Wind power potential in low environmental sensitivity areas of Spain: a regional assessment *

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Abstract

The large-scale deployment of wind power required to meet climate targets increasingly faces challenges related to environmental impacts and social acceptance. In Spain, these challenges have motivated the development of the Environmental Sensitivity Index (ISA), a national zoning tool that classifies the territory according to its environmental sensitivity to wind and solar PV power plants. In this study, we combine the ISA index for wind energy with a high-resolution wind atlas (NEWA) to estimate, for the first time, Spain's wind power potential that is both economically viable and restricted to areas of low environmental sensitivity. Results show that approximately 7.24% of the national territory meets these criteria, corresponding to a techno-economic potential of 361 GW, well above current policy targets. Consequently, land availability is unlikely to be a limiting factor at the national level for a large-scale, economically viable and environmentally-friendly expansion of wind power capacity. However, this potential is highly unevenly distributed across regions, reflecting the heterogeneous spatial patterns of wind resources and low-sensitivity areas. Hence, ad hoc planning criteria, such as imposing uniform wind power capacity densities across regions or pursuing regional energy self-sufficiency, could lead to uneven environmental pressures and inefficient use of the available wind resource. Integrated spatial planning approaches are therefore essential to reconcile climate mitigation objectives with environmental protection and social acceptance.

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1 Introduction

According to the IPCC, the large-scale deployment of solar and wind capacity is among the most cost-effective measures to reduce greenhouse gas emissions [IPCC, 2022]. Consequently, most national strategies to meet Paris Agreement commitments combine a massive expansion of solar and wind power with high levels of electrification across several sectors, including transport, heating, and industry. The Spanish National Energy and Climate Plan (NECP, or PNIEC in Spanish) [MITECO, 2024] sets 2030 targets of 57.7 GW for onshore wind and 72.1 GW for solar PV in mainland Spain. Under scenarios of deep economy-wide electrification, consistent with the long-term decarbonisation strategy targeting net-zero emissions by 2050 [MITECO, 2020a], these figures may need to increase by a factor of two or three.

Although specific targets exist to improve energy efficiency and exploit rooftop renewable potential –particularly for solar PV–, a rapid, large-scale expansion of utility-scale wind and solar capacity remains essential. In what can be considered the early stages of this process, concerns about social acceptance have emerged at multiple levels [Ellis and Ferraro, 2016, Rodríguez-Segura et al., 2023], e.g. local groups opposing perceived landscape impacts, agricultural and livestock sectors expressing fears of competition for space or resources, and environmental organizations highlighting potential risks for ecosystems and biodiversity. Some of these concerns arise from past experiences of poor practices by large corporations. Others, however, may not always be sufficiently contrasted with scientific assessments indicating that the long-term local and global impacts of unmitigated climate change may substantially outweigh the local impacts associated with the accelerated deployment of renewable generation capacity. These debates have gained prominence in the public sphere, contributing to a somewhat confusing environment for public opinion formation.

In this context, the Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITECO) developed a national zoning in 2020 [MITECO, 2020b]. The aim was to assess the environmental sensitivity of the territory to the installation of wind farms and solar PV plants using comprehensive and consistent criteria. As a result, the Environmental Sensitivity Index (ISA, by its Spanish acronym) was developed as a national zoning tool that classifies the territory into five levels of environmental sensitivity. The ISA's spatial distribution is publicly available as a 25×25 m high-resolution raster dataset.

On the other hand, wind energy assessments are usually develop to estimate how much capacity could be deployed in a region under specific assumptions [McKenna et al., 2022]. They typically draw on atmospheric model simulations of meteorological variables. For near-surface wind speeds (e.g., at 100 m height), the model's spatial and temporal resolution is critical, as low resolution can underestimate wind speeds, particularly in mountainous regions [Jiménez et al., 2013]. Reanalysis products tend to be accurate in simulating mesoscale-regional circulations (e.g. [Lucio-Eceiza et al., 2019, Lucio-Eceiza et al., 2020]) and provide a physically consistent, General Circulation Model based and observationally guided, interpretation of reality [Bengtsson et al., 2007, Nakamura et al., 2025] that has been shown to be useful for many applications. Reanalysis resolution has progressively increased but lack the necessary orographic detail to realistically represent complex terrain [Wu et al., 2024, Zuo et al., 2025]. ERA5 [Hersbach et al., 2020] reaches ca. 27 km horizontal resolution and has been one of the most widely used global reanalysis datasets, with improved representation of surface wind speed related parameterizations. Additionally, regional reanalysis and dynamical downscaled products have been developed [Jourdier, 2020, Nakamura et al., 2025] that attempt enhancing resolution and orographic detail to improve model performance over complex terrain, this being of major relevance for wind speed and wind power applications [Murcia et al., 2022, Schicker et al., 2023]. CERRA [Ridal et al., 2024] is perhaps the best example of a recent reanalysis product, improving, relative to ERA5, resolution and performance, reaching a resolution of 5.5 km with a clear added value over mountains and coasts [Galanaki et al., 2023]. The New European Wind Atlas (NEWA) [Hahmann et al., 2020, Jourdier, 2020, Murcia et al., 2022] is a dynamical downscaling from ERA5, using a regional model that reaches a resolution of 3 km over Europe. It is specially oriented to provide the wind resource community with wind-related (wind speed/power) information, and has been optimized for the simulation of wind fields at hub heights. NEWA has been found to provide added value over complex terrain areas but also produce notable biases over other areas where it does not improve ERA5 [Jourdier, 2020, Schicker et al., 2023, Soukissian et al., 2025].

In the literature, several types of wind power potential are distinguished. According to [McKenna et al., 2022], four categories are commonly used: (i) the physical potential, referring to the total energy content of the wind within a region; (ii) the geographical potential, which quantifies the area available for wind turbine installation after applying technical, ecological, and social constraints; (iii) the technical potential, defined as the power (or energy) that can be installed (or generated) once turbine characteristics and other technical factors are considered; and (iv) the economic potential, a subset of the technical potential that includes only projects that are economically viable under given assumptions. While the physical and geographical potentials are typically of limited relevance for energy policy, the technical and economic potentials are considered highly policy-relevant [McKenna et al., 2022].

In this study, these concepts are used in an operational sense to disentangle the effects of environmental sensitivity and wind resource availability in the wind power potential estimated for Spain. Specifically, we define the *technical potential* as the wind power potential located exclusively in areas classified as ISA level 4 (the lowest environmental sensitivity level), denoted P_{ISA4}. The *economic potential* is here used to refer the wind power potential located in areas with sufficiently high wind capacity factor (CF) to assume economic viability, and is denoted P^{CF^*}. Finally, we define the *techno-economic* potential as the intersection of the above two potentials, corresponding to economically viable wind power potential located in low-sensitivity areas, denoted $P_{\text{ISA4}}^{CF^*}$.

To the best of the authors' knowledge, this study is the first to combine the ISA index developed in Spain with a high-resolution wind atlas, namely NEWA. The assessment is conducted at the NUTS-2 level[1] for 16 of Spain's 17 autonomous communities (the Canary

[1]See supplementary materias. For a description of the NUTS levels, see https://eur-lex.europa.eu/EN/legal-content/glossary/nomenclature-of-territorial-units-for-statistics-nuts.html

Islands are excluded because they lie outside the spatial domain of the NEWA dataset).

The remainder of the paper is structured as follows. Section 2 describes the datasets used in this study. Section 3 presents the methodology for estimating the different potentials defined above. Section 4 reports the main results, together with the main limitations of the study, and Section 5 summarizes the key findings. A complete set of results for each NUTS-2 region is provided in the Supplementary Materials.

2 Data

This section briefly describes the two datasets used in this study: the wind speed field from the New European Wind Atlas (NEWA), and the zoning of environmental sensitivity to wind power development in Spain.

2.1 The New European Wind Atlas (NEWA)

The NEWA wind atlas [Hahmann et al., 2020, Dörenkämper et al., 2020] provides wind speed and direction at several heights in the planetary boundary layer (PBL). It includes a mesoscale and microscale wind climatology for over the whole European region. This work focuses on the mesoscale climatology of NEWA, which is based on simulations with the Weather Research and Forecasting model (WRF, [Skamarock et al., 2008]) and considers a 30-year-long simulation over the European domain at 3 km spatial and 30 min temporal resolution. This simulation was driven with boundary conditions provided by the The fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5; [Hersbach et al., 2020]).

The WRF model configuration selected for the NEWA wind atlas is based upon the assessment of a number of short sensitivity simulations that were evaluated against mast data [Hahmann et al., 2020]. The mesoscale model outputs from the NEWA production run have been based on a modified version of the WRFv3.8.1, with changes in the Mellor-Yamada-Nakanishi-Niino (MYNN) planetary boundary layer (PBL) scheme and and also in the ice accumulation estimations. The 30-year WRF climatology simulation consists of sequential seven days runs with a 24 h spin-up overlapping with the last day of the preceding weekly run. Such selection pursues to assure the balance of the the mesoscale flow aerodynamic characteristics of the terrain, however, these runs do not preserve the memory of processes longer than several days, as for instance the hydrothermodynamics of the soil, which in turn it is also well know to produce a non-negligible effect on the land-surface interactions and therefore of the atmospheric fields such as the wind [Jiménez et al., 2011]. Nudging is applied to prevent drifting from the large-scale atmospheric forcing fields from ERA5 reanalysis [Vincent and Hahmann, 2015].

The NEWA mesoscale simulated wind was produced by blending independent WRF simulations with identical configurations over 10 partially overlapping tiles [Hahmann et al., 2020], ensuring that each country of the European Union would be fully enclosed in at least one domain. To efficiently parallelize the simulations, each innermost domain was run separately from the others. Altogether these subdomains cover the NEWA target area, that is, all EU member states plus Norway, Switzerland, the Balkans, and Turkey, including offshore areas up to 100 km off the corresponding coast and the complete North and Baltic seas. Tiles have also been designed so that they overlap at least 30 grid points with adjacent domains.

In this work, only the simulated wind speed at 100 m height for the year 2013 from the NEWA mesoscale dataset was used. Time averaging and spatial bilinear interpolation were applied to obtain a wind field with a temporal resolution of 1 hour, and a horizontal resolution of 0.05° (∼5 km over the Iberian Peninsula). Future work will consider extending the time period to enable a multi-year analysis.

2.2 Environmental Sensitivity Index (ISA)

In 2020, the Spanish Ministry for the Ecological Transition and the Demographic Challenge (MITECO) developed the Environmental Sensitivity Index (ISA, by its Spanish acronym), a national tool to assess the environmental sensitivity of the territory to the installation of wind farms and photovoltaic plants. The tool aims to support decision-making and strengthen public participation in the early planning and permitting stages of renewable energy projects by providing consistent, transparent, and publicly available information across the entire country. It is important to note that the ISA neither replaces the need for an Environmental Impact Assessment for each specific project nor pre-determines its outcome.

The methodology relies on multi-criteria evaluation techniques implemented in Geographic Information Systems (GIS), combined with a comprehensive review of technical documentation and relevant legislation. A wide range of indicators are incorporated, see Table 1. Two types are defined: exclusion and weighting indicators. Exclusion indicators directly identify areas with the highest sensitivity level (level 0), whereas weighting indicators are aggregated to determine the ISA.

From the distribution of the resulting numerical ISA values, five ISA levels were defined, from 0 (maximum sensitivity) to 4 (low sensitivity). It is important to note that the assessment is technology-specific, producing different ISA level maps for wind power and solar PV. Figure 1 illustrates the spatial distribution of ISA levels corresponding to wind energy. Table 2 shows the share of national territory associated with each ISA level.

3 Methodology

This section describes the procedure used to estimate three different wind power potentials: the technical potential, restricted to areas with low environmental sensitivity to wind farms (P_{ISA4}); the economic potential, restricted to areas with high wind power capacity factor (P^{CF^*}); and the techno-economic potential, the intersection of the two of them ($P_{\text{ISA4}}^{CF^*}$). The process is illustrated for region ES11 (Galicia), although the same methodology is applied to all NUTS-2 regions in Spain, except the Canary Islands, which are not covered by the NEWA dataset.

Table 1: Indicators considered in the ISA. Ponderation column show the relative weight. Acronyms from Spanish legislation are included (LIC: Sites of Community Importance; ZEC: Special Areas of Conservation).

Indicator	Exclusion	Ponderation
Urban areas	×	
Water bodies and flood zones	×	
Plans for threatened species: critical areas	×	
Plans for threatened species: rest		0.166
Protection areas for birds against collision and electrocution on high voltage power lines		0.121
Ecological connectivity and wild highways		0.021
Important Bird and Biodiversity Conservation Areas in Spain		0.067
Habitats of Community Interest (HIC): prioritary		0.114
Habitats of Community Interest (HIC): rest		0.030
Natura 2000 sites - Special Protection Areas for Birds (ZEPA)	×	
Natura 2000 sites (LIC and ZEC subject to regional legislation, or for quiropter conservation)		0.249
Natura 2000 sites (rest of LIC and ZEC)	×	0.249
Protected Natural Areas	×	
Wetlands of international importance (Ramsar)	×	
Specially Protected Areas of Mediterranean Importance		0.052
Biosphere Reserves (core and protected areas)	×	
Biosphere Reserves (transition areas)		0.024
Sites of Geological Interest		0.068
Visibility		0.062
The Camino de Santiago	×	
Traditional livestock routes	×	
Public Utility Forests		0.028
UNESCO World Heritage sites	×	

Table 2: Percentage of territory associated with each ISA level for wind energy.

ISA level	Environmental sensitivity	Surface (%)
0	Maximum	50.9
1	Very high	5.5
2	High	8.1
3	Moderate	15.3
4	Low	20.2

Spatial distribution of the ISA

The raster containing the ISA levels is first filtered for the selected region (see Figure 2, a more detailed representation of Figure 1 for Galicia). The surface area corresponding to each sensitivity level, $A_{\text{ISA}i}$ for $i = 0, ..., 4$, is calculated and expressed as a percentage of the region's total area (see figure legend). In addition, Table 3 compiles these results for all regions considered. As the table shows, environmental sensitivity to wind farms is distributed unevenly across the territory. For example, the percentage of area labelled with

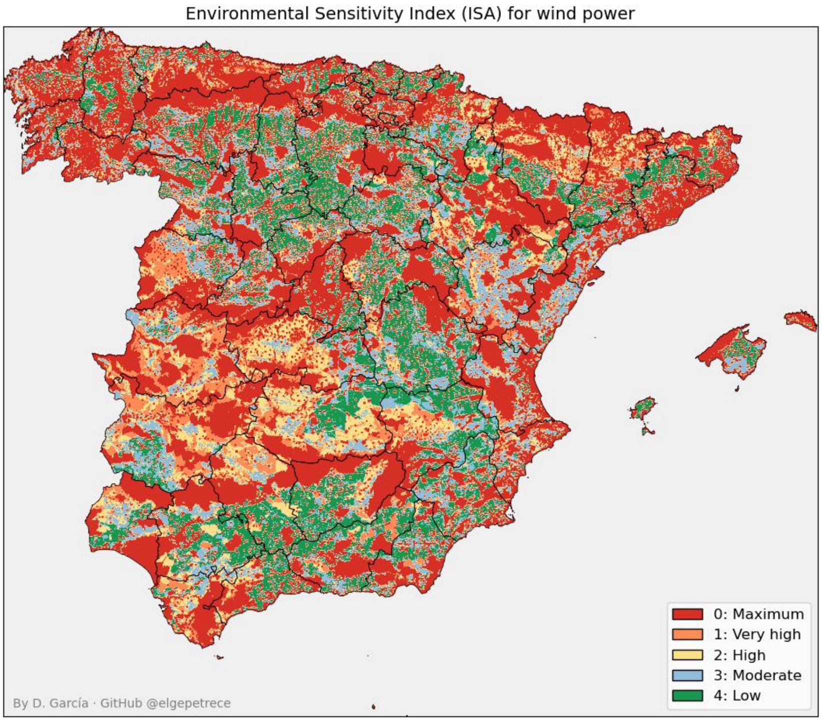


Figure 1: Environmental sensitivity index to wind farms (ISA levels). Source: [García Pérez, 2025]

level 0 (maximum sensitivity) ranges from 38% to 75%. For level 4 (low sensitivity, the level of interest in this work), it ranges from 5% to 35%.

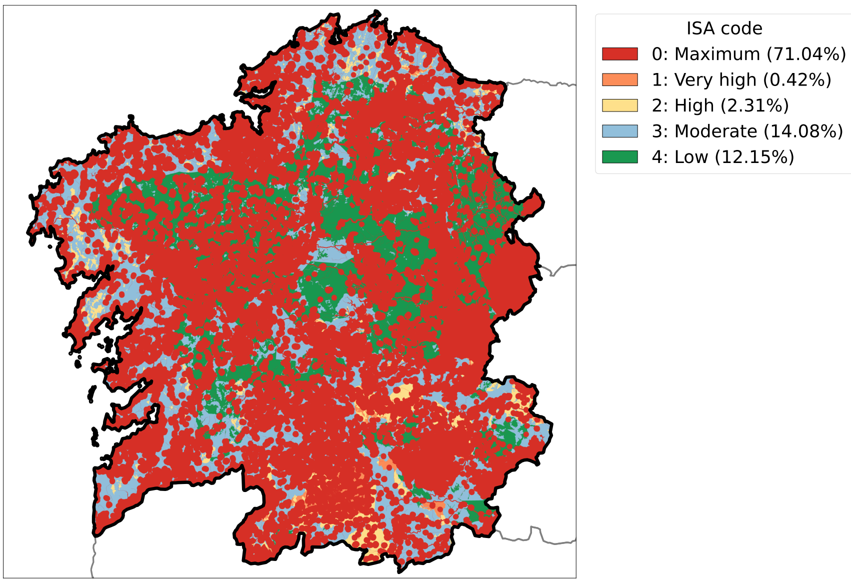


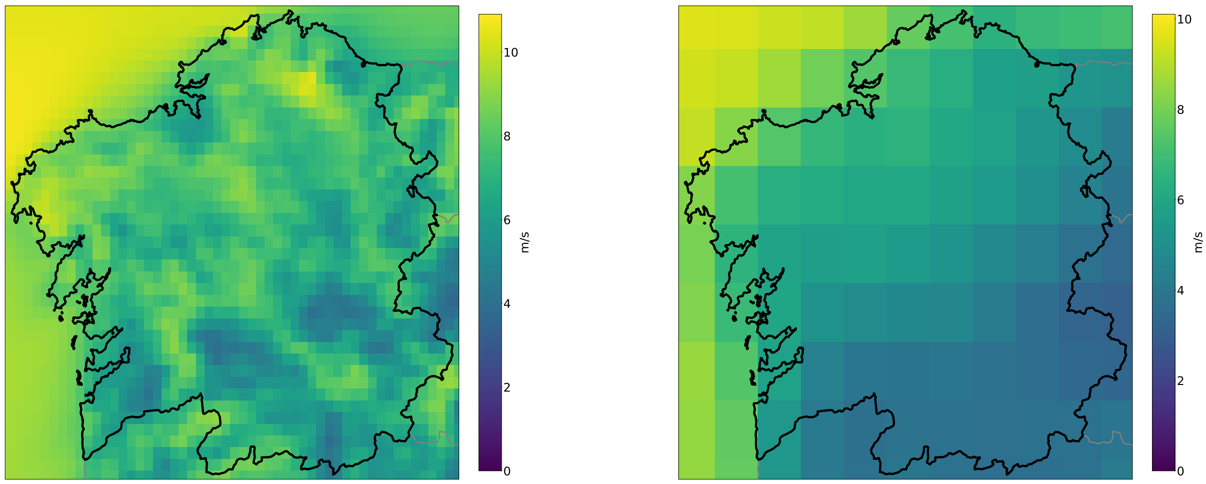
Figure 2: ISA levels for Galicia.

Table 3: Spain's regions surface, and percentage per ISA level.

NUTS-2 code	Name	Area ($\times 10^3$ km^2)	A_{ISA0} (%)	A_{ISA1} (%)	A_{ISA2} (%)	A_{ISA3} (%)	A_{ISA4} (%)
ES11	Galicia	29.57	71.04	0.42	2.31	14.08	12.15
ES12	Principado de Asturias	10.60	70.73	5.91	5.56	8.15	9.65
ES13	Cantabria	5.33	69.81	0.38	0.96	9.73	19.12
ES21	País Vasco	7.23	60.25	0.23	0.87	9.90	28.75
ES22	Comunidad Foral de Navarra	10.39	53.15	2.79	7.02	17.62	19.42
ES23	La Rioja	5.05	57.78	0.48	4.08	11.64	26.02
ES24	Aragón	47.72	50.90	6.98	13.26	17.12	11.74
ES30	Comunidad de Madrid	8.03	72.55	0.02	0.04	6.33	21.06
ES41	Castilla y León	94.23	50.25	2.94	3.22	17.20	26.39
ES42	Castilla-La Mancha	79.46	37.98	7.25	15.34	16.21	23.22
ES43	Extremadura	41.63	44.37	20.20	14.45	15.75	5.23
ES51	Cataluña	32.11	62.38	3.58	6.17	10.83	17.05
ES52	Comunidad Valenciana	23.26	62.61	3.02	3.96	25.07	5.33
ES53	Islas Baleares	4.99	61.26	0.00	0.17	17.36	21.20
ES61	Andalucía	87.61	46.60	6.18	9.20	11.20	26.82
ES62	Región de Murcia	11.31	43.60	2.14	1.85	16.82	35.58

Wind resource

The hourly wind speed time series at 100 m height from the NEWA dataset is then used to characterize the wind resource. Figure 3 compares the spatial distribution of mean wind speed obtained from NEWA (left) and ERA5 (right) for the same reference year (2013). The comparison highlights the critical role of spatial resolution in accurately capturing high-wind areas, particularly in mountainous terrain. In the ERA5 case, high wind speeds are mainly associated with grid cells that include both land and ocean surfaces, the latter typically exhibiting higher wind speeds.



(a) NEWA (b) ERA5

Figure 3: Spatial distribution of the mean wind speed at 100 m height for NEWA (left) and ERA5 (right) datasets.

Hourly and annual wind capacity factors

The hourly wind capacity factor for hour t and weather cell w, $CF_{t,w}$, is computed using the Python library atlite.[2] The Vestas V112–3 MW wind turbine power curve model is assumed, see Figure 4.

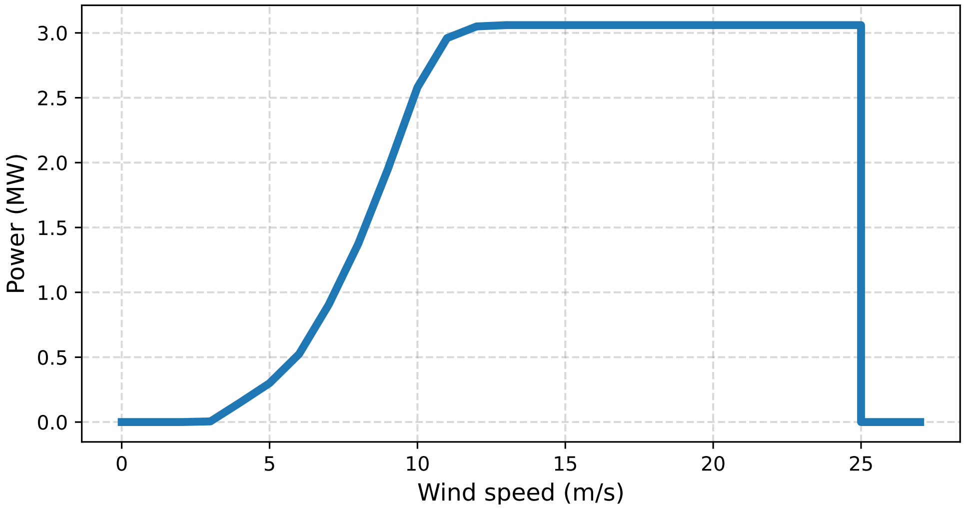


Figure 4: Power curve of the wind turbine Vestas V112–3 MW.

Several simplifying assumptions are applied in the computation of hourly capacity factors: (i) The use of a single turbine type is a simplification, as the choice of turbine depends on local site characteristics (e.g., wind regime, turbulence intensity). (ii) A 3 MW turbine was selected as the representative configuration. While this choice is appropriate in the short to mid term, it may be too conservative for estimating the long-term potential, given the steady increase in wind turbine rated capacity [McKenna et al., 2022]. (iii) Wind speed is taken at 100 m, slightly above typical current hub heights. This approach avoids the need for vertical extrapolation, which would introduce additional uncertainty. Moreover, hub heights are expected to continue increasing over time, aligning with this assumption [McKenna et al., 2022]. (iv) A correction factor of 0.93 is applied to account for wake and other system losses. Previous studies estimate onshore wind farm losses at 2–4% [El-Asha et al., 2017]; here, a conservative 7% loss is assumed.

The annual wind capacity factor for each weather cell, CF_w, is then obtained by time-averaging hourly values:

$$CF_w = \frac{1}{8760} \sum_{t=1}^{8760} CF_{t,w}. \tag{1}$$

Figure 5 shows the spatial distribution of the resulting annual capacity factor.

[2]https://github.com/PyPSA/atlite

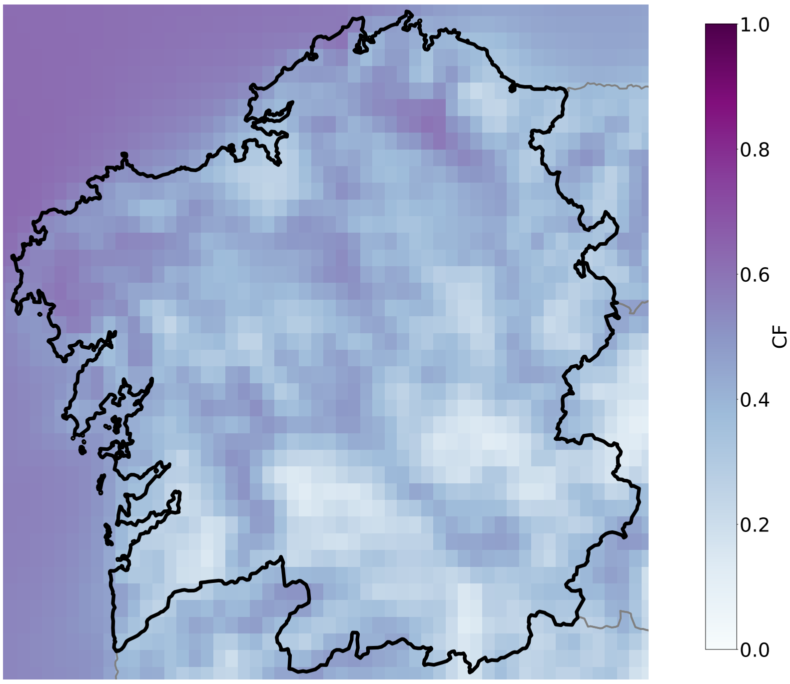


Figure 5: Spatial distribution of the annual capacity factor at 100 m height, CF_w.

Potential wind power

For each weather cell w, the area corresponding to ISA level i is obtained, $A_{\mathrm{ISA}i,w}$. Assuming a spatial power density of d MW·km^{-2}, the corresponding installable wind power capacity per ISA level and weather cell, $P_{\mathrm{ISA}i,w}$, is calculated as:

$$P_{\mathrm{ISA}i,w} = d \cdot A_{\mathrm{ISA}i,w}. \tag{2}$$

It is noted that $P_{\mathrm{ISA}i,w}$ represents an estimation of the technical wind power potential at weather cell w, where the eligible land is defined according to the corresponding ISA level i. In this work, the assumed wind power density is $d = 10$ MW·km^{-2}. According to [McKenna et al., 2022], typical values range from about 1.1 MW·km^{-2} for a 1 MW wind turbine to 18.6 MW·km^{-2} for a 3 MW wind turbine.

Figure 6 shows, for each ISA level i, the pairs ($P_{\mathrm{ISA}i,w}$, CF_w) arranged in cumulative wind power capacity (x axis) and decreasing capacity factor (y axis)

From this, three wind power potentials are defined:

- Technical potential at ISA level i, $P_{\mathrm{ISA}i}$. It represents the wind power capacity that could be installed in the considered region taking into account only areas classified as ISA i. It is defined as:

$$P_{\mathrm{ISA}i} = \sum_{w \in \Omega} P_{\mathrm{ISA}i,w}, \tag{3}$$

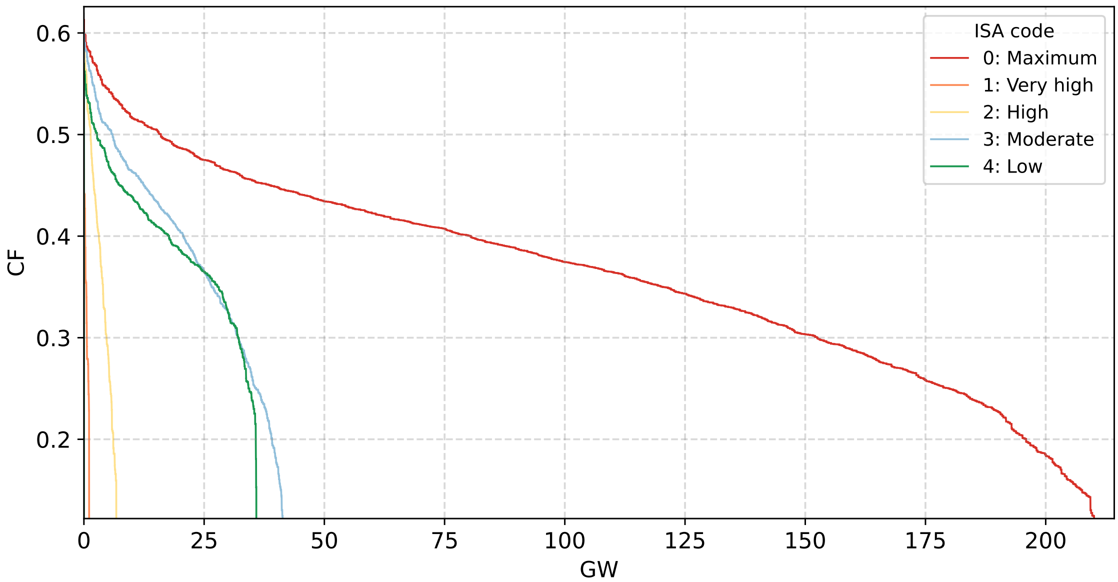


Figure 6: Distribution of the potential wind power capacity per ISA level in decreasing CF order.

where Ω is the set of weather cells that overlap the considered region. In Figure 6, $P_{\text{ISA}i}$ corresponds to the endpoint of the curve associated to the ISA level i, i.e. the intersection with the horizontal axis.

- Economic potential, P^{CF^*}. It corresponds to the wind power capacity that could be installed in the region, and that is considered economically viable. The economic viability is here estimated by considering only weather cells with an annual capacity factor greater than or equal to a certain threshold, CF^*. In Spain, the average capacity factor for onshore wind is around 0.25 [REE,]. In this study, a conservative threshold of $CF^* = 0.30$ is adopted, identifying areas with above-average capacity factors. Mathematically:

$$P^{CF^*} = \sum_{i=0}^{4} \sum_{w \in \Omega^*} P_{\text{ISA}i,w}, \tag{4}$$

where Ω^* denotes the subset of weather cells Ω with an annual capacity factor equal or above CF^*.

- Techno-economic potential at ISA level i, $P^{CF^*}_{\text{ISA}i}$. It corresponds to the wind power capacity that could be installed in areas classified as ISA i and are considered economically viable. It is given by:

$$P^{CF^*}_{\text{ISA}i} = \sum_{w \in \Omega^*} P_{\text{ISA}i,w}. \tag{5}$$

Graphically, $P^{CF^*}_{\text{ISA}i}$ corresponds to the intersection of the ISA i curve in Figure 6 with a horizontal line at CF^*.

Note that, by definition, $P_{\text{ISA}i} \geq P^{CF^*}_{\text{ISA}i}$ because the techno-economic potential at ISA i level is a subset of the technical potential at this ISA level. Likewise, it also holds that $P^{CF^*} \geq P^{CF^*}_{\text{ISA}i}$, because the economic potential is the addition of the techno-economic potentials at each individual ISA level:

$$P^{CF^*} = \sum_{i=0}^{4} P^{CF^*}_{\text{ISA}i}. \tag{6}$$

The techno-economic potential at ISA 4 level, $P^{CF^*}_{\text{ISA4}}$, represents the wind power potential that is both economically viable and located in areas of low environmental sensitivity, which constitutes the main focus of this study. For the region considered in this section, Galicia (NUTS-2 code ES11), this potential amounts to $P^{CF^*}_{\text{ISA4}} = 32.1$ GW. This value is a subset of both the technical potential at ISA 4, estimated at $P_{\text{ISA4}} = 35.9$ GW, and the economic potential, estimated at $P^{CF^*} = 221.9$ GW.

These three potentials are shown in the Venn diagram in Figure 7, which illustrates whether the regional wind power potential is primarily constrained by environmental sensitivity or by wind resource availability. In the case of Galicia, the diagram indicates that most low-sensitivity areas are characterised by a high wind resource, as a large fraction of the technical potential P_{ISA4} overlaps with the economically viable potential P^{CF^*}. In addition, substantial high-resource areas are also found in locations classified under other ISA levels, as a large share of P^{CF^*} lies outside P_{ISA4}. These patterns are consistent with the well-documented wind resource availability in Galicia, which is strongly influenced by Atlantic weather regimes.

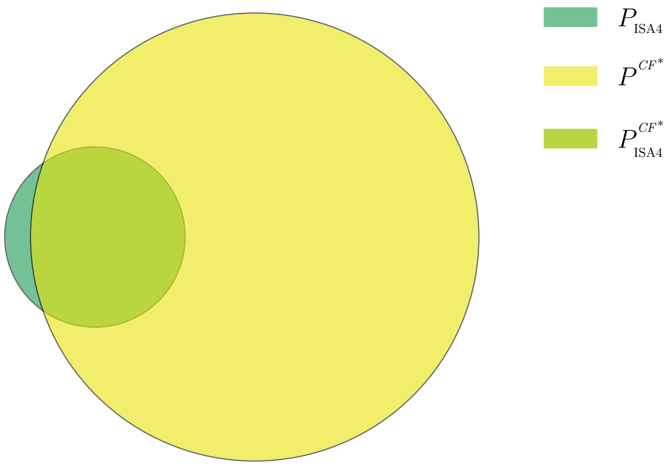


Figure 7: Venn diagram with wind power potential in ISA 4 areas, P_{ISA4}, in areas with $CF \geq 0.3$, P^{CF^*}, and matching both criteria, $P^{CF^*}_{\text{ISA4}}$.

A different pattern is observed in the Venn diagram for the Murcia region (ES62), see Supplementary Materials, where the technical potential (P_{ISA4}) is high, but only a small fraction of it is economically viable. The diagram also shows that there is little economic potential in this region regardless of the ISA level.

Finally, the spatial distribution of the techno-economic potential at ISA 4 level, $P^{CF^*}_{\mathrm{ISA4},w}$ can also be obtained, as displayed in Figure 8. The figure shows the wind power capacity that can be installed in each weather cell according to the available land labeled as ISA 4.

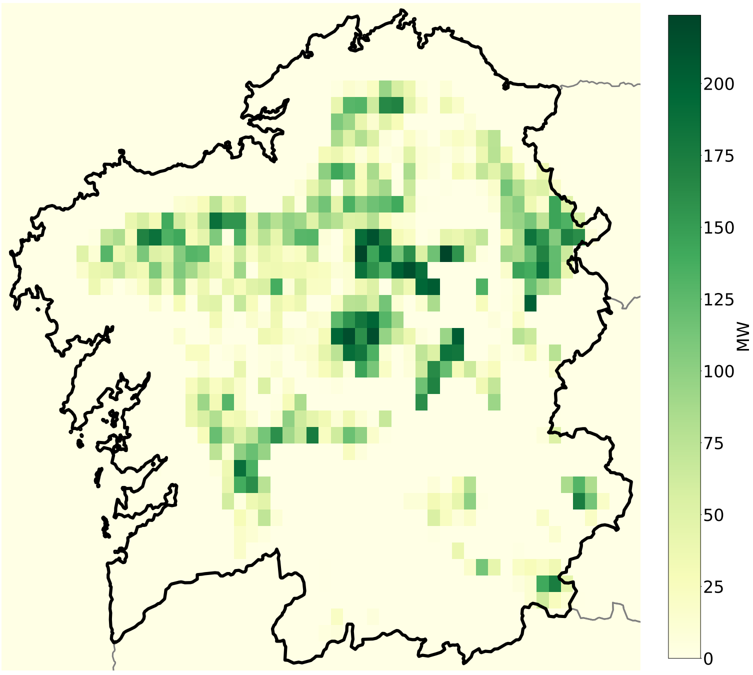


Figure 8: Spatial distribution of the techno-economical potential at ISA 4 level, i.e. wind power potential limited to areas with low environmental sensitivity (ISA 4) and high wind resource ($CF \geq 0.3$).

4 Results and discussion

Table 4 summarises the results obtained for each NUTS-2 region. Aggregated results for Spain as a whole are reported in the last row. The table presents: (i) the wind power technical potential in low sensitivity areas, P_{ISA4}; (ii) the economic potential, P^{CF^*}; (iii) the techno-economic potential in low sensitivity areas, $P^{CF^*}_{\mathrm{ISA4}}$; (iv) the percentage of the regional territory characterised by low environmental sensitivity to wind farms and high wind resource, $A^{CF^*}_{\mathrm{ISA4}}$ (%); (v) the installed wind power capacity in 2024 for comparison purposes, P_{2024}; (vi) the estimated annual electricity generation associated with the identified techno-economic potential, $E^{CF^*}_{\mathrm{ISA4}}$; and (vii) the share of this estimated generation with

Table 4: Summary of results.

NUTS code	Name	P_{ISA4} [GW]	P^{CF^*} [GW]	$P^{CF^*}_{\text{ISA4}}$ [GW]	$A^{CF^*}_{\text{ISA4}}$ (%)†	P_{2024} [GW]	$E^{CF^*}_{\text{ISA4}}$ [TWh]	$E^{CF^*}_{\text{ISA4}}$ ($\%_{2024}$)‡
ES11	Galicia	35.93	221.93	32.10	10.86	3.89	115.60	865.04
ES12	Principado de Asturias	10.23	46.08	5.41	5.10	0.70	18.08	198.95
ES13	Cantabria	10.18	22.61	4.58	8.59	0.04	13.99	380.13
ES21	País Vasco	20.79	26.70	5.00	6.91	0.15	14.46	93.04
ES22	Comunidad Foral de Navarra	20.18	71.54	13.04	12.55	1.36	40.64	787.90
ES23	La Rioja	13.13	25.51	5.96	11.80	0.45	19.09	1203.50
ES24	Aragón	56.02	303.85	36.76	7.70	5.04	118.86	1158.93
ES30	Comunidad de Madrid	16.91	10.07	1.86	2.32	0.00	5.50	20.25
ES41	Castilla y León	248.66	495.64	124.94	13.26	6.62	385.81	2851.93
ES42	Castilla-La Mancha	184.50	278.68	88.03	11.08	4.86	258.76	2271.64
ES43	Extremadura	21.77	20.00	1.05	0.25	0.04	2.91	59.03
ES51	Cataluña	54.75	68.48	10.85	3.38	1.37	34.64	79.30
ES52	Comunidad Valenciana	12.40	55.55	2.46	1.06	1.24	7.21	26.89
ES53	Islas Baleares	10.59	16.32	1.86	3.72	0.00	5.15	83.52
ES61	Andalucía	234.97	125.86	20.78	2.37	3.61	60.63	157.17
ES62	Región de Murcia	40.26	13.68	6.51	5.75	0.26	18.42	202.60
ES	Spain*	991.27	1802.48	361.17	7.24	29.62	1119.76	466.57

* Except Canary Islands.
† Percentage over total region area.
‡ Percentage over region electricity demand in 2024.

respect to the region's electricity demand in 2024, $E^{CF^*}_{\text{ISA4}}$ ($\%_{2024}$). A more detailed set of results for each region, including the figures corresponding to Figures 2, 5, 6, 7 and 8, is provided in the Supplementary Materials.

The results allow for several key observations. First, the techno-economic wind power potential in Spain amounts to 361 GW, roughly six times the onshore wind capacity target of about 60 GW set in the PNIEC [MITECO, 2024]. While the wind capacity required to achieve net-zero emissions depends strongly on system-level assumptions, this result indicates that economically viable wind power potential in low-sensitivity areas is unlikely to be a limiting factor across a wide range of decarbonisation scenarios.

Second, exploiting the estimated techno-economic potential would require approximately 7.24% of the national territory. By comparison, achieving the PNIEC target would require around 1.2% of the land area, while the wind power capacity installed by 2024 corresponds to approximately 0.6% of the territory under the same power density assumptions. These figures indicate that, at the national scale, land availability is unlikely to constitute a binding constraint for wind power deployment.

Third, the estimated potential is highly unevenly distributed across regions. The share of land required to exploit the techno-economic potential in each region ranges from as little as 0.25% in Extremadura (ES43) to more than 13% in Castilla y León (ES41). This heterogeneity stems from the strongly uneven spatial distributions of both wind resources and low-sensitivity areas. To delve into this question, Figure 9 shows the regional distribution of the three wind power potentials analysed in this study: technical (left), economic (centre), and techno-economic (right). To remove the influence of regional size, the results are expressed in terms of potential density, defined as potential capacity per unit area. Under this representation, colours indicate the relative suitability of each region for wind power deployment from different perspectives. For instance, the technical potential map shows that the Region of Murcia (ES62), located in southeastern Spain, exhibits the highest technical potential density, reflecting a relatively large share of low-sensitivity areas. From an environmental standpoint alone, this would suggest favourable conditions for wind power deployment in this region. However, the economic potential map indicates that Murcia is characterised by one of the lowest economically viable potentials due to limited wind resources. Conversely, Galicia (ES11) displays the opposite situation: very high wind resource availability but a comparatively limited extent of low-sensitivity areas. The techno-economic potential map combines both criteria, yielding a markedly different regional pattern in which Castilla y León, located in north-central Spain, emerges as the region with the highest overall suitability.

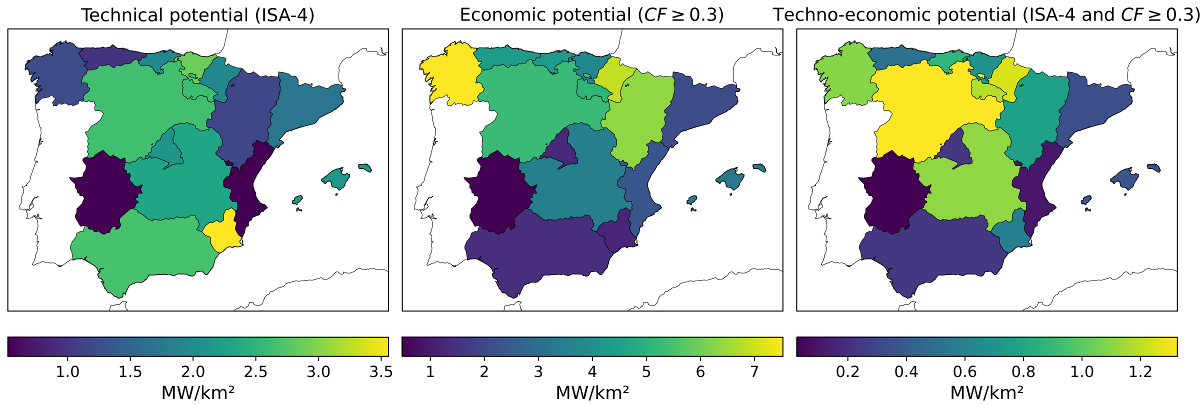


Figure 9: Power density for technical potential, P_{ISA4} (left), economic potential, P^{CF^*} (center), and techno-economic potential, $P^{CF^*}_{\text{ISA4}}$ (right).

Two main conclusions can be derived from this aspect: (i) considering wind resources or environmental sensitivity in isolation leads to markedly different assessments of regional suitability for wind power deployment compared to a joint consideration of both criteria; and (ii) ad hoc planning approaches such as imposing similar wind power capacity densities across all regions, often perceived as a fair way to distribute the impacts of wind power deployment, could, in practice, lead to an inefficient use of wind resources and uneven environmental pressures, given the strong spatial heterogeneity revealed by the analysis.

Finally, Table 4 shows that several regions have enough techno-economic wind power potential in low-sensitivity areas to meet their current electricity demand, in some cases exceeding it by up to one order of magnitude (e.g. Castilla y León, Castilla-La Mancha, La Rioja and Aragón), while others do not. In six regions, the estimated electricity generation from the techno-economic potential remains below 95% of current demand, with particularly low values in the Comunidad Valenciana (26.9%) and the Comunidad de Madrid (20.2%). This regional contrast suggests that ad hoc planning criteria based on regional self-sufficiency, often perceived as an equitable approach because it links renewable generation to local demand, may in practice place excessive pressure on some regions while underexploiting the available potential in others. Further research is required to evaluate the extent to which an appropriate combination of wind and solar PV generation could support self-sufficiency-based planning. Nevertheless, solar PV potential and its environmental sensitivity are also expected to exhibit significant spatial heterogeneity.

Limitations of the study

The estimated wind power potentials are a direct consequence of the assumed power density of $d = 10$ MW km^{-2} applied to the land available under the selected criteria (economic viability and/or low environmental sensitivity). This parameter represents an average and relatively conservative value according to the literature, but it may vary in practice depending on turbine size, layout design, and wind farm configuration.

As described in Section 3, hourly capacity factors were computed assuming a single 3 MW wind turbine model. This choice represents a simplification of real-world conditions, which are characterised by a diversity of turbine models and by a clear trend towards increasing nameplate capacities over time.

Economic viability was defined through a capacity factor threshold of $CF^* = 0.30$, applied to the estimated wind resource at the grid-cell level. Despite the relatively high spatial resolution of the NEWA dataset, its ability to capture very local wind features remains limited. As a result, small-scale areas with particularly favourable wind conditions may not be fully represented. Consequently, the estimated potentials may be conservative, and their spatial distribution within each region may be underestimated.

Similarly, environmental suitability was defined based on the ISA 4 level. The ISA index is subject to future updates, which may modify the results obtained here. Additionally, the ISA index does not eliminate the need for an environmental impact assessment, which could yield negative results in areas labeled as ISA 4 and positive results in areas with other ISA indices associated with higher environmental sensitivity.

The analysis is based on a single meteorological year. Extending the assessment to multiple years would improve the robustness of the results by accounting for interannual variability. Although the main conclusions of this study are not expected to change qualitatively, future work will address this limitation.

Finally, it should be emphasized that this analysis does not directly translate into power system planning recommendations. Optimal system configurations should instead be derived from integrated analyses that account for all renewable generation and storage technologies, demand profiles, and the available transmission grid capacity [Gallego-Castillo and Victoria, 2025, Gallego-Castillo et al., 2025].

5 Conclusions

This study identifies, for the first time, Spain's wind power potential that is both economically viable and restricted to areas with low environmental sensitivity to wind farms. The analysis integrates high-resolution spatial datasets and provides detailed results at the NUTS-2 regional level.

At the national scale, the results indicate that 7.24% of Spanish territory combines low environmental sensitivity with high wind resources. The associated wind power potential amounts to 361 GW, roughly six times the onshore wind capacity target set for 2030 in the Spanish National Energy and Climate Plan (NECP, or PNIEC in Spanish), with an estimated generation representing more than 4.5 times current electricity demand. This finding indicates that a large-scale, economically viable and environmentally-friendly expansion of wind power is technically feasible in Spain. Nonetheless, Spain's abundant solar photovoltaic (PV) resource implies that wind energy will supply only part of total electricity demand, and that the required installed wind capacity will most likely remain well below the identified potential. For instance, the PNIEC sets a 2030 target for solar PV capacity that is approximately 25% higher than that for onshore wind.

The spatial distribution of the identified potential is highly heterogeneous, as areas with low environmental sensitivity and high wind resources are unevenly distributed across the country. Consequently, exploiting low-sensitivity and high-resource areas would result in higher project densities in some regions than in others. In addition, while the estimated wind power potential is insufficient to meet current electricity demand in some regions, it exceeds demand by up to one order of magnitude in others. This heterogeneity represents a fundamental feature that should be accounted for in renewable energy planning, as it may contribute to regional disparities in deployment pressures and social acceptance. In this context, ad hoc planning approaches, such as imposing similar wind power capacity densities across all regions or aiming for regional self-sufficiency by directly linking renewable deployment to local electricity demand, may seem equitable, but could in practice place excessive environmental pressure on some regions while underexploiting the available potential in others. This would result in a suboptimal spatial allocation of renewable capacity, leading to higher installed capacity requirements to achieve the same decarbonization targets, increased land use, and ultimately higher environmental impacts.

This study also shows that jointly considering wind resources and environmental sensitivity leads to a markedly different assessment of regional suitability for wind power deployment than evaluating each criterion independently.

Overall, these results highlight the importance of integrated spatial planning approaches and contribute to ongoing discussions on what constitutes a just energy transition, in which the distribution of environmental and social impacts across regions must be carefully balanced against the urgency of climate change mitigation.

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