Interplay between the potential of photovoltaic systems and agricultural land use

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Highlights

- Technical potential for utility-scale solar PV projects in rural areas is assessed.
- Agriculture and nature conservation land use shorten solar PV farms potential.
- Limited PV potential ca still cover substantial shares of local annual electricity consumption.
- 1 MW CPV projects show the highest land-use efficiency and productivity.
- PV contributes significantly to region energy independence.

Abstract

The recent decrease in solar photovoltaic (PV) investment cost has transformed the attractiveness of the technology. Southern Europe has one of the highest levels of solar radiation in the world, and policy makers are very keen to take full advantage of this resource for electricity and heat production. However, physiographic characteristics and specific land uses (e.g. agro-forestry and nature conservation) present important spatial constraints. This paper proposes a methodology for the evaluation of utility-scale solar PV projects' (>1 MW) technical potential. The municipality of Évora (Portugal) was used as a case study, considering topographical features and spatial planning regulations. Three compatible scenarios for solar PV farms and other competing land uses were studied. The assessment was carried out using a geographic information system and statistical tools. It was conducted for four sizes of PV project (1, 10, 20 and 30 MW) consisting of two different technology types: concentrated PV and crystalline-silicon tracking PV. Concentrated PV 1 MW projects were found to have greater adaptability for use in available areas dispersed throughout the territory, while preserving land for agriculture and nature conservation. The scenario with land primacy for agricultural purposes reduced PV technical potential by more than half (from 2494 to 1116 MW). Nevertheless, the remaining potential was sufficient to cover substantial shares of local annual electricity consumption. The results provided support for future spatial planning regulations and local sustainable energy action plans.

Keywords

Solar Photovoltaic Potential; Competing Land Uses; Geographic Information System, Agro-Forestry; Nature Conservation

1. Introduction

Solar photovoltaic (PV) technologies are seen worldwide as an essential part of any power sector technology portfolio aiming for climate change mitigation and energy security (e.g. AMPERE, 2015; Greenpeace, 2015; IEA, 2017, Hawken et al., 2017). PV contribution to electricity generation has increased in numerous countries: e.g. 7% of Germany's net electricity consumption in 2014 (EEA, 2016; Wirth, 2015), 8% in Italy, 3.8% in Spain, and 2.5% in Japan (IEA-PVPS, 2015; Jäger-Waldau, 2016). Total worldwide PV-installed capacity reached 177 GW in 2014 (IEA-PVPS, 2015) and 219 GW in 2015 (IRENA, 2017). This value is expected to increase to 1519 GW in 2040 corresponding to an average annual growth rate of 9.3% (from 2013 to 2040) for a global average temperature increase of 2ºC (IEA, 2015).

The solar energy received by the Earth in one day (120000 Terawatts) has the capacity to meet global energy demand for 20 years (Chu & Meisen, 2011). This potential is especially evident in the case study region (see following section 2.1) with a high number of daylight hours (2200 to 3000 in the Iberian Peninsula) and high daily irradiance (5000 $W/m^2/day$). The Southern Iberian Peninsula has the highest level of global horizontal irradiation (GHI) in Europe (Figure 1). Despite the region's high solar resource availability, its exploitation is still considerably untapped. This fact is amplified when compared with the PV-installation capacity of countries with fewer available solar resources. For example, Germany in 2014 was the world leader in PV installed capacity (IEA-PVPS, 2015). In 2015, China and Japan overtook Germany's pole-position (IEA, 2017; Jäger-Waldau, 2016).

From an economic perspective, the cost of PV systems has declined significantly in the last decade. In various countries, grid parity[1] was reached in 2013 (IEA, 2014). The levelised costs of electricity (LCOE) for solar PV (large, ground-mounted) reached 8 ct€/kWh at the end of 2016 in Germany. Moreover, the energy payback time for Concentrator Photovoltaic (CPV) systems in southern Europe is now less than one year (Fraunhofer, 2017).

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[1] Grid parity refers to the moment when an alternative energy source can produce power at a levelized cost of electricity (LCOE) that is less than or equal to the price of purchasing power from the electricity grid.

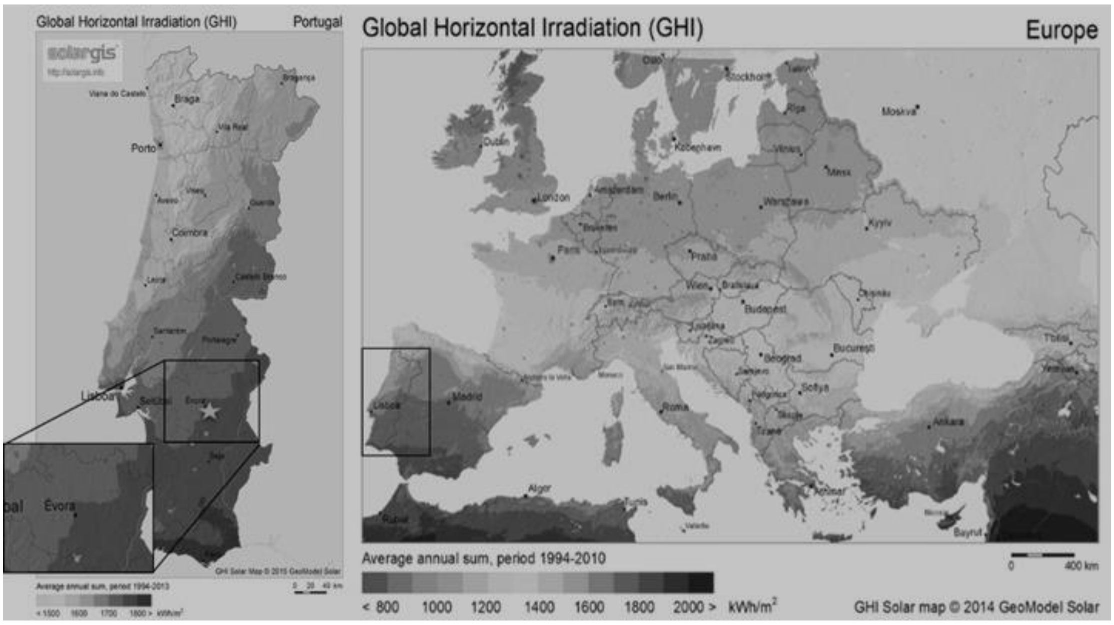

Figure 1 - Global horizontal irradiation (GHI) in Europe and Portugal. The star in the map on the left denotes the location of the case study region (municipality of Évora) (Solargis, 2018).

The LCOE for solar PV (large, ground-mounted) in Portugal in 2014 was lower than for a combined cycle powerplant (90 €/MWh and 91.30 €/MWh, respectively), considering a 7% discount rate (IEA/NEA, 2015). In Portugal the breakthrough of PV technology occurred in 2008 with the installation of 47 MW of capacity. Of this, 37 MW were utility-scale facilities (compared with only 15 MW in 2007) and 10 MW were micro-generation[2] systems. The total PV installation capacity reached 852 MW in 2017, from which 395 MW were utility-scale projects (DGEG, 2015a; DGEG, 2018). Current installed capacity lags behind the objectives set out in the National Renewable Energy Action Plan (NREAP): 720 MW in 2020 (PNAER, 2013), 2.7 GW in 2030 (Seixas et al., 2014), and 9.3 GW in 2050 (Seixas et al., 2012). The under-developed PV market *gold mine* in this region exemplifies the importance of solar PV technical potential assessments. Nevertheless, the consideration of competing land uses was necessary, as it may restrict the large deployment of PV projects.

Renewable energy technical potential refers to the available energy resource, while considering various determinants, such as technology conversion efficiency, technical limitations, the available land to install it upon, and ancillary features (Resch et al., 2008). For most resources, the technical potential is dynamic, meaning that if technological efficiency can be improved, so can technical potential.

Different methodologies and tools have been used to assess the technical potential of utility-scale solar PV projects in diverse regions (Vieira et al., 2016). Janke (2010) used multicriteria methods in a geographic information system (GIS) model to determine which land cover classes had high solar resource potential and which areas were suitable for wind and solar farms. Arán Carrión et al. (2008) and Uyan (2013) applied a decision-support system for the selection of optimal sites for large and grid-connected PV plants, considering land use, agricultural land, and protected areas. Gunderson et al. (2014) used a fuzzy logic approach to study potential sites in the Black Sea region suitable for PV power plants. Sliz-Szkliniarz (2013) quantified the

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[2] Micro generation – Decree-Law n. º 363/2007, November 2nd, updated by the Decree-Law n. º 118-A/2010, October 25th and by the Decree-Law n. º 25/2013, February 19th.

potentials of different renewable energy sources for electricity generation (RES-E) to explore potential planning issues associated with the development. Although methods to assess the technical potential of utility-scale solar PV projects are standard procedures, little attention was given to possible conflicts between PV plants and agro-forestry production. In this manner, Sacchelli et al. (2016) conducted a comprehensive literature review on PV energy versus food production trade-offs. The impact of the PV systems' economic profitability was related to local characteristics and crop yields. The local characteristics included the disposal of non-irrigated arable land and the presence of constraints, particularly landscape maintenance, morphological variables, and the specialization index. Important work has been carried out on this topic, but significant improvement in understanding potential conflicts at the micro-scale is needed. Detailed analysis into the local interplay between policies, land uses, and solar PV technical potential is essential. In an assessment of the 28 member States in Europe, Perpiña Castillo et al. (2016) focused on the regional potential for solar power generation, highlighting the absence of similar studies to compare and validate results.

Innovative solutions to overcome this challenge are increasing. Dinesh and Pearce (2016) and Dupraz et al. (2011) analysed the concept of co-developing the same land area for both solar PV power and conventional agriculture. Although the conclusion proved that the concept was a viable solution for locations with intense competition for land resources, it was restricted to shade-tolerant crops.

Solar energy potential assessments in urban Portugal have increased, specifically on building roofs and façades (Brito et al., 2012; Redweik et al., 2013). However, no assessment has been made focusing on utility-scale PV. Spatial regulations constrain the eligible areas and consequent PV project implementation levels. Additionally, it is necessary to consider the PV project's compatibility with agricultural land and nature conservation areas. Within this work, nature conservation refers to preservation-based natural habitats and ecosystem protection land use, especially from human exploitation (further details in section 2.2.1).

The overall objective of this paper is to present the technical solar PV power potential at the utility-scale level, using a case study region with a high solar irradiation level and significant agricultural land areas. This work also aims to analyse the competition for land use between PV deployment, agro-forestry, and nature conservation. A combination of three competing land-use scenarios with two different PV technologies were used: concentrated PV (CPV) and crystalline-silicon tracking PV (Ci-Si track) with four project sizes (1, 10, 20 and 30 MW).

2. Methodology

This section describes the methodology used to assess the technical potential for utility-scale solar PV in a rural area in southwestern Europe – specifically Évora municipality in Portugal.

The framework applied to Évora municipality (section 2.1) was comprised of two main phases:

1) Location and quantification of suitable areas for PV system installation, considering land-use regulations and competition scenarios (section 2.2);
2) Quantification of corresponding potential installed capacity and electricity generation, accounting for two generic PV technologies and four different plant sizes (section 2.3).

The analysis used ArcGIS software[3] to address multiple and diverse spatial and thematic variables (e.g. terrain slope, protected natural areas, and solar exposure). Figure 2 presents the overall methodology flowchart.

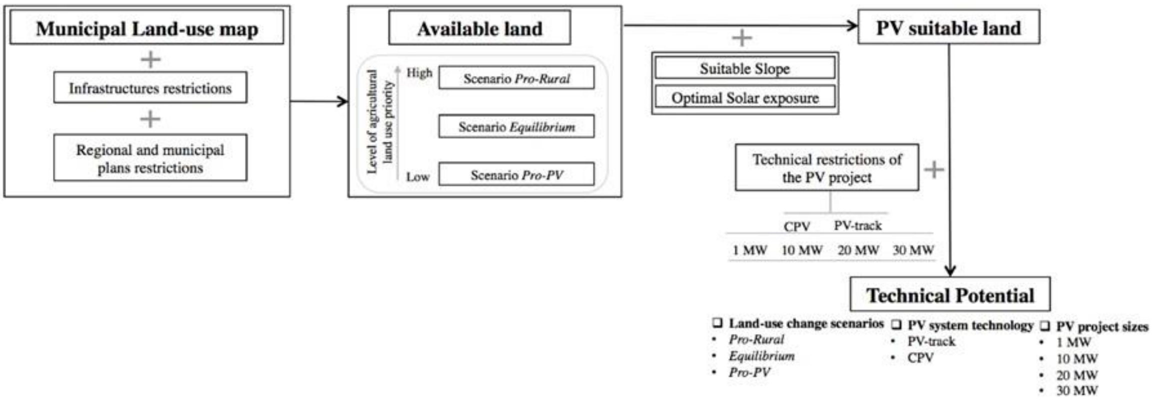

Figure 2 - Overall methodology flowchart

2.1 Case Study

Évora municipality is located in the Alentejo region of Portugal (latitude 38°34′00″ N, longitude 7°54′00″ W) covering 1307 km^2 and with approximately 57000 inhabitants (INE, 2011). The reasons it was selected as a case study were:

1) It is one of the European regions with the highest solar irradiance;
2) It has an extensive wide open rural area of 70000 ha, covering 54% of the total area (130700 ha) (CME, 2014);
3) The municipality is fully committed to a transition to a low carbon energy system (Évora is a signatory member of the Covenant of Mayors for Climate & Energy);
4) It was the first city in Portugal equipped with a massive electricity smart metering system (over 31000 smart meters) (EDP, 2015);
5) It has been used for several studies on smart cities (Simoes et al., 2018), grid management, smart meter data analysis, and consumer profiles (Gouveia and Seixas, 2016; Gouveia et al., 2017, Gouveia et al., 2018), and solar PV rooftop assessment (Moreira, 2016).

In 2017, there were four solar PV farms in the Évora municipality, with a combined total of 12.4 MW. There are two types of technologies in place. One 1.3 MW concentrated PV facility has been in operation since 2014, and another 1.1 MW facility of PV cells (*Cycloid* unit) has been operational since 2012. There were also 239 small solar PV installations (<1 MW), accounting for 1.2 MW in 2014 (MEE, 2015). The Évora municipality consumed 261 GWh of electricity (DGEG, 2015b) in 2013, representing only 0.5% of total national consumption.

The case study region has important agro-forestry resources. The rural areas are mainly cultivated with cereals, pasture and forest patches of cork and holm oak. Olive groves, vineyards, and irrigated crops complete the diversity of this region (CME, 2014) (Figure 3). Cork forest represents an important economic contribution to the Mediterranean region (González-García et al., 2013). Portugal has the largest area of cork oak forest in the world at 737 ha, and 84% is within the Alentejo region (APCOR, 2014) where Évora is located. 50% of

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[3] ArcGIS 10.1 version was used

total world cork production (APCOR, 2014) takes place in Alentejo, adding 30% gross value to the national silvicultural and forest exploitation activities sector (INE, 2013a). The cork industry also provides employment across its supply chain and stimulates the establishment of companies in close proximity to the production location (Sierra-Pérez et al., 2015).

Likewise, vineyards are predominant in the region with relevant social-economic benefits for the local population. Vineyards also provide important national income through exportation, which was 725 M€ in 2013 (INE, 2013b). This type of crop generates local direct and indirect employment opportunities along its production chain, as well as tourism opportunities. The municipality of Évora is home to many national wine-producing brands.

Therefore, although the region has ideal conditions for PV deployment (demonstrated by the number of projects in place and the GHI level), the agricultural and forestry land uses impose competition.

A combination of these factors justifies the necessity for further investigation in the area.

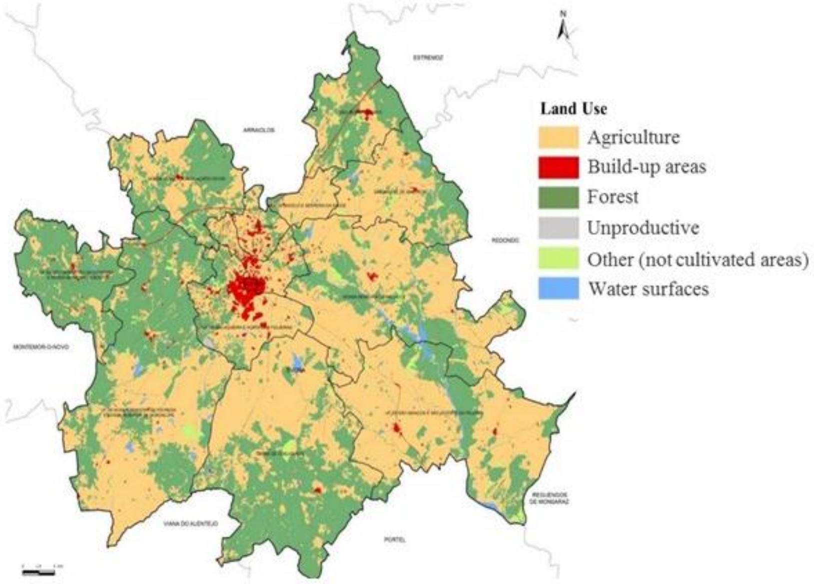

Figure 3 – Évora municipality land-use map (adapted from CME (2014))

2.2 Land for Utility-Scale PV Systems

The first step in estimating the technical potential for PV utility-scale projects is to locate and quantify the available and suitable land area. Available area (Figure 4) refers to the rural land with eligible characteristics for PV project installation. The determinants to identify the amount of available area are: the land-use regulations in place (local planning) constraining the uses and categories of land-use where the implementation of large-scale PV projects are not permitted (e.g. urban areas, road and rail networks, water lines, dam reservoirs, and flood zones). The suitable area is a refinement of the available area with adequate terrain conditions (e.g. slope and solar exposure) (Figure 5). The following sections describe the constraints (physical and regulatory) that set the basis for the potential available land area for large-scale PV system installation.

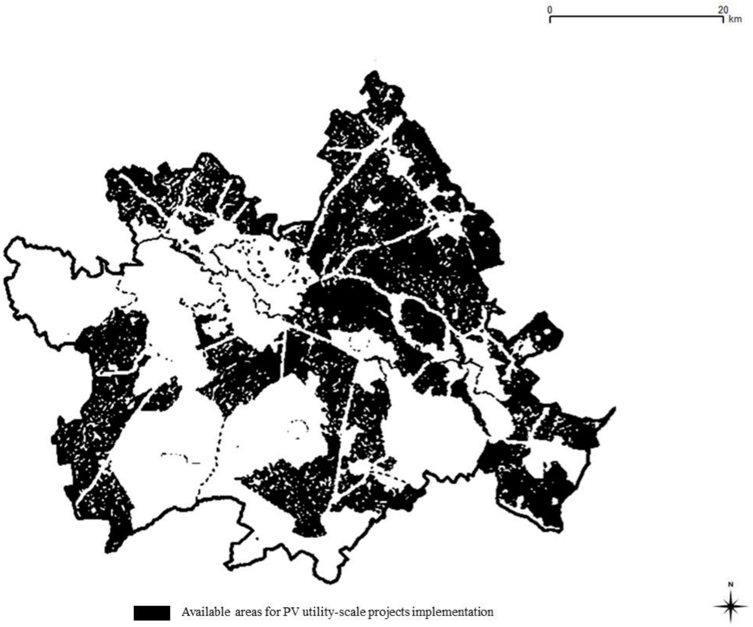

Figure 4 –Available areas for PV utility-scale project implementation in the Évora municipality

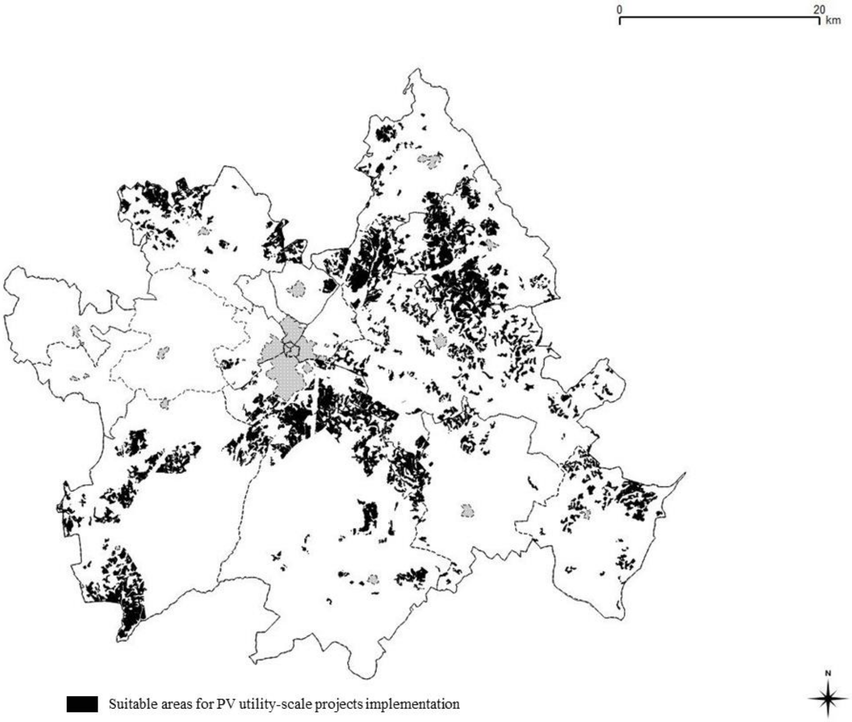

Figure 5 – Suitable areas for PV utility-scale project implementation in the Évora municipality

2.2.1 Land-Use Regulations

Municipal regulations define administrative easements and public utility land-use restrictions that can limit the implementation of renewable energy exploitation projects. The municipal land use plan in place for Évora (MMP, 2008; MMP, 2012) states different suitability of non-urban land-use classes for the installation of PV plants, as shown in Table 1. All land-use classes under protection were excluded from possible PV installation areas, except for those explicitly detailing permission (e.g. Évora aquifer and water reservoirs). Protection zones not eligible for PV plant installation include:

- agriculture and ecological reserves,
- protected natural areas (e.g. Natura 2000 network),
- protected water supply infrastructure reservoirs,
- electrical lines,
- the national road network,
- regional roads, and
- unclassified roads.

In the current assessment, all the spatial features with protected characteristics (e.g. water bodies) were buffered by 200m to exclude possible solar projects from those areas.

Detailed analysis of current land-use legislation and municipal instruments concluded that only some sub-classes of *rural and forest lands* and *environmentally protected lands* allow for the implementation of PV projects. Within these two groups, the sub-classes *agricultural and forestry undifferentiated areas*, *protected zones of the Évora aquifer* and *protected areas of water supply (basin reservoirs)* were assumed appropriate for the potential installation of PV projects. When the permission of any RES-E projects was not explicitily stated or there was no legal barrier to the installation of high and medium voltage stations, the corresponding land-use classes were assumed to be ineligible for PV project implementation. In summary, the available land for PV plants resulted from the subtraction of all the municipality land area with infrastructure restrictions, including urban areas declared ineligible by regulation.

Table 1 – Eligibility of land-use classes for PV project installation, as stated in the municipal master plans (MMP, 2008; MMP, 2012;)[4]

Land-use classes		**Eligibility for solar PV projects**
Areas for exploration of geological resources		No
Reserved areas for industrial activities		No
Areas for tourist occupation		No
Dispersed building areas		No
	Sub-classes	
Rural and forest lands	Surrounding rural areas to the city of Évora	No
	Small property areas	No
	Agricultural and forestry undifferentiated areas	Yes
	Agricultural Irrigation areas	No
	Protection zones of the Évora Aquifer	Yes
Environmental protection lands	Special heritage areas	No
	Protection areas of water supply basin reservoirs	Yes
	Birdlife protection areas	No
	Surrounding areas of public water reservoirs	No

2.2.2 Land-Use Competition Scenarios

Across the selected eligible land-use classes, two additional limitation layers for PV deployment were applied: agricultural crop areas and forestry lands. The agricultural and forestry sectors still play an important economic and cultural role in the region, hence the level of competition for land is high. Therefore, four types of agricultural crops and forestry (as

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[4] A deeper analysis of the allowed activities and infrastructures in the sub-classes under *Rural and forest lands* and *Environmental protection lands* concluded the non-existence of restrictions regarding renewable energy technology deployment for particular land-use subclasses.

shown in Table 2) defined the ineligible lands for PV deployment, due to strategic importance to the local and national economy.

Social economic value of specific land uses, and the percentage of land dedicated to each specific use were selected as criteria to rank agricultural crops and forestry lands. The land use percentage of each crop was used to quantity the potential for land conversion. This assumed that greater cover percentage meant greater difficulty in adapting the land for PV system installation.

With the remaining available land for PV system installation, three land-use competition scenarios were defined by varying restriction levels. The scenarios are as follows:

1. *Pro-PV* scenario – This scenario favours intensive installation of utility-scale PV over agricultural purposes. This translates into a high range of land use classifications regarding agricultural and forestry lands that are available for PV system use. As presented in Table 2, the agricultural and forestry lands classified as *poor grassland subject to trampling* and as *abandoned olive trees* are susceptible to be substituted with utility-scale PV.
2. *Equilibrium* scenario – This scenario considers a flexible, balanced land use in the adoption of PV electricity generation. Croplands and forestry with current occupation rates lower than 10%, thus not requiring significant terrain clearance efforts, are suitable for substitution with utility-scale PV.
3. *Pro-Rural* scenario – This scenario favours agricultural production over PV for electricity generation. In this sense, all types of croplands are maintained as they are, except those with low economic and natural value (e.g. *Poor grassland subject to trampling*) and those with minimal terrain adaption necessary (e.g. *Soil without vegetation cover*). This additional restriction is of utmost relevance, due to the economic importance of the agricultural sector to the case study region (national agriculture added 26% gross value in 2013) (INE, 2013c).

Table 2 – Agriculture and forestry lands' susceptibility to change considered in each scenario

Agriculture and forestry lands	**Land-use change scenarios**		
	Pro-PV	***Equilibrium***	***Pro-Rural***
Vineyards	**Not susceptible to change**		
Cork oak forests - *montado*			
Cork oak crops			
Mixed crops with cork oak			
Poor grassland subject to trampling	**Susceptible to change**	**Susceptible to change**	**Susceptible to change**
Gorse			
Xerophilic grassland			
Soil without vegetation cover			
Irrigation cereals and dry cereals			
Cistus and Sargasso areas			
Mixed Mediterranean scrubs			
Ruderals formations			
Crops with current land occupation rate lower than 50%[1,2]			
Crops with current land occupation rate higher than 50%[1]			

[1] Crops included: Arable irrigated crops, dryland arable crops, dryland olive trees, olive grove and vineyard (dryland), irrigated olive trees, other dryland orchards, abandoned olive trees.

[2] The *Equilibrium* scenario considered crops with occupation rates lower than 10%.

2.2.3 Suitable Areas for Utility-Scale PV Systems

Available land for each of the three land-use competition scenarios was then weighted by the terrain features (i.e. slopes and solar exposure) rendering the land suitable for PV installation.

These key parameters to assess the technical feasibility of solar PV projects were expressed as vector maps in ArcGIS. The optimal terrain slope was less than 3%, based on Lopez et al. (2014). Using a conservative approach, optimal solar exposure was measured from the southeast (135°) to the southwest (225°), although the installation of the PV panels could be adjusted to a wider range of solar exposure and slopes. The outputs of the available land analysis combined with these terrain features were defined as suitable areas for PV system installation.

2.3 Technical Potential of Utility-Scale PV Systems

The technical potential of the utility-scale PV projects was assessed considering the following two PV technology types and four classes of power capacity:

1. Solar-PV system with single-axis tracking device and crystalline silicon solar cells (c-Si) (PV-track), calculated for average PV installation size (1, 10, 20, and 30 MW). The c-Si-based system was chosen, as it constituted approximately 90% of global module production capacity in 2014 (Metz et al., 2015) and is the most mature PV technology (MIT, 2015), with low average market price and a high efficiency of 25% (NREL, 2015).
2. Concentrated-PV (CPV) system with two axes and multi-junction high-efficiency solar cells for the average project size (1, 10, 20, and 30 MW). The CPV system was chosen due to its high efficiency of 40% (NREL, 2015). CPV systems are also receiving significant levels of investment encouragingly, even within the territory under study, improving the technology's economic feasibility. Moreover, according to Carvalho et al. (2011), the CPV and the single-axis tracking system are the most profitable technologies.

The land area required by each PV technology and system size is presented in Table 3. The land area occupied by the solar panels includes the space between (direct area), as well as the area required for maintenance (total area) (Ong et al., 2013).

Table 3 - Land area requirements for PV projects (adapted from Ong et al., 2013)

PV-Installed capacity (MW)	Direct area (ha)		Total area (ha)	
	PV-track	CPV	PV-track	CPV
< 20	2.6 ha/MW	2.8 ha/MW	3.5 ha/MW	3.7 ha/MW
1	2.6	2.8	3.5	3.7
10	26	28	35	37
> 20	3.6 ha/MW	2.5 ha/MW	3.4 ha/MW	3.3 ha/MW
20	72	50	68	66
30	108	75	102	99

Suitable land patches for implementation of each type and power class of solar PV project were determined through GIS spatial analysis. Multiple-unit projects for each power class were assumed. No combinations of power capacities were considered.

Potential electricity generation was derived using the electricity production indicator (GWh per MW installed) for each PV technology type. This indicator considered data in current facilities (EDP Distribuição, 2016). The selected facilities were located in the case study region and represented the two PV technologies under study: 1.88 GWh/MW for CPV and 1.63 GWh/MW for PV-track. The energy output estimation by PV systems at a specific location was generated through models and platforms, such as Solargis (2018) or PVGIS (2018). These models have been found to slightly overestimate production when compared with actual values for *in-situ* projects. This is due to unpredictable real conditions that are not considered in these tools (e.g. module temperature, irradiation intensity, angle of solar incidence, spectral deviation from the standard spectrum, shading, transmission losses, conversion losses in the inverter, and operational failures) (Eltawil and Zhao, 2010; Rahman et al., 2015). Therefore, the use of real electricity production data from projects in operation increased the technical potential assessment's robustness. The next section describes the results achieved.

3. Results

3.1 Land Suitability for Utility-Scale PV Systems

Excluding municipal plan restrictions and existing urbanized infrastructure, a total of 27133 ha of rural area were identified as available for PV project installation. The available area corresponds to 21% of Évora municipality's total area (130900 ha).

The total available area was then reduced to 6951 ha when a priority for agricultural crops was considered (*Pro-Rural* land-use competition scenario). When all croplands suitable for substitution in favour of utility-scale PV projects were considered (*Pro-PV* land-use competition scenario), the area reduced to 16711 ha. The increment in priority to agricultural uses induced 38% to 74% less available area for the implementation of PV facilities for the *Pro-PV* and *Pro-Rural* scenarios. The impact of restricting the available area to locations with optimal slope and solar exposure (suitable area) represented a reduction of 24% of the available area (equal to all land-use competition scenarios), stressing the importance of effective project design.

Total required land by type of PV system technology, resulting from the application of the land area requirements (Table 3) to the amount of suitable area for PV systems, is presented in Table 4. The results show that the 1MW PV-track systems under the *Pro-PV* scenario could occupy 68% of the total suitable areas. Land-use efficiency indicator (ratio between total PV system required area and the total amount of suitable land area) varies depending on the type of PV technology and the landscape patchiness. For the 1MW PV-track systems under the *Pro-PV* scenario, the land-use efficiency was 68%, while for the *Pro-Rural* scenario it was 74%. The land-use change scenario favouring agricultural crops (*Pro-Rural* scenario) delivered a more productive land mix for the 1 MW PV-track system implementation. 30 MW projects held a land-use efficiency of 1% regardless of the PV technology or the land-use scenario, resulting in a high suitable land surplus. The required land was more significant for the 10 MW projects.

Smaller PV projects showed higher available land use efficiency, due to the capacity to occupy more scattered areas throughout the territory.

Table 4 – Land suitability and useful areas for each land-use scenario according to PV system technology and project dimension

Land-use competition scenarios	Available land (ha)	Suitable land (ha)	Total required land for solar PV projects (ha)							
			1 MW		10 MW		20 MW		30 MW	
			PV-track	CPV	PV-track	CPV	PV-track	CPV	PV-track	CPV
Pro-PV	16 711	12 845	8 728	8 614	1 154	938	352	352	104	104
Equilibrium	10 887	8 308	5 716	5 619	821	713	258	258	104	104
Pro-Rural	6 951	5 244	3 905	3 852	675	556	258	258	104	104

Figure 6 portrays the spatial distribution of the four power classes of PV-track system projects in Évora municipality for each land-use competition scenario. The possible locations for 1 MW PV projects are spread over the whole municipality with a higher concentration in the northeast. The PV project predominance in the *Pro-PV* scenario in the northeast was demonstrated – as represented in orange on the map. The more restrictive PV implementation scenario (*Pro-rural*), shown in red on the map, indicates a concentration in the northeast zone but also south of Évora city. PV projects' potential proximity to the urban city zone can enhance the benefits by reducing the electricity distribution network modifications and/or extension requirements. This also minimises transmission losses and additional costs. Évora municipality's west shows minimum potential for PV facility locations. This is consequence of the high "Natura 2000" network protected area in that region (e.g. Monfurado site).

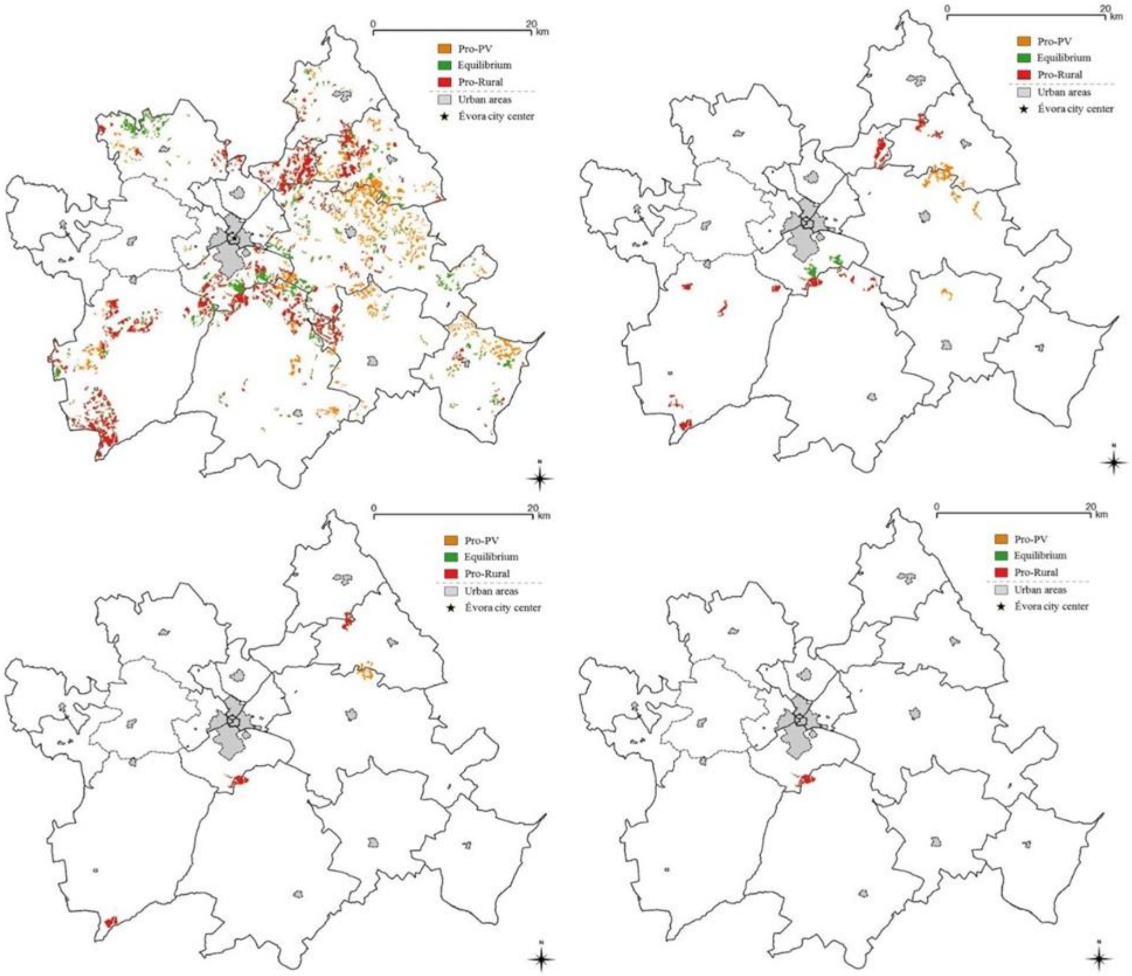

Figure 6 - Location of PV-track systems for each land-use competition scenario (top left – 1 MW, top right – 10 MW, bottom left – 20 MW, bottom right – 30 MW)

The potential locations for the 20 MW PV projects are practically coincident with all the different land-use competition scenarios for the two types of PV technologies. It should be emphasised that the suitable land for the 30 MW PV projects was primarily located south of Évora's urban area (in red on the bottom right map) and close to an existing CPV solar farm. This is also supported by the conclusions drawn by Perpiña Castillo et al. (2016); i.e. in Portugal, the most suitable areas match the locations of existing solar power plants.

These locations, 3.5 km from Évora's urban area, have a reduced need for transport and distribution power lines. This results in lower investment costs and minor electricity losses, as the consumers are closer to the electricity generation sites.

3.2 Technical Potential of Utility-Scale PV Systems

The potential PV utility-scale system installed capacity for each land-use competition scenario is presented in Table 5. The higher land-use efficiency of the 1 MW projects translated into the corresponding higher installed capacity values. In the *Pro-PV* scenario, the potential installed capacity of 1 MW projects was five times the 2015 national PV-installed capacity (451 MW (DGEG, 2015a)). It also represents 40% of the total national capacity of coal and gas power plants (5890 MW), surpassing the capacity of the two coal power plants (1871 MW) (DGEG, 2015c). These values also correspond to more than half the national PV contribution (4500 MW) to attain a 100% RES-E in Portugal in 2020, as stated by Krajačić et al. (2011). For the conservative *Pro-Rural* scenario and the 1 MW project size, the installed capacity could represent over twice the 2015 national PV-installed capacity and up to 60% of the current coal powerplant capacity. The results illustrate that the national targets for a PV installed capacity of 720 MW in 2020 (PNAER, 2013) can be met through the available PV technical potential in Évora municipality alone. This is in line with regulatory changes of rural land-use from agricultural to PV systems (i.e. *Pro-Rural* scenario).

Table 5 - PV utility-scale installed capacity potential for each land-use competition scenario

Land-use competition scenarios	PV utility-scale potential (MW)							
	1 MW		10 MW		20 MW		30 MW	
	PV-track	CPV	PV-track	CPV	PV-track	CPV	PV-track	CPV
Pro-PV	2 494	2 328	330	250	100 (5 systems)		30	
Equilibrium	1 633	1 519	240	190	80 (4 systems)		30	
Pro-Rural	1 116	1 041	190	150	80 (4 systems)		30	

Although the installed capacity of CPV technology was lower than the PV-track in all land-use competition scenarios, the electricity production was higher (Table 6). This is due to CPV's higher efficiency in electricity production. Table 6 also shows the productivity by unit area indicator. It is possible to perceive the higher technical viability of CPV technology, as it can produce more electricity with a lower installed capacity and land occupation than the PV-track.

Table 6 - PV utility-scale electricity production potential and productivity for each land-use change scenario

Land-use change scenarios	PV utility-scale electricity production potential (GWh)							
	1 MW		10 MW		20 MW		30 MW	
	PV-track	CPV	PV-track	CPV	PV-track	CPV	PV-track	CPV
Pro-PV	4 065	4 377	538	478	195	226	58	68
Equilibrium	2 662	2 855	383	363	142	165	58	68
Pro-Rural	1 819	1 957	315	282	142	165	58	68
	PV utility-scale electricity productivity per unit area (GWh/ha)							
	0.47	0.51	0.47	0.51	0.55	0.64	0.56	0.65

Expected electricity produced through utility-scale PV systems in the case study region could represent a reduction of up to 50% of national electricity imports (DGEG, 2015d). This also corresponds to the existing national coal powerplant installed capacity (1871 MW). In this way, the generated PV electricity may allow for an output reduction of the two national coal power plants of up to 37%. This also represents a reduction of 1.7 Mt of coal imports and an economic savings worth 98 M€ (coal price – 55 €/t (DGEG, 2015e)). The utility-scale PV potential under a *Pro-PV* scenario with smaller size projects (1 MW) has the capacity to produce enough electricity to cover the annual municipality's electricity demand (261 GWh (DGEG, 2015b)). Even when considering the scenario with prevailing rural land for agricultural purposes (*Pro-rural* scenario), the amount of electricity generated would still be capable of covering the municipality's current electricity needs. The increase of rural land priority to agricultural uses (*Pro-Rural scenario*) could mean a 55% reduction in electricity generated, as compared to the *Pro-PV scenario*.

Results showed a high quantity of available area for PV deployment. The different restriction levels on the available land area for PV plant deployment, as a proxy for competitiveness with agricultural uses, had an impact of 38% to 74% less available area. When considering the optimal terrain conditions for PV plant deployment (defined as suitable land area), there was an additional reduction of 14% and 6% (*Pro-PV* and *Pro-rural* scenarios, respectively). The addition of each PV system land requirement per project size resulted in 68% (*Pro-PV* scenario) and 74% (*Pro*-Rural scenario) of the effective land area for PV systems. Although total suitable land area in the more flexible scenario (*Pro-PV*) was higher than in the more restrictive one (*Pro-Rural*), there were fewer locations with the necessary size for PV deployment. Thus, minimising the impact of restrictive land use for agricultural activities would assist PV deployment.

Solar farms of 1 MW (up to 2494 units) and 10 MW (up to 30 units) present further advantages, due to better available land exploitation. In total, the two smaller sizes can provide a higher quantity of electricity than projects of a larger size (20 MW and 30 MW). The 30 MW projects offer higher levels of electricity production, but corresponding higher area requirements act as a constraint for deployment.

4. Conclusion and Discussion

PV growth rates have been high in recent years, but still require massive deployment to address global and regional sustainable economic and environmental development challenges. A crucial unlock factor is the identification of available optimal locations for PV utility-scale installations that generate less competition with other uses. Interactions between different rural land uses (energy production vs. agriculture) is a growing concern (Sacchelli et al., 2016). This paper contributes to this topic through the analysis of the effects on the available technical potential for PV utility-scale projects considering different competing land-use scenarios within a municipality.

The utility-scale PV systems technical potential assessment considered PV technology's land requirements and spatial constraints under multi-level land planning instruments. By defining land-use suitability to change scenarios, it was possible to assess the effect of competing uses of land (agricultural vs. renewable electricity production) in a region with high solar resource availability and vast rural areas.

Results showed that for the case study region, land use for PV utility-scale deployment can be limited by other competitive land uses, such as agriculture, forestry, nature conservation, and urban infrastructure. The estimated technical potential of PV utility-scale electricity generation could cover 100% of the case study's electricity consumption in most scenarios. This hypothesis is comparable to similar assessments; e.g. ground-mounted solar PV could cover nearly 60% of Ontario's projected peak electricity demand in 2025 (Nguyen and Pearce, 2010).

This study found that the competition for land between a potential massive deployment of utility-scale solar PV and agro-forestry should be a vital component considered in the analysis and identification of optimal locations for PV installations. This was supported in similar studies (Calvert & Mabee, 2015; Sacchelli et al., 2016; Castillo et al., 2016). The impact of agricultural predominance over PV system deployment could cut potential electricity generation in half. Although this impact depends on regional land use particularities, the study results were in line with Sacchelli et al. (2016), who noted that agricultural lands that were not allowed to be used for PV energy production could reduce the potential between 24.5% (Molise) and 60.9% (Calabria) in northern Italy. Moreover, the outcomes of this work provided valuable information and insight into different stakeholders, namely municipal spatial planners, private companies, and investors. This study could also facilitate decision-making processes for the selection of sites for solar farm implementation and clean energy objectives (Calvert & Mabee, 2015).

Several potential improvements could be addressed in future research. These include the validation of scenario assumptions with local stakeholders and municipal decision makers and potential inclusion of master plans land use variability. The present work also lacks the attribution of ecosystem services provided by each crop type (see, for instance, Robertson et al. (2014) and Förster et al. (2015) studies). By including these additional crops benefits, the agricultural uses could gain more importance over PV system deployment. Nevertheless, to properly balance the economic equilibrium, financial benefits of PV plants should also be considered.

Further research toward the development of solar PV in rural areas should include the complementary use of PV systems with specific agriculture studies (e.g. cork forest) (Dupraz et al., 2011; Dinesh & Pearce, 2016).

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5. References

AMPERE, 2014. AMPERE Database, EU FP7 AMPERE Project. Available at: https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB/dsd?Action=htmlpage&page=about#regiondefs.

APCOR, 2014. Cork yearbook 2014. Associação Portuguesa da Cortiça. Available at: http://www.apcor.pt/wp-content/uploads/2015/07/AnuarioAPCOR2014.pdf.

Arán Carrión, J., Espín Estrella, A., Aznar Dols, F., Zamorano Toro, M., Rodríguez, M., Ramos Ridao, A., 2008. Environmental decision-support systems for evaluating the carrying capacity of land areas: Optimal site selection for grid-connected photovoltaic power plants. Renew. Sustain. Energy Rev. 12, 2358–2380. doi:10.1016/j.rser.2007.06.011.

Brito, M. C., Gomes, N., Santos, T., Tenedório, J. A., 2012. Photovoltaic potential in a Lisbon suburb using LiDAR data. Sol. Energy 86, 283–288. doi:10.1016/j.solener.2011.09.031

Calvert, K., Mabee, W., 2015. More solar farms or more bioenergy crops? Mapping and assessing potential land-use conflicts among renewable energy technologies in eastern Ontario, Canada. Appl. Geogr. 56, 209–221. doi:10.1016/j.apgeog.2014.11.028.

Carvalho, D., Wemans, J., Lima, J., Malico, I., 2011. Photovoltaic energy mini-generation: Future perspectives for Portugal. Energy Policy 39, 5465–5473. doi:10.1016/j.enpol.2011.05.016.

Chu, Y., Meisen, P., 2011. Review and Comparison of Different Solar Energy Technologies.

Global Energy Network Institute (GENI). Available at: https://www.geni.org/globalenergy/research/review-and-comparison-of-solar-technologies/Review-and-Comparison-of-Different-Solar-Technologies.pdf.

CME, 2014. [Municipal forest fire prevention plan 2014 – 2018] Plano municipal de defesa da floresta contra incêndios 2014 – 2018 Caderno I Diagnóstico.

DGEG, 2015a. Renováveis. Estatísticas Rápidas. [Renewable Energy Statistics] Directorate General for Energy and Geology. April 2015.

DGEG, 2015b. Consumo de energia elétrica por sector de atividade em 2013. [Electricity conumpion by sector] Directorate General for Energy and Geology. April 2015.

DGEG, 2015c. Potência instalada nas centrais produtoras de energia elétrica. [Installed power for electricity generation] Directorate General for Energy and Geology. April 2015.

DGEG, 2015d. Balanço energético nacional 2013. [National Energy Balance 2013] Directorate General for Energy and Geology. June 2015.

DGEG, 2015e. Combustíveis fósseis. Estatísticas Rápidas. [Fossil Fuels Statistics] Directorate General for Energy and Geology. June 2015.

DGEG, 2018. Renováveis. Estatísticas Rápidas. Directorate General for Energy and Geology. September 2018.

Dinesh, H., Pearce, J. M., 2016. The potential of agrivoltaic systems. Renew. Sustain. Energy Rev. 54, 299–308. doi:10.1016/j.rser.2015.10.024.

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y., 2011. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. Renew. Energy 36, 2725–2732. doi:10.1016/j.renene.2011.03.005.

EDP Distribuição, 2015. Data on electricity production and installed capacity of utility-scale production systems PV on Évora municipality by sector and zone. EDP Distribuição S.A, Lisbon, Portugal.

EDP, 2015. InovGrid Évora. EDP Distribution S.A.

EEA, 2016. Renewable energy in Europe 2016 Recent growth and knock-on effects. European Environment Agency, Copenhagen, Denmark. Available at: https://www.eea.europa.eu/publications/renewable-energy-in-europe-2016.

Eltawil, M. A., Zhao, Z., 2010. Grid-connected photovoltaic power systems: Technical and potential problems - A review. Renew. Sustain. Energy Rev. 14, 112–129. doi:10.1016/j.rser.2009.07.015.

Förster, J., Barkmann, J., Fricke, R., Hotes, S., Kleyer, M., Kobbe, S., Kübler, D., Rumbaur, C., Siegmund-Schultze, M., Seppelt, R., Settele, J., Spangenberg, J. H., Tekken, V., Václavík, T., Wittmer, H., 2015. Assessing ecosystem services for informing land-use decisions: A problem-oriented approach. Ecol. Soc. 20. doi:10.5751/ES-07804-200331.

Fraunhofer (ISE), 2017. Photovoltaics Report. Fraunhofer, Institute for Solar Energy. Available at:.ise.fraunhofer.de.

Greenpeace. (2015). World Energy [R]evolution, a sustainable world energy outlook. Retrieved from: http://www.greenpeace.org/international/Global/international/publications/climate/2015/EnergyRevolution2015Full.pdf

González-García, S., Dias, A. C., Arroja, L., 2013. Life-cycle assessment of typical Portuguese cork oak woodlands. Sci. Total Environ. 452–453, 355–364. doi:10.1016/j.scitotenv.2013.02.053.

Gouveia, J. P., Seixas, J., 2016. Unraveling electricity consumption profiles in households through clusters: Combining smart meters and door-to-door surveys. Energy and Buildings. 116, 666–676.

Gouveia, J. P., Seixas, J., Mestre, A., 2017. Daily Electricity Profiles from Smart Meters - Proxies of Active Behaviour for Space Heating and Cooling. Energy, 141. 108-122 https://doi.org/10.1016/j.energy.2017.09.049.

Gouveia, J. P., Seixas, J., Long, G., 2018. Mining households' energy data to disclose fuel poverty: Lessons for Southern Europe. Journal of Cleaner Production 178, 534-550. https://doi.org/10.1016/j.jclepro.2018.01.021.

Gunderson, I., Goyette, S., Gago-Silva, A., Quiquerez, L., Lehmann, A., 2014. Climate and land-use change impacts on potential solar photovoltaic power generation in the Black Sea region. Environ. Sci. Policy 46. doi:http://dx.doi.org/10.1016/j.envsci.2014.04.013.

Hawken, P., Wilkinson, K., Frischmann, C., Allard, R., Bayuk, K., Gouveia, J. P., Mehra, M., Toensmeier, E., Chissel, C., 2017. Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming. Edited by Paul Hawken. Penguin Books. April 2017. ISBN-13: 978-0143130444.

IEA, 2014. Technology Roadmap: Solar Photovoltaic Energy. International Energy Agency, Paris, France.

IEA, 2015. World Energy Outlook 2015. International Energy Agency, Paris, France. doi:10.1787/weo-2014-en.

IEA, 2017. World Energy Outlook 2017. International Energy Agency, Paris, France. doi:http://dx.doi.org/10.1787/weo-2017-en.

IEA and NEA, 2015. Projected Costs of Generating Electricity – edition 2015. Organisation for Economic Co-operation and Development - International Energy Agency and Nuclear Energy Agency. France. Retrieved from https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf.

IEA-PVPS, 2015. TRENDS 2015 in Photovoltaic Applications: Survey Report of Selected IEA Countries between 1992 and 2014.

INE, 2013a. Contas Económicas da Silvicultura – 2013 Statistics Portugal. Avaialable at /http://www.ine.pt/.

INE, 2013b. Estatísticas Agrícolas – 2013. Statistics Portugal. Avaialable at /http://www.ine.pt/.

INE, 2013c. Contas Regionais para o período 2000 a 2013. Statistics Portugal. Avaialable at /http://www.ine.pt/.

IRENA, 2017. REthinking Energy: Accelerating the global energy transformation,
International Renewable Energy Agency (IRENA). Available at: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/IRENA_REthinking_Energy_2017.pdf.

Jäger-waldau, A., 2016. PV Status Report 2016. European Commission, Joint Research Centre, Directorate C, Energy Efficiency and Renewables Unit, Ispra, Italy. doi:10.2790/749737.

Janke, J. R., 2010. Multicriteria GIS modeling of wind and solar farms in Colorado. Renew. Energy 35, 2228–2234. doi:10.1016/j.renene.2010.03.014.

Krajačić, G., Duić, N., Carvalho, M. D. G., 2011. How to achieve a 100% RES electricity supply for Portugal? Appl. Energy 88, 508–517. doi:10.1016/j.apenergy.2010.09.006.

Lopez, A., Roberts, B., Heimiller, D., Blair, N., Porro, G., 2014. U. S. Renewable Energy Technical Potentials: A GIS- Based Analysis 40. doi:NREL/TP-6A20-51946.

MEE, 2015. Renováveis na Hora - Sistema de Registo de Microprodução e Miniprodução [micro and mini generation]. Ministry of Economy and Employment. Available at:

[http://www.renovaveisnahora.pt/web/srm].

Metz, A., Demenik, G., Ritcher, A., Vlasenko, Timur, 2015. International Technology Roadmap for Photovoltaic (ITRPV) Sixth Edit, 1–38. Available ta: http://www.itrpv.net/.

MIT, 2015. The Future of Solar Energy: An Interdisciplinary MIT Study. Cambridge, MA. Available at: http://energy.mit.edu/research/future-solar-energy/.

MMP, 2008. [Municipal Master plan] Regulamento do Plano Diretor Municipal de Évora. Diário da República no 18/2008, II série. Relatório do Plano Diretor Municipal de Évora. Dezembro 2007. Estudos de Caracterização do Território do Município de Évora.

MMP, 2012. [Municipal Master plan Update] Alteração ao regulamento do Plano Diretor Municipal de Évora. October 2012.

NREL, 2015. Best Research-Cell Efficiencies. National Renewable Energy Laboratory, National Center for Photovoltaics. Avaliable at: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg.

Ong, S., Campbell, C., Denholm, P., Margolis, R., Heath, G., 2013. Land-Use Requirements for Solar Power Plants in the United States. National Renewable Energy Laboratoru (NREL). Available at: https://www.nrel.gov/docs/fy13osti/56290.pdf.

Perpiña Castillo, C., Batista e Silva, F., Lavalle, C., 2016. An assessment of the regional potential for solar power generation in EU-28. Energy Policy 88, 86–99. doi:10.1016/j.enpol.2015.10.004.

PNAER, 2013. Estratégia para as Energias Renováveis - PNAER 2020. [NREAP - National Renewable Energy Action Plan]. Resolução do Conselho de Ministros n.o 20/2013.

PVGIS, 2018. Photovoltaic Geographical Information System web application. Institute for Energy and Transport (IET) of the Joint Research Center (JRC). Available at: http://re.jrc.ec.europa.eu/pvgis/.

Rahman, M.M., Hasanuzzaman, M., Rahim, N., 2015. Effects of various parameters on PV-module power and efficiency. Energy Convers. Manag. 103, 348–358. doi:10.1016/j.enconman.2015.06.067.

Redweik, P., Catita, C., Brito, M., 2013. Solar energy potential on roofs and facades in an urban landscape. Sol. Energy 97, 332–341. doi:10.1016/j.solener.2013.08.036.

Resch, G., Held, A., Faber, T., Panzer, C., Toro, F., Haas, R., 2008. Potentials and prospects for renewable energies at global scale. Energy Policy 36, 4048–4056. doi:10.1016/j.enpol.2008.06.029.

Robertson, G. P., Gross, K. L., Hamilton, S. K., Landis, D. A., Schmidt, T. M., Snapp, S. S., Swinton, S. M., 2014. Farming for ecosystem services: An ecological approach to production agriculture. Bioscience 64, 404–415. doi:10.1093/biosci/biu037.

Sacchelli, S., Garegnani, G., Geri, F., Grilli, G., Paletto, A., Zambelli, P., Ciolli, M., Vettorato, D., 2016. Land Use Policy Trade-off between photovoltaic systems installation and agricultural practices on arable lands : An environmental and socio-economic impact analysis for Italy. Land Use Policy 56, 90–99. doi:10.1016/j.landusepol.2016.04.024.

Seixas, J., Fortes, P., Dias, L., Barroso, J., Martinho, S., Gouveia, J., Ferreira, F., Gomes, P., Tente, H., Baptista, P., 2014. GHG Emission scenarios and technological options for decarbonization in Portugal in 2020 and 2030 Study for the Portuguese Environmental Agency. Lasting values, Lda and CENSE, FCT of NOVA University of Lisbon.

Seixas, J., Fortes, P., Dias, L., Dinis, R., Alves, B., Gouveia, J., Simões, S., 2012. Low Carbon RoadMap - Portugal 2050 - Energy and Waste Greenhouse emissions, Study for the Executive Committee of the Climate Change Commission. E-value, SA and FCT of NOVA University of Lisbon.

Sierra-Pérez, J., Boschmonart-Rives, J., Gabarrell, X., 2015. Production and trade analysis in the Iberian cork sector: Economic characterization of a forest industry. Resour. Conserv. Recycl. 98, 55–66. doi:10.1016/j.resconrec.2015.02.011.

Simoes, S., Dias, L., Gouveia, J. P.; Seixas, J., De Miglio, R., Chiodi, A., Gargiulo, M., Long, G., Giannakidis, G., 2018. INSMART - Insights on modelling EU cities decarbonisation pathways. Energy Strategy Reviews (20), April 2018, Pp. 150–155.

SlizSszkliniarz, B., 2013. Land Use Policy Assessment of the renewable energy-mix and land use trade-off at a regional level : A case study for the Kujawsko – Pomorskie Voivodship. Land Use Policy 35, 257–270. doi:10.1016/j.landusepol.2013.05.018.

Solargis, 2018. PV planner. Available from: http://www.solargis.info/pvplanner.

Uyan, M., 2013. GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region Konya/Turkey. Renew. Sustain. Energy Rev. 28, 11–17. doi:10.1016/j.rser.2013.07.042.

Vieira, R.G., Guerra, F. K. O. M. V., Vale, M. R. B. G., Araújo, M. M., 2016. Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator. Renew. Sustain. Energy Rev. 64, 672–681. doi:10.1016/j.rser.2016.06.089.

Wirth, H., 2015. Recent Facts about Photovoltaics in Germany. Freiburg.

Nomenclature

€ – Euro

CPV – Concentrated photovoltaic

c-Si – Crystalline silicon

GHI – Global horizontal irradiation

GIS – Geographic information system

GW – Gigawatt

GWh – Gigawatt-hour

ha – Hectare

MW – Megawatt

PV – Photovoltaic

RES-E – Renewable energy sources for electricity generation