AGRIVOLTAIC – STUDY OF THE POTENTIAL IN PORTUGAL CONTINENTAL

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ABSTRACT: The objective for the share of renewable energy in Portugal's total energy consumption was raised from 47% to 51% in the revised National Energy and Climate Plan for 2030, highlighting Portugal's commitment to reducing emissions, enhancing renewable energy usage, and improving energy efficiency. Agrivoltaics systems can be one of the strategies to accomplish this goal. These systems allow the combination of food and energy production in the same space in a synergistic way, avoiding land-use competition between PV and agriculture. This study analyzes the technical potential of agrivoltaics in mainland Portugal, a country particularly suitable for its implementation due to its high solar potential and diversified agriculture. The study used public geographic information system databases to perform systematic mapping of the viable areas. The methodology used was based on a multicriteria geospatial analysis, which included the identification of agricultural and pasture areas (based on the 2023 Land Use Charter), the exclusion of zones with legal restrictions such as National Agricultural Reserve (RAN), National Ecological Reserve (REN), and Natura 2000 Network, and the areas with a terrain slope >10%. The analysis revealed that the Alentejo region has the greatest technical potential, due to its predominantly flat topography, high solar radiation, and low density of environmental restrictions. The study estimated the potential for installed photovoltaic (PV) power through overhead configuration.
Keywords: agrivoltaics; photovoltaic energy; agriculture; sustainable development; territorial planning

1 INTRODUCTION

Over the last few decades, the ongoing climate changes, combined with the increasing need for energy production and growing pressure on natural resources, has imposed considerable challenges on the sustainability of economic, social, and environmental systems. While the energy sector seeks to transition to clean and renewable sources, the agricultural sector faces challenges such as water scarcity, soil degradation, reduction of biodiversity, and the search for greater resilience and efficiency in production systems [1].

In this scenario, agrivoltaics or AgriPV presents itself as a promising solution, allowing for the combined use of the same area of land for agricultural production and electricity generation through photovoltaic solar panels. By combining energy and food production in the same location, this strategy fosters a more efficient use of rural land, reducing land-use conflicts and promoting synergies between strategic sectors [2].

The adoption of agrivoltaics has increased in European countries with a Mediterranean climate, such as France, Italy, and Spain. In Southern Europe, the high levels of solar radiation and the strong agricultural traditions make this technology particularly promising [3,4]. In addition, countries with more temperate climates, such as Germany and the Netherlands, are also developing agrivoltaic solutions adapted to their specific climatic conditions. In these countries, public policies, incentive programs, and specific regulations have helped to consolidate the agrivoltaic model as a viable option for achieving climate goals and strengthening food security [5, 6, 7, 8].

In Portugal, the outlook is also promising: the country has high levels of solar radiation (>1,800 kWh/m²/year in most of the territory), extensive coverage of agricultural areas, and solid commitments to decarbonization, established in the National Energy and Climate Plan (PNEC 2030), which foresees a significant increase in the contribution of photovoltaic (PV) energy to the country's energy matrix [9]. However, there are still important gaps to be solved at the national level, such as the lack of specific regulations for the agrivoltaic sector, the scarcity of applied technical-scientific studies, and the lack of a systematic mapping of the territory to identify areas with technical, legal, and environmental viability for the implementation of this type of system.

Identifying these areas is essential to boost the adoption of agrivoltaics in Portugal, contributing to more sustainable territorial energy planning that considers legal constraints of the lands, as well as their potential to be used in AgriPV projects. Thus, this study aims to fill this gap through a multicriteria geospatial analysis that examines the agrivoltaic viability of the territory in the different regions of mainland Portugal, considering criteria such as legal constraints on land use, as well as its current use and slope.

2 METHODOLOGY

2.1 Definition of Criteria for the Selection of Potential Areas.

To define the areas suitable for the installation of agrivoltaic systems, it's necessary to consider criteria that encompass agronomic, environmental, and technical-spatial dimensions [2, 10, 11].

In this analysis, the selection criteria were divided into three main categories:

- Current land use: The selection of eligible areas was based on vector data from the Land Use Map of 2023 (COS 2023), where classes with the greatest compatibility with agrivoltaic systems were selected: agricultural use and pasture [12].
- Legal and environmental restrictions: Areas that intersect with the Natura 2000 Network, the National Agricultural Reserve (RAN), and the National Ecological Reserve (REN) were excluded due to legal restrictions that make the installation of energy infrastructures unfeasible [13, 14, 15].

- Topographic conditions: Two slope categories were analyzed (≤10% and >10%) based on the methodology for assessing agricultural suitability and the installation of photovoltaic panels [16, 17].
- The analysis consisted of:
- Intersection between agricultural and pasture areas (COS 2023) with the restriction layers (Natura 2000, RAN, and REN).
- Topographic filtering to retain areas within slopes categories ≤10%.
- Calculation of the potential photovoltaic energy installation capacity in the identified useful areas, based on simulations using the PVSyst 8.0.13 software [18].

2.1.1 Land Use: Classification by COS 2023

The first spatial selection criterion used in this analysis was the current land use designation. Areas designated for agriculture and pasture were selected, as recorded in the 2023 Land Use Map (Carta de Ocupação do Solo, COS) [12]. This map represents the most recent cartographic database for mainland Portugal. Figure 1 presents the land use classification map, which shows the spatial distribution of the main land use and land cover categories for mainland Portugal.

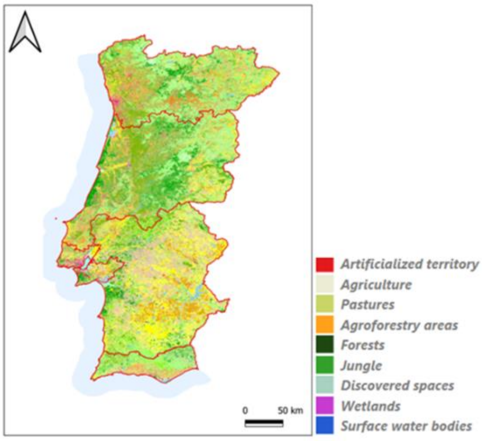

Figure 1: Land Use and Land Cover Map according to COS 2023.

The land use categories selected for agrivoltaic use in this project were:

- Agriculture: This class or category of land use and cover includes the crop regions shown on this land use and land cover map.
- Pasture: This class or category includes all regions occupied by pasture.

Figure 2 shows the eligible areas for pasture and agriculture in mainland Portugal.

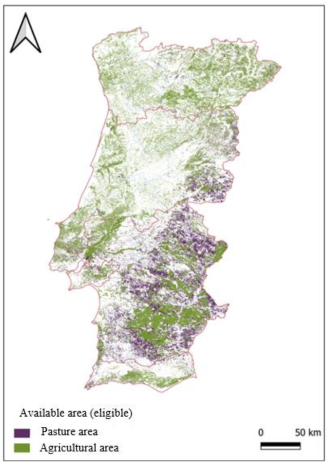

Figure 2: Combination of the map of eligible areas (pasture and agriculture)

The selection of these land use classes was based on their technical and ecological feasibility for integration with photovoltaic systems. These uses allow for the continuation of agricultural or livestock activities with controlled levels of shading, without significantly affecting productivity [10, 19].

2.1.2 Map of areas with legal restrictions.

The second step involved removing areas that intersect with zones of legal restrictions (Rede Natura 2000, REN, RAN) to ensure that the agrivoltaic systems comply with land-use planning regulations. This removal is essential for the development of agrivoltaic systems to comply with the legislation governing environmental preservation and sustainable land use, ensuring territorial compatibility with current public policies.

Figure 3 shows the areas occupied by each of these protection zones.

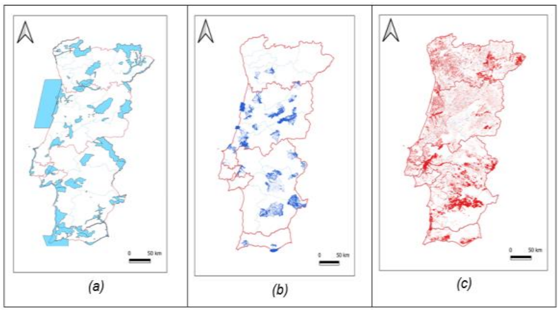

Figure 3: Map of the Natura 2000 Network (a); REN (b); and RAN (c).

2.1.3 Slope of the Land.

Land slope was the third criterion evaluated to identify suitable areas for agrivoltaic systems. The energy and economic sustainability of agrivoltaic installation is heavily affected by the terrain's inclination. Land with steep slopes presents technical challenges for both the installation of photovoltaic panels with ideal orientation and for agricultural activity.

The exclusion of regions with a slope above 10% is intended to ensure:

- That the orientation and inclination of the photovoltaic modules are ideal to maximize solar radiation capture [16].

- A decrease in system installation costs, by reducing the need for earthmoving and land leveling services.
- Improved accessibility and safety during operations, facilitating the movement of agricultural machinery and the maintenance of the energy infrastructure [19].

This technical criterion is essential to ensure the technical and economic viability of agrivoltaic projects, especially when implemented on a large scale in rural regions. There are various technical and scientific studies that discuss the definition of a slope threshold for land slopes. Some studies indicate that land with slopes up to 3% are ideal for agrivoltaic projects with high agro-productive integration, as it reduces the need for earthworks and maximizes land use [2, 20]. According to the U.S. Environmental Protection Agency and the National Renewable Energy Laboratory, conventional ground-mounted photovoltaic solar plants can accommodate slopes up to 10%, although this increases project costs and complexity [16]. In this study, a threshold of 10% slope was used to determine whether land is suitable for AgriPV projects or not. Figure 4 presents the map with areas with slopes ≤10 and >10% in mainland Portugal.

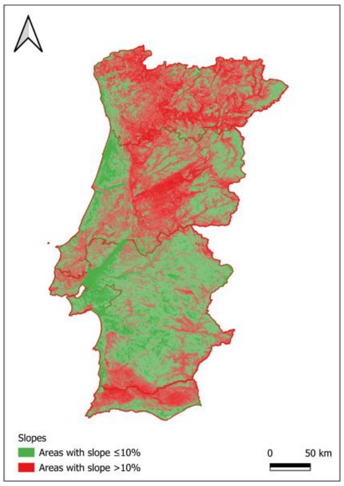

Figure 4: The map of the areas with the two different slopes ≤10% and >10% in mainland Portugal.

2.2 Estimation of the potential for PV installation capacity.

Determining the potential for photovoltaic energy installation capacity is a fundamental step in analyzing the economic potential of agrivoltaic systems. This allows for the quantification of the installed potential capacity of the areas considered technically viable. In this sub-chapter, we present the methodology used to determine the photovoltaic installation potential, expressed in kilowatt-peak (kWp), based on the useful area identified in each region.

2.3.1 Technical Reference Parameters

The potential for photovoltaic energy installation capacity was calculated based on a standard configuration of a monocrystalline Trina Solar microcrystalline silicon bifacial module with a nominal power of 655 Wp and a total area of 3.106 m² [21]. This value indicates the ground area required for each panel, excluding additional structural spaces.

The potential for photovoltaic energy installation capacity was calculated using the following equations:

$$Nm = Int\,\frac{Au}{Am} \qquad \text{(Eq1)}$$

$$PPV = Nm * Pm \qquad \text{(Eq2)}$$

Where: Nm is the number of modules, which is given by the integer quotient between the useful area, Au (m2), and the module area, Am (m2).
PPV is the total photovoltaic potential (kWp).
Pm is the nominal power of each module (kWp).

This calculation was performed for all analyzed regions, based on the useful area values obtained after applying the geospatial criteria previously mentioned. The results are presented in gigawatt-peak (GWp).

2.3.2 Structural Configurations

In this analysis an agrivoltaic plant with an overhead configuration was considered.

Overhead configuration: In this setup, the modules are raised relative to the ground typically > 3 m, allowing for agricultural or grazing activities to take place underneath the photovoltaic systems. Figure 6 shows the PVsyst design of the elevated configuration analyzed in this study, which considered the following parameters:

- Alignment and Orientation: The photovoltaic array was oriented to the south (azimuth = 0°).
- Module Tilt: A fixed tilt of 25° was adopted.
- Installation Height: The modules were installed at a height of 4.0 m above the ground, and the spacing between rows is 5 m.
- Bifacial Photovoltaic Module: A dual-glass monocrystalline silicon bifacial PV Trina Vertex module with a nominal power of 655 Wp an area of 3.106 m² per module [21].
- Total Area Occupied: The simulation considered a plot of 1 hectare (10,000 m²).
- A reference location in the Central region of mainland Portugal was selected for the simulations in the PVsyst software. This location was chosen to adequately represent the average solar irradiation and climate conditions of mainland Portugal.

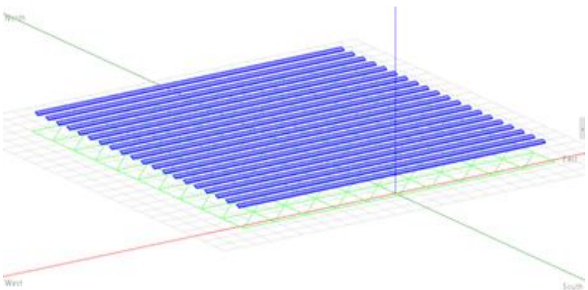

Figure 6: Schematic drawing of the elevated configuration considered in PVsyst [18].

3 RESULTS AND DISCUSSION

The geospatial analysis showed that a total of 1263 kha area suitable to be used for AgriPV, the analysis evidenced significant regional variations in the distribution of suitable areas between the different regions.

3.1 Area affected by legal restrictions.

Figure 7 presents the fractions of the agricultural and pasture areas affected by legal limitations in each region of Portugal's mainland.

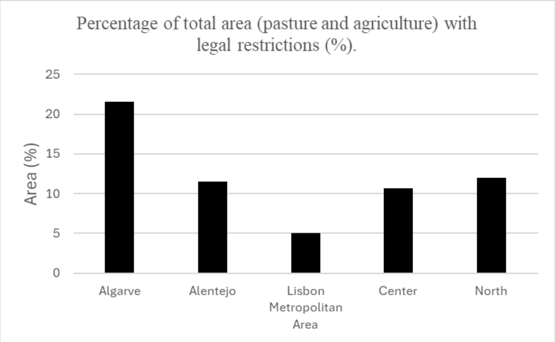

Figure 7: Percentage of agricultural and pasture areas affected by legal restrictions in each region.

It can be observed that Algarve has the highest percentage of areas impacted by legal restrictions with 22% areas intercepting protected zones, while the Lisbon Metropolitan Area has the lowest percentage, with only 5% of its agricultural and pastureland subject to legal restrictions.

3.2 Pasture and agricultural area with a slope >10%.

The analysis of agricultural and pasture areas excluded due to slopes greater than 10% indicates that there are significant topographical restrictions for implementing agrivoltaic systems in mainland Portugal.

Figure 8 shows the percentages of the total agricultural and pasture area excluded for having slopes >10% in each region of mainland Portugal.

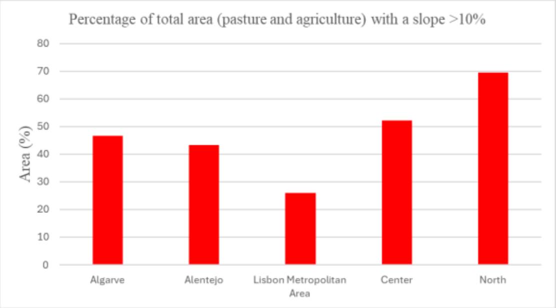

Figure 8: Percentage of total agricultural and pasture areas excluded due to a slope >10% in each region.

It's observed that the North region has the largest area excluded (69.9%), reflecting the strong presence of steep terrains. Center (51%) and the Algarve (46.6%) regions also have very significant areas excluded due to their high slope. The Alentejo registers 43.0% of area excluded, while the Lisbon Metropolitan Area has the lowest percentage of area excluded due to the slope with 26%.

3.3 Analysis of the useful areas.

Figure 9 shows the regional distribution areas (agricultural and pasture) which are considered suitable for agrivoltaic projects in mainland Portugal.

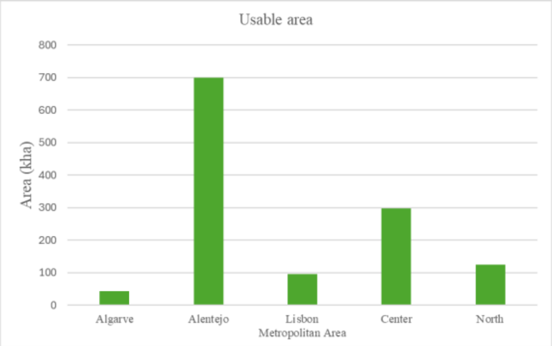

Figure 9: Areas of agriculture and pasture are usable for AgriPV.

Figure 9 indicates that, in the Algarve, the availability of area for agrivoltaic implementation is quite restricted compared to other regions, having 44 kha considered usable for AgriPV. Alentejo stands out as the region with the greatest potential, with a total area of 700 kha. This result is particularly interesting due to the high solar potential available in this region. In Lisbon Metropolitan Area, there are 96 kha considered usable for AgriPV, while Center and North regions of respectively 299 kha and 124 kha are usable for agrivoltaic projects.

3.4 Estimation of Photovoltaic Installation Potential

The analysis focused on the overhead configuration, considering the usable areas previously determined for each region.

3.4.1 Calculation of the potential for photovoltaic energy installation capacity in the useful areas.

- Calculation of the potential for photovoltaic energy installation capacity of the elevated configuration.

To determine the number of PV panels and PV power that can be installed on a specific plot of land, equations 1 and 2 were used.

Considering the bifacial PV panels above described, and assuming a maximum ground coverage ratio (GCR) of 35%, it was concluded that it is possible to install 1,125 modules on a 10,000 m2 area, which results in a total installed capacity of 736.9 kWp. Using this feature and considering the usable area for each region, the respective potential for PV capacity installation was obtained.

Table 1 shows the distribution of the potential for PV capacity installation with overhead configuration (GCR=35%) by region. The results show the significant differences in the potential available in the different regions.

Table 1: Potential for PV capacity installation in each region.

Region	**PV capacity (GWp)**
Algarve	32
Alentejo	515
Lisbon Metropolitan Area	71
Center	220
North	92

As expected, Algarve shows lowest potential, while concentrates the largest PV installation potential reaching 515 GWp, which reflects both the vast available area and favorable topographic conditions. The Center region stands out as the second most relevant in terms of PV installation potential with 220 GWp. While Lisbon Metropolitan Area and North region have a moderate potential for the installation of PV capacity.

4 CONCLUSIONS

The analysis of the energy production potential proved to be a fundamental step to evaluate the technical potential of agrivoltaic systems in mainland Portugal. The integration of geospatial criteria, such as land use, slope, and legal restrictions, and considering an overhead structure with a GCR=35%, enabled a detailed regional analysis of the potential for PV capacity installation. This approach also allowed for an assessment of the impact of the legal constrains and terrain slopes, on the usability of agricultural and pasture areas for agrivoltaics.

The Alentejo region stood out, the region with highest potential with 515 GWp, confirming its leadership potential for large-scale agrivoltaic deployment. The Center region followed with 220 GWp, while the North and Lisbon Metropolitan Area registered 92 GWp and 71 GWp, respectively. The Algarve presented the lowest value, with 32 GWp. These results show that the Alentejo and Center together account for the largest share of the national potential, making them key territories for the expansion of overhead agrivoltaic systems in Portugal.

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