Supplementary Methods 1 - Scoping review keywords for typification of energy-land systems

To select the main elements for a framework of solar and wind energy-land systems, we carried out a systematic literature review following the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) approach. We selected a set of keywords characterizing the object of study (solar and wind land systems) and process studied (typology). We tested keywords interactively in Scopus. We finally used the following search string to search titles, abstracts and keywords: ("*energy landscape*" OR "energy socio*" OR "energy social*" OR "Energyscape" OR "Landscapes of carbon neutrality" OR "Landscapes of energ*" OR "Photovoltaic landscape*" OR "wind landscape* " OR "solar landscape*") AND ("solar*" OR "wind*") AND ("typ*" OR "clust* " OR "group*"). We further limited the results to subject areas: energy, environmental sciences, multidisciplinary, agricultural and biological sciences, social sciences, and earth and planetary sciences.

Supplementary Methods 2 - Characterization of projects for energy-land systems typification

Each project was categorized based on the selected variables defining energy-land systems (Table S1). Because our data were compiled from diverse sources, we applied multiple approaches for this categorization. For projects that underwent an environmental impact assessment (EIA) or an environmental incidence analysis (EIncA), we coded the content associated with each variable in the impact assessment report, the environmental agency's evaluation report, and the final licensing report, depending on availability (Tables S1). For georeferenced projects lacking an EIA or EIncA, spatial data provided information on energy type, capacity and proponents; remaining variables were characterized through spatial overlays or specific assumptions (Table S1). For the spatial analysis, we used a refined polygon layer of solar projects (Alves et al., 2026) to update our solar project areas in the triangulated spatial data set. For wind projects, we added a 10-meter buffer to each wind turbine point to calculate the area of land cover change. This 10-meter distance represents a conservative estimate for analysing the land cover impact of the turbine foundations.

Supplementary Methods 3 - Social and ecological marginalization variables

To relate energy-land system types and socio-ecological contexts, we overlayed spatial information of projects with the following variables that indicate different aspects of social and ecological marginalization.

Land degradation index

This index monitors long-term ecosystem productivity loss at 1 km resolution (1970-2010) (ICNF, 2020b) by combining net primary production (NPP) and rain use efficiency (RUE). It uses satellite data (SPOT VEGETATION), climate records, and landcover data (Corine2006) to isolate human-induced degradation from natural rainfall variations, classifying land trends of plant biomass as increasing, fluctuating, static, or regressive (do Rosário, 2004).

Vegetation quality index

This index evaluates vegetation susceptibility to desertification (ICNF, 2020c) for the year 2000, at 1 km resolution, based on six variables: (i) resistance and recovery capacity regarding fire; (ii) degree of soil erosion protection provided by plant structures; (iii) ability of species to survive water stress; (iv) horizontal percentage of soil covered by vegetation; (v) structural cover or the vertical analysis of plant layers (tree, shrub, herb) and (vi) how close the vegetation is to its natural potential state. The values of the six previous indicators were cross-referenced and processed using a Principal Component Analysis to define a gradient of vegetation quality from "low" to "very high" (do Rosário, 2004).

Aridity index

This index measures the degree of aridity (ICNF, 2020a) by calculating the ratio between precipitation and potential evapotranspiration (ETP) at 1 km resolution. It identifies "dry areas" such as dry sub-humid, semi-arid, and arid zones. The data is modelled using kriging techniques to account for altitude and meteorological station readings (do Rosário, 2004).

Energy poverty vulnerability index (IVEM)

This index assesses a municipality's (NUTSII) propensity for energy poverty in 2021 (Carvalho et al., 2023) using an econometric model at the resolution of the municipality. It crosses census data (ICOR, 2021) with municipal indicators, including demographics (age, gender, nationality), employment status, education levels, housing conditions (overcrowding, ownership), and gross household income.

Distance to health facilities

It measures accessibility based on driving time from 1km population cells to the nearest healthcare services in the year 2023 (EUROSTAT, 2025). The model uses a complex road network graph (considering bridges, speed limits, and directions) and calculates both the time to the single nearest service and the average time to the three nearest services.

Population density

It measures settlement intensity (INE, 2023), expressed as the number of inhabitants per square kilometre (inhabitants/km^2) at the municipality level for the year 2023 (NUTSII).

Active population index

It is the ratio between the population potentially entering the labour market (ages 20–29) and those potentially exiting (ages 55–64) (INE, 2024a). It indicates the capacity of a population to replace its workforce at the municipality level (NUTSII) for the year 2023.

Average income

It computes the average gross declared income per taxpayer at the parish level (NUTS III) for the year 2023 (INE, 2024b). It includes non-exempt income before deductions for employment (category A) and pensions (category H) for residents and non-residents earning in Portugal.

Rural land prices (2020)

The average value of transacted rural properties per municipality in 2020 (INE, 2021). It encompasses the total economic value of the land, including water, plantations, and permanent buildings, divided by the total number of transactions in a given period.

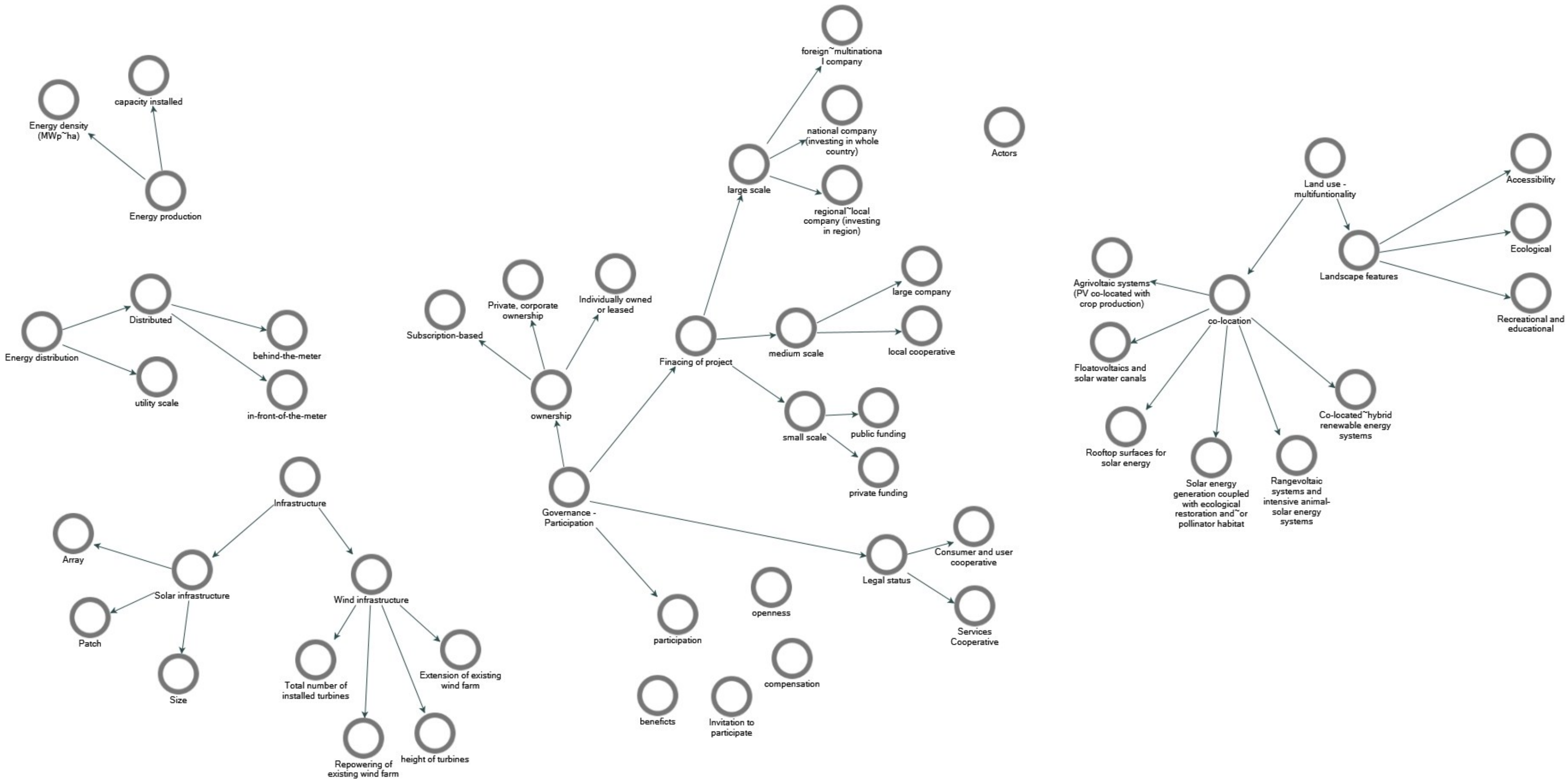

Figure S1- Codemap from the literature review mapped against main categories of Ostrom's framework of socio-ecological systems for project characterization.

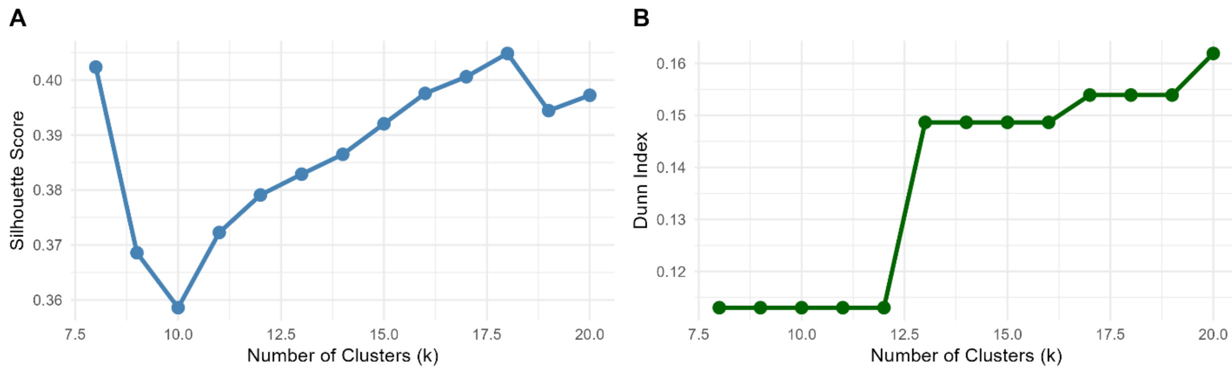

Figure S2 - Cluster validation metrics: (A) Silhouette score and (B) Dunn index across tested clusters.

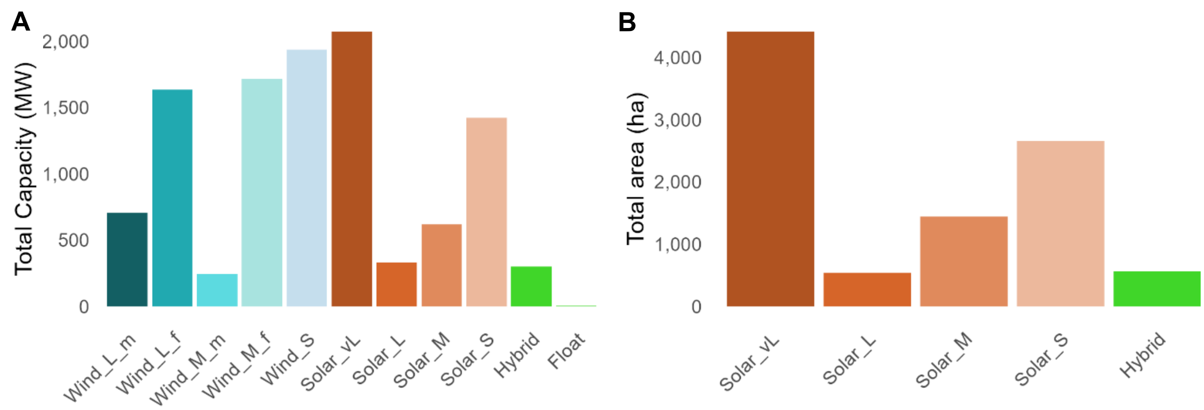

Figure S3 - Total installed capacity per type of utility scale energy-land system (A) and total project area for utility-scale solar energy-land system per type (B).

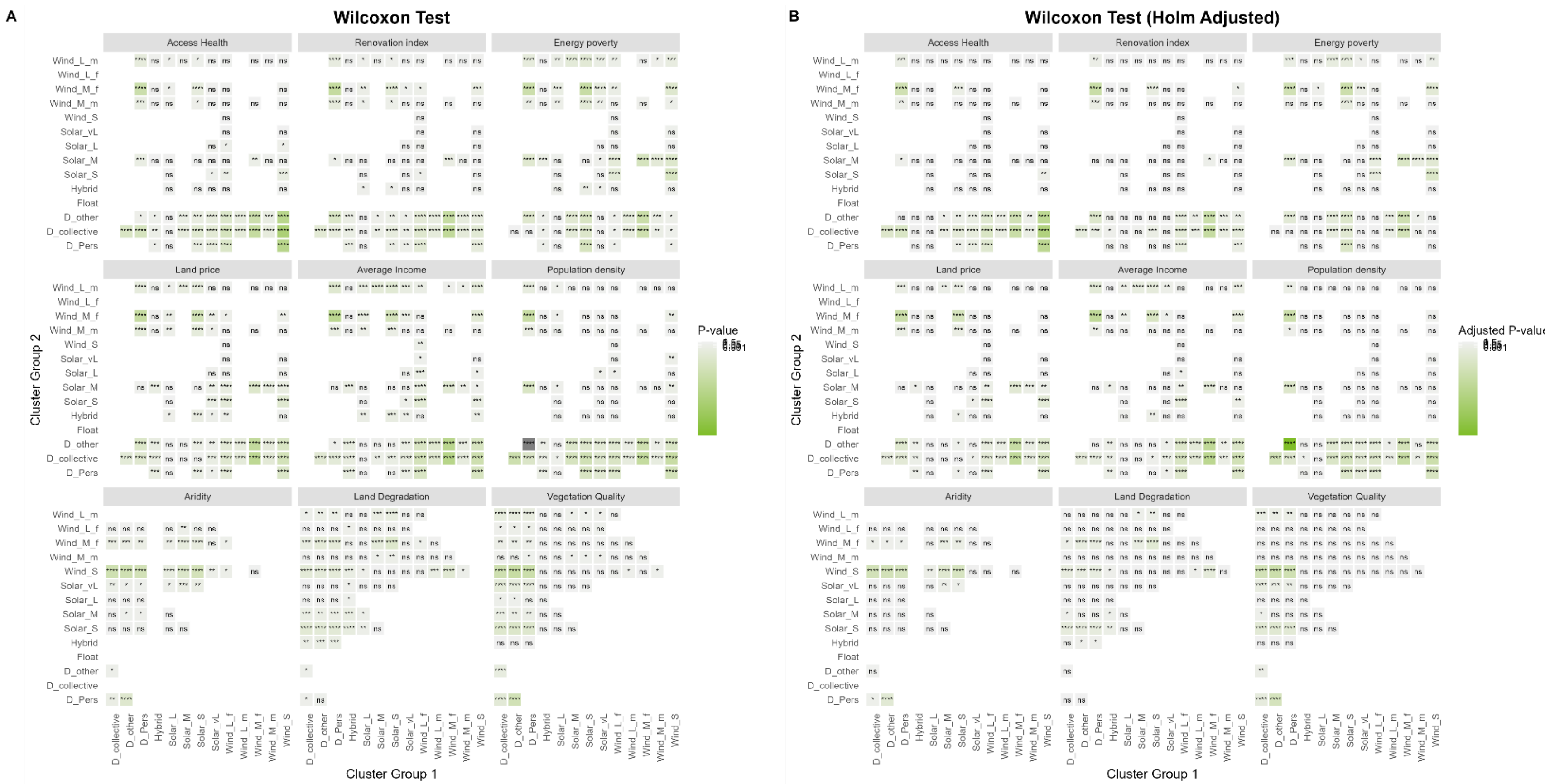

Figure S4 – Heatmap of pairwise cluster differences, displaying non-corrected significance analysis (A) and Holm-corrected significance analysis (B).

Table S1: List of reviewed peer reviewed papers for typology design

N	Record title	Reference
1	Distributed energy generation and sustainable development	(Alanne and Saari, 2006)
2	Contentious eye-catchers: Perceptions of landscapes changed by solar power plants in Slovenia	(Bevk and Golobič, 2020)
3	Landscape user experiences of interspace and overhead agrivoltaics: A comparative analysis of two novel types of solar landscapes in the Netherlands	(Biró-Varga et al., 2024)
4	Mutually-Beneficial Renewable Energy Systems	(Burke, 2018)
5	Scales of solar energy: Exploring citizen satisfaction, interest, and values in a comparison of regions in Portugal and Spain	(Campos et al., 2023)
6	Just participation in wind energy: The role of social innovations	(Campos et al., 2025)
7	David against Goliath? Challenges and opportunities for energy cooperatives in Southern Europe	(Delicado et al., 2023)
8	Conceptualizing the patterns of land use conflicts in wind energy development: Towards a typology and implications for practice	(Frantál et al., 2023)
9	Renewable Energies and European Landscapes: Lessons from Southern European Cases	(Frolova et al., 2015)
10	Techno–ecological synergies of solar energy for global sustainability	(Hernandez et al., 2019)
11	Insights to accelerate place-based at scale renewable energy landscapes: An analytical framework to typify the emergence of renewable energy clusters along the energy value chain	(Hoicka et al., 2025)
12	A review of land use, visibility and public perception of renewable energy in the context of landscape impact	(Ioannidis and Koutsoyiannis, 2020)
13	Eleven Reasons Why Behind-the-Meter Distributed PV Lowers Electricity, Health, and Climate Costs for Everyone	(Jacobson, 2024)
14	A typology of actors and their strategies in multi-scale governance of wind turbine conflict within forests	(Juerges et al., 2020)
15	The geographies, typologies, and trends of community-based organizations for solar energy in the United States	(Knox-Hayes et al., 2023)
16	How can energy prosumerism align with sufficiency and justice principles? A typology for policymakers, researchers and practitioners	(Korsnes et al., 2024)
17	Complex Systems and Social Practices in Energy Transitions	(Labanca, 2017)
18	Are big and small solar separate things?: The importance of scale in public support for solar energy development in upstate New York	(Nilson and Stedman, 2022)
19	Next generation solar power plants? A comparative analysis of frontrunner solar landscapes in Europe	(Oudes and Stremke, 2021)
20	Towards a typology of solar energy landscapes: Mixed-production, nature based and landscape inclusive solar power transitions	(Oudes et al., 2022)

21	Energy landscapes in a crowded world: A first typology of origins and expressions	(Pasqualetti and Stremke, 2018)
22	Impact on the perceived landscape quality through renewable energy infrastructure. A discrete choice experiment in the context of the Swiss energy transition	(Salak et al., 2022)
23	‘Photovoltaic landscapes’: Design and assessment. A critical review for a new transdisciplinary design vision	(Scognamiglio, 2016)
24	Agrivoltaics and landscape change: First evidence from built cases in the Netherlands	(Sirnik et al., 2024)
25	Research through design for energy transition: two case studies in Germany and The Netherlands	(Stremke and Schöbel, 2019)
26	When democracy meets energy transitions: A typology of social power and energy system scale	(Thombs, 2019)
27	The economics of solar PV self-consumption in Thailand	(Tongsopit et al., 2019)
28	A Standardized Classification and Performance Indicators of Agrivoltaic Systems	(Willockx et al., 2020)

Table S2: Summary of energy-land system variables and classification approach.

Variable	Category	Summary of variable and classification approach
Energy type	Agrivoltaic, Hybrid, Solar, Floatvoltaic, Wind	Main wind and solar energy technologies in Portugal. "Agrivoltaic" refers to solar technology co-located as a dual land system for both agriculture and energy production. In "Solar," energy production is the primary goal, though other uses like grazing may sporadically occur. This information was available for all projects.
Installed capacity (log)	Continuous value	The maximum output (MW) the facility is designed to produce, indicating production intensity. To improve comparability, a logarithmic transformation was applied. This information was available for all projects.
Proponent	Other (non-specialized) Cooperative and NGOs, Other (non-specialized) Private Company, Personal, Public, RE Private company, RE Cooperative and NGOs	The main actor responsible for project development. This information was available for all projects.
Energy system	Self-consumption (UPAC), Micro-production (UPP), Utility-scale, Energy community (CER), Collective self-consumption (ACC)	Legally recognized production and distribution forms associated with specific governance structures. For georeferenced projects with missing data, classification was inferred from project names. For decentralized projects with unclear status, a "self-consumption" (UPAC) classification was assumed, as most post-2019 projects fall under this regime due to legislative limits on UPP, Order No. 27/2020, of 23 March (Gonçalves, 2018). • <u>Individual Self-Consumption (UPAC in Portuguese):</u> Individual self-consumption refers to the production of electricity for use within facilities associated with a single electrical installation, regardless of whether it is connected to the public grid. Any surplus electricity not consumed locally may be sold to the grid (Decree-Law No. 15/2022, 14 January). • <u>Collective Self-Consumption (ACC in Portuguese):</u> Collective self-consumption is the production of electricity for two or more electrical installations, with the self-consumption production units (UPACs) installed on or near those facilities. Members may act as consumers, producers, or both. Typically, sharing is overseen by a Collective Self-Consumption Management Entity (EGAC)—such as a condominium, company, local community, or third party—which represents the collective before operators and administrative authorities.

		Participants are responsible for formulating internal regulations and establishing the management entity (Decree-Law No. 162/2019, 25 October). Any surplus electricity not consumed locally may be sold to the grid. These units may be owned by a third party, and surplus electricity can be monetized through sale. • Energy community (CER in Portuguese): A CER is a legal entity, whether for-profit or non-profit, based on open and voluntary membership. Members, partners, or shareholders may be individual or collective persons of a public or private nature, including small and medium-sized enterprises or local authorities. The entity is autonomous from its members but effectively controlled by them, provided that: i) Members are located in the vicinity of the renewable energy projects or engage in related activities; ii) Projects are owned and developed by the legal entity; iii) The primary objective is to provide environmental, economic, and social benefits to members or local areas rather than financial profit. CERs are also entitled to access all energy markets (Decree-Law No. 162/2019, 30 December). • Micro-production (UPP in Portuguese): This category includes the Small Production Unit (UPP) regime, which utilizes a single production technology with a maximum installed capacity of 1 MW. All energy produced is intended for sale to the grid (DGEG). This includes UPP projects registered under Decree-Law No. 153/2014 (20 October), as well as legacy micro-production units and mini-production units (Decree-Law No. 25/2013, 18 February). • Utility-scale: This refers to energy production technologies with an installed capacity exceeding 1 MW, intended exclusively for the total sale of energy to the grid (Decree-Law No. 15/2022, 14 January).
Co-land governance	Protected area and Commons, Protected area or Commons, Other	The colocation of energy project with other land governance entities, namely, protected areas and communal land (baldios). Both represent important institutions of land governance in areas of solar and wind energy production For georeferenced projects not evaluated under EIA/EIANCA, we overlaid the project locations with maps of communal lands and protected areas. Specifically, we used data for the National Network of Protected Areas including National Parks, Natural Parks, Nature Reserves, Protected Landscapes, and Natural Monuments (ICNF, 2020d), and

		data on communal lands (*Baldios*) provided by the Institute for the Financing of Agriculture and Fisheries (IFAP, 2015). For non-georeferenced decentralized projects, we assumed no overlap.
Compensation schemes	1, 2, 3	Number of compensation schemes associated with the energy project, grouped by economic, environmental or cultural schemes. For all utility-scale projects, we assumed there would always be at least one scheme, economic compensation (in the form of rent). For decentralized projects we assumed no compensation (0) as this is not a typology of project that typically requires compensation (e.g. renting land). Below we present how we grouped identified compensation measure with examples of measures identified in EIA/EINCA: • Economic: Rental of land, financial compensation allocated to the municipality and parish councils, transfer of capital gains to municipality, job creation, boost the local/regional economy, compensation for expropriations, support for the local Technical-Vocational School in its areas of solar expertise. • Cultural: Actions related to research, safeguarding and enhancement, as well as dissemination of cultural heritage, supporting rural tourism, creation of a centre for environmental education and interpretation, restoration of the mill, recording archaeological finds and their study, installation of leisure equipment in the adjacent area. • Environmental: Financial participation in plans to monitor impacts on wolves, combating forest fires, restoration of riparian habitats, planting of oak trees, habitat management for golden eagle, planting of native species, measures for the black vulture population, information to the public about the sensitivity of the surrounding areas.
Transparency	0-5	Degree of project communication to local communities and entities. We assumed that utility-scale projects not undergoing an EIA or EIncA had little to no communication (assigned a value of 1). For decentralized projects, this variable was deemed not applicable (0), as this project typology typically does not require formal communication measures. For all other projects, if any of the communication measures listed below were identified, the project was assigned the highest value. Below we present how we grouped identified communication measure with examples of measures identified in EIA/EINCA: • communication of construction (2): communication of deployment works to the public.

		• communication of project (3): awareness-raising actions, communicate the project and its risks to owners and the public, providing information about the park, its advantages and the surrounding flora and fauna, production of project dissemination materials. • after construction, communication mechanism (4): mechanism to report complaints. • during construction, two-way communication (5): actions to inform and consult the public on the progress of works. • long-term communication of project (5): environmental education with schools and the community, visited by students on educational visits, tourist and educational visits to raise awareness of natural values. • before construction, two-way communication (5): EIA clarification session, health information session, information sessions for affected people, information sessions on magnetic fields.
Participation	0-3	Degree of participation of local communities or entities in project design. We assumed that utility-scale projects not undergoing an EIA or EIncA had little to no participation (assigned a value of 1). For decentralized projects, this variable was deemed not applicable (0), as this project typology is under different participation logics (Campos et al., 2023). For all other projects, if any measure within this category was identified, the project was assigned the highest value. Below we present how we grouped identified participation measures with examples of measures identified in EIA/EINCA • coordinated construction with host (1): coordinated barriers with owners and parish, transport line defined in consultation with affected owner, in coordination with owners and municipality to define vegetation management procedures, opening of accesses in collaboration with owners, negotiation of line construction periods with owners, execution of works adjusted with landowners, green structure maintained in agreement with owner. • coordinated construction with affected locals and local authorities (2): collaboration with municipality to ensure availability of land, positioning negotiated with national forestry authority, participation and monitoring by the Northern Forest District, line layout in consultation with Municipal Council, collaboration with municipalities to define the route and accesses.

		• <u>prior consultation of local authorities and/or affected populations (3)</u>: consult local authorities and affected populations, Prior consultation of local authorities and/or affected populations.
Co-location with other land uses	Complementary land uses (pasture, cropping or beekeeping), Commercial, Industrial, Energy, Institutional, None, Residencial	We classified land uses reported to occur within the project area based on information provided in the EIA or EIncA. For projects where only georeferenced information was available, we assumed no co-location. In the case of decentralized projects, we assumed co-location based on the site of energy production.
Green infrastructure: interior	0-5	Level of green infrastructure such as trees, shrubs, vegetation or water bodies within the solar project. Higher levels reveal an attempt to support biodiversity aspects within the solar project area. Based on a combination of visual analysis and content analysis of EIA/EIncA, we categorized the degree of green infrastructure integrated within the interior of solar projects. For projects that were georeferenced and for which both a visual assessment and impact assessment information were available, priority was given to the visual assessment to maintain comparability across implemented sites. If a project was still in the construction phase or had not yet been implemented, the evaluation was based strictly on the provided assessment documentation. The scoring system evaluated two primary characteristics: the spacing between solar panel arrays and the presence of ecological structures. We assigned the lowest scores to projects featuring no spacing between arrays. Scores increased progressively for projects that incorporated wider spacing, reflecting a higher potential for natural regeneration, and for those that integrated specific ecological features such as herbaceous vegetation, shrubs, trees, or water bodies.
Green infrastructure: curtains	0-4	Level of green infrastructure like trees or shrubs surrounding the solar project. Higher levels reveal an attempt to diminish visual impacts of the solar project. This variable was ascertained based on visual analysis and content analysis of EIA/EINCA. We categorize the degree of green infrastructure based on the number of sides of the solar project covered by trees or shrubs. For projects that were georeferenced and for which both a visual assessment and impact assessment information were available, priority was given to the visual assessment to maintain comparability across implemented sites. If a project was still in the construction phase or had not yet been implemented, the evaluation was based strictly on the provided assessment documentation.

Previous land cover: main land cover	Agriculture, Artificial – rural, Artificial-industrial, Artificial-urban, Artificial, Forest, Grasslands, Mixed cover, Olive groves, Production forest, Vegetation, Vineyard, Shrubland, Water body	Land cover replaced by the solar project. Main land cover corresponded to the land cover that occupied more than 60% of the project area. If no land cover fulfilled this criterion, we categorized it as "mixed covers". For project not evaluated though EIA/IANCA, land cover areas were calculated by overlaying georeferenced projects with land cover maps from the specific year (1995, 2007, 2010, 2015, 2018, or 2023) preceding the project's start date (COS1995v2, COS2007v3, COS2010v2, COS2015v2, COS2018v3 and COS2023v1). We used the Land Use and Occupancy Maps created by the Directorate-General for Territory for this purpose (DGT, 2025b, a). For decentralized project not georeferenced, we gather this information from textual analysis of project information.
Previous land cover: conservation elements	No, yes	Presence of "*montado*" trees, or rocky outcrops. *Montado*" represents important conservation elements of lowland areas while rocky outcrops represent important geological and conservation features in high-altitude regions (Fitzsimons and Michael, 2017; Hespanhol et al., 2011). The removal of protected "*montado*" trees requires authorization and compensations (Decree-Law No. 11/2023, of 10 February), moreover, represent a cultural important tree that attracts wide attention to the project (Alves et al., 2026; Silva and Sareen, 2021). Rocky outcrops often harbour protected habitats (Decree-Law No. 140/99, of 24 April). These two elements were selected due to their consistent relevance in environmental impact assessments evaluations. For project not evaluated though EIA/IANCA, this was evaluated by identifying the presence of outcrops, holm oaks (*Quercus ilex*), and cork oaks (*Quercus suber*) when overlaying georeferenced projects with land cover maps from the specific year (1995, 2007, 2010, 2015, 2018, or 2023) preceding the project's start (DGT, 2025b, a). For non-georeferenced decentralized projects, we assumed none of these conservation elements were present.
Solar project area	0-4	Area covered by solar project. This information was available for all utility-scale solar projects. Area is presented in ha. To improve comparability across projects, we applied a logarithmic transformation to this variable. We then reclassified the data into four categories using equal intervals to minimize discrepancies arising from variations in project mapping. We did not include the project area for any wind project given the higher landscape embeddedness of wind turbines, making a consistent accounting difficult. Furthermore, we did not include area for decentralized projects, given limited information.

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