Interplay between the potential of photovoltaic systems and agricultural land use

Luís Dias*, João Pedro Gouveia, Paulo Lourenço, Júlia Seixas

CENSE – Center for Environmental and Sustainability Research, NOVA School of Science and Technology, NOVA University Lisbon

*Corresponding author. Address: CENSE – Center for Environmental and Sustainability Research, NOVA School of Science and Technology, NOVA University Lisbon 2829-516 Caparica, Portugal
Tel.:+351 21 294 83 74
E-mail address: luisdias@fct.unl.pt (Dias, L.)

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 can 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/m²/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 parity¹ 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).

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-generation2 systems. The total PV installation capacity reached 852 MW in 2017, from which 395 MW were utility-scale projects (DGE, 2015a; DGE, 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 multriteria 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

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 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 km² 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

---

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

**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

---

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 quantify 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 adaptation 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>
<thead>
<tr>
<th>Agriculture and forestry lands</th>
<th>Land-use change scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Pro-PV</strong></td>
</tr>
<tr>
<td>Vineyards</td>
<td></td>
</tr>
<tr>
<td>Cork oak forests - montado</td>
<td></td>
</tr>
<tr>
<td>Cork oak crops</td>
<td></td>
</tr>
<tr>
<td>Mixed crops with cork oak</td>
<td></td>
</tr>
<tr>
<td>Poor grassland subject to trampling</td>
<td>Not susceptible to change</td>
</tr>
<tr>
<td>Gorse</td>
<td></td>
</tr>
<tr>
<td>Xerophilic grassland</td>
<td></td>
</tr>
<tr>
<td>Soil without vegetation cover</td>
<td></td>
</tr>
<tr>
<td>Irrigation cereals and dry cereals</td>
<td>Susceptible to change</td>
</tr>
<tr>
<td>Cistus and Sargasso areas</td>
<td></td>
</tr>
<tr>
<td>Mixed Mediterranean scrubs</td>
<td></td>
</tr>
<tr>
<td>Ruderals formations</td>
<td></td>
</tr>
<tr>
<td>Crops with current land occupation rate lower than 50%</td>
<td>Susceptible to change</td>
</tr>
<tr>
<td>Crops with current land occupation rate higher than 50%</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Agriculture and forestry lands’ susceptibility to change considered in each scenario
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>
<thead>
<tr>
<th>PV-Installed capacity (MW)</th>
<th>Direct area (ha)</th>
<th>Total area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PV-track</td>
<td>CPV</td>
</tr>
<tr>
<td>&lt; 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.6</td>
<td>2.8</td>
</tr>
<tr>
<td>10</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>&gt; 20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>72</td>
<td>50</td>
</tr>
<tr>
<td>30</td>
<td>108</td>
<td>75</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Land-use competition scenarios</th>
<th>Available land (ha)</th>
<th>Suitable land (ha)</th>
<th>Total required land for solar PV projects (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 MW PV-track</td>
</tr>
<tr>
<td>Pro-PV</td>
<td>16 711</td>
<td>12 845</td>
<td>8 728 CPV</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>10 887</td>
<td>8 308</td>
<td>5 716 CPV</td>
</tr>
<tr>
<td>Pro-Rural</td>
<td>6 951</td>
<td>5 244</td>
<td>3 905 CPV</td>
</tr>
</tbody>
</table>

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).
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

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

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

<table>
<thead>
<tr>
<th>Land-use change scenarios</th>
<th>PV utility-scale electricity production potential (GWh)</th>
<th>1 MW</th>
<th>10 MW</th>
<th>20 MW</th>
<th>30 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PV-track</td>
<td>CPV</td>
<td>PV-track</td>
<td>CPV</td>
<td>PV-track</td>
</tr>
<tr>
<td>Pro-PV</td>
<td>4 065</td>
<td>4 377</td>
<td>538</td>
<td>478</td>
<td>195</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>2 662</td>
<td>2 855</td>
<td>383</td>
<td>363</td>
<td>142</td>
</tr>
<tr>
<td>Pro-Rural</td>
<td>1 819</td>
<td>1 957</td>
<td>315</td>
<td>282</td>
<td>142</td>
</tr>
</tbody>
</table>

**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 € (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).

Acknowledgments

The work supporting this paper was partly funded by the European project InSMART – Integrative Smart City Planning (EU FP7 Grant agreement no: 314164). The authors would like to thank Évora municipality, namely its InSMART project team members, for providing essential information. The authors would also like to thank Katherine Mahoney for her English revisions at the final stage. Finally, the authors acknowledge and appreciate the support given to CENSE by the Portuguese Foundation for Science and Technology through the strategic project UID/AMB/04085/2013.

5. References


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


IRENA, 2017. Rethinking Energy: Accelerating the global energy transformation,


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


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