LAND USE INTENSITY AND LAND OCCUPATION OF UTILITY-SCALE PHOTOVOLTAIC POWER PLANTS IN CONTINENTAL PORTUGAL

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ABSTRACT: Details about Portuguese PV stations are scarce: no public access is provided to project files and environmental impact assessments (EIA) - public-domain information - are mandatory only for power plants of 50 MW or higher capacity, a small minority. In our research, we measured the land use intensity (LUI) of utility-scale PV power plants in continental Portugal and estimated their future land occupation from the capacity additions forecast by the government and from the expected future improvements in LUI due to the increase in PV panel efficiency. A novel method, with land occupation depending simultaneously on the evolution of capacity and panel efficiency, was developed for the purpose. We found 3.336 ha/MW for the average LUI of all stations in operation in continental Portugal, with the LUI varying with mounting type. For land occupation by PV plants in 2050 we found large areas albeit small when compared with other land cover types, e.g. 30 000 hectares would be 1.3% and 0.9% of the current areas dedicated to agriculture and forestry, respectively. However, with EIAs required only for large stations there will be opportunities for land-use conflicts and deep landscape alterations.
Keywords: Large Grid-connected PV Systems, Land use intensity, PV land occupation, Environmental Effect

1 INTRODUCTION

In the last twelve years, Portugal has seen significant developments regarding photovoltaic (PV) solar energy. In 2008, the 45.8 MW Amareleja solar plant started operation and was announced as the world's largest PV power plant [1]. In 2019, at the first auction of unsubsidized PV, a successful bidder committed to supply electricity at 14.8 € per MWh for fourteen years, a worldwide record [2].

Despite all the excitement and Portugal's admission to the "gigawatt club" there is little detailed information about Portuguese PV power plants: the project files cannot be accessed by the public and (public-domain) environmental impact assessments (EIA) are mandatory only for plants of 50 MW or higher capacity, currently a small minority.

The research presented in this paper had two objectives. The first was to calculate the capacity-based land use intensity (LUI) of utility-scale PV power plants in continental Portugal, i.e. those having one MW or higher installed capacity. The second was to estimate future land occupation by PV plants from the government's plans for PV capacity additions [3] and from the improvements in LUI due to the increases in PV panel efficiency.

A novel method, in which land occupation reflects, simultaneously, the evolution of PV capacity and PV panel efficiency, was developed for this purpose.

2 MATERIALS & METHODS

2.1 Land use intensity of PV stations

The land-use intensity of a PV station is the ratio of the total land area it occupies to its installed power or energy delivered yearly to the grid, being commonly stated in hectare per megawatt of installed power (capacity-based LUI) or hectare per megawatt-hour of delivered energy (generation-based LUI). The former may also be expressed as a "power density", in W_{DC}/m^2 or MW_{DC}/ha. To determine the capacity based LUI of PV plants in continental Portugal we needed their full land areas, installed capacities, and mounting types (since the LUI depends on whether the panels are fixed or tracking the daily movement of the Sun). We have used two credible Portuguese sources and performed area measurements using satellite imagery. The first source was the "e2p" database of operating PV plants maintained by INEGI, a research institute, and APREN, an association of renewable energy suppliers. It contains locations, installed capacities in MW_{DC}, administrative data (plant name, owner, developer, dates), and in some cases technology details [4]. The second source was the online GIS map and database by DGEG, a government agency [5]. It includes licensing data (plant name, owner, status, dates) of planned and operating solar plants and, in many cases, station perimeters that rarely match the actual ones seen on satellite imagery. The sources do not agree on the PV stations in operation in continental Portugal: "e2p" records 104 operating plants while DGEG's database records only 89 - while reporting a total of 221 stations, either planned or operating. Filtering "e2p" for one MW or higher capacity we selected 78 ground-mounted plants, to which we added one station identified only in DGEG´s map. Grouping contiguous stations when they were phases of the same project, we obtained a set of 64 station perimeters, which were inspected and measured using Google Earth Pro ™ (including its image timeline and Street View, where available). To confirm findings, we also resorted to all press releases or project references in company sites that could be found about the PV stations. Regarding land occupation our main criterion was to identify the protection fence of each station and measure its inner areas. Grid connection infrastructure (e.g. substations, power lines) was left out. Figure 1, below, illustrates the area measurement process. From perimeter area measurements and installed DC power we calculated the LUI for each station and obtained global and separate distributions according to mounting type. Individual LUI values, $A_P(i)$, were calculated from $P_M(i)$ values taken from the “e2p” database [4] and the area measurements. Dividing the areas by installed capacities yielded $A_P(i)$ in hectare per MW_{DC}. We obtained values for 46 fixed-arrays, 10 single-axis tracking, and 8 dual-axis tracking stations, to be presented in the Results section.

Figure 1: “Ferreira do Alentejo” PV station: installed capacity 12.7 MW_{DC}, total land area 56.5 hectare.

2.2 Future land occupation of PV stations

Future land occupation by PV stations can be derived by simultaneously integrating total installed power, P_M, and average land use intensity, A_P, both dependent on time (Equation 1). Modelling time-dependency linearly yields Equation 2, with K_1 as the growth rate of P_M and M_a relating A_P with K_2, the growth rate of the average PV panel efficiency (Equation 3).

E_{f*} represents E_f (the panel efficiency, normally defined as a percentage) in MW/hectare. With A_P measured in hectare/MW, M_a becomes a unit less constant.

It should be noted that M_a is an “area multiplier”, yielding the total area of a PV station from the total area of its panels. An average value for M_a must be estimated, as shown below.

$$\boldsymbol{A_T(t) = \iint dP_M dA_P} \quad (1)$$

$$\boldsymbol{A_T(t) = K_1\, M_a \int_{t_0}^{t} \frac{1}{E_{f*}}\, dt = K_1\, M_a \int_{t_0}^{t} \left(\frac{1}{E_{f*}(t_0) + K_2(t - t_0)}\right) dt} \quad (2)$$

$$\boldsymbol{A_p = \frac{M_a}{E_{f*}}} \quad (3)$$

Note also that the integral in Equation 2 lacks a term for the initial occupation, $A_T(t_0)$, the area at time t_0. Whether or not this area should be included depends on the time horizon of the projections. For time horizons of 30 or more years the land occupied by existing stations will all be taken by new stations or other uses: the initial area should therefore be discarded. For time horizons shorter than 30 years (the usual lifetime of PV stations) the initial area should be partly included, depending on the age of the existing PV plants at time t_0.

2.2.1 Estimating M_a

The area multiplier M_a can be calculated from Equation 3 by estimating a value for E_{f*}. As this is the average PV panel efficiency (in MW/hectare) of all the stations used to calculate the LUI, one possible approach is to assume for each station a panel efficiency consistent with the year it started operation. We therefore selected fixed-arrays stations for which the operation starting year was known (43, in total) and assumed that they were equipped with mono-Si or poly-Si panels having the compound efficiency reported in [6]. (The value for 2019 was extrapolated by us.) The results are shown in Table I, below. Computing a weighted-average value for E_f (with the number of stations as weights), converting to E_{f*}, and then multiplying it by the average A_P for fixed-arrays stations (Cf. Results section) yields an estimate for M_a. Table II, below, illustrates the calculation.

Table I: Estimating the weighted-average PV panel efficiency (43 PV plants, fixed-arrays).

Year	**No. PV stations**	**E_f (%)**	**E_f (weighted average, %)**
2008	1	14.4	
2009	2	14.5	
2010	3	14.8	
2011	1	14.9	
2012	3	15.0	
2013	4	15.3	
2014	15	15.6	
2015	5	15.8	
2016	1	16.3	
2017	3	16.8	
2018	4	17.3	
2019	1	18.5	
			15.7

Table II: Calculating M_a, the area multiplier.

A_P (ha/MW)	**E_{f*}** (MW/ha)	**M_a**
3.075	1.57	4.83

3 RESULTS

The distributions for LUI results, segregated by the mounting type of the sampled PV stations, are summarized in the box plots diagrams of Figures 2, 3 and 4, below. All values shown are in hectare per megawatt of installed power (MW_{DC}).

The distribution for all stations (N=64) is not represented but can be summarized by 3.336, 2.989, 2.224, and 4.247, respectively its mean, median, Q1, and Q3 values.

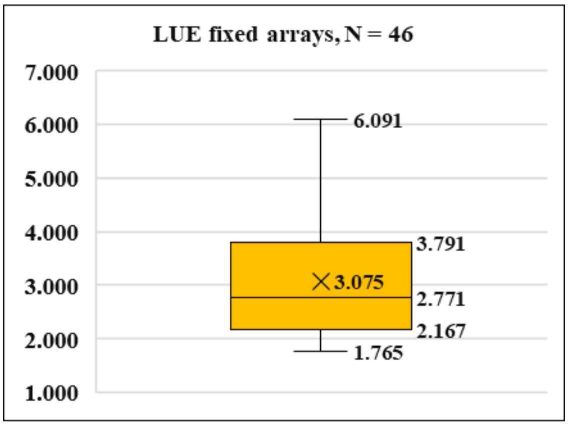

Figure 2: Distribution for fixed-arrays stations.

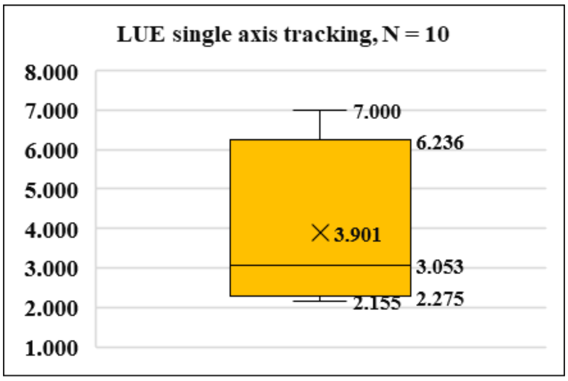

Figure 3: Distribution for single-axis tracking stations.

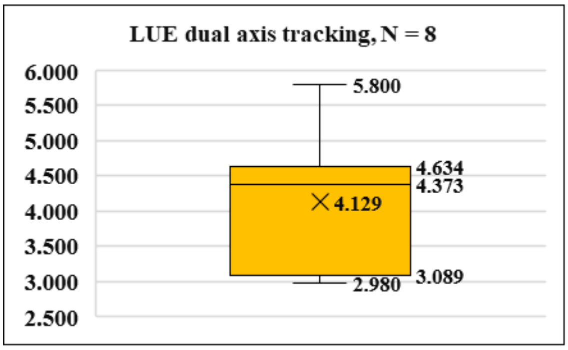

Figure 4: Distribution for dual-axis tracking PV stations.

PV land occupation in 2050 in continental Portugal was estimated using Equation 2 with two power demand scenarios for utility-scale or “centralized” solar energy, defined in the Portuguese official roadmap to carbon neutrality [3].

P_M values at the end of each decade until 2050 were calculated using the average PV output for continental Portugal found in [7]. Fixed-arrays PV stations were assumed to be dominant. PV capacity in 2020 was set equal to 0.9 GW [8]. Average panel efficiency for this simulation was assumed to increase linearly from 20% in 2020 to 24%, 28%, and 32% at the end of each decade until 2050.

Table III, below, shows the two PV electricity scenarios, with the demand values in GWh at the end of each decade [3] and the corresponding installed capacities required by the PV output defined in [7].

Table III: Demand scenarios of the Portuguese roadmap to carbon neutrality in 2050 [3].

Scenarios	**Years**	**Demand** (GWh)	**P_M** (GW_{DC})
“Peloton” **(PL)**	2030	12.8	8.2
	2040	21.4	13.7
	2050	25.8	16.5
“Yellow Jersey” **(YJ)**	2030	9	5.8
	2040	17.7	11.3
	2050	24.7	15.8

Table IV, below, shows K_1 and K_2 - linear growth rates of installed power and efficiency, respectively - calculated for each decade in the two scenarios. Together with M_a, they form the set of parameters required by Equation 2. The table also shows the partial and total results of the simulation: land areas occupied by PV plants at the end of each decade, and in the year 2050.

Table IV: Growth parameters and land occupation results for the two demand scenarios.

Years	**K_1** (MW_{DC}/yr.)	**K_2** (%/yr.)	**A_T** (hectare)
2020-’30	730	0.04	16 071
2030-’40	550	0.04	10 238
2040-’50	280	0.04	4 516
Total PL			30 825
2020-’30	490	0.04	10 988
2030-’40	550	0.04	10 429
2040-’50	450	0.04	7 393
Total YJ			28 810

4 CONCLUSIONS

Concerning land use intensity of PV solar plants, our work is close to [9][10][11] with new measured results for a European country.

Future PV land occupation is addressed in [11][12][13]. Our dynamic estimation model can be contrasted with the static approach of [11], relying instead on the simultaneous evolution of installed capacity and panel efficiency. In fact, since PV stations have lifetimes of 30 years any future land occupation will have contributions of stations with different panel efficiencies. This dynamic is captured in our integral expression, a piece-wise linear model based on the time dependence of both installed capacity and panel efficiency.

Estimating M_a only from presumed panel efficiencies is a limitation of our work. Our team is currently researching complementary methods to estimate M_a that are independent of actual panel efficiencies.

As stated in the Results section, we found an average value of 3.336 hectares per MW_{DC} for the LUI of all utility-scale PV power plants in continental Portugal. This is higher than the value reported in [9] for PV plants in California (2.857 ha/MW_{DC}), although our range of values is smaller. The LUI also varies with the mounting type, consistently with the country-wide USA figures reported in [10].

The areas estimated for PV land occupation in 2050 are large. For instance, 30 000 hectares would correspond to almost 80% of all the area currently taken by roads and railroads; and 26 % of the urban growth in the twenty years between 1995 and 2015. But when compared with the areas of other land uses, they are comparatively small: just 1.3% of agriculture and 0.9% of forestry. It would correspond to just 0.3% of the area of continental Portugal [14].

Future capacity additions to produce green hydrogen and to export electricity could increase PV land occupation beyond the estimates for the current scenarios. On the other hand, unexpected breakthroughs in PV efficiency would reduce the total area.

The figures above allow us to conclude that the main issue regarding future PV land occupation in continental Portugal lies not in its total area but where and how the area will be distributed. A main concern is that environmental impact assessments are currently required only for power stations of 50 MW or higher capacity. This leaves plenty of opportunity for land-use conflicts and deep landscape alterations, especially in the countryside.

5 REFERENCES

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