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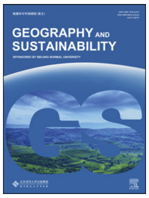

Research Article

Beyond renewable energy targets: Understanding the land use implications of solar energy facilities in Continental Portugal

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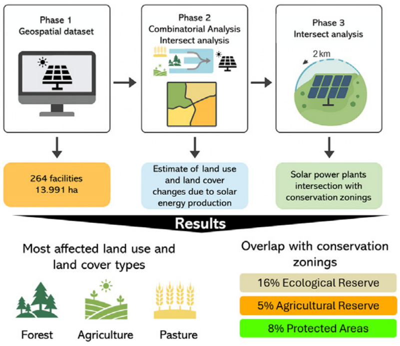
HIGHLIGHTS

- Portugal's decarbonisation strategy prioritises utility-scale solar energy (USSE).
- USSE facilities reveal an uneven spatial distribution.
- USSE deployment has predominantly changed stable forest and agricultural areas.
- USSE facilities overlap with designated conservation reserves.
- Planned facilities are expected to mainly disturb forest land and ecological reserve.

GRAPHICAL ABSTRACT



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ABSTRACT

The growing demand for land to accommodate renewable energy infrastructure has intensified competition with biodiversity conservation, agriculture, and ecosystem services. In Portugal, electricity system decarbonisation relies heavily on utility-scale solar energy (USSE) facilities, yet the spatial extent of land transformation associated with photovoltaic development has not been systematically assessed. This study provides an assessment of the land occupancy of USSE facilities and associated land use and land cover (LULC) changes in continental Portugal over the past two decades, as well as their spatial relationship with areas designated for land and nature conservation. A geospatial database of USSE installations ($\geq$1 MW) was developed through the integration of multiple data sources using geographic information systems (GIS). The geometric consistency of spatial features was ensured through harmonisation and validation procedures involving GIS-based corrections supported by Sentinel-2 satellite imagery. Spatial overlay analyses were conducted with multitemporal LULC datasets and with land-use planning constraints, including areas classified for nature conservation, ecological reserves, and agricultural reserves. The results indicate that USSE deployment has been predominantly located in the southern regions of Portugal, although the location of planned projects indicates a northward shift. The implementation of USSE facilities has been mainly associated with LULC changes in forest land, agricultural areas, pastures and shrubland. Spatial overlaps were observed with areas classified within the national ecological and agricultural reserves. These patterns may be indicative of growing land-use conflicts, but the extent to which these developments align with land-use planning objectives and conservation priorities requires further examination.

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1. Introduction

The transition towards renewable energy (RE) sources emerged as a key policy goal driven by agendas focused on climate change mitigation, environmental conservation, and sustainable development (Hawken, 2017; Owusu and Asumadu-Sarkodie, 2016). Clean energy technologies are regarded as instrumental for addressing these challenges and are aligned with the United Nations Sustainable Development Goals (SDGs) (Pan et al., 2023) and the Paris Climate Agreement (Akaev and Davydova, 2020). Decarbonising the energy sector is therefore fundamental for achieving carbon neutrality by 2050, a commitment made by numerous nations responsible for the majority of global greenhouse gas emissions at COP22 (Ghezloun et al., 2017).

Global RE deployment has accelerated markedly in recent years. According to the International Renewable Energy Association, in 2024, RE capacity experienced its most significant expansion to date, amounting to 585 gigawatts (GW). Solar energy contributed approximately 77 % of this growth, representing an increase of 452 GW (IRENA, 2025). Despite this progress, further acceleration is required to meet long-term decarbonisation targets (IRENA, 2023). This rapid expansion implies substantial future land demand for RE infrastructure, raising concerns about potential tensions between climate mitigation strategies and land conservation objectives (Lamhamedi and de Vries, 2022).

Energy systems have long been a key element in changing landscapes, and the large-scale substitution of conventional energy sources with RE introduces novel energy landscapes, due to material and infrastructural demands (Pasqualetti and Stremke, 2018). The comparatively low power density (W/m^2) of renewable technologies relative to fossil-based electricity generation (van Zalk and Behrens, 2018) is expected to be a major driver of landscape change. Huber and McCarthy (2017) suggested that the continued development of RE is likely to increasingly focus on rural areas, due to their ample space, low population density, and typically lower land costs. This spatial shift of energy production, particularly concerning utility-scale solar energy (USSE) facilities, has given rise to increased concern regarding land use and land cover (LULC) changes in areas relevant for food production, forestry, and nature conservation.

Emerging scholarship has highlighted the risk that insufficiently coordinated energy transitions may exacerbate land-use conflicts. Kiesecker and Naugle (2017) note that insufficient planning could unintentionally trigger a new crisis centred on land-use changes. Projections of RE land requirements suggest that solar energy is anticipated to require substantial land area in the coming decades (Nøland et al., 2022; van de Ven et al., 2021). As a result, land appropriation for USSE projects can generate land-use conflicts linked to environmental and aesthetic concerns, effects on property values, or discrepancies between national goals and local interests (Clausen and Rudolph, 2020; Mulvaney, 2017; Sokołowski and Heffron, 2022). Land-use conflicts emerge from spatial competition and conflicting interests among stakeholders due to the way land is used, structured, and managed (Wang et al., 2025). In the context of solar energy development, Goldberg (2023) identifies competing views on farmland conversion. USSE facilities displace agricultural production and, in some cases, raise concerns about food security. From this perspective, conflict can be conceptualised as the replacement of an established land-use function, activity, or productive utilisation by a new function. Conflicts between forestry and solar energy production have also been documented. Zhang et al. (2024) evaluated spatial land-use conflicts between forests and USSE facilities, demonstrating the widespread occurrence of such tensions. Additional potential conflicts involve biodiversity conservation. Rehbein et al. (2020) demonstrate that the siting of multiple RE facilities poses risks to globally significant biodiversity areas and natural values. Beyond conflicts with pre-existing land uses, competition may also occur among RE technologies themselves, as differences in production potential and land-use efficiency create differential spatial demands (Calvert and Mabee, 2015).

Within energy geography scholarship, increasing attention has been directed to such conflicts, framed as scalar and spatial dilemmas. Bridge et al. (2013) have theorised how different potential geographical futures are at play in the transition to a low-carbon economy. Moreover, Huber and McCarthy (2017) highlight how the transition from energy systems reliant on underground resources to RE facilities, characterised by spatial extensiveness, may produce substantial land-use implications. Land-use conflicts have also been conceptualised as manifestations of new “green” frontiers, wherein RE facilities, justified by climate protection narratives, may legitimise land appropriation and dispossession, particularly in marginalised or rural areas (Stock and Birkenholtz, 2021). Political ecology perspectives emphasise the revaluation of land from socioecological wealth to economic resource, often triggering social conflict and resistance (Müller and Pampus, 2023; Mulvaney et al., 2025). Conflicts have additionally been examined through environmental and social justice frameworks, focusing on distributional inequities, deficiencies in participatory processes, and local opposition phenomena (O’Neil, 2020; Sovacool et al., 2025; Wójcik and Jeziorska-Biel, 2023).

The energy-land nexus has become increasingly prominent in the context of energy system decarbonisation. Land management issues associated with the spatial requirements of RE deployment have been recognised for some time (Walker, 1995), but evidence suggests that reliance solely upon low-conflict zones may impede several countries from achieving national RE targets (Kiesecker et al., 2024). Land-use conversion associated with photovoltaic (PV) facilities has been documented in diverse contexts, including farmland occupation and incursion into areas of ecological sensitivity (Blaydes et al., 2025; Cole et al., 2022; De Marco et al., 2014; Ferreras-Alonso et al., 2024; Hernandez et al., 2015; Valera et al., 2022). Documented effects include habitat degradation, fragmentation, disruption of species movement, and broader implications for wildlife conservation (Lovich and Ennen, 2011; Levin et al., 2023). Additionally, the impacts of these facilities are diverse (Abbasi and Abbasi, 2012; Dhar et al., 2020; Hernandez et al., 2014) and not necessarily confined to the land directly affected, often extending into surrounding areas (Niebuhr et al., 2022). While increased RE production is widely recognised for its global benefits, local impacts of USSE facilities have led to contestation and local resistance, and not-in-my-backyard (NIMBY) responses (Batel et al., 2013; O’Neil, 2020). Consequently, dual tensions arise between supporters of rapid RE expansion and those who resist specific projects due to concerns over land pressure and social impacts (Lamhamedi and de Vries, 2022).

While land-use conflicts can be analysed through multiple theoretical lenses, they fundamentally arise from the occupation and transformation of land where competing demands and divergent interests intersect. Land-use conflicts are conceptualised in this study through a spatial approach (see Fienitz, 2023), which focuses on the incompatibility of land uses within the same area, manifesting as competition or mutually obstructive activities. Under this framework, conflicts are understood as arising whenever a new land-use function, such as RE production, replaces or interferes with an established function or activity. Extant research shows that the deployment of solar PV power plants changes land-use patterns (e.g., Barral et al., 2023; Blaydes et al., 2025; Hernandez et al., 2015). To elucidate the emerging land-use conflicts associated with solar energy deployment, spatial explicit approaches based on LULC change analyses can provide important insights into the land-use types most frequently converted to accommodate USSE facilities. Recent advancements in geographic information systems (GIS) have enhanced the potential for improving the transparency and evidential basis of spatial planning processes related to RE deployment. These technologies may offer valuable support for the integration of spatially explicit data into planning frameworks, thereby facilitating more informed decision-making (Bosch and Kienmoser, 2024; Rösch and Fakharizadehshirazi, 2025; Wang et al., 2025).

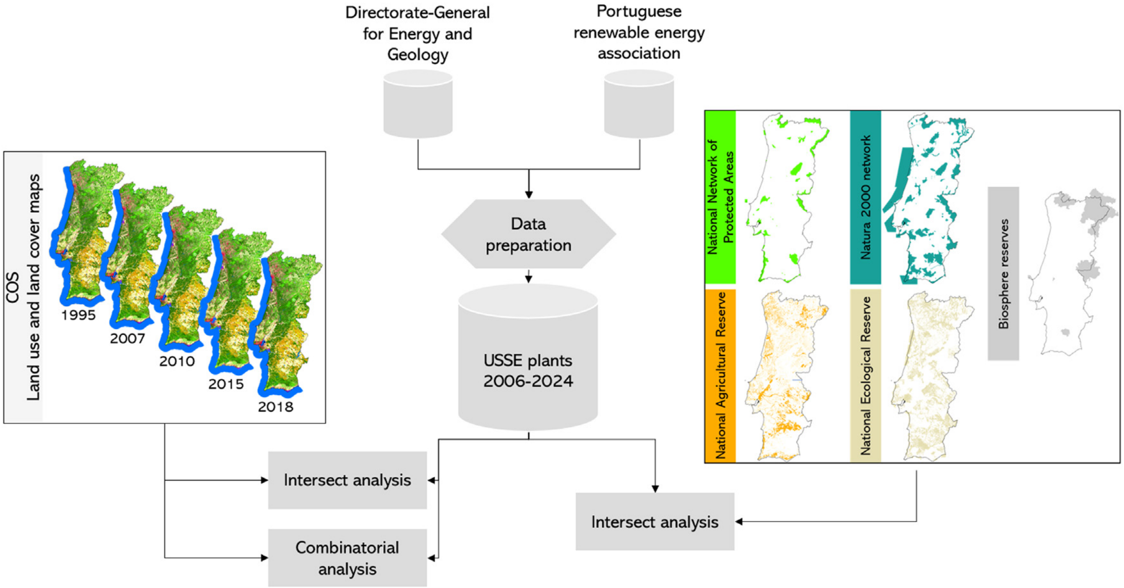

Fig. 1. Diagram of the methodological phases.

This study focuses on the land use implications of PV USSE development in continental Portugal. While Portugal has significant solar energy potential, its current installed capacity remains relatively low in comparison to other European countries (Perpiña Castillo et al., 2024). However, with national energy policy targets aiming for 20.8 GW of PV capacity (15.1 as utility-scale) by 2030 (República Portuguesa, 2025a), substantial LULC changes are anticipated to accommodate these facilities. Previous studies have identified that most of the PV facilities in Portugal have led to the conversion of agricultural areas (Barral et al., 2023; Poggi et al., 2018). However, these studies are limited in scope, particularly in terms of geographical coverage, and have not comprehensively addressed planned projects or their spatial relationship with land and nature conservation areas. This study seeks to address these gaps by adopting an exploratory approach using GIS to: (i) identify the spatial distribution of operational and planned USSE facilities ($\geq$ 1 MW); (ii) estimate LULC changes associated with these facilities; and (iii) assess the extent of spatial overlap between USSE facilities and areas designated for land and nature conservation. By providing a more comprehensive understanding of how PV USSE development has reconfigured Portuguese landscapes, the findings are expected to inform spatial planning and policy discussions surrounding solar energy development in Portugal.

2. Materials and methods

The methodological approach comprised several sequential phases (Fig. 1). The first phase involved the development of a geospatial database. Due to the absence of a unified register of PV USSE facilities in Portugal that complies with standardised information quality protocols, various datasets were compiled and subsequently harmonised. The second phase comprised the application of spatial analysis techniques to examine LULC changes through a historical series of land-use maps. In the third phase, the database of USSE facilities was intersected with land and nature conservation zonings.

2.1. Study area

Portugal is located in the southwesternmost part of the European continent (Fig. S1 in the Supplementary materials), with a population of approximately 10.3 million and a population density of 112 hab/km^2 (INE, 2022). In 2018, forest land accounted for 39 % of the continental territory, followed by agricultural areas at 26 %, as reported in the official Portuguese COS LULC map (DGT, 2019). Over the past two decades, considerable transformations in urban, agricultural, and forest land uses have been observed, with spatially asymmetric patterns (Abrantes et al., 2019; Alves et al., 2022). Between 1995 and 2018, global trends pointed to a reduction in agricultural land, a reconfiguration of forest composition—notably a decline in maritime pine and an increase in eucalyptus plantations—and the expansion of urban areas, particularly in peri-urban and rural contexts (Abrantes et al., 2023; Alves et al., 2022).

Continental Portugal was selected as a case study given the increasing land implications associated with RE development, and several characteristics justify its relevance. A primary factor is the suitability of the territory and its high solar energy production potential, which makes the country attractive for investment in USSE facilities. Owing to its location in the southwestern extremity of Europe, Portugal benefits from high solar irradiation (~1,400–2,000 kWh/m^2/year; Silva et al., 2020), positioning it as one of the EU countries with the greatest solar energy potential (Perpiña Castillo et al., 2024). The production of RE has notably increased in recent decades, primarily through hydroelectric and wind power technologies (Nunes, 2018), but the installed PV capacity was only approximately 5.6 GW by the end of 2024, with around 3.4 GW associated with USSE facilities (DGEG, 2025). This places Portugal below several less sunny European countries in terms of per capita PV installed capacity (EurObserv'ER, 2024). However, a significant expansion of USSE facilities is forthcoming.

A second relevant aspect concerns the ambitious national targets for solar PV energy, which significantly exceed current installed capacity and are likely to result in accelerated deployment in the coming years. Notably, the national carbon neutrality target has been brought forward from 2050 to 2045. In addition, the most recent revision of the National Energy and Climate Plan (NECP) foresees a substantial increase in final electricity consumption, intended to accommodate emerging industries—such as data centres and battery production—alongside the intensified electrification of industrial processes, and the expansion of the electric vehicle fleet. As a result, solar PV technology is expected to constitute a key component of the future energy mix. The Portuguese 2024 revision of the NECP has accordingly raised the 2030 target for installed PV capacity to 20.8 GW, of which 15.1 GW are to be developed through utility-scale projects (República Portuguesa, 2025a). This objective implies an almost 4.5-fold increase in installed utility-scale PV capacity relative to 2024 levels. Such a rapid expansion is likely to in-

Table 1
Land and nature conservation datasets used.

Name	Significance	Source
National Agricultural Reserve	A land-use planning tool identifying areas with high agricultural potential, subject to strict constraints on energy development	snig.dgterritorio.gov.pt/
National Ecological Reserve	A biophysical structure encompassing ecologically sensitive or hazard-prone areas, where energy projects may be conditionally permissible	
Areas Classified for Nature Conservation	Legally protected areas for nature conservation where the deployment of energy facilities is generally prohibited: National Network of Protected Areas Natura 2000 Network (Sites of Community Importance - SCI and Special Protection Areas - SPA) Zones UNESCO Biosphere Reserves	geocatalogo.icnf.pt/catalogo.html snig.dgterritorio.gov.pt/

tensify land-use conflicts and increase the incidence of disputes related to project permitting and USSE locations.

A third relevant aspect relates to the legal and regulatory framework, which has been modified to facilitate project implementation. In the aftermath of the REPowerEU initiative, launched in response to the energy crisis triggered by the Russian invasion of Ukraine, significant legal changes were introduced in Portugal to reduce land constraints on RE development (República Portuguesa, 2022, 2023). These included the simplification of administrative procedures and exemptions from environmental impact assessment (EIA) for projects not located in designated sensitive areas or occupying less than 100 hectares (ha) of solar PV panel area. Additionally, participatory processes that could result in modifications to project design or execution were reduced due to projects being exempt from EIA.

Finally, the recent trajectory of USSE expansion in Portugal has been marked by increasing social contestation. Large-scale PV facilities have generated substantial opposition (Silva, 2023; Wallace et al., 2025). According to Silva (2023), this opposition has involved both local communities and environmental organisations, with concerns focusing on the anticipated environmental, landscape, and economic impacts associated with land-use change, as well as procedural injustices during the planning and consultation phases. Moreover, multiple projects have become the subject of public controversy and legal challenges, with the Public Prosecutor's Office initiating judicial proceedings according to recent reports in national media (Sanlez, 2025; Suspiro, 2021).

The intersection of these factors renders the Portuguese context a particularly pertinent case study for the analysis of solar energy development. Given the anticipated expansion in the number and spatial footprint of RE generation facilities, it is likely that the implementation of energy transition objectives will emerge as a critical driver of LULC changes. However, the extent and characteristics of land occupied by USSE facilities in Portugal remain insufficiently understood, and no extensive monitoring is being developed.

2.2. Data

A geographic polygon dataset of USSE facilities was constructed by integrating data from the Portuguese Directorate-General of Energy and Geology (DGEG) and the Portuguese Renewable Energy Association (APREN). The DGEG data (https://www.dgeg.gov.pt/pt/servicos-online/informacao-geografica/energia/energia-eletrica/) contained point and polygon features with incomplete attributes such as permitting dates, developers, and installed capacity. This source is considered the most reliable official source of information, including operational facilities and planned projects with a capacity reservation permit for connection to the public service electricity grid. It is important to note that the dataset includes only planned projects with granted capacity reservation titles, excluding additional planned projects that are still subject to EIA. The APREN dataset (https://e2p.inegi.up.pt/) exhibited a more limited scope, encompassing only USSE facilities affiliated with its members and primarily represented as point features with variable completeness in attribute data.

To assess LULC changes, Carta de Uso e Ocupação do Solo (COS) maps were used (DGT, 2019). These multitemporal polygon-based maps feature a minimum mapping unit of 1 ha (DGT, 2019). The hierarchical nomenclature includes aggregated (nine classes) and detailed (83 classes) classification levels. Although higher-resolution LULC products such as COSc (10 m) are available for continental Portugal (Costa et al., 2023), the COS maps provide the longest published time series, which is critical for understanding changes since the deployment of the first USSE project in Portugal. The Portuguese Directorate-General for Territory recognises the COS maps as the authoritative source of LULC data for continental Portugal, reporting an overall thematic accuracy exceeding 85 % across all reference years.

Conservation areas (i.e., an area of land that is protected and that cannot be built on or used for certain purposes) included supranational and national zoning datasets, such as the Natura 2000 Network and Biosphere Reserves, alongside national instruments such as the National Network of Protected Areas, the National Agricultural Reserve, and the National Ecological Reserve (Table 1).

2.3. Georectified polygon USSE facilities database

The analysis focused on facilities with a capacity of 1 MW or greater, following established standards for centralised or utility-scale PV. This capacity threshold is considered in Portuguese legislation as "conventional" PV solar energy when electricity is injected into the public service grid, whereas lower capacity units are typically considered self-consumption or small production units. Also, smaller installations have fewer LULC changes since most of them are integrated into pre-existing built environments and are subject to simpler permitting procedures.

The harmonisation procedures comprised several sequential operations. First, installations represented as points in the DGEG and APREN datasets were converted into polygons, with the delineation guided by the COS mapping specifications (DGT, 2019) and by the visible extent of panel arrays in the satellite imagery. Second, multiple records referring to installations with identical ownership, commissioning dates, and spatial proximity (≤20 m) were aggregated to avoid artificial fragmentation. Third, areas not occupied by the facility were excluded to ensure that each polygon captured only the effective land changed. Finally, topological corrections were applied, including the removal of overlapping geometries and the adjustment of polygon boundaries when positional inconsistencies were detected through photointerpretation (Fig. 2). Although no ground-based measurements or cadastral data were integrated, this combination of multisource visual assessment and rule-based adjustments is expected to provide an adequate level of geometric consistency.

The database of USSE facilities was validated through photointerpretation of satellite imagery:

- Operational USSE: Identified through visual confirmation from satellite images of the facility's presence and associated LULC changes.
- Planned USSE: Polygons without visible panels, representing projects that have approved grid connections, but have not yet been built or are pending environmental permits.

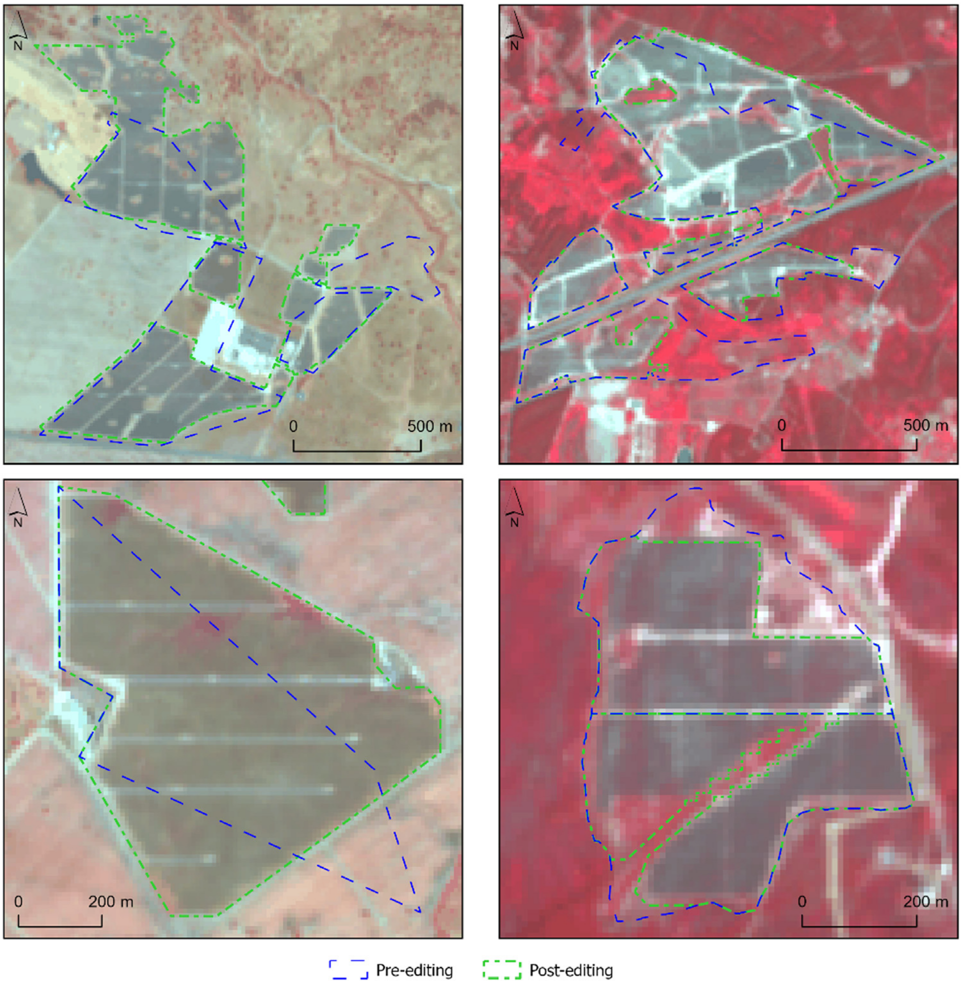

Fig. 2. Examples of polygon geometry corrections for operational facilities. The base map is a Sentinel-2 false-colour composite (RGB 8–4–3) from May 2023, with a spatial resolution of 10 m, provided by the Direção-Geral do Território (https://snig.dgterritorio.gov.pt/).

The most recent image used to distinguish between operational and planned projects was the Sentinel-2 false-colour (RGB 843) composite from December 2024. The resulting dataset is thus considered representative of facilities operational or planned up to the end of 2024. Any subsequent changes in the source datasets, such as transitions from planned to operational status or the registration of new planned projects, are not reflected.

2.4. Spatial analysis procedures

After structuring the USSE database, spatial analysis was conducted using intersection and combinatorial techniques between the USSE dataset and other GIS layers. All procedures were executed in a common coordinate referencing system (PT-TM06/ETRS89). Combinatorial analysis was used to identify the most common change trajectories across the historical LULC data series, covering the period from 1995, when the earliest map was produced, to 2018, the year of the most recent USSE data (Fig. S2 in the Supplementary materials). This method systematically captured variations in the sequence of land-use types, enabling tracing LULC dynamics preceding USSE deployment. The flows of change were represented using a Sankey diagram, with the edge weight proportional to the land area changed. For accounting for the total LULC changes, in each deployment period, USSE polygons were intersected with the immediately preceding COS map (e.g., USSE 2019–2024 intersected with COS 2018, USSE 2006 intersected with COS 1995). For planned projects, only the latest available COS was used, specifically the 2018 version. Fig. S2 provides an illustrative description of these processes.

Relative land-use occupancy metrics (%) were calculated using COS nomenclature. In addition, a modified location quotient (LQ) was computed to express the proportion of the USSE area relative to the corresponding LULC class share in continental Portugal:

$$\mathrm{LQ} = \frac{U_{1-9}}{U} / \frac{a_{1-9}}{a} \tag{1}$$

where, U_{1-9} stands for the area of the USSE facilities intersecting each of the nine most aggregated COS classes, and a_{1-9} reflects the size of each of these classes in continental Portugal. The distribution of LULC classes was based only on the class size in the 2018 COS version.

Intersect analysis was also used to assess the overlap with land and nature conservation zonings. The assessment of spatial overlap involved both direct intersection and analysis within a 2 km buffer zone; the latter was included solely for indicative purposes due to the recognised potential for impacts associated with solar power plants to extend beyond the area of installation.

3. Results

3.1. Spatial and temporal evolution of USSE deployment

The compilation of data on USSE facilities for continental Portugal has led to the identification of 264 facilities (≥ 1 MW), with approximately 13,991 ha (about 0.2 % of the total area of continental Portugal). Operational facilities accounted for 6,987 ha, with the remainder of 7,003 ha attributed to projects with grid injection capacity titles into the public electricity service grid. In this context, it is anticipated that USSE facilities' land occupancy will at least double in the next few years.

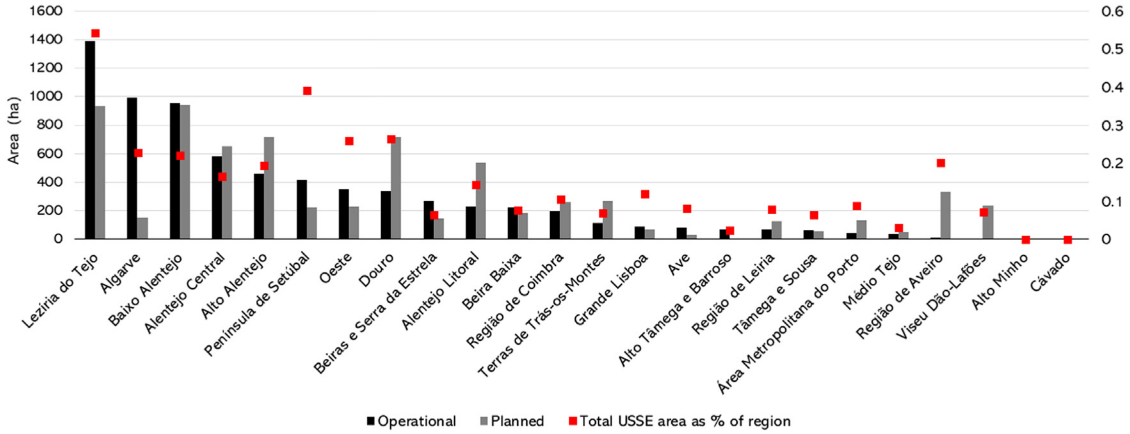

Fig. 3. Distribution of utility-scale solar energy (USSE) operational and planned facilities (≥1 MW) by NUTS III regions, presented in descending order of operational area.

The spatial distribution of projects revealed asymmetric and dynamic patterns (Fig. 3). Operational facilities (n = 165, 6,987 ha, $\bar{x}$ = 42 ha) were predominantly located in the Algarve, Baixo Alentejo, Alto Alentejo and Lezíria do Tejo regions, which together accounted for 54 % of the total area occupied by operational projects. Planned projects (n = 99, 7,003 ha, $\bar{x}$ = 71 ha), although still significantly present in southern regions, extended further north and towards the coastal zone between metropolitan areas, in proximity to the country's largest urbanised areas. Notably, regions in the North of the country, such as Aveiro or Viseu Dão-Lafões—which have not traditionally hosted operational USSE—are expected to accommodate facilities in the future.

The spatial and temporal evolution of the USSE deployment in Portugal reveals an important shift in location patterns, characterised by both geographic expansion and increasing project size (Fig. 4). While earlier facilities were concentrated in the southern regions, recent and planned projects display a broader territorial spread, including a northward shift and a greater presence in coastal regions. It is evident that over the years, the size of projects has increased. Furthermore, it is apparent from Fig. 5 that the area-weighted median of projects has shifted northward. In the case of operational projects, this centre was located between the Lezíria do Tejo and Alto Alentejo regions, whereas, for planned projects, the median centre was estimated in the Médio Tejo region.

3.2. *Land use trajectories*

The deployment of USSE facilities has resulted in changes to the Portuguese landscapes. An analysis of land use trajectories from 1995 to 2024 identifies the principal transformations that preceded USSE deployment. The Sankey diagram (Fig. 5), which illustrates the 15 most frequent trajectories and accounts for 85 % of the total operational USSE area, indicates that the majority of LULC changes occurred in areas with historically stable land use patterns, with most of these conversions occurring after 2018. Specifically, forest land consistently classified as such since 1995 constituted around 33 % of the area converted to USSE facilities by 2024. Similarly, stable agricultural areas accounted for approximately 19 % of the USSE area, while shrubland and pasture areas, also classified as stable before 2018, together represented nearly 20 %.

These patterns suggest a prevailing trend of direct conversion from long-established land uses—particularly forest and agriculture—to solar energy facilities. Although transitional sequences were also identified, such as phased conversions initiated between 2007 and 2010 and intensified between 2010 and 2015, these cases represented a smaller portion of the dataset. Isolated instances of land abandonment preceding conversion—e.g., agricultural land becoming pasture before its change into USSE facilities—were identified but remained marginal (3 %). Also, it was observed that areas of shrubland, often considered unused land, had undergone afforestation before their eventual conversion to USSE facilities.

No major change trajectory involved transitions from artificial surfaces, indicating a general avoidance of developed land. Furthermore, approximately 80 % of the USSE areas analysed were established after 2018, reflecting a recent and pronounced phase of solar energy expansion. Overall, the findings indicate that USSE development in Portugal has primarily resulted from the direct transformation of stable LULC types rather than from complex, multi-phase LULC dynamics.

3.3. *Change dynamics: past and future*

The analysis of both operational and planned USSE facilities reveals distinct patterns of LULC change, as illustrated in Fig. 6. Since the implementation of the first USSE project in 2006, deployment of USSE facilities has occurred across a variety of LULC types. The most substantial changes have taken place in classified as forest land use (41 %), followed by agricultural areas (28 %), pastures (14 %), and shrubland (14 %). Future LULC changes, with the total area expected to more than double, should all planned projects be realised, will transform an additional 7,003 ha. Of this anticipated growth, approximately 41 % is projected to occur on forest land. Agricultural areas and pastures are also expected to be affected, representing 24 % and 18 % of the projected expansion, respectively. According to the localisation quotient, pasture was the land-use class that experienced the highest relative conversion to USSE facilities, when adjusted for its overall extent within the study area (Fig. 6). This suggests an over-representation of USSE development in pasture areas relative to their spatial distribution.

A more detailed thematic analysis (Fig. 7) was conducted, focusing on the three LULC classes with the largest converted areas. Within the category of agricultural land, irrigated and non-irrigated arable land accounted for approximately 75 % of the land affected by operational USSE, followed by olive groves (19 %). Future changes, if all planned projects are built, are anticipated to represent 89 % in irrigated and non-irrigated arable land and 6 % in fruit orchards.

Approximately 90 % of the area of pastures that overlap with operational and planned facilities' land change impacts were identified in permanent pastures. These are defined as non-spontaneous grasslands and are often improved by fertilisation, cultivation, seeding, or drainage.

The expansion of USSE has also been associated with changes in several forest types. Among operational facilities, eucalyptus forests account for approximately 72 % of the converted forested area, followed by stone pine forests (9 %). The latter is a native species with a declining presence in the Portuguese landscape. Planned projects are expected to predominantly affect eucalyptus forests (66 %) and maritime pine forests (19 %).

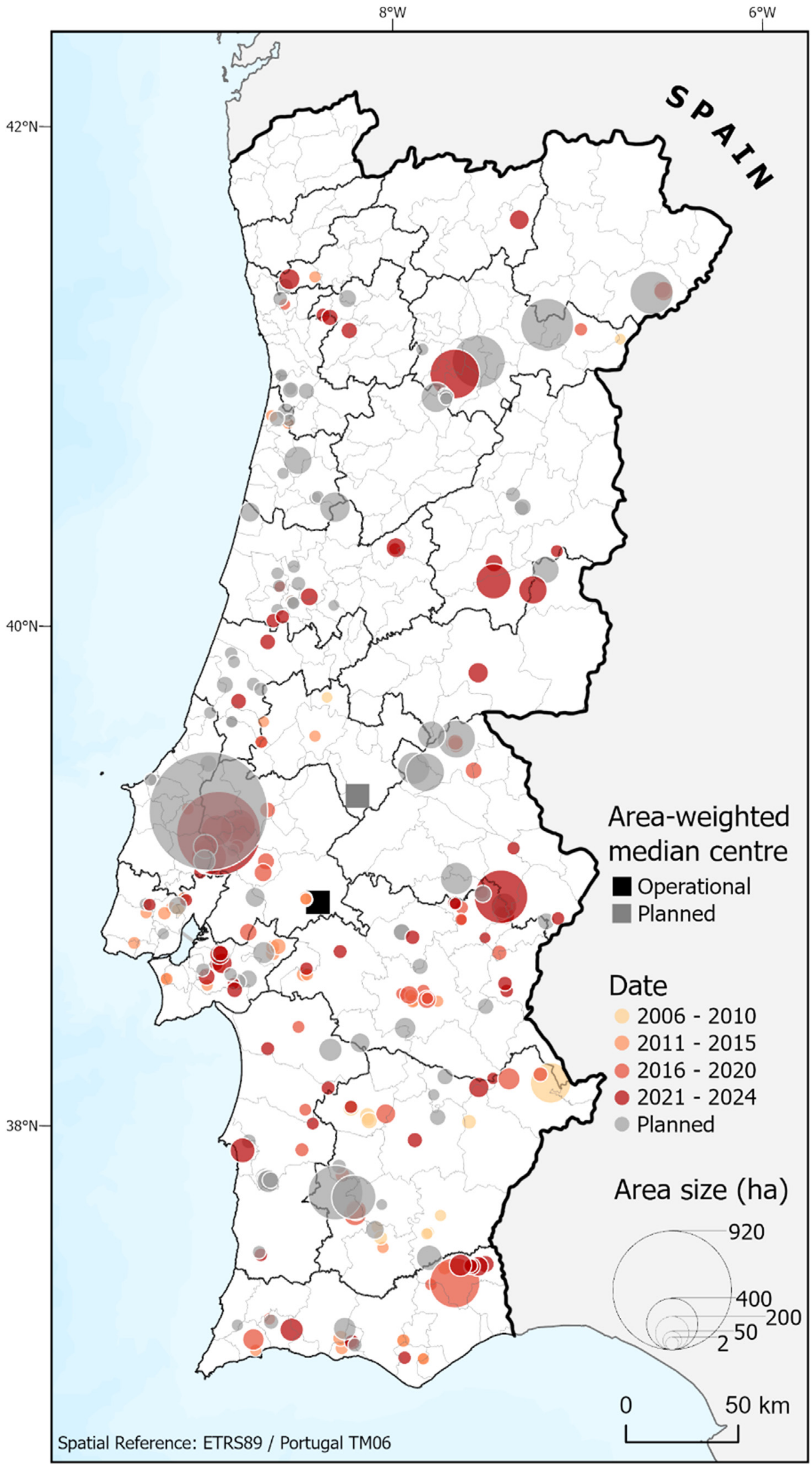

Fig. 4. Distribution of utility-scale solar energy operational and planned facilities in continental Portugal.

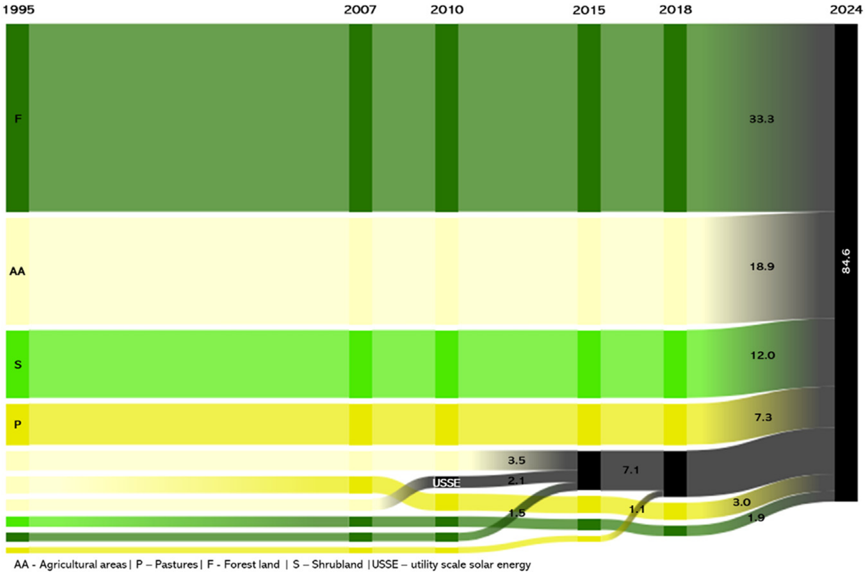

Fig. 5. Top 10 Land use and land cover change trajectories (1995–2024) as a percentage of the total utility-scale solar energy operational area (edge weight proportional to the land area changed).

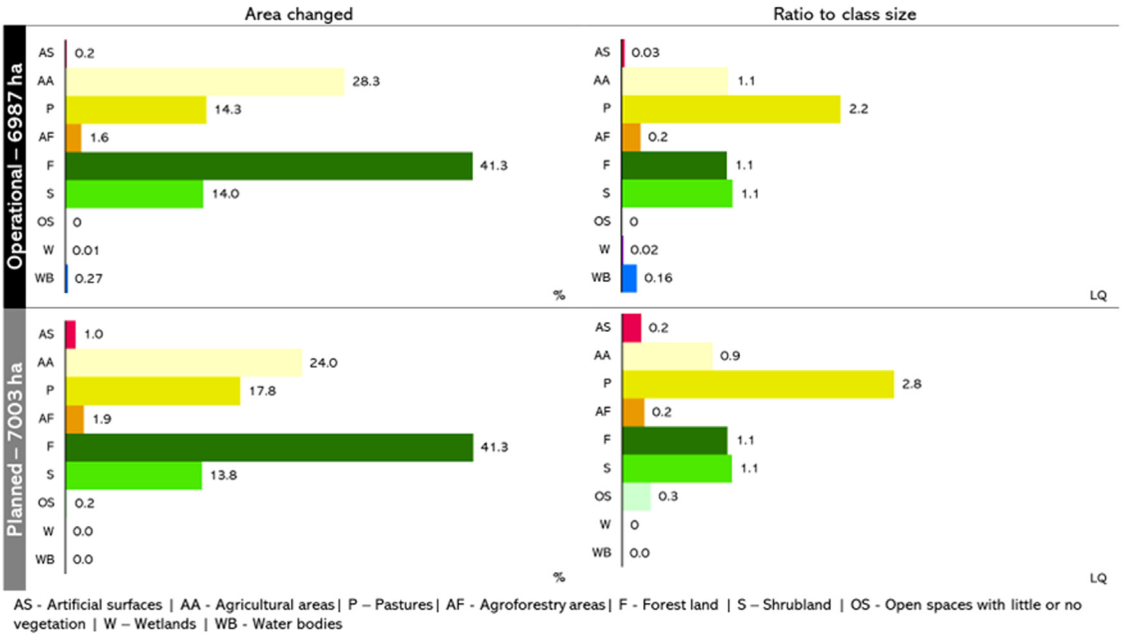

Fig. 6. Proportion of land changed by operational (2006–2024) and planned utility-scale solar energy facilities by class.

These observations suggest that land-use change linked to USSE development reflects complex and spatially differentiated patterns. The conversion of agricultural, pasture, and forested areas appears to represent a significant component of recent solar infrastructure expansion and may continue to constitute a prominent feature of future deployments.

3.4. Spatial overlaps with nature conservation areas

USSE facilities in Portugal have led to significant transformations within areas designated for land and nature conservation (Fig. 8). As of 2024, 16 % of the area occupied by operational USSE facilities overlapped the National Ecological Reserve areas, followed by Areas Classified for Nature Conservation (8 %) and National Agricultural Reserve (5 %). Planned facilities will continue to influence these conservation zones, notably the ecological reserve (13 %). Both the National Agricultural Reserve and the Areas Classified for Nature Conservation registered lower overlaps due to their more protective legal regime.

When considering a 2 km influence zone, higher spatial overlaps were assessed. The highest spatial coincidence was identified with the Agricultural Reserve and Ecological Reserve for both operational and planned projects. For operational projects, approximately 80 % of the area (more than 5,500 ha) was within 2 km of these reserve zones. In the case of planned projects, almost 100 % of the area can be found within 2 km of the National Agricultural Reserve. In the case of Areas Classified for Nature Conservation, both operational and planned facilities have an overlap of close to 25 %.

Despite lower overlaps with other Areas Classified for Nature Conservation due to more restrictive regulations, it is evident that different legal protection regimes for the territory exert varying degrees of influence on the land occupation by USSE facilities. The ongoing expansion of USSE projects underscores the need for careful consideration of land use and environmental protection policies.

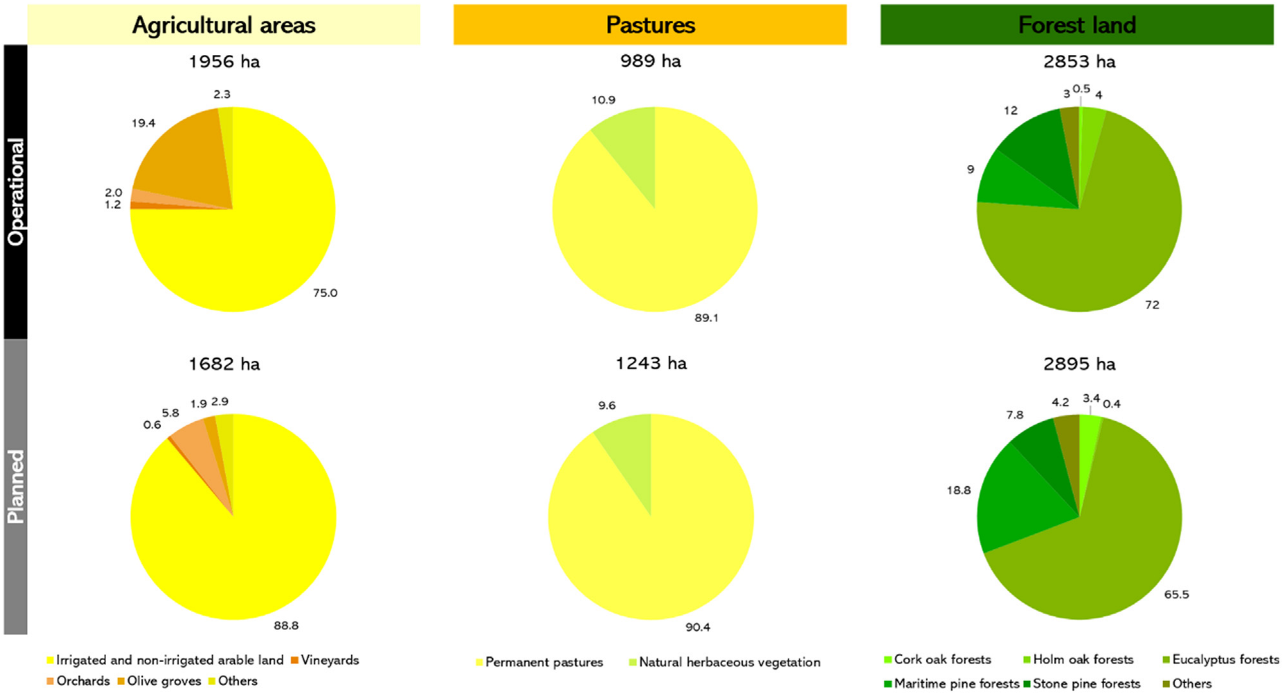

Fig. 7. Relative composition (%) of the areas converted from agricultural, forest and pasture land, disaggregated by land cover type.

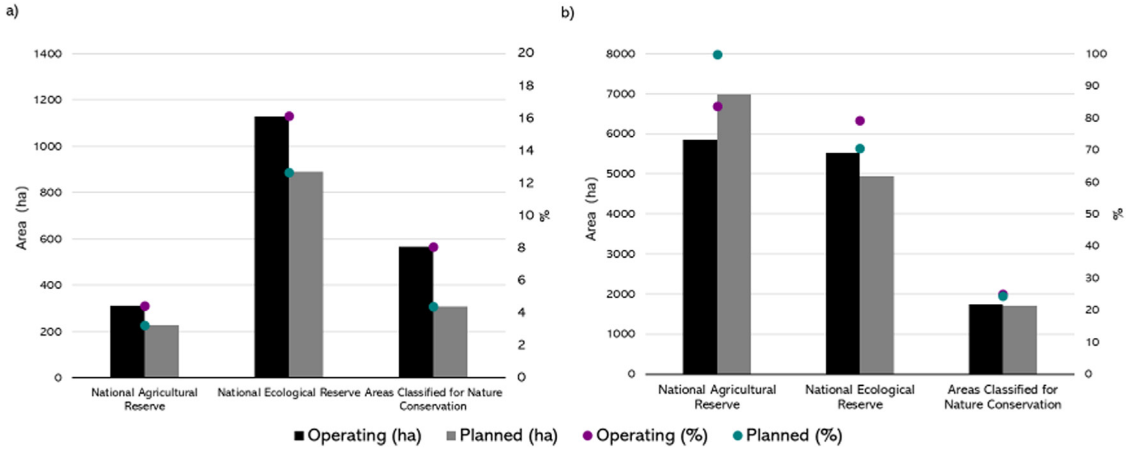

Fig. 8. Overlap of utility-scale solar energy facilities with conservation zonings: a) Intersecting; b) Within a 2 km buffer (these zonings are not spatially exclusive, so projects may intersect with multiple zoning areas due to spatial overlap).

4. Discussion

Energy geography has increasingly recognised the significance of planning the spatial dimension of the decarbonisation process. This growing recognition is reflected in the expansion of research themes and the growing use of geospatial technologies to support planning decisions (Baka and Vaishnava, 2020; Calvert, 2016). Nevertheless, Ptak et al. (2025) suggest that energy geographies occupy a marginal, if not peripheral, position in human-centred geography. Only a limited number of energy geography studies have made substantive contributions to energy planning from a territorially informed perspective (Calvert et al., 2021; Calvert and Mabee, 2015; Guo et al., 2020). Moreover, energy geography scholarship has insufficiently addressed materialising energy infrastructure, especially solar energy (Baka and Vaishnava, 2020).

Addressing some of these gaps, this study maps the geography of solar PV energy in continental Portugal and contributes to the understanding of the territorial transformation induced by USSE facilities. The GIS-based approach employed may be transferable to other geographical contexts and RE technologies to inform policymakers and stakeholders. Such spatially explicit assessments may help reconcile RE targets with land-use and conservation objectives. More significantly, it contributes to enhancing the integration between energy geography and spatial planning through a focus on LULC changes as indicators of land-use conflicts. The analysis reconstructs the spatial and temporal expansion of USSE facilities in Portugal and provides evidence regarding its land use implications. Despite these contributions, the potential of energy geography research to inform spatial planning and land management for the governance of the energy transition remains far from exhausted, as discussed in the following sections.

Beyond the Portuguese context, the results of this study provide empirical evidence relevant to theoretical debates concerning land-use conflicts and the integration of energy and spatial planning. The mapping of RE facilities constitutes an empirical basis for examining interactions between technical, economic, and policy determinants and ecological and social priorities.

4.1. Geography of PV solar energy

A key contribution of this study is the mapping of the geography of solar energy in Portugal, highlighting the historical and planned expansion of USSE facilities. The spatial distribution reveals a concentration of USSE facilities in the southern regions, particularly within rural municipalities characterised by low population densities. These regions offer advantages such as high solar radiation levels, flat terrain, and generally larger land parcel sizes. These factors are acknowledged to be critical in the siting of USSE facilities (O'Shaughnessy et al., 2023; Rediske et al., 2019).

The location of USSE projects fundamentally shapes the type and magnitude of the impacts they generate, highlighting the importance of site selection processes (Lovich and Ennen, 2011). Although land-use and legal status of land constitute important factors, the criteria for site selection are often more complex. Empirical evidence suggests that land use types are not strong determinants in the siting of large-scale PV projects (Bosmans et al., 2022), and prior research has suggested that technical and economic location factors are typically the most important in the location decisions for PV power plants in Portugal (Alves et al., 2023). In particular, proximity to infrastructure, especially grid connections, emerges as a key determinant.

Future USSE deployment is projected to continue in southern regions while expanding towards northern regions. This shift reflects the emergence of a new spatial configuration of PV energy production in continental Portugal into regions traditionally associated with wind and hydropower generation (see Nunes, 2018). This trend may contribute to a less clustered distribution of the territorial impacts associated with solar energy. Nevertheless, the planned deployment of PV projects is increasingly advancing into regions that already host significant wind and hydropower operations. The recent shift in siting patterns towards northern regions has induced distinct types of LULC changes, given the regional differences and contrasts in land-use.

The concentration of USSE facilities in sparsely populated areas with abundant solar resources may result in uneven distribution of impacts, including LULC change and biodiversity losses. Analysis of this requires analytical attention to the energy–land nexus (Lamhamedi and de Vries, 2022), as land constitutes a resource where RE production competes with other uses. Furthermore, spatial justice (Wójcik and Jeziorska-Biel, 2023), which highlights how the burdens and benefits of decarbonisation are unevenly distributed across territories and communities, is further implicated by the differential impacts of LULC changes. These perspectives underscore that future siting strategies in Portugal should not only pursue efficiency or technical feasibility but also actively integrate considerations of the long-term sustainability of land systems and social concerns.

In summary, the geography of USSE deployment in continental Portugal reflects a convergence of favourable technical and economic conditions, with southern regions emerging as the dominant locus due to optimal solar irradiance, accessible terrain, and land availability. However, the recent spatial shift towards northern areas signals an evolving energy landscape that intersects with different ecological and socioeconomic contexts. In parallel, USSE facilities have progressively increased in scale, resulting in substantially larger land occupation.

4.2. Solar power plants and landscape transformation

A second key contribution of this study concerns the reconstruction of LULC changes from a multitemporal perspective, highlighting the conversion of different LULC types into USSE facilities. Solar energy development has become an essential part of the decarbonisation strategy in Portugal (Sareen, 2024), and the expansion of USSE facilities is reshaping land-use patterns, with implications for spatial planning.

Although USSE power plants occupied a relatively small proportion of land (approximately 0.2 % of continental Portugal's land area), compared to dominant land uses across Portugal, their uneven distribution may have resulted in disproportionate pressures in certain areas. The expansion of USSE facilities in the country has led to significant LULC changes, primarily affecting agricultural, pasture, and forested areas. Planned projects are expected to primarily result in the conversion of forest land. However, pastures, which are extensively distributed in southern Portugal, have been the most impacted land use type class relative to their total area. The achievement of the ambitious solar capacity targets by 2030 is likely to exacerbate these changes. In contrast, the deployment of USSE on artificial surfaces and water bodies has been minimal. Some projects were identified in artificial surfaces such as abandoned quarries, commercial, and industrial areas; however, their share was found to be limited. It is important to note that the analysis exclusively focused on utility-scale facilities, excluding decentralised generation systems such as rooftop solar.

The findings extend previous research through a more comprehensive assessment of LULC changes associated with USSE facilities in Portugal, which were previously constrained by limited spatial and temporal coverage. Even though it had already been suggested that a functional dichotomy exists between the preservation of land with strong agricultural potential and the massive expansion of RE production across rural areas (Poggi et al., 2018). Similarly, Barral et al. (2023) documented extensive agricultural land conversion for solar energy in the southern Iberian Peninsula, including Portuguese regions. Our findings, considering the period 2006–2024, concur with these observations regarding the conversion of agricultural land for solar energy production. However, more recent developments, particularly since 2018, have increasingly led to the conversion of forest land, a pattern that appears likely to intensify with planned projects. The high prevalence of private forest ownership in the country (Pulla et al., 2013) and the economic return of PV energy production and land leasing may explain this trend. Importantly, the analysis suggests that planned projects increasingly target forests with fewer conservation concerns compared to operational facilities. This shift is significant, as it minimises potential impacts on native forests, with most changes expected to occur in eucalyptus plantations—the second-largest forest type in continental Portugal in 2018 (Alves et al., 2022). A noteworthy finding was that agroforestry systems, such as the Mediterranean *montado*, as well as associated forests, including cork oak and holm oak, were not primarily affected, according to the COS data. The destruction of *montado* ecosystems is frequently emphasised in media discussions regarding landscape changes resulting from the construction of USSE facilities, which contribute to public opposition to RE. However, the amount of area identified as altered was found to be minimal. While LULC changes affecting forests and agricultural land are often controversial, compensatory economic and ecological measures are typically implemented. For example, tree removal requires replanting in greater numbers, in addition to other mitigation measures established under the framework of EIA.

The historical neglect of the relationship between energy infrastructure and landscape transformation—often considered collateral damage (Pasqualetti and Stremke, 2018)—raises concerns regarding the spatial footprint of the ongoing energy transition. The estimated land occupation by operational USSE facilities in Portugal, when expressed as a proportion of national territory, appears to be comparable to that observed in the United Kingdom—despite the latter's substantially lower PV generation potential (Blaydes et al., 2025)—as well as to that of Spain (de Juan and Hidalgo, 2024). Projections based on the full realisation of planned developments suggest a potential doubling of this land take.

LULC changes associated with the development of USSE facilities have been documented in several European countries. Evidence from Slovakia suggests that nearly 90 % of installed USSE capacity has been located on arable land, while in the Czech Republic, the proportion is approximately 63 % (Hofierka et al., 2014). In the United Kingdom, a considerable expansion of land occupation by renewable energy facilities has been observed, largely at the expense of agricultural areas (Blaydes et al., 2025). In the Netherlands, agriculture has been identified as the land use category most frequently displaced by USSE facilities (Becker et al., 2025). Similarly, Böhm et al. (2022) estimated that more than half of the area dedicated to USSE in Germany was formerly agricultural. In similar Mediterranean contexts, Barral et al. (2023) and Diaz-Cuevas et al. (2023) reported substantial transformations in rural economies and landscapes linked to the replacement of arable crops with PV facilities. Using these studies as a benchmark, agricultural land conversion accounts for the majority of the area allocated to USSE facilities across Europe. Likewise, in Portugal, agricultural land constituted the primary category converted for PV deployment. However, recent shifts in project distribution towards northern regions have resulted in an increasing predominance of forest land conversion, marking a departure from patterns observed in other European contexts.

4.3. Challenges to land and nature conservation

A third key contribution of this study concerns the identification of potential environmental conflicts associated with the expansion of USSE facilities, due to the overlap of operational and planned facilities with land and nature conservation zones. Although data limitations may underestimate the extent of conflicts, the findings indicate that regulatory constraints appear to be steering development away from the National System of Classified Areas, such as the Natura 2000 network, Protected Areas, and Biosphere Reserves, while more flexible conservation areas remain vulnerable. Classified areas appear to exert a stronger barrier effect, as evidenced by the limited number of projects located within their boundaries. This observation is consistent with findings reported in previous studies where protected areas limit anthropogenic activities beyond their legal boundaries (Mingarro and Lobo, 2023). By contrast, agricultural and ecological reserves do not seem to exert a comparable constraint beyond their designated limits.

At the global scale, RE installations have been recognised as a potential threat to biodiversity conservation and the siting of USSE facilities within protected areas and other environmentally sensitive zones constitutes a phenomenon that is not confined to the Portuguese context (Diaz-Cuevas et al., 2023; Hernandez et al., 2015; Rehbein et al., 2020; Tinsley et al., 2024; Valera et al., 2022). Placing large, ground-mounted solar energy systems in natural environments, rather than in already degraded areas, can pose risks to biodiversity conservation. Most of the well-documented effects of USSE facilities on ecosystems and biodiversity manifest through the loss and change of habitats (Gasparatos et al., 2017). However, the impacts of USSE facilities can vary substantially depending on environmental characteristics such as ecological conditions and previous land use (Carvalho et al., 2025; Chen et al., 2024; Xiao et al., 2025). Furthermore, some negative impacts may be mitigated by sustainable landscape management approaches (Stremke and Dobbelsteen, 2013), which may maintain ecosystem services (Tölgyesi et al., 2023) such as pollinator-friendly PV plants (Dolezal et al., 2021). In this sense, the processes of LULC change may vary considerably, potentially leading to different impacts on nature conservation, which were not assessed by the methodological approach employed in this study. Even though monitoring these overlaps is essential for assessing potential environmental impacts related to habitat fragmentation, the reduction of ecosystem services and informing conservation policies.

Furthermore, the findings draw attention to concerns related to policy compliance and sustainability. Future development may face challenges in adhering to policy compliance, especially under the REPowerEU program (European Commission, 2022a) and associated initiatives (European Council, 2022) aimed at accelerating RE deployment. In the context of the European Biodiversity Strategy for 2030 and the proposed expansion of protected areas under the 30 × 30 initiative (Eckert et al., 2023), the continued deployment of USSE facilities may present a substantial obstacle to the planned enlargement of conservation zones. This potential conflict is particularly relevant given indications that progress toward energy transition targets may be occurring at the expense of afforestation efforts and the prevention of deforestation. The occupation of agricultural areas and soils designated as part of the national ecological reserve in Portugal raises questions about the alignment of solar energy development with sustainability principles (Moore-O'Leary et al., 2017) and the land-use objectives of the National Spatial Planning Policy Programme (República Portuguesa, 2019).

Legislative changes introduced in Portugal since 2022 have also weakened environmental safeguards. These amendments include, for example, exemptions from EIA for projects below 100 ha and have curtailed public participation in the permitting process (República Portuguesa, 2022, 2023). Such deregulation may result in the oversight of environmental considerations and an increased likelihood of public opposition, particularly where location-specific sensitivities are at stake (Costa Pinto et al., 2021). The manifestation of environmentally and socially contentious impacts from RE infrastructure has contributed to negative public perception and growing local resistance to USSE projects in Portugal (Brás et al., 2024; Silva and Sareen, 2021). Although the estimated land occupation by USSE facilities represents a small fraction of Portugal's total land area, the projected land requirements necessary to meet the NECP PV capacity targets by 2030 (20.8 GW, of which 15.1 GW is utility-scale) could lead to an increase in land occupation to approximately 1 % of the continental territory, given typical PV land-use intensity, potentially amplifying pressures on biodiversity and sensitive ecosystems.

4.4. Policy and planning insights

4.4.1. Governance challenges and spatial planning incoherences

While European and national policies promote the accelerated deployment of RE facilities, the absence of spatially explicit energy planning mechanisms in Portugal may have intensified governance asymmetries and land-use conflicts associated with USSE development. At the EU level, policy is driven by incentives for RE deployment as part of climate mitigation and energy security strategies. National governments are aiming for higher RE production, guaranteed tariff auctions, and the relaxation of environmental legislation. In the Portuguese context, the prioritisation of USSE development has been associated with the consolidation of benefits among large corporate actors, frequently to the detriment of community stakeholders and decentralised initiatives (Silva and Sareen, 2021). Such concentration of decision-making authority and economic opportunities at higher governance levels has been linked to distributive and procedural inequalities affecting local populations (Brás et al., 2024; Wallace et al., 2025). As recent legislative shifts in Portugal have curtailed public engagement and relaxed environmental assessments, these uneven power relations have intensified. Scalar and multilevel governance scholarship thus highlights the need for more coherent, participatory approaches that bridge scales and integrate local socio-ecological priorities with broader energy transition goals (Dobravec et al., 2021; Radtke, 2025).

The progression towards a low-carbon energy system necessitates continued monitoring and assessment of land occupancy associated with USSE development, intending to inform planning efforts aimed at mitigating its negative consequences. However, the persistent failure of climate and energy policies to fully account for trade-offs—particularly the competition for land among energy generation, agricultural production, and biodiversity conservation—has been noted in the literature (Skjærseth, 2021). Moreover, conventional spatial planning instruments may prove inadequate in addressing the land-use challenges posed by the urgency of the energy transition (Calvert et al., 2021; Koelman et al., 2018). In particular, land-use conflicts related to RE have often been neglected in land-use planning processes, being treated primarily as engineering and technological challenges (Kaza and Curtis, 2014). Therefore, the development of indicator systems for the monitoring of the land footprint of USSE facilities and of the impacts resulting from associated transformations assumes particular relevance.

The observed LULC dynamics associated with USSE facilities in continental Portugal may constitute a lack of coherence between policy recommendations and implementation in the absence of stricter zoning regulations or incentive-based siting mechanisms. For example, the European Commission recommends prioritising RE deployment in artificial, degraded, and unproductive areas while protecting Natura 2000 sites and other reserves (European Commission, 2022b). The patterns uncovered in this study deviate from these guidelines, and future expansion may exacerbate these inconsistencies. This incoherence suggests that current legal protections may be insufficient to direct development away from environmentally sensitive zones, a concern also noted in previous research (Ascensão et al., 2023; Oakleaf et al., 2017). The persistence of such misalignments suggests a need to reassess the spatial dimension of energy planning to ensure greater coherence between energy transition goals and land-use priorities.

4.4.2. *Integrating energy planning and spatial planning in Portugal*

In this context, a more integrated approach to the spatial governance of RE development appears necessary. From a policy perspective, the results of this study reinforce the importance of integrated energy and spatial planning frameworks that identify suitable areas for USSE deployment while minimising negative impacts on agriculture and biodiversity. It is important to note that in Portugal, energy planning has historically been formulated in relative isolation from spatial planning and land management policies. Key strategic documents, such as the NECP and the National Roadmap for Carbon Neutrality, are not spatially explicit and do not typically offer regionally or municipally tailored planning guidance for the identification of areas suitable for RE deployment. Consequently, the spatial organisation of the electricity system continues to depend predominantly on sectoral instruments related to energy policy and grid planning.

Regulatory mechanisms—ranging from land protection and siting guidelines (Ferreras-Alonso et al., 2024) to integrated spatial-energy planning approaches (Stoeglehner, 2020)—play a critical role in the identification of appropriate land parcels for energy production, while contributing to conflict mitigation. The relevance of context-specific planning frameworks that differentiate between urban, peri-urban, and rural characteristics has also been emphasised (Stoeglehner et al., 2011).

Our findings further suggest that energy planning frameworks must also incorporate LULC change dynamics, particularly concerning the preservation of land uses considered critical. The adaptation of RE targets to spatial constraints has the potential to limit the displacement of existing land uses. Ferreras-Alonso et al. (2024) estimate that land-use protection and siting policies could reduce the total land occupied by solar PV panels by 23 % in the EU-27, thereby minimising the conversion of cropland and forests while still meeting the established energy targets.

Spatially explicit modelling approaches have proven effective for allocating land to USSE facilities while balancing multiple land use objectives (Delafield et al., 2023; Hermoso et al., 2023; Weber et al., 2023). Additionally, policies should promote techno-ecological synergies and incorporate key ecological concepts to balance ecological, political, and socioeconomic values (Hernandez et al., 2019; Moore-O’Leary et al., 2017). Co-location strategies, such as agrivoltaics (Barron-Gafford et al., 2019) and floatovoltaics (Trapani and Redón Santafé, 2015), have been identified with the potential to enhance land-use efficiency, thereby reducing the extent of LULC changes. Several advancements within the European context have illustrated the potential for mitigation of land-use conflicts through the implementation of dual-use strategies. An example is legislation in various European countries, including Germany, Spain, Italy, and the United Kingdom, which provides funding for solar projects incorporating nature-inclusive design of solar parks based on ecological criteria and potential biodiversity gains (The Nature Conservancy and SolarPower Europe, 2024). Similarly, the integration of agricultural production with PV energy generation has increasingly been promoted through public policies. Tajima et al. (2022) provide evidence of governmental support for agrivoltaic systems in multiple countries. Such approaches may possess transferability to Portugal, where, for instance, renewable capacity auctions have traditionally prioritised the lowest bid price, with no explicit integration of environmental or social criteria and limited acknowledgement of the potential multifunctional characteristics of USSE facilities.

The alignment between RE deployment and sustainability objectives may be strengthened through the formulation of planning instruments grounded in territorially explicit frameworks. A recent initiative in this domain in Portugal was an approach developed by the National Laboratory for Energy and Geology (GTAER, 2024). This initiative, in response to the RED III, identifies areas of relatively low environmental and heritage sensitivity deemed suitable for USSE deployment. While its technical contribution is recognised, the framework currently lacks binding legal authority. Nonetheless, its integration into project permitting processes has been formally encouraged through a parliamentary resolution (República Portuguesa, 2025b). The institutionalisation of such spatial zoning frameworks may facilitate the development of coherent spatial energy policies and support site selection processes by energy developers.

Considering the geography of USSE PV energy in Portugal, it seems important to reconsider grid expansion plans in light of criteria that prioritise development in areas with comparatively lower potential of land-use conflicts. Additionally, the specification of thresholds for maximum project size and spatial density could support a more equitable distribution of land-use pressures and limit the occurrence of cumulative effects, particularly in ecologically valuable or sensitive territories. Furthermore, it is imperative to take advantage of water surfaces with floatovoltaics, leveraging the use of artificial water bodies. Besides that, the strategic repowering and hybridisation of operational facilities emerge as potentially effective for increasing energy output while containing additional land occupation. Urban planning also has a role to play in the energy transition, both through measures that enhance energy efficiency and through the facilitation of cities as energy producers. Particular attention has to be drawn to the influence of the physical and functional characteristics of urban areas’ energy demand patterns (Poggi and Amado, 2024; Stoeglehner and Abart-Heriszt, 2022). The integration of distributed PV facilities into urban areas has been suggested as a means of mitigating land-use conflicts, given that such facilities are less constrained by land requirements than utility-scale (Kaza and Curtis, 2014; Karunathilake et al., 2018; Kurdi et al., 2022; Wei et al., 2024). Nevertheless, Portuguese energy planning, as expressed in the NECP, states that decentralised PV, including rooftop installations, small producers, and self-consumption schemes, will account for less than 30 % of the 20.8 GW target set for the end of the decade (República Portuguesa, 2025a).

4.5. *Limitations and future research directions*

The scope of this study was restricted to the direct land-use implications of USSE development, excluding indirect effects associated with other components of the RE production chain. These include, for example, resource extraction and green sacrifice zones (e.g., Canelas and Carvalho, 2023), transmission and distribution grids (e.g., Dunlap, 2023), substations and additional ancillary infrastructure. Consequently, the overall land-use impact of solar energy development in Portugal is underestimated. Furthermore, the analysis of planned USSE facilities was restricted to projects with confirmed grid-connection approval up to December 2024, thereby excluding a set of planned projects lacking such guarantees, and some subject to pending EIA, leaving their future implementation uncertain. In addition, the absence of a direct assessment of ecological outcomes, particularly with respect to habitat quality and the extent of landscape fragmentation, constitutes a limitation of the analysis. Although spatial overlap between PV facilities and conservation areas was identified, this alone does not indicate the magnitude or nature of ecological impacts. Moreover, reliance solely on formally designated conservation areas provides an incomplete representation of ecological sensitivity, as suggested by findings emphasising the importance of biodiversity hotspots not covered by statutory designations (Ascensão et al., 2023).

A further limitation relates to the reliance on a LULC map that predominantly represents land use rather than land cover types, in combination with inconsistencies in temporal resolution arising from uneven intervals between available maps. Moreover, COS maps have a minimum mapping unit of one ha, restricting the detection of LULC smaller than this threshold. The temporal resolution also constitutes a potential source of uncertainty due to the possibility of undetected changes occurring between reference years. Although COS's thematic accuracy is estimated at approximately 85 %, the presence of spatial and temporal interdependence could have contributed to the spread of errors across reference periods. These limitations contribute to uncertainty in the definitive attribution of observed LULC changes to USSE development. This issue is particularly pronounced in the case of planned projects, given that the most recent version of the COS map dates to 2018. Still, regarding the limitations of geospatial information, data from the National Agricultural Network and the National Ecological Network are not available for all municipalities. Consequently, the overlap of USSE facilities with these legally designated areas is likely underestimated due to the absence of digitised and publicly accessible datasets for the entire country.

Beyond the aforementioned limitations, which may offer insights for subsequent research, four key areas have been identified: (i) new metrics for assessing the energy–land nexus, (ii) land-use competition, (iii) location determinants and (iv) energy and spatial planning.

(i) Although the environmental benefits of RE sources are widely acknowledged, comprehensive sustainability assessments that incorporate spatial implications remain relatively scarce. Existing spatial metrics tend to prioritise quantifications of land requirements (Cagle et al., 2023). However, as highlighted by Smil (2015), such metrics (e.g., power density or land-use intensity) fail to account for the initial quality of the land that was claimed. This omission hinders the capacity to assess trade-offs and conduct robust cost-benefit analyses related to LULC change. The relative impacts of alternative land conversion scenarios, such as deforestation versus the preservation of existing vegetation, merit further investigation, particularly concerning biodiversity conservation, carbon sequestration potential, and ecosystem service provision.

(ii) Observed trends in the transformation of agricultural and pasture lands underscore the need for further investigation into the implications of solar energy expansion for food production systems. For example, the decision-making processes of farmers with agricultural land abandonment and associated LULC changes are inherently complex (Gomes et al., 2019). Nonetheless, the economic attractiveness of allocating farmland for solar energy production has been well documented (Farja and Maciejczak, 2021). In this context, the potential role of solar energy development as a driver of farm abandonment in rural areas warrants further scrutiny. The extent to which agricultural policy frameworks can respond to land-use competition arising from RE-related incentives remains insufficiently understood.

(iii) A more comprehensive understanding of the determinants influencing USSE siting decisions remains necessary. The relative impact of fixed techno-economic constraints—such as transmission grid infrastructure, policy frameworks, and geographical characteristics—on the spatial expansion of USSE facilities in Portugal remains an open empirical question.

(iv) Further research is necessary to assess the degree of alignment between existing spatial planning instruments in Portugal and the siting requirements of USSE development under sustainability objectives. The effectiveness of current planning mechanisms in mediating land-use conflicts and steering solar development towards less sensitive areas remains unclear. Scenario-based modelling approaches aimed at simulating future patterns of land occupation under participatory planning approaches offer a promising avenue for anticipating spatial impacts. Within this framework, a deeper understanding of stakeholder perceptions—including those of RE developers, governmental entities, and local communities—could support the development of methodologies to assess potential degrees of spatial conflict. Such methodological frameworks may contribute to the ex-ante evaluation of proposed USSE projects in relation to socio-environmental sensitivities.

5. Conclusions

This study offers a spatially explicit characterisation of the land use implications associated with USSE deployment in continental Portugal. By developing a harmonised geospatial database and applying spatial analysis techniques, it provides the most comprehensive assessment to date in terms of thematic, spatial, and temporal coverage of PV solar energy land occupancy.

This research has three main contributions. First, it maps the geography of solar energy development in Portugal, revealing how USSE facilities have expanded across the country, alongside increases in average project size and the emergence of new spatial patterns. The second contribution concerns the reconstruction of LULC changes from a multitemporal perspective, illustrating the conversion of different LULC types into USSE facilities. The analysis demonstrates that USSE deployment has altered historically stable landscapes, particularly forests, agricultural lands, and pastures. A marked shift in siting patterns further suggests a potential intensification of landscape changes in regions that previously did not host USSE facilities. The third principal contribution relates to the identification of potential environmental conflicts arising from USSE expansion. Operational and planned projects increasingly intersect with areas designated for land and nature conservation, raising concerns regarding the compatibility of deployment patterns with ecological protection frameworks. While overlaps with strictly protected areas remain limited, increased intersections with ecological and agricultural reserves indicate growing pressures on these more permissive zoning categories. These results should be interpreted cautiously, given the potential underrepresentation of some conservation datasets and the evolving nature of regulatory frameworks.

The observed patterns of LULC change in Portugal exemplify the complexities associated with aligning RE expansion with sustainable land management. The results suggest that spatially explicit methodologies can help systematic monitoring of land-use transformations for informing spatial planning policies for the energy transition in contexts characterised by rapid RE deployment. A broader implication of these results concerns the potential evolution of spatial planning instruments. The increasing pace and scale of USSE development suggest a growing need for planning frameworks capable of anticipating future land demands and incorporating spatial criteria that address cumulative effects. The applicability of these insights may extend to other geographical contexts exhibiting similar interactions between energy infrastructure development and land-use dynamics. Overall, these findings advance the field of energy geography by providing spatially grounded insights into how RE transitions reshape land-use patterns, often challenging established planning frameworks. Although USSE facilities currently occupy a relatively small share of total land in Portugal, projected capacity targets for 2030 indicate substantial expansion, which may exacerbate land-use conflicts and increase societal resistance due to landscape transformations in tension with spatial planning objectives. Moreover, the evidence gathered is highly relevant for monitoring territorial transformations in the context of energy transition. It also has the potential to inform decision-making regarding land-use planning policies for RE development.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

André Alves: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Eduardo Gomes:** Writing – review & editing, Supervision, Conceptualization. **Eduarda Marques da Costa:** Writing – review & editing, Supervision, Conceptualization. **Mário Caetano:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Supplementary materials

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