2030, and by 2050, none of the currently installed turbines would remain operational. Lastly, assuming the maximum operational lifespan of 30 years, only 203 turbines would be obsolete by 2030; however, this figure would rise to 2,013 by 2050.

4.2 Waste quantification and territorial distribution

Table 2 presents the number of wind turbines installed in Andalusia by model and mass, distinguishing between total mass and rotor mass, which allows for an estimation of the resulting waste. The total projected waste amounts to 464,284 tonnes, of which 63,742 t (13.73%) correspond to rotor components. Gamesa is the most widespread brand in the region, accounting for 45.9% of the installed turbines, primarily the G87/2000, G90/2000, and G52/850 models.

Some models, such as ENERCON's E70/2000 and E82/2000, exhibit a higher proportion of rotor mass relative to the total (38.46%), although they represent only 7.4% of the installed units. The DESA A300 and MADE AE-30 models also show notable rotor mass percentages, exceeding 20%. However, in 77.8% of the models deployed in the region, the rotor accounts for less than 20% of the total mass, with particularly low proportions in ACCIONA's AW-1500/77 and AW-1500/70 models, and Gamesa's G47/660.

Figure 4 illustrates the high variability in wind turbine waste density across Andalusia (ranging from 0.018 to 4.75 t/ha), with notable concentrations in Huelva, the western coast of Cádiz, and the Sierra Sur of Seville, areas characterized by high wind resource potential. The average density is 0.50 t/ha, with a standard deviation of 0.69.

According to Figure 5, wind turbines are present in 64 Andalusian municipalities, with the highest numbers found in Tarifa, Jerez de la Frontera and Serón. A clear pattern emerges: the municipalities with the highest turbine concentrations tend to have low population densities, many with fewer than 1,000 inhabitants. While some may have elevated energy consumption due to industrial or service-related activities, overall electricity demand in these areas appears to be low.

This spatial distribution reflects a centralized deployment model, led by large energy corporations, with minimal involvement from local communities. Unlike countries such as Denmark or Germany, where distributed generation promotes local ownership and community participation, Spain's wind energy expansion has prioritized rapid development over balanced territorial integration.

4.3 Territorial compatibility: Wind installations and environmental sensitivity

The spatial analysis of wind turbine distribution in Andalusia, overlaid with the environmental sensitivity zoning map for wind energy (MITECO, 2023b), reveals in Figure 6, that 20.65% (421 of the wind turbines installed in Andalusia) are in areas classified as maximum sensitivity, making them incompatible with the environmental values of these territories. Additionally, 24.82% (506 turbines) and 20.01% (408 turbines) are installed in areas of very high and high sensitivity respectively, indicating low

Model	Number of installed wind turbines	Rotor Mass (t) Wind turbine	Total Mass total (t) Wind turbine	Share of model on total number in Andalusia (%)	Total mass of waste (t)	Rotor mass waste (t)	Share of rotor mass on total mass of wind turbine (%)
GAMESA G87/2000	388	40	324.5	19.05	125,906	15,520	12.33
GAMESA G90/2000	373	50	334.5	18.31	124,769	18,650	14.95
GAMESA G52/850	174	10	98.5	8.54	17,139	1,740	10.15
VESTAS V90/2000	140	36	374.5	6.87	52,430	5,040	9.61
DESA A300	126	14.5	54.5	6.19	6,867	1,827	26.61
ENERCON E82/2000	76	55	143.0	3.73	10,868	4,180	38.46
ACCIONA AW-1500/77	71	15,2	202.7	3.49	14,392	1,079	7.50
MADE AE-59	62	15,7	135.2	3.04	8,382	973	11.61
ENERCON E70/2000	75	40	104.0	3.68	7,800	3,000	38.46
GAMESA G47/660	53	7,2	94.0	2.60	4,982	382	7.67
VESTAS V90/1800	52	38	302.5	2.55	15,730	1,976	12.56
SIEMENS SWT-2.3-93	50	60	386.0	2.45	19,300	3,000	15.54
GAMESA G80/2000	47	37	313.0	2.31	14,711	1,739	11.82
ECOTECNIA 80 1.6	40	18	207.0	1.96	8,280	720	8.00
MADE AE-30	40	8.7	38.0	1.96	1,520	348	22.89
MADE AE-56	36	15.2	134.2	1.77	4,831	547	11.32
VESTAS V90/3000	24	28	291.0	1.18	6,984	672	9.62
VESTAS V100/1800	17	45	373.0	0.83	6,341	765	12.06
NEG MICON NM82/1500	11	42	320.0	0.54	3,520	462	13.13
VESTAS V100/2000	10	45	373.0	0.49	3,730	450	12.06
ECOTECNIA 44	9	6,5	65.0	0.44	586	59	10.07
MADE AE-46	8	12	77.0	0.39	616	96	15.58
ECOTECNIA 74	6	18	207.0	0.29	1,242	108	8.70
VESTAS V80/2000	6	37	265.0	0.29	1,590	222	13.96
ACCIONA AW-1500/70	4	15.2	202.7	0.20	811	61	7.52
NEG MICON NM72C/1500	4	31.4	239.24	0.20	957	126	13.17
TOTAL	**1,902**			**93.35**	**464,284**	**63,742**	

Tab. 2: Number of wind turbines and mass of generated waste by brand
Source: Authors' calculations

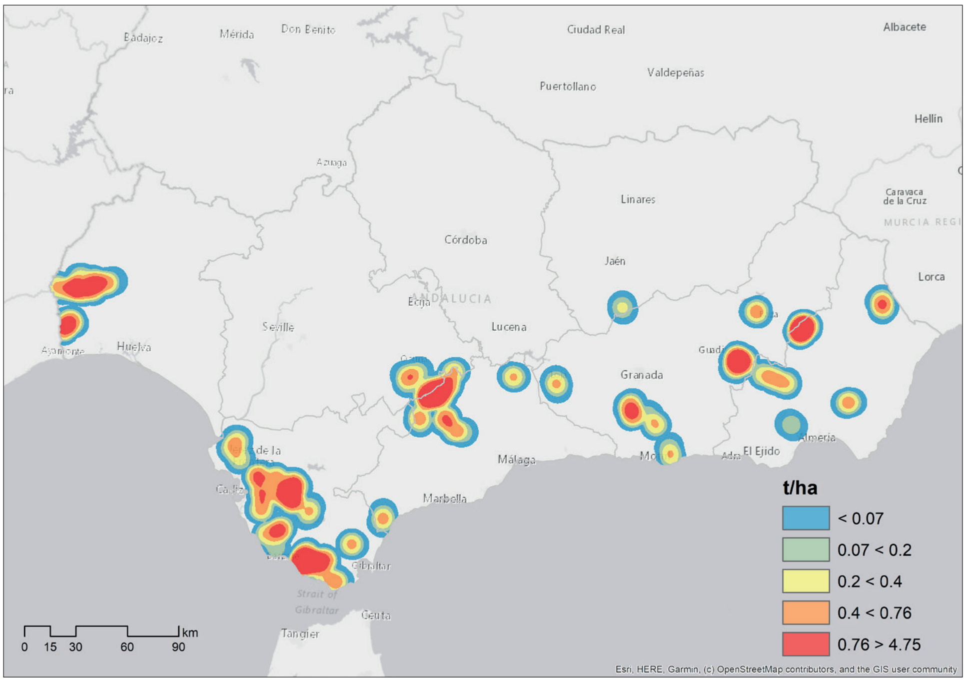

Fig. 4: Density of wind turbine waste in Andalusia, measured in tonnes per hectare (t/ha) in 2020
Source: Authors' elaboration

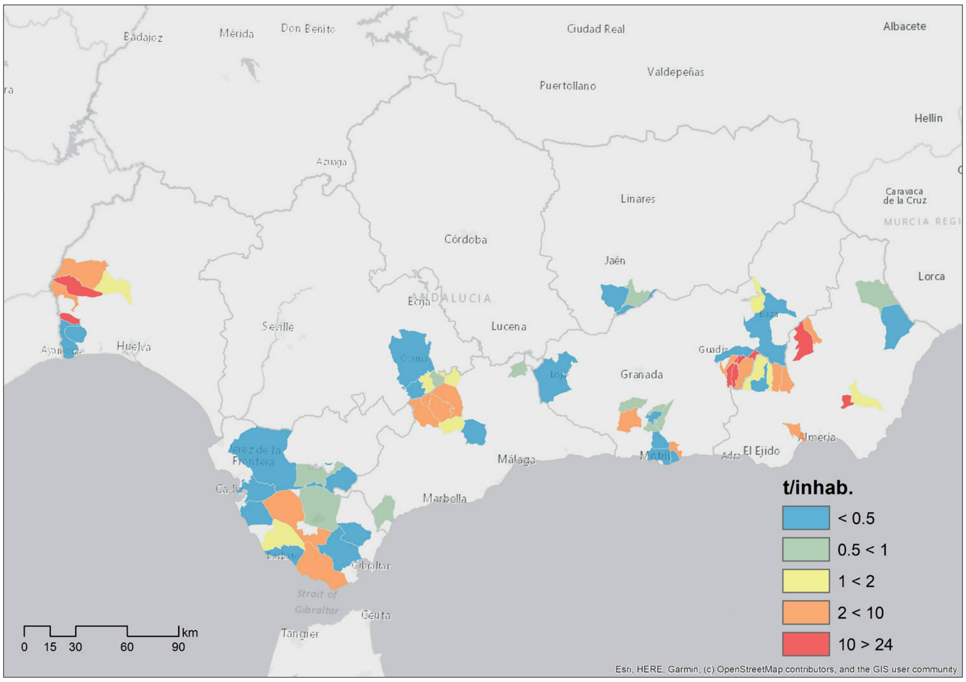

Fig. 5: Density of wind turbines waste per inhabitant (t/inhab.) by municipality in Andalusia in 2020
Source: Authors' elaboration

compatibility with their surrounding environments. Only 34.53% are situated in areas of moderate and low suggesting a more favorable integration with the landscape and ecological values.

This high concentration of wind turbines in environmentally sensitive areas suggests a disconnect between infrastructure planning and environmental protection. The presence of wind farms in these regions poses multiple risks, including habitat fragmentation and disruption of ecological corridors, particularly for bird species (Moustakas et al., 2023); land-use conflicts with traditional economic activities such as agriculture and livestock farming; and visual and acoustic impacts that affect both landscape aesthetics and rural tourism (Darabi et al., 2023).

The political framework prioritized rapid deployment over socio-environmental compatibility, focusing primarily on wind resource availability rather than on comprehensive territorial planning. In fact, by the time the Ministry established zoning regulations in 2020, 98% of the current installed wind power capacity in the region was already in place.

5. Discussion and policy implications

The transition to an energy model based on renewable sources has driven the massive development of wind energy infrastructure in recent decades. However, the aging of these installations introduces new challenges related to the end of their operational lifespan,

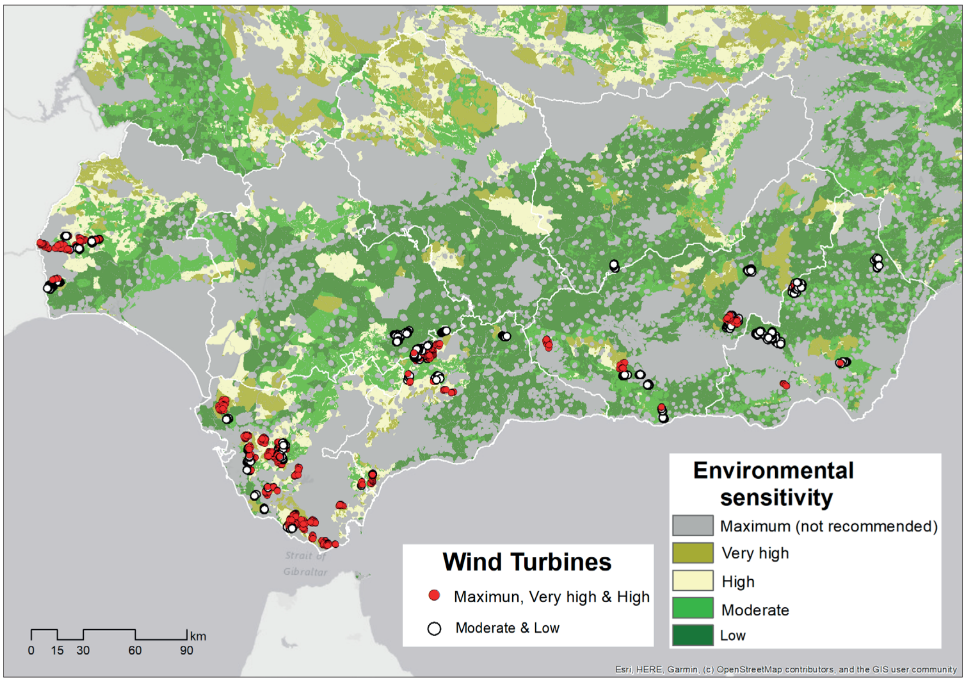

Fig. 6: Territorial compatibility of wind turbines in Andalusia
Source: Authors' elaboration

such as obsolescence, waste management and land-use conflicts. These issues not only have implications for energy efficiency and environmental sustainability but also affect territorial planning and social dynamics in the areas where wind farms are located.

By modelling different end-of-life scenarios, the study enables the estimation of infrastructure obsolescence over time. Additionally, by quantifying and geolocating wind turbine waste, it provides a critical foundation for designing targeted waste management strategies that enhance sustainability in the sector. The methodology is replicable and offers valuable guidance for policymakers and energy stakeholders in other regions. Key contributions include:

- A complete geospatial inventory of all wind turbines in Andalusia was developed using GIS. This inventory was integrated into a database containing the number of turbines per wind farm and their installation dates.
- End-of-life scenarios were calculated for each installation, based on three lifespan assumptions: 20 years (UNE-EN IEC 61400-1 standard), 25 years (Majewski et al., 2022; Jiménez et al., 2022), and 30 years (as indicated by manufacturers, e.g., Delaney et al., 2023), thus determining the degree of obsolescence of wind farms in the region.
- Turbine models were identified, and their total and rotor weights were obtained from publicly available databases such as https://www.thewindpower.net/, allowing for the estimation of rotor waste, which is particularly challenging to recycle.
- Based on this dataset, the projected volume of waste generated in each of the three-time horizons were calculated for the entire region of Andalusia.

Regarding wind power obsolescence, this study expands previous research (Serri et al., 2018), by introducing multiple end of operational lifespan scenarios (20, 25, and 30 years) and assessing their impact to 2030 and 2050, in line with European objectives for the implementation of renewable energy. Unlike previous studies that focused primarily on the technical and economic dimensions of wind repowering, this research incorporates geospatial analysis to determinate the obsolescence levels and power losses of different territories. These findings advance our understanding of potential energy self-sufficiency scenarios and underscore the necessity of employing multi-criteria decision-making approaches as suggested by Bezbradica et al. (2016) and Solbrekke and Sorteberg (2024).

Another aspect of great relevance is that the total waste mass in Andalusia amounts to nearly half a million tonnes, with 63,742 t corresponding to rotor mass, the most challenging component to recycle. Moreover, this waste is not distributed homogeneously over the territory. Rural municipalities, with lower energy consumption per capita (except where industrial activity is significant), tend to register the highest waste values reinforcing the territorial disparities in the energy transition. While industrial zones with high energy demands exist, the predominant trend aligns with previous studies (Rodríguez-Sojo, 2022), demonstrating that communities with limited direct energy benefits are disproportionately affected by the territorial impacts and other negative externalities of wind energy development. These results highlight the necessity of integrating waste generation assessments into territorial planning and energy governance frameworks to promote more equitable outcomes.

Beyond technical assessments, this study also provides insights into broader governance and policy challenges. One of the key issues identified is the uneven distribution of the burdens associated with wind energy expansion. Spain's centralized deployment model means that decisions and economic benefits are concentrated at the regional or national level, while local communities bear the environmental and social costs. This dynamic is particularly evident in Andalusia, where most wind farms are owned by large energy corporations, offering limited financial returns to local populations. Furthermore, the lack of participatory mechanisms in Spain has led to local resistance, as wind energy is often perceived as an imposed strategy rather than an inclusive transition process. The absence of comprehensive territorial planning in wind energy development is further evidenced by the environmental sensitivity analysis. This study reveals that 65.47% of the wind turbines in Andalusia are in areas where their compatibility with environmental values is lower or non-existent. Only one-sixth of the wind farms are situated in locations that meet the established criteria. This high concentration of wind turbines in environmentally sensitive areas suggests a lack of coordination between infrastructure planning and environmental protection. This finding underscores the misalignment between infrastructural planning and ecological conditions, despite wind energy being established in Andalusia since the 1990s. Additionally, Directive 2023/2413 (EC, 2023b), emphasizes the need for Member States to identify 'priority areas for renewable energy,' highlighting the urgency of revising current planning frameworks to minimize conflicts between energy development and environmental preservation.

Unlike other European countries that have implemented stricter regulations and financial security measures – such as mandatory decommissioning bonds to cover turbine dismantling costs – Spain relies on the thoroughness and seriousness of Environmental Impact Assessments (EIA) conducted at the project level. This means that incomplete EIAs can hinder effective end-of-life planning of wind projects. The lack of regulation can lead to projects perpetuating themselves in the territory, generating permanent modifications and huge amounts of unmanaged waste that manifest themselves as traces of the various energy transitions (Frolova et al., 2025), as already indicated by Windemer and Cowell (2021) and Clementi (2019). However, this approach would lead to a substantial loss of wind energy capacity in the short term, a concern documented in similar studies in Germany (Unnewehr et al., 2021; Grau et al., 2021). It is also essential for the EU and Spain to include in their regulation, wind turbine waste as a specific category, as is already the case for waste from solar panels (Márquez-Sobrino, 2024), some countries are trying to approve regulations about this issue (WindEurope, 2020a).

The findings of this study can inform decision-making processes concerning the end-of-life management of wind farms. One possible strategy is to dismantle turbines located in environmentally sensitive areas once they reach the end of their operational life, thereby mitigating ecological impacts. However, this would entail a significant short-term loss in wind power capacity, as already documented in Germany (Unnewehr et al., 2021; Grau et al., 2021). It is also recommended to select turbine models whose rotor accounts for a smaller proportion of the total mass, as the rotor remains the most challenging component to recycle (thewindpower.net). In less sensitive areas, alternative strategies such as extending the operational lifespan or replacing turbines with models featuring a lower rotor-to-mass ratio may be appropriate. Moreover, incorporating indicators such as waste density per hectare or per capita into planning processes could help relieve pressure on the most affected municipalities. These recommendations align with the work of Majewski et al. (2022) and Tazi et al. (2019), who emphasize the unresolved nature of waste management in renewable energy systems and the urgent need for more integrated planning approaches. As noted by Poggi et al. (2015), spatial planning can mediate the complex interactions between the environment, economy, and society, and serves as a key tool for advancing toward net-zero fossil fuel energy systems.

The challenges identified highlight the urgent need for stronger regulatory frameworks to ensure responsible wind farm management and to prevent the perpetuation of infrastructures across the territory (Frolova et al., 2025), aligning the expansion of renewable energy in Andalusia with long-term sustainability and territorial equity goals. A more balanced governance approach is required, one that promotes territorial equity, enhances local participation, and ensures a fair distribution of benefits. Establishing clearer regulations, integrating communities into decision-making processes, and ensuring that wind energy projects directly contribute to local development are essential steps toward a more just and sustainable energy transition.

Although this study provides a robust framework for assessing wind turbine waste and obsolescence, it presents certain limitations, such as the reliance on 2020 data, which necessitates periodic updates, and a focus limited to wind turbines. Future research should broaden the scope to include other components, such as substations and electricity evacuation and transmission infrastructure. Nonetheless, the findings offer valuable guidance for policy design by integrating waste management, repowering strategies, and spatial planning, thus contributing to a more resilient and equitable energy transition.

6. Conclusions

This study examines the territorial and environmental implications of wind turbine obsolescence in Andalusia, with a focus on spatial disparities, waste generation, and end-of-life infrastructure scenarios projected for the 2030 and 2050 policy horizons.

Findings indicate that by 2030, between 9.97% and 90.87% of wind farms in the region will have reached the end of their operational life, depending on whether a 30, 25, or 20year lifespan is assumed. By 2050, nearly all wind farms will have completed their lifecycle (100% for 20- and 25-year lifespans, and 98.82% for 30 years). These obsolete wind farms, whether repowered, dismantled, abandoned, or extended, represent a potential loss of installed capacity that must be strategically addressed.

In parallel, the projected waste volume – an estimated 464,284 tonnes, including 63,742 tonnes of rotor materials – underscores the urgent need for infrastructure-specific waste management strategies. The spatial distribution of this waste varies considerably across municipalities, revealing localized challenges that require tailored solutions.

Moreover, the study highlights the critical need to factor in the sensitivity of the territory where wind farms are installed. It shows the difficult integration, in terms of the territorial, social, and environmental consequences of this planning model of existing wind installations into the territory. The findings show that nearly two-thirds of turbines are in areas of high or very high environmental sensitivity, while only one-sixth are in low-sensitivity areas.

Finally, the results underline the need for clearer regulatory frameworks and stronger accountability mechanisms to ensure responsible infrastructure management. The availability of indicators such as degree of obsolescence, territorial sensitivity and waste density, and territorial sensitivity are essential for informing decision-making processes at the end-of-life stage and for improving the strategic planning of future installations. These indicators can help anticipate emerging risks, guide investment in decommissioning logistics and recycling technologies and support the design of policies aligned with circular economy principles. By doing so, they contribute to a more just, efficient, and territorially balanced energy transition.

Acknowledgements

Authors thank for the support of MAPER@I project TED 2021-129484A-I00 funded by MICIU/AEI/10.13039/501100011033 and by the European Union "NextGenerationEU"/PRTR. The authors also sincerely thank the editor and anonymous reviewers for their insightful comments and constructive suggestions, which significantly enhanced the quality of this article.

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Please cite this article as:

Márquez-Sobrino, P., Pérez-Pérez, B., & Díaz-Cuevas, P. (2025). Addressing wind turbines obsolescence and waste estimation: A geographical approach to decision-making. Moravian Geographical Reports, 33(3), 185–195. https://doi.org/10.2478/mgr-2025-0015