DESIGN AND METHODOLOGY FOR AN AGRIVOLTAIC PILOT PROJECT IN THE ALENTEJO REGION

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ABSTRACT: This paper presents a study for an agrivoltaic pilot project in the Alentejo region, aimed at identifying the average percentage increase in efficiency between different types of photovoltaic panels (monofacial and bifacial modules) due to cooling effects from shading, when installed over monoculture rotations and intercropping systems with crops that benefit from Shade Avoidance Syndrome (SAS). The study will utilize the existing photovoltaic installations at the Renewable Energies Chair (CER) on the Mitra campus of the University of Évora, located in Nossa Sra. da Tourega, Évora municipality. Strategies were developed to integrate agricultural production with the existing photovoltaic system in two zones: the control zone (corridors distributed between the rows of solar panels) and the reference zone (unaffected by the operational aspects of the solar power plant). Two cropping configurations are proposed, both implemented simultaneously and in duplicate across the control and reference zones, over a two-year cycle. In the first year, monoculture rotation of tomato and lettuce will be carried out; in the second year, the crops will be intercropped. In addition to monitoring climate parameters between the zones, the study aims to conduct a comparative analysis of the biomass yield from each crop configuration in both zones.
Keywords: Agrivoltaic systems, Crop efficiency, Renewable energy integration, CO_2 Footprint, Solar Plant Retrofitting

1 INTROCUCTION

According to the European Environment Agency, since 2012, the evolution of CO_2 equivalent emissions levels in the agricultural sector has been increasing since 2012, exceeding emissions from the industrial sector and, currently, from the energy supply sector [1]. The topic of agrivoltaics, which combines photovoltaic panels and agricultural cultivation, is gaining strength on the agenda of the agricultural society as an option for replacing fossil energy sources in the agricultural sector and as a provider of potential net gains in agricultural production [2].

The Alentejo region, in Portugal, is the most representative region in terms of arable land for organic production, concentrating two thirds of the total of approximately four thousand agricultural holdings in the country [3]. Furthermore, according to the report by LNEG (National Laboratory of Energy and Geology) on the estimation of technical potential for Renewable Energy in Portugal, the country has great potential for solar energy, especially in regions such as the Algarve, the interior of Alentejo and Beira Baixa [4].

Growing lettuce under photovoltaic panels is an example of an agrivoltaic interaction that benefits from SAS (Shade Avoidance Syndrome) [5]. Shade provides better conditions for lettuce growth by reducing the soil temperature and increasing soil moisture. In turn, energy production becomes more efficient due to the cooling effect of the photovoltaic panels caused by the transpiration of plants underneath.

In a study conducted in the Apulia, region of southern Italy [6], tomato crops were grown under a photovoltaic structure that does not meet the ground height standards commonly associated with agrivoltaic systems designed for machine-assisted cultivation, ensuring only 3% light intensity (below the minimum of recommended indicated in the same study). The results indicated that the tomato fruits grown under the photovoltaic panels were more consistent with a regular seed development, while 50% of the fruits grown in full sunlight had underdeveloped or absent seeds.

A study carried out to estimate direct and indirect GHG (Greenhouse Gas) emissions and the carbon footprint per kilo of vegetables produced, showed that GHG emissions resulted from the intercropping of cucumbers, tomatoes and lettuce were approximately 35% lower than in monocultures [7]. Therefore, in addition to the agroeconomic advantages of intercropping systems [8], and from the perspective of GHG emissions, this practice can be considered as the least impactful cultivation system due to the sharing of infrastructure and the optimization of inputs, for example: energy consumption used for irrigation, heating greenhouses, and operating agricultural machinery; use of fertilizers and pesticides; transport (distribution of agricultural inputs); and agricultural waste (decomposition and waste management) [9].

The Mediterranean region, in which Alentejo is located, stands out as particularly susceptible to the phenomenon of the increase in the severity of extreme weather events – such as heat waves and droughts [10]. Research concludes that agrivoltaic systems, by combining solar panels and agricultural cultivation, can optimize agricultural production by reducing the stressful conditions of drought and heat on agricultural crops, thus increasing the climate resilience of the agricultural system [11].

Thus, the overall aim is to evaluate agrivoltaics in Alentejo and its synergistic benefits across the food-energy-soil nexus in relation to photovoltaic systems (monofacial and bifacial modules) or isolated agricultural configurations (crops in monoculture rotation and with intercropping).

2 CASE STUDY

2.1 Microgrid SolGrid

In 2023, CER arranged the installation of a photovoltaic infrastructure with horizontal North-South axis with solar tracking, connected to the SolGrid experimental grid, presented schematically in Figure 1.

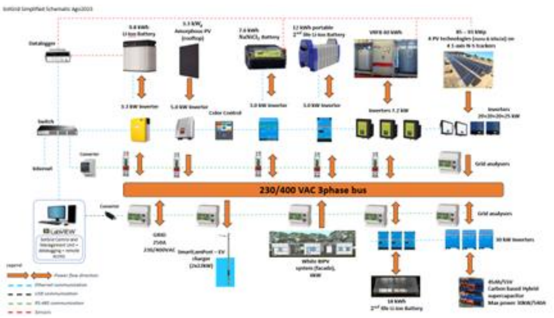

Figure 1: SolGrid Simplified Schematic Aug2023

2.2 Existing Technologies and structure

The existing solar plant is made up of four different photovoltaic technologies (two mono and two bifacial). These structures occupy an area of about 1400 m^2 on the Mitra campus of the University of Évora.

The total area for cultivation, testing zone, is approximately 950 m^2 with five rows influenced by the modules' shade and 190 m^2 with one row without panel coverage as reference zone. The height of the panels above the ground, without inclination, varies between 160 cm and 130 cm, as the terrain is in slopes.

The first left row (Figure 2) consists of 3 strings of Longi Hi-MO monocrystalline modules. Each of these strings has 17 modules, making a total of 51 modules and 22.7 kWp installed. The second row consists of 3 strings of Longi Hi-MO bifacial modules. Each of these strings has 17 modules, making a total of 51 modules and 22.7 kWp installed. The third row consists of 3 strings of LG brand monocrystalline modules. Each string consists of 18 modules, making a total of 54 modules and 19.4 kWp installed. The fourth and last row (right) consists of 3 strings of LG bifacial modules. Each string has 17 modules, making a total of 51 modules and 20.9 kWp. The 207 installed modules, with a power of 85.7 kWp, are connected to 4 inverters.

Four 1-axis North-South PV trackers with:

- Monofacial PV Modules (monocrystalline type n, full cell); 21% efficiency; max power degradation -0.33%/year.
- Bifacial PV Modules (monocrystalline type n, full cell); 20%-22.4% efficiency; max power degradation -0.33%/year.
- Monofacial PV Modules (monocrystalline type p, half-cell); 20.5% efficiency; max power degradation -0.45%/year.
- Bifacial PV Modules (monocrystalline type p, half-cell); 20.5% efficiency; max power degradation -0.45%/year.

PV Systems + Inverter:

- 19.44 kWp + Ingeteam 3Play 20TL S.
- 20.91kWp / 23.715 kWp (with 200W/m^2 backside) + Ingeteam 20 TL.
- 22.7kWp + SMA STP 20000TL-30Play.
- 22.7kWp / 27.23kWp (with 20% radiation backside) + SMA STP 25000TL-30Play.

Technical Specifications:

- Full remote control over the trackers and positioning.
- Astronomical algorithm NREL SOLPOS over PLC (precision ±0.01º).
- Trackers with backtracking algorithm implementation.
- Additional high-precision voltage and current sensors deployed on all strings.
- Precision in-plane pyranometer and albedo pyranometer.
- Tower with ultrasonic wind sensor.

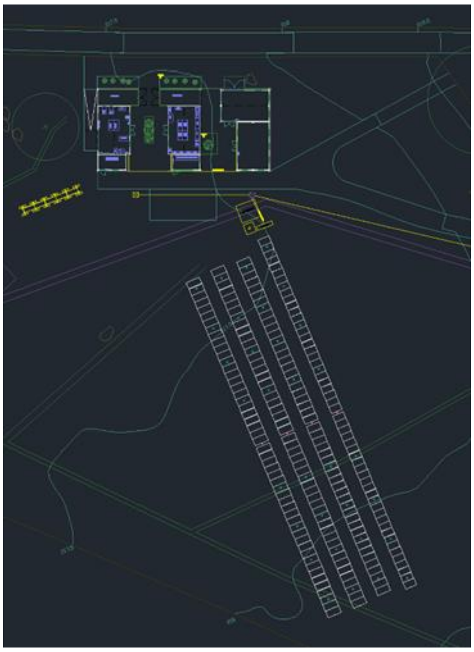

Figure 2: Photovoltaic infrastructure connected to the microgrid

2.3 Location and climate

This pre-existing Solar Photovoltaic Plant, Figure 3, is located at the Mitra campus of the University of Évora, located in the Portuguese Municipality of Évora – Nossa Sra. da Tourega (38° 30′ 08″ N, 8° 02′ 37″ W).

Figure 3: Solar PV Plant

The climate in this site, as in most of the Alentejo, is characterized by hot, dry summers and mild, wet winters [10]. According to the Civil Protection Agency, the Alentejo is a territory susceptible to the occurrence of heat waves, particularly in the sub-regions of Alto Alentejo and in the easternmost areas of Central Alentejo and Baixo Alentejo [11] [12].

2.4 Soil

In August 2023 soil samples were analysed to prepare a report on physical and chemical parameters. Figure 4 shows a top view of the diagram of the division of the land into subareas for identifying soil samples (rows A, B, and C – Control zones; row R – Reference zone).

Dividing the land into subareas allows a more precise application of resources, such as fertilizers and water. This not only improves resource efficiency, but also reduces costs and minimizes the environmental impact.

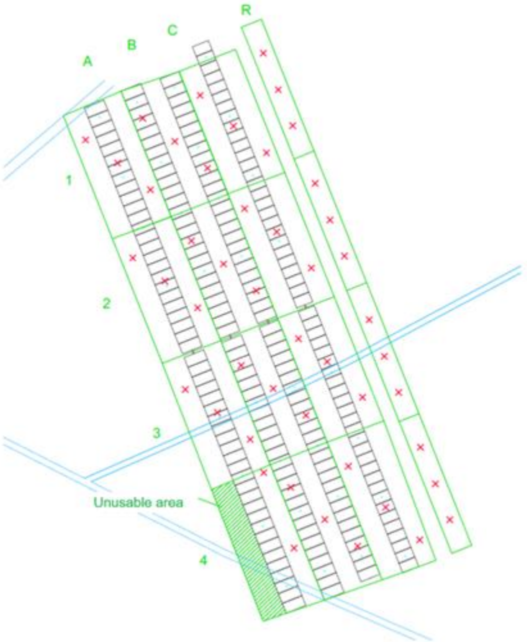

Figure 4: Soil Sample Subareas

From the graphs in Figure 5, we can observe the preliminary results of the soil analysis that present, by physical-chemical parameter and rows, the following statistical measures: the median, the interquartile range (IQR – variation between the first and third quartile) and possible outliers.

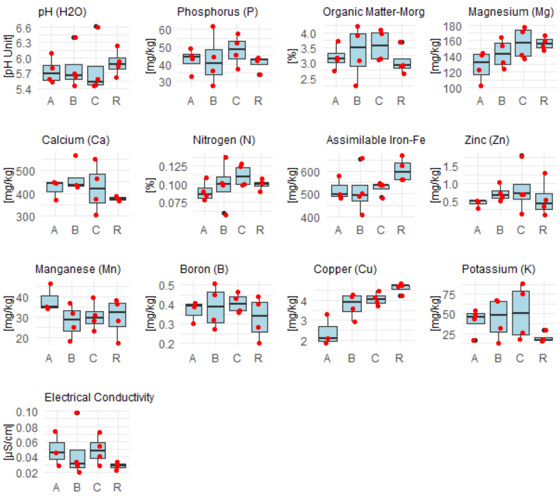

Figure 5: Results of the soil analysis of the study area

In the statistical analysis of the soil to diagnose the initial conditions of this work, the assumptions for normality and homoscedasticity were tested using, respectively, the Shapiro test and the Levene test. Only for the pH parameter was there insufficient evidence to reject the null hypothesis that the residuals are normally distributed.

The results of the mean comparison tests (ANOVA and Kruskal-Wallis) suggest that, for most parameters, there are no differences between the groups (A, B, C and R), i.e., the soil type does not have a significant impact on the levels of the parameters within the demonstrated sample. Only for the Cu parameter, the tests indicated a significant difference between the groups. Tukey and Duncan tests were used to detail the difference within the analysed sample, and both agree that soil A is different from the other soils (B, C, R).

The need to apply lime (T CaO/ha), for the specific conditions evaluated, is “Not Recommended”.

The result of the physical test “Textural Analysis” presented, in qualitative terms, the classification “Medium”.

3 CULTIVATION STRATEGY

3.1 Monocultures rotation

Monoculture rotation, or crop rotation, is defined as the succession of crops over time, in an orderly manner, and which is repeated in a cyclical manner. The concept of “afolhamento” refers to the division of land into different parts, or sheets, which are cultivated with different crops in successive years. This helps prevent soil nutrient depletion, as different plants have different nutritional needs and contribute to soil health, whether by introducing organic matter, or due to the biological porosity created by the roots of crops [13].

3.2 Intercropping

Intercropping is defined as the simultaneous cultivation of two or more species cultivated in the same area during the entire growing season, or during part of this season [14]. Studies indicate that the consortium presents some advantages in relation to other types of cultivation, including: the reduction of the cultivated area necessary for the same production (greater efficiency and effectiveness of the agricultural area); reduction of soil erosion (better efficiency of vegetation cover); lower incidence of diseases (pests); and the increase in economic benefits attributed to the efficient use of water and light, allowing increased crop productivity and improved biodiversity and ecological services [8].

3.3 Choosing tomatoes and lettuce for cultivation strategies

The choice of tomatoes and lettuce for rotation and intercropping in the Portuguese Alentejo, proposed in this study, is based on several agronomic and economic factors, such as: crop complementarity (the different nutrient needs and growth patterns allow for a more efficient use of resources soil and water); efficiency in land use (intercropping, for example, allows better use of space, increasing productivity per unit area); and economic benefits (crop diversification can mitigate economic risks by providing a more stable source of income for farmers) [8].

Furthermore, vegetables play an important role in Portuguese diets, as an accompaniment to many main dishes throughout the year and, especially about raw lettuce and tomatoes, with a higher seasonal rate of consumption during the summer months [15].

4 MONITORING

To calculate the environmental impact indicators of the different photovoltaic configurations on the crops, an appropriated monitoring system must be designed. Meteorological conditions are already being measured by the existing weather station. All other agronomic parameters suggested for monitoring are soil moisture; soil Temperature; air temperature at plant height; air Temperature above plant; PAR at ground level; PAR at plant height; photosynthesis; salinity; nutrients; leaf temperature; leaf humidity sensor; CO_2 concentration; electrical conductivity; e pH. The PV production, in turn, is monitored through the Workstation Lenovo ThinkStation P620 (high-performance workstation for SolGrid control).

The monitoring equipment currently installed at the Solar Photovoltaic Plant are temperature and humidity sensors, PAR and SoilVUE (depth profile of soil temperature, moisture and electrical conductivity).

5 SOLAR PLANT RETROFITTING

Studies highlight that different photovoltaic technologies have enormous potential due to the possibility of adjusting their spectral characteristics according to the characteristics of plants and the ability to optimize the use of solar energy [16].

A fundamental feature of this project is to reduce efficiency losses in the different modules of an existing solar plant, while at the same time obtaining positive gains in tomato and lettuce crops due to the shadow effect, i.e., promoting agrivoltaic through interaction between retrofitting different photovoltaic technologies and agricultural practices.

6 PROCEDURES

For the retrofitting of the photovoltaic solar plant in this agrivoltaic pilot project, the following activities are defined:

i. Inspection and maintenance schedule of the existing photovoltaic system (cleaning and others).

ii. Preparation of cultivation programs (first year with the rotation, respectively, of tomatoes and lettuce and, in the second year, the intercropping of these crops).

iii. Levelling the land.

iv. Design and installation of the irrigation system according to the water needs of tomato and lettuce crops, to make the requirements for crop rotation and intercropping compatible.

v. Installation/replacement of monitoring system equipment based on inspection of existing equipment.

vi. Soil quality analysis schedule based on demand by type of crop.

vii. Soil suitability (fertilization and others) for the start of cultivation based on the results of quality analysis.

viii. Initial procedures for growing crops (research and acquisition of tomato and lettuce seedlings/seeds).

ix. Field Work Schedule after confirming the type of initial cultivation.

After the previous activities are completed, crop cultivation can begin.

In a crop rotation between tomatoes and lettuce, tomatoes are generally planted first. This is because tomatoes are a plant that demands more nutrients and has a longer growth cycle. After the tomato harvest, lettuce, which has a shorter growth cycle and is less demanding in terms of nutrients, can be planted [8].

Finally, monitoring the parameters during each stage of cultivation is extremely important for data analysis and comparison with the different aspects of the agrivoltaic systems proposed in this study (rotation and consortium). From Table 1 it is possible to observe the outline of study methods and objectives:

Table 1: Outline of study methods and objectives

RESULTS		Control Zone		Reference Zone
		Modules Monofacials	Modules Bifacials	-
1st year	Tomato Rotation	**→ The effect of shade:** Was there a difference in the growth and quality of biomass, soil temperature and soil moisture? **→ The potential for carbon sequestration:** Was there a difference in carbon sequestration by the soil? **→ The impact on energy generation:** Was there a difference in energy efficiency?		
	Lettuce Rotation			
2nd year	Intercropping (tomato and lettuce)			

7 CONCLUSIONS

The innovative contribution that the study intends to produce is aimed at the Alentejo agricultural society, which seeks ways to maintain its productive and profitable agriculture, considering the climatological challenges expected for Alentejo and, also, aligned with what is within its reach in preserving the environment in addition to its own borders.

Statistical comparisons between soil moisture data and energy efficiency data from different solar panels, and other results from the food-energy-soil nexus, are expected to fill an important gap in the search for solutions to environmental issues that threaten agriculture and that promote new agrivoltaic projects in the region.

The evaluation of the project will be based, in the future, on expectations of greater efficiency in energy production and improvement in the quality of biomass in lettuce and tomato agriculture, in rotation and intercropping, as a differentiator for the agricultural sector in Alentejo. This study outlines the design and methodology for an agrivoltaic pilot project in the Alentejo region, providing an innovative framework for integrating renewable energy generation with agricultural production. The proposed approach offers a viable solution to address the growing challenges posed by climate change, particularly in regions with hot and dry climates like Alentejo, where efficient use of land and resources is crucial. By combining photovoltaic systems with crops that benefit from shade and optimizing land use through monoculture rotation and intercropping, this pilot project contributes to the development of sustainable agricultural practices and renewable energy production.

The innovative aspect of this study lies in its focus on the food-energy-land nexus, a critical issue for both the region and the country. It addresses the urgent need for adaptation strategies that balance energy demands with food security, while ensuring the preservation of soil quality and biodiversity. The results of this project have the potential to significantly inform future agrivoltaic implementations, offering a replicable model for other regions facing similar challenges. Furthermore, the project reinforces the role of renewable energy in driving sustainable agricultural development, aligning with national and global efforts to mitigate the impacts of climate change.

8 FUTURE WORK

The potential of Alentejo for actions to combat drought and CO_2 equivalent emissions in the agricultural sector is considerable and needs to be better explored [17]. Building on the design and methodology of this agrivoltaic pilot project in the Alentejo region, several avenues for future research are identified. Within the scope of this project, to explore the rotation and intercropping of different crops in agrivoltaic systems to understand, mainly:

- the potential for energy efficiency due to the cooling of the panels inherent to the agrivoltaic system.
- the potential for carbon sequestration by the soil due to the microclimate with lower temperatures [18]; and
- the quality of the biomass that benefits from the SAS.

9 ACKNOWLEDGEMENTS

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