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LAND SYSTEMS Discussions

A multiform energy transition: typifying wind and solar energy-land systems in Portugal

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Abstract. The expansion of solar and wind power creates complex "energy-land systems" defined by interactions between governance, land use, and energy production. While critical for the energy transition, utility-scale projects often face social contestation rooted in the socio-ecological marginalization of rural areas. Addressing these challenges requires a granular, nationwide understanding of renewable energy systems and their local contexts. Focusing on Portugal, we categorized 760 renewable energy projects and used multivariate cluster analysis to identify 18 energy-land system types. Deployment contexts were analysed using indicators of socio-ecological marginalization, including land degradation, energy poverty, income levels, demographic dynamics, and land prices. Our findings reveal that geography and scale are primary drivers of energy-land system diversity. Wind systems in the North favour co-location (e.g., pasture, beekeeping) and co-governance (e.g., protected areas, commons), while solar systems in the South are distinguished by production levels and externality mitigation.

Furthermore, we found that large-scale projects are frequently located in highly marginalized regions and incorporate more socio-ecological measures. Conversely, smaller utility-scale projects tend to occupy more productive, less marginalized land. These patterns illustrate trade-offs between deployment strategies—such as few large projects versus several small ones—with direct implications for energy policies. To our knowledge, this study presents the first nationwide analysis of energy-land systems, providing a replicable approach for system characterization. By adopting a land-system perspective, this research supports planning decisions aimed at creating multifunctional, equitable systems that better align rural needs with the requirements of the energy transition across various scales.

Short summary:

Solar and wind renewable energy projects are vital for clean energy, but such projects are increasingly socially and politically contested. The deployment of such projects creates complex "energy-land systems". In Portugal we find 18 distinct system types and their wider socio-ecological contexts. Although large projects include more socio-ecological measures they often occupy highly marginalized regions. Understanding projects and their context allows supporting future planning decisions.

Solar and wind power are vital for clean energy, but projects face rising social and political opposition. These developments form complex "energy-land systems" that impact local communities. In Portugal, we identified 18 distinct system types across different regional contexts. Although large-scale projects incorporate more social and environmental measures, they often occupy marginalized areas. Understanding these local dynamics helps planners design fairer, better-integrated energy projects.

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Keywords: Energy landscapes, Energy justice, Socio-ecological marginalization, Renewable energy, Socio-ecological systems, Utility-scale solar and wind projects

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1. Introduction

The energy transition hinges on the rapid uptake of renewable energy (RE). While solar and wind are the fastest-growing energy sources, they also have a larger land footprint than conventional fossil-based systems (Birol, 2008; Smil, 2015; van Zalk and Behrens, 2018). Consequently, RE deployment is increasingly constrained by land use competition, social acceptance, and limitations for grid access, among other factors (Dunlap et al., 2025). As the energy transition is still underway and far from phasing out fossil fuels (Fressoz, 2024), many countries are struggling to meet their climate goals, such as the European Union's (EU) objective to reach net-zero by 2050 (European Parliament, 2021). Meeting these targets will require more RE projects, intensifying the demand for land.

The deployment of wind and solar PV energy projects is reshaping landscapes, creating new renewable energy-land systems (ELS). We define ELS as the complex interactions of people, nature and energy systems occurring on landscapes that include infrastructure for energy production, storage, transportation, and distribution. These systems are characterized by specific actors, project types, goals, and forms of governance. Analysing this interplay requires a holistic framework such as Ostrom's Socio-Ecological System Framework, originally applied to resource management (Ostrom, 2009). Concepts such as energyscapes—defined as the place-based manifestation of a sociotechnical system linking energy supply, demand, and local socio-ecological characteristics—emphasize this complexity (Harlan and Baka, 2024; Howard et al., 2013; Nadaï and van der Horst, 2010; Pasqualetti and Stremke, 2018). RE developments can compete with, be synergistic, or complement pre-existing land uses, offering varied multifunctional potentials (Becker et al., 2025; Oudes et al., 2022). For example, a solar park might integrate green infrastructure for ecological benefits, allow for complementary economic activities like grazing or beekeeping, or feature co-ownership models that influence decision-making (Asa'a et al., 2024; Blaydes et al., 2021; Clausen and Rudolph, 2020; Hernandez et al., 2019). Such an integrated and granular understanding of renewable energy projects as ELS is still missing.

Investigating how the energy transition is changing landscapes and land-use practices can provide insights on how to navigate this transition sustainably. While some work has explored RE projects along multiple dimensions, these studies are often limited to singular features (e.g., technology, landscape, size, goals, or actors) or to a small sample of projects (Alves et al., 2026; Becker et al., 2025; Oudes et al., 2022). We currently lack an understanding of the major types of ELS created at a country scale, which has implications for social acceptance. Social acceptance is a complex concept (Batel, 2020), but two aspects are most relevant: 1) the project characteristics (e.g., size, ownership, compensation, local community participation)

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and 2) the socio-ecological contexts of its deployment (Campos et al., 2023; Cousse, 2021; Enserink et al., 2022; Roddis et al., 2020).

Because most utility-scale projects are sited in rural landscapes, due to land availability and grid capacity, rural populations are often disproportionately burdened (Brown et al., 2024; Naumann and Rudolph, 2025). This uneven distribution of impacts has led to "green sacrifice zones" in marginalized areas, highlighting the risks of an unjust energy transition (Scott and Smith, 2017; Wallace et al., 2025; Zografos and Robbins, 2020). Understanding the socio-ecological context of deployment helps evaluating both the positive and negative impacts of RE land systems in rural areas.

The course of the energy transition in any given place is modulated by the interplay of policies, land-use planning, and dominant actors, which determines the permissible scale, location, and characteristics of RE projects. RE planning is increasingly integrated into land-use planning, e.g. through the identification of “Renewables acceleration areas” in the EU Member States where licensing and environmental evaluation requirements are simplified (European Parliament and of the Council, 2023). The objective is to minimize socio-ecological impacts by prioritizing marginal land (e.g., brownfields). However, the reality of deployment is complicated by spatial restrictions imposed by the grid capacity, the availability of suitable land, and the divergent interests and power relations of stakeholders. In the absence of strict regulations, utility-scale projects can be sited on productive or culturally or ecologically sensitive land, potentially reinforcing marginalization through the loss of economic activities or landscape value (Sorman and Stock, 2024). Therefore, there is a need for a siting approach that better links the type of project to the specific socio-ecological contexts to promote the delivery of multiple benefits. Such a context-specific approach can help to not only achieve climate targets but also foster rural revitalization and a just energy transition.

To develop a framework for designing context-specific RE projects, we focus on Portugal as a case-study. Portugal has seen rapid RE deployment since the 2000s, reaching an installed capacity of over 20 GW in 2025 (DGEG, 2025b). The vast majority (86%) of this capacity is utility-scale, primarily wind, solar, and hydropower, overwhelmingly in rural areas, with the remaining (14%) being decentralized solar (DGEG, 2025b). Strategic policy documents, such as the *Roadmap to Carbon Neutrality* (Government of Portugal, 2019b), and the *National Energy and Climate Plan* (Government of Portugal, 2024), aim to double the total installed capacity by 2045. So far, this transition has primarily relied on private entities incentivized to develop centralized utility-scale projects, through policy instruments like feed-in tariffs for early wind and solar developments, followed by contracts-for-difference linked to grid capacity auctions and market-exposed projects as solar became increasingly economically viable (Peña et al., 2017; Sareen, 2024). This political focus on centralized developments led to a slow uptake of decentralized projects, mainly solar (Campos et al., 2023; Sareen, 2021). The rapid deployment of utility-scale projects has unfolded against a

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backdrop of severe socioeconomic challenges in some of Portugal's rural areas, characterized by exodus, decaying services, frequent forest fires, land abandonment in some areas, and intensive industrial agriculture development in others (Ferreira et al., 2024; Jones et al., 2011). The roll-out of RE has faced growing resistance from local communities and environmental organizations, particularly against large solar and wind projects (Brás et al., 2024).

Seeking to guide a more sustainable energy transition, some authors have argued for improved planning and adaptation of RE projects design, site selection, and governance according to their socio-ecological context (Sequeira, et al., 2025). The novelty of this paper lies in looking back at RE developments in Portugal with high-granularity to identify the major ELS created and assess whether they promote a rural revitalization by generating co-benefits, integrating local needs, and supporting multifunctional landscapes.

To achieve this goal, we first review existing typologies of energy-land and socio-ecological systems, and map these against Ostrom's socio-ecological system framework. We then typify solar and wind land systems based on several indicators and contrast them with proxy variables for social and ecological marginalization of landscapes. We focus on mainland Portugal and ask: (i) What are the major types of solar and wind energy-land systems in Portugal? (ii) How are these types spatio-temporally distributed? (iii) What is the contribution of each of these types to total renewable energy production in Portugal? and (iv) How do different types of energy-land systems relate to geographies of social and ecological marginalization in Portugal?

2. Methods

We first identified important elements for a framework of solar photovoltaic (PV) and wind ELS from the literature. We then collected all available information on solar and wind projects in Portugal and characterized each project according to the created framework. We then performed a cluster analysis based on project characteristics. The resulting types were analysed in terms of their spatio-temporal distribution and their contribution to total energy production. Finally, these types were crossed with indicators of socio-ecological marginalization of areas.

2.1. Identifying elements of energy-land systems

We conducted a scoping literature review on types of solar and wind energy landscapes and socio-ecological systems. We used the Scopus database, searched on 29/01/2025, focusing on categorizations of solar and wind ELS (see keywords in SM1). This search resulted in 80 articles. Those were further filtered for articles focused on typification or classification of energy projects, resulting in 15 articles. We further included by snowball sampling 13 additional papers, totalizing 28 articles reviewed (Table S1). We identified defining characteristics of ELS, including forms of participation, types of actors, ownership, co-location or landscape features. Based on Ostrom's framework for social-ecological systems (Ostrom, 2009), we selected and organized the variables considering four dimensions: users, resource units, resource systems, and governance (Table 1, Fig. S1).

2.2. Solar and wind projects collection and characterization

We gathered information on solar PV and wind projects in Portugal from spatial data, environmental impact and incidence assessments, public inventories, and data requests submitted to energy companies and cooperatives.

Spatial data on these projects were sourced from official public databases (APA, 2025; DGEG, 2025a), previous mapping efforts (Alves et al., 2026; Magalhães. et al., 2024), Alves, 2026), and global platforms like Global Energy Monitor (GEM Wiki, 2025) and Solar Asset Mapper (Phillpott et al., 2025), between February and May 2025. We collected available Environmental Impact Assessments (EIA) from the Portuguese Environmental Agency portal and Environmental Incidence Assessments (EIncA) from the Regional Coordination and Development Commission of each Portuguese region. To accelerate deployment of RE projects, licensing has been streamlined under the new "Simplex Ambiente" regulation in 2023 (Government of Portugal, 2023), which changed the thresholds for mandatory EIAs from 50 MW to 100 hectares for solar PV or 20 turbines for wind projects. Thus, recent solar and wind projects that undergo an EIA or EIncA either meet these size thresholds, are near other projects that totalize these values, or are located in sensitive areas (e.g., protected areas, or National Agricultural or Environmental Reserves) (Government of Portugal, 2023). The spatial and EIA/EIAncA data primarily focus on utility-scale energy projects. We did not analyse EIA of repowering projects.

To capture the decentralized RE segment, we also collected information on individual projects from different platforms and company websites (e.g., GoParity) and from previous studies on collective energy projects (Ferreira, 2025). We also requested data from energy companies and energy cooperatives, with only one response received. Finally, we generated dummy projects classified as typical personal solar panels (below 6 kW) to include a sample of individual self-consumption projects following the Portuguese distribution system operator (DSO) categorization. To understand the spatial dimension of decentralized projects, we used the aggregated data on self-consumption and collective self-consumption projects available from the Portuguese DSO data platform (E-REDES, 2025b, a).

Data were triangulated to provide a complete picture of each solar and wind project. When information from different sources did not match, we gave priority to information from governmental sources (DGEG and APA). From the spatial data, we only included projects already established or in construction, based on

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a visual identification on orthophoto maps from 2023 at the earliest. To include some of the expected variability in the near future, we also included newly accepted projects in the planning phase (licensed and with allocated network capacity), including hybrid, large-scale solar, and floatovoltaic projects.

Each project was then categorized based on the variables defining ELS (Table 1). For every project that underwent an EIA or EIncA, we performed a content analysis in Nvivo software (version 14) of the impact assessment report, its evaluation report by the environmental agency, and the final licensing report. The resulting categorization represents stated project information rather than materialized outcomes. The other projects were characterized by overlaying georeferenced projects with land cover data from the year preceding the project year and with maps of communal land (see SM2, Table S2). We also conducted a visual analysis of green infrastructure in solar projects — i.e. vegetation and spacing within the project area and presence of "green curtains". The decentralized projects not georeferenced were categorized only based on the available textual information. For the last two groups (non-EIA/EIncA projects georeferenced and not), we made informed assumptions regarding unavailable variables. For instance, we assumed that projects which did not require an EIA would include very low to no public participation, given the non-obligatory nature of public involvement in those cases (see SM 2, Table S2). Those decisions were informed based on policy and consensus reached in multiple conversations with local experts on energy project developments in Portugal from research organisations, energy companies, cooperatives and energy associations. We did not include the project area for wind projects given the higher landscape embeddedness of wind turbines, making a consistent accounting difficult.

Table 1 - Energy-land systems typology framework by dimensions, variables, and sub-variables type of classification and specific data categories.

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Dimension	Variable	Sub-variable	Classification	Categories
Energy units	Energy type		Categorical	Agrivoltaic (primary goal agriculture), Floatvoltaic, Hybrid, Solar, Wind
	Energy production	Installed capacity (log)	Continuous	
Users	Proponent		Categorical	Other cooperative and NGOs, Other private company, Personal, Public, RE private company, RE cooperative and NGOs
Governance system	Energy system		Categorical	Collective self-consumption (Coll self-cons), Micro-production (Microprod), Renewable energy community (REC), Self-consumption (Self-cons), Utility-scale
	Co-land governance		Categorical	Protected area and commons, Protected area or commons, Other
	Forms of participation	Transparency	Degree	0-5, degree of project communication measures by comprehensiveness
		Compensation schemes	Degree	Cultural, Economic, environmental, Number of compensation schemes associated with the energy project, grouped by schemes type
		Participation	Degree	0-3, degree of participation of local communities in project design
Resource systems	Co-location	Land uses	Categorical	Complementary land uses (pasture, cropping or beekeeping), Commercial, Energy, Industrial, Institutional, Residential, None
		Green infrastructure: Curtains	Degree	0-4, degree of green infrastructure integrated within the interior of solar projects
		Green infrastructure: Internal	Degree	0-4, number of sides of the solar project covered by trees or shrubs
	Previous land cover	Main land cover	Categorical	Agriculture, artificial, artificial-industrial, artificial-rural, artificial-urban, forest, grasslands, mixed cover, olive groves, production forest, vegetation, vineyard, shrubland, water body
		Conservation elements (protected trees, *montado*, and geologically important outcrops)	Boolean	No, yes

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	Solar project area	Degree	0-4, degree of solar project area categorized in four groups

2.3.Identifying major types of energy-land systems

We classified projects using hierarchical clustering methods (Kaufman and Rousseeuw, 2009). As we included both continuous and categorical data, we calculated a distance matrix using Gower's distance (Gower, 1971). Solutions ranging from six to 20 clusters were analysed, to allow for sufficient diversity of ELS. We evaluated the hierarchical dendrogram with the Cophenetic Correlation Coefficient (CCC) and used evaluation metrics Silhouette analysis and Dunn index to select the optimal solution for number of clusters (Kaufman and Rousseeuw, 2009). Finally, each project was assigned to its resulting cluster. Cluster characteristics were summarized based on the aggregate features of classified projects.

2.4. Spatial and temporal distribution of energy-land system types

We differentiated centralized and decentralized project types due to differences in data availability. For the centralized, utility-scale types, the dataset was comprehensive, allowing for analyses of the spatial distribution and year of licensing or deployment of each project. By contrast, the analysis of decentralized types relied on a sample of projects. The primary and most complete temporal and spatial information came from an administrative dataset of collective and non-collective decentralized projects (E-REDES, 2025a, b), aggregated to the parish level. Given the limited information in this dataset, we assumed that self-consumption projects with an installed capacity below 4 kW were household-level projects. The remaining capacity intervals of self-consumption projects (4-30 kW, 30-1000 kW, and above 1000 kW), we could not link with our types and thus we grouped them into an "other decentralized" type. Another group included all collective decentralized projects. Collective decentralized projects might be included with self-consumption projects due to the absence of disaggregated data regarding installed capacity for collective versus individual self-consumption units. For these datasets, the temporal information is only available from 2022, which prevented analysing trends for the decentralized types.

We presented the spatial distribution of ELS types by Portuguese regions (NUTII) and overlayed types on an adapted map of urbanisation levels (Wolf et al., 2020). These levels were simplified into three categories: rural, urban, and urbanization, the latter representing areas in rural or peripheries of urban areas that have experienced growth in population density and services. Finally, we calculated the total installed capacity by type and computed total area for utility-scale solar projects by type.

2.5. Indicators of socio-ecological marginalization

We identified geographic variables that indicate social and ecological marginalization: land degradation index combining indicators of net primary production and rain use efficiency; vegetation quality index

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combining indicators of fire risk, erosion protection, drought resistance, vegetation cover (horizontal), structural cover (vertical), and proximity to climax); aridity index combining evapotranspiration and precipitation; energy poverty vulnerability index; distance to a health facility; population density; index of people in active age; average income; and rural land prices (see SM3 for details and data sources).

All energy-land system types were overlaid on these spatial data. Variables were represented at resolutions ranging from municipalities, parishes, 1-km grid and polygons. We computed median values for continuous variables and modes for categorical variables.

We conducted a pairwise comparison across types to identify which cluster pairs were significantly different. We used non-parametric Wilcoxon Rank-Sum Test for the continuous and categorical variables after reclassifying categorical variables to ordinal values (e.g., from "very low density rural" = '1' to "urban" = '4'). We further tested the Wilcoxon Rank-Sum Test with and without a p-value Holm correction to control family-wise error rate. The use of the Holm adjustment decreases the probability of false positives (type I error), being more conservative, but increases the probability of false negatives (type II error) (Sidebotham and Chen, 2026). For this analysis, we excluded types with fewer observations than five.

3. Results

3.1. Major types of energy-land systems

We identified 18 ELS types, which were organized into four major groups: utility-scale wind, utility-scale solar, other utility-scale, and decentralized types (Fig. 1 and 2, Table 2). These categories reflect the diversity of wind and solar deployment configurations in Portugal. This 18-cluster solution was associated with good overall evaluation metrics, including a Silhouette value of 0.41 and Dunn index of 0.15 and a hierarchical dendrogram with a Cophenetic Correlation Coefficient of 0.80 (Fig. S2).

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Figure 1- Schematic representation of resulting energy-land system typology, grouped by major category and with number of projects assigned to each type.

The clustering primarily distinguishes utility-scale ELS from decentralized configurations. Within the utility-scale category, solar and wind form two primary subgroups. At a more detailed level, wind ELS are predominantly distinguished by their co-location with other land uses, co-governance systems, public participation, transparency and types of compensation; notably, installed capacity appears with a secondary role. In contrast, solar ELS are organized more by their installed capacity, the presence of protected trees and similarly, socio-ecological measures such as green infrastructure, public participation, transparency, and types of compensation. Wind ELS occur mostly on shrubland while utility-scale solar occurs in a mix of previous land uses including agriculture and productive forests.

Solar or wind projects characterised by large installed capacities, or those situated in protected areas and communal lands, frequently incorporated several socio-ecological measures, including compensation schemes, high levels of public participation, and transparency. The opposite was true for small-scale solar and wind projects. “Other utility-scale” clusters typified hybrid wind-solar ELS and floating photovoltaics (floatvoltaics). Decentralized types grouped projects by installed capacity, energy systems, proponents, and co-location with other land uses.

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An inverse relation was observed between the number of projects in each ELS category and their size: small utility-scale are more numerous, while large-scale projects are fewer (Fig. 1, Table 2). For utility-scale solar, the majority are small-scale ELS (100 cases), and the lowest number of projects is associated with large-scale solar ELS (11). For wind energy, small-scale is the most numerous (124), and large-scale with many socio-ecological measures (12) the least numerous type. “Other utility-scale” included the lowest number of cases, with 6 and 3 for hybrids and floatvoltaics, respectively.

Below we provide details on four ELS, with examples of projects:

- The type “large utility-scale wind with many socio-ecological measures” encompasses projects located in communal and protected areas, co-located with complementary land uses and featuring a large average installed capacity. This type includes projects ranging from 6 turbines (10 MW) to 88 turbines (263 MW). These two projects involved prior consultation with local communities, cooperation with local parishes and municipalities, and the implementation of educational and touristic visits highlighting local natural values. Additional measures included conservation efforts for local wolf populations, protection of heritage sites, municipal payment schemes, and the promotion of extensive grazing within the wind park.
- The “small utility-scale solar” type consists primarily of projects that do not undergo an Environmental Impact/Incidence Assessment (EIA/EIncA), with some exceptions. For example, a small solar project with 7 MW installed capacity was established in a private property in a protected area, thus requiring an EIncA. The project proposed some mitigation measures such as an herbaceous cover within the arrays. The developer communicated with the local population regarding the construction calendar to avoid accidents with construction transport vehicles.
- An example of a “utility-scale hybrid” ELS is a proposed solar plus wind project to be connected to an existing hydropower facility, comprising 83.9 MW of solar and 22.5MW of wind on both private and communal land. This project describes several green infrastructure elements and the potential co-location with complementary land uses within the project area (pasture and cropping).
- The “collective self-consumption in public or civil society organisations”, a decentralized ELS, includes projects on rooftops of facilities of a public or civil society organisation (e.g., schools, firefighter headquarters, municipalities). These are mostly financed, installed and managed by specialized energy companies that develop collective self-consumption energy schemes where the electricity is sold on-site by organizations and households enrolled in the project, at prices lower than conventional supplier tariffs.

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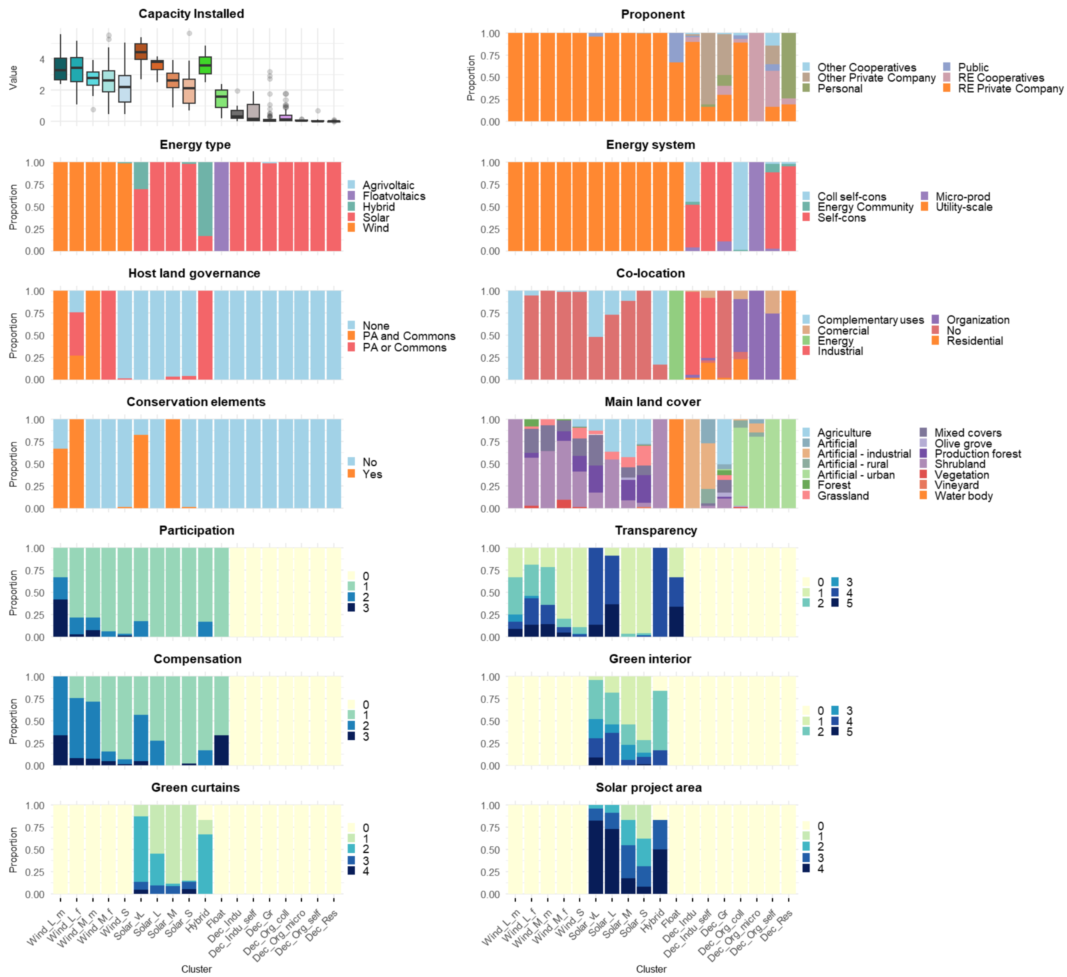

Figure 2. - Proportional distribution of variable categories used for ELS typification across identified clusters. Each bar represents the relative composition within a cluster.

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Table 2.- Descriptive summary of resulting energy-land systems, including cluster names, description and median (25-75 percentile) installed capacity and utility-scale solar project area.

Cluster name	**Description**	**Median (25-75 perc) installed capacity and area**
Large utility-scale wind with many socio-ecological measures (Wind_L_m)	Utility-scale wind projects, developed by energy companies on protected and communal land. This cluster includes a high proportion of analysed conservation elements (outcrops), low transparency but high participation and diverse compensation schemes. Projects feature medium to high installed, in former shrublands, and co-located with complementary land uses, as pasture or cropping.	25.4 MW (13.4-63.4)
Large utility-scale wind with few socio-ecological measures (Wind_L_f)	Utility-scale wind projects, developed by energy companies, located partially on communal land or protected areas. Characterized by a high proportion of analysed conservation elements (outcrops), high transparency, but low participation and medium compensation. They feature medium to high installed capacity. Former land cover includes mixed uses, shrubland, production forest, and forests, with no co-location.	30.7 MW (12-60)
Medium utility-scale wind with many socio-ecological measures (Wind_M_m)	Utility-scale wind projects, developed by energy companies on protected and communal land. Characterized by no analysed conservation elements, high transparency but low participation, medium compensation, and medium installed capacity Former land cover consists of shrubland and mixed uses, with no co-location.	15.5 MW (9.4-22.5)
Medium utility-scale wind with few socio-ecological measures (Wind_M_f)	Utility-scale wind projects, developed by energy companies on communal land or protected areas. Characterized by no analysed conservation elements, low transparency and participation, limited compensation, and medium installed capacity Former land cover consists of shrubland and mixed uses, with no co-location	13 MW (5.7-24.6)
Small utility-scale wind (Wind_S)	Utility-scale wind projects, developed by energy companies on non-communal land. Characterized by no analysed conservation elements, very low transparency and participation, limited compensation, and low installed capacity Former land cover is diverse: shrubland, olive groves, production forest, agriculture, and mixed uses, with no co-location.	8 MW (2.5-18)
Very large utility-scale solar with many socio-ecological measures (Solar_vL)	Very large utility-scale solar, including some hybrid projects, with very large areas and a very high proportion of interior and curtain green infrastructure. Projects are not on communal land, feature a high proportion of analysed conservation elements ("*montado*" trees), show very high transparency, low participation, diverse compensation schemes, and high installed capacity. Located in former production forests and grasslands, sometimes associated with complementary land uses.	82.4 MW (52.1-143.8), 156 ha (94.3-305)
Large-scale utility-scale solar with few socio-ecological measures (Solar_L)	Utility-scale solar projects characterized by large areas and a high proportion of interior and curtain green infrastructure. Rarely situated on communal land, with no analysed conservation elements, very high transparency, low participation, unidimensional compensation, and high installed capacity. Located in former agricultural areas and shrubland and feature some complementary land uses.	44 MW (26.8-49), 61.7 ha (56.7-78.9)
Medium utility-scale solar (Solar_M)	Utility-scale solar projects with medium areas and a low proportion of interior and curtain green infrastructure. Projects are not on communal land but include analysed conservation elements ("*montado*" trees). Features include very low transparency and participation, unidimensional compensation, and medium installed capacity. Located in former	12.7 MW (7.8-20.9), 28.2 ha (16.1-47)

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	agricultural areas, grasslands, production forests, and mixed uses, with low co-location.	
Small utility-scale solar (Solar_S)	Utility-scale solar projects with small areas and a low proportion of interior and curtain green infrastructure. Projects are not on communal land, contain no analysed conservation elements, and feature very low transparency and participation, and unidimensional compensation. They have lower installed capacity and are located in former production forests, mixed uses, grasslands, and agricultural areas, with no co-location.	7.4 MW (2.2-14.1), 16.3 ha (6.4-33)
Utility-scale hybrid (Hybrid)	Utility-scale hybrid projects with a very large area and lower interior and curtain green infrastructure. Projects are partially on communal land, few include analysed conservation elements, and show high transparency, low participation, and mostly unidimensional compensation. They have high installed capacity are located on former shrubland and feature some complementary land uses.	39.1 MW (19.9-61.9)
Utility-scale floatvoltaics (Float)	Utility-scale floatvoltaic projects are not on communal land, with no analysed conservation elements. They exhibit medium to high transparency, no participation, unidimensional compensation, and low installed capacity. Located on water bodies and co-located with existing energy uses (dams).	4 MW (2.11-7)
Decentralized industrial (Dec_Indu)	Industrial PV (both self-consumption and collective self-consumption) with high installed capacity. Majority developed by non-specialized private companies. Located in industrial areas and co-located with industrial facilities	0.406 MW (0.26-1)
Decentralized industrial self-consumption (Dec_Indu_self)	Industrial PV (mostly self-consumption) with high installed capacity. Majority developed by RE companies. Located in industrial areas and co-located with industrial facilities	0.184 MW (0.040-2)
Decentralized ground-mounted (Dec_Gr)	Ground-mounted PV (self-consumption and some micro production and collective self-consumption) with average capacity. Managed by a mix of non-specialized and specialized private companies, with little involvement from renewable energy cooperatives. Located in former agricultural, urban, grasslands, mixed uses, and shrubland areas, with no co-location.	0.087 MW (0.007-0.140)
Decentralized collective self-consumption in public or civil society organisations (Dec_Org_coll)	Small-scale PV (collective self-consumption) with very low capacity but relatively higher capacity than other institutional solar. Managed mostly by renewable energy private companies. Located in urban areas and co-located with public or civil society organisations uses.	0.157 MW (0.068-0.475)
Decentralized self-consumption in public or civil society organisations (Dec_Org_self)	Small-scale PV (self-consumption and the few energy communities) with very low capacity. Managed by renewable energy cooperatives, private companies, and non-specialized NGOs. Located in urban areas and co-located with public or civil society organisations uses.	0.031 MW (0.017-0.073)
Decentralized micro production in public or civil society organisations (Dec_Org_micro)	Small-scale PV (micro production) with very low capacity. Managed by renewable energy cooperatives. Located in urban areas and co-located with public or civil society organisations uses.	0.058 MW (0.047-0.080)
Decentralized residential self-consumption (Dec_Res)	Residential associated PV (self-consumption and collective self-consumption) with very low capacity, primarily for personal use. Some projects involve RE private companies. Located in urban areas, co-located with residential uses.	0.003 MW (0.002-0.004)

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3.2. Distribution of major types of energy-land systems

The installed capacity and land footprint of utility-scale ELS highlights a major difference between wind and solar. For wind ELS (Fig. S3), the highest accumulated capacity is found in the small size type (1984 MW), while the "very large-scale solar" type holds the highest accumulate installed capacity overall (2214 MW). This latter group also has the largest accumulated land footprint (4575 ha), followed by the small-scale solar type (2665 ha). The hybrid and floatvoltaic types contribute a very small capacity compared to the other ELS.

The spatio-temporal distribution of utility-scale ELS suggests a sequential transition from wind-dominated developments in northern regions towards solar expansion in southern regions (Fig. 3). Most wind ELS are concentrated in the North, with the exception of the category "large wind with more socio-ecological measures" that exhibits a more dispersed geography countrywide. Utility-scale solar distribution varies by capacity: small- and medium-scale projects are concentrated in the Alentejo region, while large-scale types are prevalent in the Algarve and Setúbal. Very large-scale projects are primarily located within the Oeste e Vale do Tejo and Central regions. Both small utility-scale wind and solar types show a wider geographical distribution compared to their larger-scale counterparts. Currently, hybrid and floatvoltaic systems are largely restricted to the North and Central regions. Decentralized projects are widely distributed, with higher concentrations in the North and Centre regions.

Temporal patterns indicate gradual wind deployment from the early 1990s until approximately 2012, initially dominated by small-scale installations, followed by larger developments from around 2003 and a peak in 2009. Subsequent years were characterised by a decline in wind deployment coinciding with increasing solar development. Solar expansion commenced around 2012 and continued through the most recent observation year (2025). Early solar development was dominated by small-scale systems, followed by medium-scale installations and a shift towards large-scale projects from approximately 2017. This trajectory culminated in 2022–2023 with the commissioning of very large-scale systems. More recent periods also include the emergence of hybrid wind–solar and floatvoltaic configurations, resulting in more complex energy landscapes.

Most utility-scale projects are located in rural areas (Fig. 3), whereas decentralized projects tend to be located in urban, suburban and areas of urban growth.

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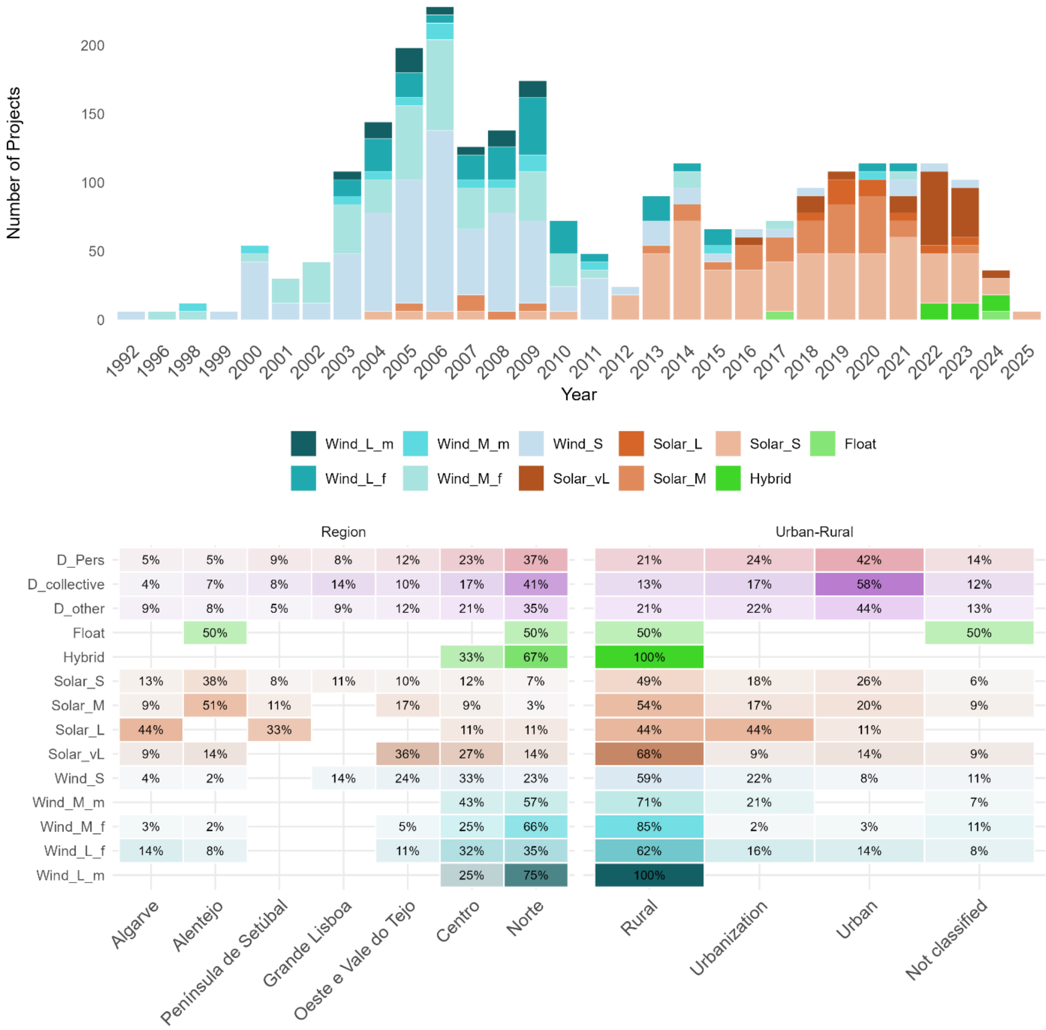

349

350 Figure 3 – Bar plot of temporal distribution of utility-scale ELS types approval year over time on the top.
351 Heatmap of spatial distribution of types by NUTS II region ordered from South to North (bottom left), and
352 ELS types distribution by urbanization level (bottom right).

353 ## 3.3. Geographies of social and ecological marginalization

354 Overlay analysis of ELS types with indicators of social and ecological marginalization reveals consistent
355 differentiation across four dimensions (Fig. 4): (i) decentralized versus utility-scale, (ii) utility-scale solar
356 versus wind, (iii) small versus large utility-scale, and (iv) large utility-scale with many versus few socio-
357 ecological measures.

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Decentralized ELS are generally found in less socially marginalized contexts than utility-scale ELS. This difference is more profound for utility-scale wind than for solar ELS (Fig. 4, Fig. S4). More specifically, decentralized developments are found in locations with significantly higher accessibility to health facilities, a higher active population index, higher average incomes and population densities, and lower levels of energy poverty.

Utility-scale wind ELS are located in the most socially and environmentally marginalized areas (Fig. 4, Fig. S4), characterized by the lowest values across all social variables, and by poor vegetation quality and highly degraded land. Utility-scale solar ELS are typically found in areas relatively drier compared to northern Portugal. However, these areas are less socially marginalized than the contexts of wind projects, featuring the lowest energy poverty overall, the highest land prices, and average incomes comparable to decentralized ELS locations. Hybrid ELS occur in contexts similar to wind groups.

Within utility-scale solar and wind, large-scale ELS are typically located in more socially and environmentally marginal contexts than small-scale ones. For utility-scale solar, this pattern is statistically significant for the land degradation index, health accessibility, land price, energy poverty, and average income—particularly when comparing small to very large solar types. For example, small and medium scale projects are more common on productive land, while large projects are preferentially sited in more degraded landscapes. Similarly, in the utility-scale wind group, significant differences exist between small and larger wind ELS regarding vegetation quality, land degradation, energy poverty, and average income (Fig. 4, Fig. S4).

Large wind ELS with many socio-ecological measures and very large solar ELS are generally in the most socially and environmentally marginal areas. For wind, this type is in areas with significantly higher energy poverty and lower average income when compared with large wind ELS with few socio-ecological measures. For solar, this type is in areas with significantly lower land prices (Fig. 4, Fig. S4).

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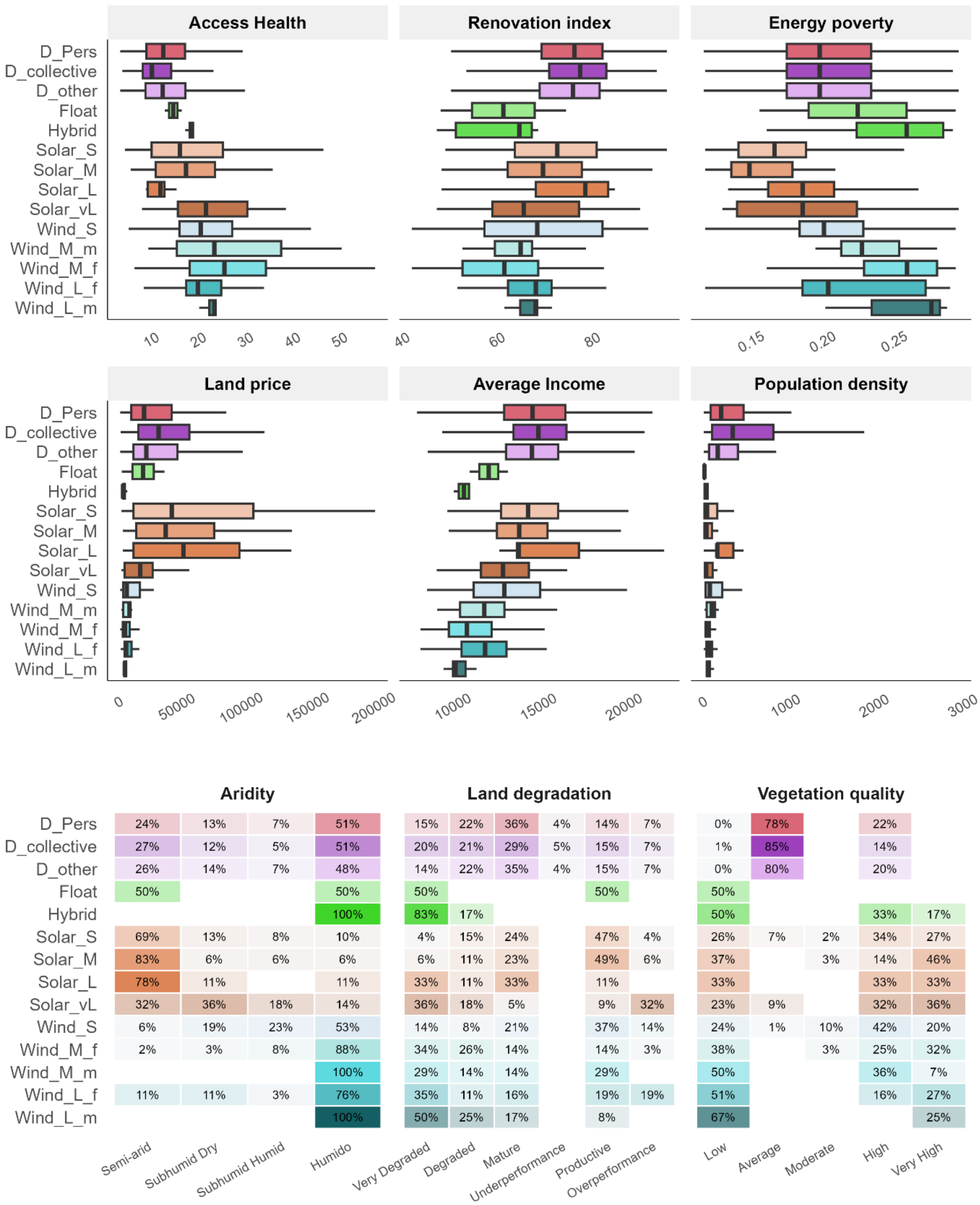

Figure 4. Distribution of energy land system types across socio-ecological marginalization variables.

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4. Discussion

By characterizing 760 solar and wind projects in Portugal, we identified 18 distinct ELS types, ranging from utility-scale wind and solar to decentralized systems, and their respective contexts of socio-ecological marginalization. This yielded four major insights.

First, the identification of multiple ELS highlights the geographically contextualized, multiform nature of the energy transition. A clear trend is observed: utility-scale wind energy developments were initially concentrated in the marginalized northern regions of Portugal, followed by a shift toward utility-scale solar PV generation in the productive southern regions. While this distribution historically fostered distinct wind and solar ELS, recent hybrid and large-scale solar projects are shifting solar landscapes towards marginalized contexts, which were previously associated with wind. Second, decentralized ELS exhibit a more multifunctional character than centralized ones. Being embedded in populated areas through co-location with other land uses, these systems engage a broader array of actors and energy systems under more diverse governance structures. Third, utility-scale ELS types are sited in specific socio-ecological contexts. Larger-scale projects, particularly those incorporating more socio-ecological measures, are often sited in highly marginalized regions, whereas smaller utility-scale solar projects tend to occupy less marginalized and more productive areas. This illustrates the trade-off inherent to different deployment strategies: "few big *versus* many small."

Finally, this study provides the first granular analysis of ELS at a national scale. It provides a methodological approach that can be adapted to specific research and planning needs and offers a framework for fostering a place-based energy governance that integrates local ecological and social concerns. Ultimately, this research points toward pathways for more multifunctional, equitable ELS that better align energy production with the dual demands of the energy transition and rural revitalization

4.1. A structured multiform energy transition

The 18 identified solar and wind ELS types highlight the diversity of projects, governance models, and land-use configurations emerging from Portugal's energy transition. A highly structured geographical trend — initially concentrated in utility-scale wind energy in northern Portugal, followed by a shift toward utility-scale solar in the South — has shaped this multiform energy transition. Temporally, the focus shifted as prime areas for wind were increasingly scarce, feed in tariffs were discontinued for utility-scale projects, and the technological developments in solar led to a sharp decrease in costs, making it competitive for direct participation in electricity markets (Delicado et al., 2016; Sareen, 2024; Vieira et al., 2024). Spatially, the distribution of wind and solar is reflected on the diversity of ELS. Wind ELS are primarily distinguished by their co-location with other land uses, co-governance systems, participation dimensions, rather than

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installed capacity alone. This is largely due to the historical concentration of wind projects in high-altitude northern regions where optimal wind conditions coincide with protected areas and communal lands (*baldios*) (Delicado et al., 2017). These communal areas are often more contractually accessible for large-scale concessions compared to the small, fragmented land parcels typical of northern Portugal (Piet, 2016). For wind energy land systems, their overlap with protected areas and communal lands underscores the importance of co-governance, often necessitating biodiversity compensation or co-location with communal grazing activities. However, their remoteness also means that utility-scale wind ELS frequently coincide with contexts of high socio-ecological marginalization, often characterized by high energy poverty, limited healthcare access, depopulation, and low productivity landscapes.

In contrast, solar ELS are primarily distinguished by installed capacity, the presence of conservation elements (*montado* trees), and, similarly to wind, the implementation of socio-ecological measures such as green infrastructure and participatory frameworks. This reflects the early concentration of solar in the protected oak-rich landscapes of the Algarve, Alentejo, and Setúbal regions, where the terrain is flat, solar irradiance is high, and land consolidation (large land parcels) is higher than in northern Portugal (Piet, 2016). These utility-scale solar ELS also feature a higher prevalence of agricultural areas, pastures (grasslands), and production forests as prior land covers compared to landscapes preferred for wind projects. Consequently, solar ELS contexts are characterised by medium levels of socio-ecological marginalization. While they are often sited in areas with drier than northern regions, they are less socially marginalized than wind ELS contexts, featuring lower energy poverty, higher land prices, and more productive land. This suggests that, in general, solar PV developments are more closely integrated into already active economic landscapes, compared with wind projects. This may be reflected in the higher level of contestation that many solar projects have faced compared to early wind projects (Wallace et al., 2025).

More recently, solar projects have focused on the "Oeste e Vale do Tejo" and the Centre region (Alves, 2026), a shift likely driven by grid availability. A similar trend applies to hybrid ELS, which are reshaping energy landscapes in the North and Centre regions as solar is integrated into existing wind-energy sites. Thus, hybrid projects are pulling solar development into the more marginal, high-altitude contexts previously reserved for wind. This complexification of ELS signals a new phase of the transition where solar energy increasingly mirrors the socio-environmental footprint of wind, potentially intensifying the pressure on Portugal's most remote and marginalized regions but also representing an opportunity to create new benefits for these communities.

4.2. Multifunctional decentralized energy-land systems for multiple justice dimensions

By being co-located with other land uses and involving a diverse array of actors and energy systems, decentralized ELS exhibit a more multifunctional character than utility-scale systems. Typically found in

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urban settings, decentralized ELS benefit from their proximity to energy demand in populated areas, taking advantage of the considerable solar PV generation potential in the built environment (Kakoulaki et al., 2026). Therefore, these systems are located in less socially marginalized contexts compared to the other ELS. These contexts are characterized by high healthcare accessibility, high average income, and greater population density. Renewable energy production is embedded within the urban landscape; rather than replacing existing land uses, it is co-located with them. Geographically, decentralized projects show a dispersed distribution with a high focus on the North and Centre regions of Portugal, despite the best solar conditions being in the south (Cavaco et al., 2016). This might be explained by higher infrastructure suitability for rooftop solar, higher population density, and predominance of industrial activities (Kakoulaki et al., 2026).

Currently, decentralized solar ELS contribute approximately 3.1 GW of installed capacity (comprising both self-consumption and micro-production), representing 45% of all solar power installed in Portugal (DGEG, 2025b). The National Energy and Climate Plan for 2030 foresees a strong growth in renewable power generation, with an emphasis on centralized solar power, which would result in a share of decentralized solar ELS of about 27% by 2030 (Government of Portugal, 2024). These figures stand in contrast to the European average of 61% decentralized solar (Kakoulaki et al., 2026). Still, the sector of solar PV self-consumption has seen significant growth since 2021, with capacity surging from 522 MW to 2,436 MW (DGEG, 2025b). This may be a result of declining installation costs, increasing electricity prices, targeted government subsidies (e.g., *Fundo Ambiental More Sustainable Buildings grants for solar PV installations*), and the emergence of collective self-consumption business models (Lage et al., 2024; Mello et al., 2024).

However, the true inclusivity of decentralized ELS is questionable. The phasing-out of feed-in tariffs for solar micro-production in 2016 and the self-consumption regulations introduced in 2019 (Government of Portugal, 2019a), hampered the expansion of micro-production and shifted prosumers toward a self-consumption logic, with a recent uptick in collective models (Sareen & Nordholm, 2021). Within collective models, energy communities can represent more democratic models, however they face severe bureaucratic hurdles, such as licensing constraints and high complexity, insufficient knowledge in local organisations, and a lack of financial, technical, and legal support for their establishment (Delicado et al., 2023; Ferreira, 2025; Sequeira et al., 2024a). Rather than the citizen-driven energy communities initially envisioned by the EU's Renewable Energy Directive, the void in collective models has been filled by the burgeoning sector of collective self-consumption dominated by incumbent energy companies, mostly focused on commercial and industrial projects (Campos et al., 2023; Ferreira, 2025; Sareen, 2021; Sequeira et al., 2024b). As of September 2025, only three energy communities were fully functional in Portugal in comparison to 647 collective self-consumptions units. Finally, self-consumption models may also become less accessible due to increased VAT on solar components and to the end of national funding mechanisms, particularly for low-income and energy-poor families (Agência Lusa, 2025; Sequeira et al., 2024a). This illustrates the significant gap between possible avenues for a "just transition" and the material reality of how persistent barriers and dominant energy governance models support or foreclose possible ELS.

4.3. Trade-offs in "few big versus several small" deployment strategies

The development of wind and solar ELS in Portugal shows an evolution from small- and medium-scale ELS toward larger ELS types (Bento and Fontes, 2015), with a recent surge in "very large" solar projects. This evolution is reflected in both the number of projects and their respective accumulated capacities. While small-scale wind ELS still represent the majority of projects and of accumulated capacity for the wind sector, the solar sector displays a different pattern. Although small-scale solar projects are more numerous, "very large-scale" solar ELS provide the highest share of capacity (2.2 GW in 2025). This indicates a strategic turn toward a few "mega-solar" projects to meet transition goals. This path may be considered efficient for energy production but may cause heightened socio-ecological impacts and therefore is likely to meet growing and more organised social opposition (Brás et al., 2024). This shift results from the combined impact of technological progress, the drive for economies of scale, and government strategies such as capacity auctions and direct agreements for grid access that have incentivized the intensification of production (Sareen, 2024). Grid capacity might also play a pivotal role on the spatial distribution of ELS types. Large-scale solar ELS show higher geographical clustering than the smaller ones, reflecting a more constrained and strategic logic of deployment in areas with grid capacity and land availability. By contrast, small-scale ELS (both wind and solar) are more geographically distributed, suggesting fewer siting constraints regarding both regulatory requirements and land-use competition.

Beyond geography, our findings highlight the diversity within utility-scale ELS configurations. Large utility-scale ELS or those situated in protected areas, communal lands or areas with conservation elements incorporate more socio-ecological measures. These include compensation schemes, higher levels of participation and greater transparency compared to their smaller counterparts. Because these projects often require mandatory environmental impact assessments and attract public attention, they include more extensive ameliorating measures to secure social and regulatory approval. However, these large-scale projects are often sited in more marginalized contexts than their smaller counterparts. This may be explained by three factors: (i) larger projects may only achieve social or regulatory license if the target areas are perceived as not productive, potentially reinforcing the creation of "sacrifice zones" (Dunlap et al., 2025); (ii) marginalized populations may possess less political or social capital to contest large-scale land acquisitions (Sorman and Stock, 2024); and (iii) renting or acquiring large contiguous land parcels is often

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easier in regions where economic activity and land prices are low, e.g. due to land use limitations imposed by environmental protection regulations.

Recent updates to project permitting in Portugal have not only lowered the thresholds for requiring an Environmental Impact Assessment but have also introduced tighter timelines for public participation and secured tacit approval mechanisms (Government of Portugal, 2023). Permitting changes have hindered genuine efforts of environmental impact assessment and public participation towards a more bureaucratic, shorter, and less accessible procedure (Lopes et al., 2017). The nature of obligatory local compensation has also changed. In the 2000s, wind projects associated with grid auctions and supported by feed-in-tariffs were obligated to provide an annual compensation to municipalities equivalent to 1.5% of revenues. Solar projects were not subject to an equivalent requirement until 2023, when a different form of compensation was introduced: either the installation of self-consumption projects or a one-time monetary payment based on installed capacity and supported by the publicly-managed Environmental Fund (*Fundo Ambiental*). Unlike countries that actively promote co-ownership or local economic participation, Portugal relies heavily on a model where financial involvement is restricted to compensation schemes (Bakelants et al., 2025; Rielli et al., 2026). Any additional measure addressing social and environmental impacts are analysed on a case-by-case basis, where project approval remains a complex interaction between regulators, authorities, developers, and the public (Loomis et al., 2022; Lopes et al., 2017; Rozema and Bond, 2015). Importantly, the effectiveness of these socio-ecological measures within larger ELS remains contested. While participation and economic compensation are often mandated, research suggests they have limited impact on local development (Delicado et al., 2016; Oliveira et al., 2025). Empirical evidence regarding the efficacy of environmental mitigation measures remains scarce (Gómez-Catasús et al., 2024).

Smaller projects or those in less sensitive areas typically display fewer socio-ecological measures, reflecting their perceived lower environmental impact. By falling below EIA thresholds, they "fly under the radar," avoiding the costs associated with transparency, compensation, and green infrastructure. This discussion highlights a debate between "few big" and "many small" projects. Few large ELS, which typically incorporate many socio-ecological measures, are preferentially sited in highly marginalized areas. Conversely, a large number of small projects, often lacking significant safeguards due to their expected smaller impacts, occupy more productive land. Thus, on one hand, large-scale projects face higher scrutiny and propose more ameliorating measures, but their cumulative impact is systematically spatially concentrated. This may create the risk of further marginalization if socio-ecological measures fail to fully mitigate impacts. On the other hand, small-scale deployments may incrementally fragment productive landscapes with minimal oversight, if their deployment is not aligned with current economic activities and nature protection.

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4.4. Land system science approach to navigating a just energy transition

As nations accelerate their energy transitions, it is urgent to consider the specific types of ELS being created and supported under current policy and regulatory frameworks and which remain foreclosed.

In the Portuguese context, several current drivers, including limited incentives for pluralistic participation, recent high-capacity utility-scale tenders, streamlined licensing processes, and new prospects for energy-intensive activities, such as data centres and green hydrogen (Government of Portugal, 2019b), may restrict the diversity of future ELS. This trajectory risks locking these systems into a narrow logic defined by either very large-scale utility projects in marginalized regions or small-scale utility projects on productive land. Since social acceptance remains a critical bottleneck, policy must address the ways in which burdens on land systems are disproportionately placed on rural landscapes to meet national or distant energy demands (Naumann and Rudolph, 2025). Such imbalances foster a perception of geographic and energy injustice that fuels local resistance and erodes trust in the energy transition (Krüger, 2022; Mamonova and Franquesa, 2020). This tension may become particularly acute as EU Member states designate “Renewables acceleration areas” for streamlined deployment of renewable energy projects. As countries pursue energy self-sufficiency, it is essential to move beyond models that, while technically effective, may fall short of the justice dimensions required for a fair distribution of the burdens and benefits of the energy transition (Sovacool et al., 2025).

To address inequities, policy and regulation should move toward incentivizing forms of land uses that better align energy production with rural needs. Administrative simplification to accelerate the energy transition must be paired with a logic of socio-ecological justice and land system sustainability (Boudet et al., 2025; Loomis et al., 2022). Such an approach requires clear mandates for benefit-sharing, transparency, and co-design imperatives that respond directly to the local contexts of deployment (Boudet et al., 2025; ICLEA, 2025). For example, future grid capacity auctions could integrate social, environmental, and participation metrics into their decision criteria. Financial incentives, such as feed-in tariffs or low-interest loans, could be used to mobilize a wider network of actors as agents in the energy transition. These incentives would support innovative production models (e.g., agrivoltaics and battery storage), self-consumption, and energy community systems that promote renewable energy integration and energy poverty mitigation while remaining conscious of grid limitations and production sufficiency (Calado et al., 2025). Enhanced financial participation schemes could be promoted in low-income municipalities. Similarly, agrivoltaics could be incentivized on productive lands through specific regulations designed to preserve agricultural capacity while providing additional income sources for farmers (Ali Khan Niazi and Victoria, 2023). Ultimately, policymakers could utilize the ELS framework to plan a balanced mix of ELS that goes beyond current configurations and implement more participatory, context-specific planning.

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This study has three main limitations. First, data heterogeneity posed challenges as available information varied across projects. While projects subject to an EIA provided detailed textual descriptions, georeferenced solar and wind projects required assumptions based on proxy indicators and expert knowledge (Table S2). Furthermore, for decentralized projects, we relied on a representative sample due to the limited data availability. Second, the project design and socio-ecological measures outlined in an EIA represents a procedural intention rather than a verified outcome. As these assessments occur during the planning phase, they may not fully capture the materialized reality or long-term social or ecological performance of an operational project (Enserink et al., 2022). Third, this study did not analyse repowering projects under EIA. Such projects might include new social or ecological mitigation measures. ELS may thus change over time with repowering.

The development of this typology offers more than a classification system. It can serve as a modular framework for tracing the energy transition by making visible different ELS in different contexts, allowing to rethink current energy governance practices towards a more place-based governance of energy transition that accounts for the complexities of local land systems. Such an approach can be adapted through the selection of variables to reflect key socio-ecological dimensions of ELS, allowing the typology to be designed for specific research or planning needs. Future work can leverage on such typologies to understand how specific policy incentives influence trends in ELS, what are the location factors driving different project sitting or how ELS are linked to actual socio-ecological impacts.

5. Conclusions

The siting of solar and wind projects is creating new energy-land systems characterized by specific landscape elements, objectives, and governance structures. Through a national-scale typification of energy-land systems in Portugal, this study demonstrates that the energy transition is neither uniform nor purely technical, but instead unfolds through geographically contingent pathways shaped by policy instruments, land availability, and socio-ecological conditions. While wind and solar projects once occupied distinct socio-ecological regions, marginalized northern highlands and productive southern plains respectively, the emergence of hybrid projects and "mega-solar" installations is bridging geographies, increasingly concentrating the footprint of the transition within the Centre and North regions of Portugal.

The under-development of decentralized, multifunctional systems in Portugal, which currently lag behind European averages, represents a missed opportunity to foster a more democratic and equitable energy transition that includes a wider network of agents, alleviates energy poverty and shares the benefits of renewable energy generation. Finally, this research highlights tensions in current deployment strategies. The "few big" utility projects model, while efficient for meeting national capacity targets and subject to more regulatory oversight, risks reinforcing patterns of geographic injustice and faces stronger social backlash due to their high impacts on land systems. Conversely, "many small" utility projects often bypass the socio-ecological safeguards required of larger installations, leading to a progressive replacement of productive landscapes.

Beyond the Portuguese case, the typology of energy-land systems developed in this study offers a transferable analytical lens examining how energy governance materialises across landscapes, enabling comparative assessment of technological, landscape and social outcomes across national contexts. Such knowledge can be used for a more nuanced, place-based energy governance, that ensures a just transition that aligns energy production with rural revitalization and equitable distribution of energy systems benefits. In such context, energy governance could, among other measures, prioritize co-designing the energy transition, administrative simplification for energy communities, incentivize agrivoltaics to preserve agricultural capacity, and integrate social and participation metrics into capacity auctions. By navigating the trade-offs between scale, location, design, agents, and governance, decision-makers can move towards an energy landscape that is not only carbon-neutral but also socio-ecologically resilient and spatially just.

6. Code and data availability

All datasets and code used here are referenced and are either publicly available or will be made available in a publicly accessible database.

7. Author contribution

AB and EFL conceptualized the study, AB did data curation and analysed the data, AA and VF shared data, AA, MMS, RAS, VF, EFL contributed to the methodology and validated results. AB prepared the original draft, all co-authors reviewed and edited final draft, EFL acquired funding.

8. Competing interests

The authors declare that they have no conflict of interest.

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the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

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