Universidade de Évora - Escola de Ciências e Tecnologia

Mestrado em Engenharia da Energia Solar

Dissertação

Agrivoltaic - Assessment and guidelines for a pilot in Alentejo

Lisa Bunge

Orientador(es) | Luís Fialho

Évora 2024

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A dissertação foi objeto de apreciação e discussão pública pelo seguinte júri nomeado pelo Diretor da Escola de Ciências e Tecnologia:

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Für meine Eltern

Agrivoltaic - Assessment and Guidelines for a Pilot in Alentejo

Abstract

This dissertation explores the integration of photovoltaic power plants with agriculture and nature conservation through agrivoltaic and ecovoltaic principles. Agrivoltaic promotes a synergistic relationship between agriculture and photovoltaic energy production, optimising land use and improving crop cultivation under photovoltaic panels. Ecovoltaic in turn, focuses on enhancing ecosystem services within photovoltaic facilities, with an emphasis on habitat and biodiversity conservation.

The study uses the upcoming Cercal Power photovoltaic power plant in Cercal do Alentejo as a case study to explore agrivoltaic and ecovoltaic compatibility strategies. Agrivoltaic initiatives include crop cultivation, livestock activities, and beekeeping, while ecovoltaic strategies involve habitat requalification and biodiversity enhancement. Two approaches for agrivoltaic crop cultivation were considered: retrofitting the commercial photovoltaic facility and an additional agrivoltaic pilot. Additionally, a matrix database tool was developed to evaluate the potential impact of various agrivoltaic and ecovoltaic strategies on different indicators, simplifying the planning process for future photovoltaic power plants.

Keywords: Photovoltaic Energy; Agriculture; Nature Conservation; Agrivoltaic; Renewable Energy

Agrivoltaico - Avaliação e Orientações para um Piloto no Alentejo

Resumo

Esta dissertação explora a integração de centrais fotovoltaicas com agricultura e conservação da natureza através dos conceitos agrivoltaico e ecovoltaico. O agrivoltaico promove uma relação sinérgica entre agricultura e produção fotovoltaica, otimizando o uso do terreno e melhorando a produção agrícola. O ecovoltaico procura melhorar os serviços de ecossistemas através da conservação de habitats e biodiversidade.

A futura central fotovoltaica Cercal Power no Cercal do Alentejo é usada como caso de estudo para explorar estratégias de compatibilização agrivoltaicas e ecovoltaicas. As iniciativas agrivoltaicas incluem o cultivo de culturas, atividades pecuárias e apicultura, enquanto as estratégias ecovoltaicas envolvem a requalificação de habitats e aumento da biodiversidade. Foram consideradas duas abordagens para o cultivo agrivoltaico: adaptação da instalação fotovoltaica comercial e um piloto agrivoltaico. Foi também desenvolvida uma ferramenta para avaliar o potencial impacto de várias estratégias agrivoltaicas e ecovoltaicas em diferentes indicadores, simplificando o processo de planeamento para futuras centrais fotovoltaicas.

Palavras-chave: Energia Fotovoltaica; Agricultura; Conservação da Natureza; Agrivoltaico; Energias Renováveis

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Abbreviations

ADEME - Agency for the Ecological Transition
AI - Artificial Intelligence
APA – Agência Portuguesa do Ambiente
CAP – Common Agricultural Policy
CAPEX – CAPital EXpenditure
CF – Capacity Factor
CO_2 – Carbon Dioxide
COP21 - 21st Climate Change Conference
CORINE – COordination of INformation on the Environment
DIN - Deutsches Institut für Normung
DLR – Deutsches Zentrum für Luft- und Raumfahrt
EC – European Commission
EIA – Environmental Impact Assessment
EIC - Electronics-Instrumentation and Control
ENCNB 2030 - Estratégia Nacional de Conservação da Natureza e Biodiversidade 2030
EPC – Engineering, Procurement, and Construction
EU – European Union
GCR – Ground Coverage Ratio
GHG – Greenhouse Gases
ha – Hectare
IEA – International Energy Agency
IRENA – International Renewable Energy Agency
ISE – Institute of Solar Energy Systems
IUCN – International Union for Conservation of Nature
km – Kilometre
KPI – Key Performance Indicators
kV - Kilovolt
kWp – Kilowatt peak
LAI – Leaf Area Index
LAOR – Land Area Occupation Ratio
LER – Land Equivalent Ratio
LCOE – Levelised Cost Of Electricity
m - Metre
MAFF - Ministry of Agriculture, Forestry and Fishery
Marcs - Modular ARC System
METI - Ministry of Economy, Trade and Industry
MWp – Megawatt peak
NEDO - New Energy and Industrial Technology Development Organization
NPK - Nitrogen (N), Phosphorus (P) and Potassium (K)
NVDI - Normalised Difference Vegetation Index
NZE – Net Zero Emissions
O&M – Operation and Maintenance

OET - Organic Electronic Technologies
OPEX - OPerating-EXpenditure
PAR – Photosynthetically Active Radiation
PNEC 2030 – Plano Nacional Energia e Clima 2030
PPA - Power Purchase Agreements
ppr – Price-Performance Ratio
PR – Performance Ratio
PV – Photovoltaic
PVGIS - Photovoltaic Geographical Information System
RAN – Reserva Agrícola Nacional
REN – Reserva Ecológica Nacional
RNC 2050 – Roteiro para a Neutralidade Carbónica 2050
SDG – Sustainable Development Goals
SLA – Specific Leaf Area
SLW – Specific Leaf Weight
SROA - Serviço de Reconhecimento e Ordenamento Agrário
STC – Standard Test Conditions
THEIA - Translucency and High Efficiency In Agrivoltaic
TMY - Typical Meteorological Year
UN – United Nations
USA – United States of America
V -Volt
W - Watt
WUE – Water-Use Efficiency

Nomenclature

A_{ground} – Cultivated ground surface
A_{PV} – Surface area of PV modules
A_t – Annual total cost
E – Electricity generated
E_{AC} – AC energy output
F – Final merit factor
i – Discount interest rate in %
I_i – Impact classification on the key indicator i
I_s – Solar irradiation
I_0 – Initial investment cost
n – Useful economic life in years
p – Annual extra cost of an agrivoltaic system
pb – Performed benefits of the agricultural production
P_p – Peak power
t – Number of years
w_i – Relative weight of the key indicator i
Y_f – Final energy yield

η – Efficiency

Chapter 1
Introduction

1.1 Context

This dissertation is about the dual use of photovoltaic power plants with agricultural activities and nature conservation strategies, following the agrivoltaic and ecovoltaic approaches. The study was elaborated in the scope of the research line of the Renewable Energy Chair of the University of Évora focused on mitigation measures of possible environmental impacts caused by photovoltaic power plants. The motivation for exploring agricultural and nature conservation initiatives to be integrated into photovoltaic power plants emerged from the service provision and collaboration with the investment company Aquila Capital.

The company is planning a new photovoltaic power plant in the parish Cercal do Alentejo, south Portugal, called Cercal Power, and was used as a case study for this dissertation. Considering the inherently impoverished environmental conditions of the site, characterised by poor and drought soils, limited biodiversity, and the dimension of the overall project area of 816 ha, the aim is to identify actions based on farming activities and targeted on biodiversity enhancement to be integrated into the standard commercial photovoltaic system.

The formulation of the agrivoltaic and ecovoltaic strategies began with an analysis of the environmental impact assessment of the project site and the defined layout of the commercial photovoltaic power plant. The agrivoltaic initiatives aim to optimise the land's potential, maximising its utility for both energy production and agricultural activities. On the other hand, the focus of the ecovoltaic strategies is enhancing the environmental conditions and ecosystem services within the project site and close surroundings. The defined strategies were proposed to the project's owner, who will evaluate the proposed actions according to the interests and objectives for the photovoltaic facility and project site.

Throughout this work, it was noted that, due to the wide range of topics and its extensive scope, the study and approach for the photovoltaic plant in Cercal do Alentejo is too ambitious for a master's dissertation. Nevertheless, an effort was made to lay the groundwork for an integrated approach to the concepts of agrivoltaic and ecovoltaic.

1.2 Dissertation Structure

The dissertation is divided into 5 Chapters:

Chapter 1 introduces the basic concepts used throughout this work: photovoltaic energy, agriculture, and nature conservation. It also highlights some strategies and targets from the main European and Portuguese initiatives that address climate change, agriculture, and biodiversity conservation. After, the central concepts of the dissertation are introduced: agrivoltaic and ecovoltaic.

Chapter 2 contains the state-of-the-art of agrivoltaic. This chapter is the result of exhaustive research and includes references to the evolution of the worldwide installed photovoltaic capacity and LCOE; agricultural practices; and lastly agrivoltaic, starting with a brief reference to its history, a new proposed classification, some actual projects, used technologies, scientific research, potential, and associated costs, concluding with national and international legal frameworks and guidelines relevant to agrivoltaic projects.

Chapter 3 focuses on the case study of the PV power plant in Cercal do Alentejo, by describing the technical aspects of the PV facility and the environmental properties including soil, water resources, existing natural areas, habitats, and the floral and faunal diversity of the site and close environment.

Chapter 4 is the core of this dissertation. It starts with exploring agrivoltaic and ecovoltaic compatibility strategies for the new photovoltaic system in Cercal do Alentejo, aiming to mitigate the environmental impact of the power plant. The agrivoltaic strategies rely on crop cultivation and livestock activities and include a conceptual design of a purely agrivoltaic system. The ecovoltaic strategies, in turn, are based on renaturation and habitat requalification efforts, as well as actions to minimise the visual impact. Parallel to these strategies proposed for Cercal Power, a tool based on a matrix database encompassing various agrivoltaic and ecovoltaic strategies and their potential impacts on some relevant agricultural, energy production, environmental, and socioeconomic indicators was developed. This tool aims to select suitable agrivoltaic and ecovoltaic strategies for any future photovoltaic power plant considering a set of relevant key indicators chosen by farmers, investors, and project planners.

Lastly, Chapter 5 is the conclusion of the study and outlines future steps for the photovoltaic power plant at Cercal do Alentejo.

1.3 Research Questions

This dissertation is aimed at answering the following research questions:

1. What is agrivoltaic?
2. How to define agrivoltaic?
3. What is the difference between agrivoltaic and ecovoltaic?
4. Are there international and national legal frameworks for agrivoltaic?
5. What is the current state-of-the-art of agrivoltaic?
6. Is it possible to have a classification system for agrivoltaic applications?
7. What agricultural and nature conservation actions can be integrated into the forthcoming photovoltaic power plant in Cercal do Alentejo? How?
8. How to define and choose the most suitable agrivoltaic and ecovoltaic strategies?

1.4 Publications

Along with the elaboration of this dissertation, the following scientific publications and documents were produced:

- L. Bunge, L. Fialho and P. Horta, "Assessment and Guidelines for an Agrivoltaic Pilot in Alentejo," for the *40th European Photovoltaic Solar Energy Conference and Exhibition*, Lisbon, 2023 [1]: Chapter 4 includes the content of this paper and a poster presented at the 40th European Photovoltaic Solar Energy Conference and Exhibition, held from the 18th to the 22nd of September 2023 in Lisbon;
- Deliverables to Aquila Capital (not published): these documents were delivered within the service provision for the company:
  - Agrivoltaic and ecovoltaic compatibility strategies for Cercal Power;
  - Agrivoltaic conceptual pilot design;
  - Agrivoltaic and Ecovoltaic Compatibility Strategies selection tool.

1.5 General Concepts

1.5.1 Photovoltaic Energy

Photovoltaic (PV) energy is a revolutionary technology that harnesses sunlight to generate electricity through PV or solar cells. Due to the photovoltaic effect, observed for the first time by the French scientist Edmond Becquerel in 1839 [2], certain materials known as semiconductors can convert sunlight directly into an electric current.

PV panels are made of interconnected cells that capture sunlight and convert it into usable electricity, making them suitable for various settings and energy needs. From powering residential homes and commercial buildings to providing energy for remote areas and even supplying electricity to the grid, PV systems offer versatile and scalable solutions. Considered a clean and renewable energy source, PV energy has gained significant attention as a sustainable alternative to traditional fossil fuel-based power generation.

1.5.2 Agriculture

The word agriculture, also known as farming, is derived from the Latin word "*ager*", which means land or field, and "*cultura*", meaning cultivation [3]. It involves the production, improvement, protection, processing, marketing, and extension of crops using natural resources, such as soil and its properties, sunlight, water, air, and temperature. It refers to the activity of cultivating crops for production and economic purposes by exploiting soils. Crops are every organism, plant or animal, with an economic value that are cultivated and harvested for different purposes, e.g. for food, medicine, textiles, industry, and fuels [3].

Agronomy, in turn, derives from the Greek words "*agros*", meaning field, and "*nomos*", meaning manage, and is the science and economics of crop production management [3]. Agronomy involves understanding the relationship between the soil, the plants, and the environment to define the best methods and techniques for crop production.

1.5.3 Nature Conservation

Nature conservation is the care and protection of Earth's natural resources and biodiversity, genes, and ecosystems so that they can persist for future generations [4]. Population growth, accompanied by an increase in human activities and intervention in nature, causes the loss of Earth's biodiversity and species extinction due to habitat destruction, climate change, invasive species, overexploitation, and pollution. The International Union for Conservation of Nature (IUCN) is the global authority for the natural world and its conservation. Its Red List of Threatened Species has listed 142,577 species and more than 210 million ha of area pledged for restoration [5].

The significance of nature conservation cannot be overstated, and it should be considered whenever a decision involves changing or interfering with the natural environment. Every ecosystem plays a crucial role in maintaining the ecological balance of our planet. If we persist in threatening nature and its biodiversity, the loss of numerous species will continue, leading to adverse effects on both the health of nature itself and our own well-being.

1.6 International and National Commitments for Climate Change, Agriculture and Biodiversity

1.6.1 European Commitments

The European Union (EU) has defined a set of action plans to tackle climate change and biodiversity loss, promote the use of renewable energies, enhance sustainable agricultural production, and ensure food suppliance and security. All these commitments are linked together and have the same main objectives, which are predominantly reducing greenhouse gases (GHG) emissions in all sectors; providing clean, safe, and affordable energy through renewable energy sources; protecting and preserving nature and its values; and promoting sustainable agriculture with high quality, safe and affordable food.

1.6.1.1 Birds Directive – 1979, Habitats Directive – 1992 and Natura 2000

The first law adopted by the EU to protect biodiversity was the Birds Directive in 1979, further complemented by the Habitats Directive in 1992 [6]. Both provide a general protection regime for all birds and natural habitats of Europe, and legal mechanisms that cover 1,000 faunal and floral species and 230 habitats.

Later, the European Commission (EC) created a coherent ecological network of protected sites, known as Natura 2000 [6] (see Figure 1.1). This network is the largest of protected areas in the world, stretching across all 27 countries of the EU, with over 18 % land area and more than 8 % of marine territory, and aims to protect threatened species and habitats listed in the Birds and Habitats Directives [7].

1.6.1.2 Paris Agreement - 2015

The Paris Agreement was set at the United Nations' (UN) 21st Climate Change Conference (COP21) in Paris, on the 12th of December 2015, and entered into force on the 4th of November 2016 [8]. Today, the agreement involves 193 Member States and the EU [8] and is the first universal legally binding climate change agreement [9]. The long-term goals defined in the agreement are [8]:

- Substantially reduce global GHG emissions to limit the global temperature increase in this century to 2 °C while pursuing efforts to limit the increase even further to 1.5 °C;
- Review the countries' commitments every five years;
- Provide financing to developing countries to mitigate climate change, strengthen resilience and enhance abilities to adapt to climate impacts.

Within this Agreement, the EU has committed to reduce GHG emissions by at least 40 % by 2030, compared to 1990 [9].

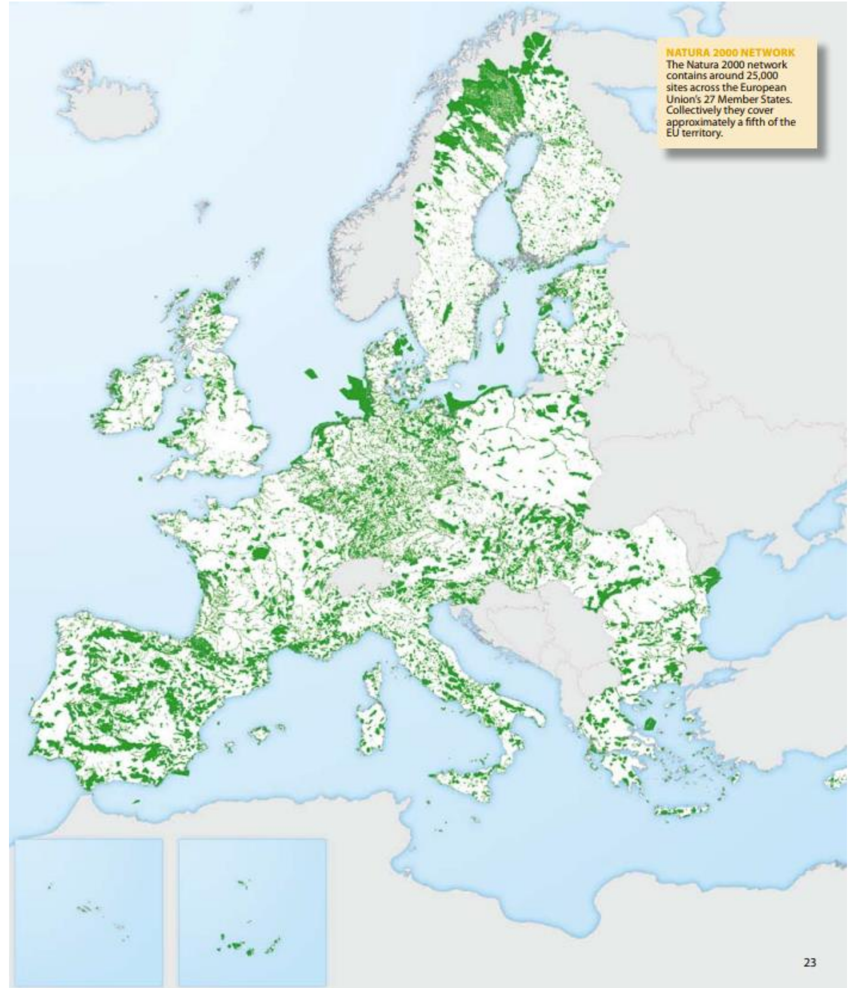

Figure 1.1: Natura 2000 sites [6].

1.6.1.3 2030 Agenda for Sustainable Development – 2015

The 2030 Agenda for Sustainable Development is a plan of action for people, the planet and prosperity, that seeks freedom for all, extinguishing poverty in all forms, and preserving nature [10]. The Agenda is made of 17 Sustainable Development Goals (SDG) and 169 targets that will stimulate action until 2030. These targets include:

- Doubling the agricultural productivity by 2030;
- Ensure sustainable food productions that respect ecosystems and promote climate change adaption;
- Increase water-use efficiency in all sectors;
- Increase the share of renewable energy in the global energy mix by 2030;

- Combat desertification, restore degraded land and soil, and strive to achieve a land degradation-neutral world by 2030;
- Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity, and protect and prevent the extinction of threatened species;
- Integrate ecosystem and biodiversity values into national and local planning, development processes, poverty reduction strategies and accounts by 2020.

1.6.1.4 European Green Deal - 2019

The European Green Deal aims to transform the EU into a climate-neutral, sustainable, and fair society by 2050 and is part of the strategy for the UN's Sustainable Development Goals [11].

The European Green Deal objectives are:

- Increase the EU's climate ambition for 2030 and 2050: the EC has already set a vision to achieve climate neutrality by 2050, through “A Clean Planet for All” and defined the European “Climate Law” which puts the neutrality goal in legislation;
- Supply clean, affordable and secure energy;
- Mobilise industry for a clean and circular economy;
- Build and renovate in an energy and resource-efficient way;
- Accelerate the shift to sustainable and smart mobility;
- From “Farm to Fork” – designing a fair, healthy and environmental-friendly food system;
- Preserve and restore ecosystems and biodiversity;
- A zero-pollution ambition for a toxic-free environment.

1.6.1.5 Farm to Fork – 2020

The Farm to Fork strategy is the heart of the Green Deal and it aims to achieve a sustainable and healthy food system, considering the citizens' and the environment's health [12]. The strategy was designed to reduce the environmental and climate footprint of the EU's food systems, by ensuring a neutral or even positive environmental impact of the food chain and access to sufficient, nutritious, sustainable, and affordable products. The achievement of these goals has a link to the promotion of renewable energy sources in the agricultural systems to decarbonise the sector.

1.6.1.6 EU Biodiversity Strategy for 2030 – 2020

The EU's main initiative to protect biodiversity is the Biodiversity Strategy for 2030 [13]. Following this agenda, at least 30 % of the EU's land and 30 % of the sea should be protected and about 10 % of each should be strictly protected. These include all remaining primary and old-growth forests and areas with high biodiversity value. Also, it states that the preservation of nature is linked to agriculture once farmers play a vital role in preserving biodiversity, as well as biodiversity is important for agricultural activities by providing safe, sustainable, nutritious, and affordable food [13].

1.6.1.7 New Common Agricultural Policy – 2023

The Common Agricultural Policy (CAP) is a partnership between society and agriculture to ensure a stable food supply approaching food, the environment, and the countryside [14]. On the 2nd of December 2021, the EC approved the reform of the CAP and each EU country had to submit its CAP strategic plan for 2023 until 2027 [15]. These new strategies are focused on fairer, greener, and more performance-based policies, and are linked to the targets of the European Green Deal, Farm to Fork and biodiversity strategies.

1.6.2 Portugal's Initiatives

1.6.2.1 Agriculture

To meet the objectives defined by the EU, EC and UN, Portugal has defined its own strategic plans to improve the agricultural sector, such as the Resolution of the Council of Ministers nº 86/2020, of the 13th of October, about the approval of the Innovation Agenda for Agriculture 2020-2030 (*Agenda de Inovação para a Agricultura 2020-2030*) [16]. The agenda is aimed to tackle specific challenges as climate change, natural resource scarcity, demographic growth, and higher consumption. Portugal faces the same global and EU challenges, with some specificities such as the greater impact of climate change, edaphoclimatic constraints, the decrease in arable land and the substantial increase in pastures. The national agricultural practice faces increasing risks of desertification, the low concentration of organic matter in soils and higher water scarcity levels in certain regions of the country.

Additionally, agriculture is responsible for about 10 % of the national GHG emissions, which have stabilised without any decrease [16]. To tackle this, Portugal has defined 12 initiatives, including the reduction of GHG emissions in the agricultural sector through the integration of renewable energy facilities on a decentralised basis and self-consumption, increase in carbon sequestration in the soil, and the promotion of practices with greater climate resilience.

Moreover, the Portuguese Government defined a National Strategy for Biological Agriculture (*Estratégia Nacional para a Agricultura Biológica*) [17] to promote the production of biological crops and biological food kinds.

1.6.2.2 Climate Change and Renewable Energies

The Portuguese government committed itself in 2016 to ensure the neutrality of its emissions by the end of 2050 through the deep decarbonisation of the national economy, as a contribution to the Paris Agreement and in line with the most ambitious efforts underway at the international level [18]. Carbon neutrality by 2050 means achieving a neutral balance between GHG emissions and carbon sequestration, so substantial reductions in emissions and/or substantial increases in national sinks are necessary, highlighting that the national commitment does not use international carbon credits.

To achieve this, the Roadmap for Carbon Neutrality 2050 (*Roteiro para a Neutralidade Carbónica* (RNC 2050)) [18] was developed in 2019, which identifies the main vectors of decarbonisation in all sectors of the economy, policy options and measures, and the path of emission reduction in different socio-economic development scenarios. To achieve carbon neutrality by 2050, GHG emissions must be reduced between 85 % and 90 % compared to 2005.

The electricity production sector is currently one of the main national emitters of GHG emissions (about 29 %) and, as such, should be one of the main contributors to decarbonisation, achieving a share of 100 % by renewable energies in 2050 [18]. PV technology shall assert itself with greater evidence by increasing its expression and reaching 13 GW centralised and 13 GW decentralised by 2050.

The development of the RNC 2050 was carried out in conjunction with the preparatory work of the National Energy and Climate Plan 2030 [19] (*Plano Nacional Energia e Clima 2030* (PNEC 2030)), which is the main instrument of energy and climate policy for the decade 2021-2030, establishing the new national targets for reducing GHG emissions, renewable energy, and energy efficiency in line with the carbon neutrality goals [18]. Its goals include promoting decarbonisation of the economy, energy efficiency, renewable energies and energy independence, sustainable mobility, agriculture, and carbon sequestration. In numeric values, the ambitious targets for the 2030 horizon are [19]:

- National GHG emissions reduction of 45 % to 55 % compared to 2005;
- Incorporate 47 % of energy from renewable sources into the gross final energy consumption;
- Reduce primary energy consumption by 35 % with a view to better energy efficiency;
- Achieve 15 % electricity interconnections.

1.6.2.3 Nature and Biodiversity

In 2018, Portugal approved the Natural Strategy for Nature and Biodiversity Conservation 2030 (*Estratégia Nacional de Conservação da Natureza e Biodiversidade* 2030 (ENCNB 2030)) [20], aiming to:

1. Enhance the conservation grade of the natural heritage;
2. Promote the recognition of the natural heritage value;
3. Foment the appropriation of natural values and biodiversity.

These strategies are supported by action plans, programs, and investments, and foster agricultural systems and policies that respect nature and biodiversity conservation, protection and recovery of species, and the transition to a low-carbon and sustainable economy.

1.7 Agrivoltaic Approach

With the fast world population growth, energy and food demand are increasing, leading to a higher need for available areas for energy and food production. Yet, transforming wild natural areas for new crops and power systems can present challenges, threatening natural ecosystems and their biodiversity. Agrivoltaic systems present a potential solution, making use of the same land unit for both applications, food and power production.

Agrivoltaic is a relatively recent concept of the coexistence of PV systems, to generate electricity, and agricultural activities on the same land unit. It is also known as “Dual Use” and “Agri-Photovoltaik” in the German research context, “Agrovoltaic” in the French and US, “Photovoltaic Agriculture” in the Chinese, and “Solar Sharing” in the Japanese context [21].

Agrivoltaic can be defined as the dual land use for agricultural production and energy generation through PV systems promoting a synergistic relationship between both. Agricultural activities can include the cultivation of crops underneath or between module rows, as well as livestock grazing. In this manner, the same site yields two outcomes: energy and agricultural products. Important is, that the combination provides advantages for both activities compared to the isolated productions on separate land units. Crops that are sensitive to intense solar radiation can benefit from the added shading provided by the PV panels, which also allows the retention of higher moisture levels in the soil [22, 23, 24], decreasing evaporation and thus irrigation needs [22, 23, 24, 25]. Knowing that the efficiency of PV panels is inversely proportional to temperature, PV systems can benefit from the cooler microclimate created by the presence of plants underneath the panels. Furthermore, agrivoltaic can diminish land-use conflicts between agriculture and energy production, allowing both PV systems to occupy agricultural lands and farmers to increase their crop yield and benefit from the decentralised renewable energy self-consumption. In some cases, agrivoltaic can support rural areas by minimising environmental pressure and offering solutions against severe weather conditions such as droughts [26].

1.8 Ecovoltaic Approach

Following the EU Biodiversity Strategy 2030 [13], the use of renewable energy will be crucial in tackling climate change and addressing biodiversity loss. Thus, the EU prioritises, among others, PV parks that provide biodiversity-friendly measures and soil cover. Also, the SDG foresee the integration of ecosystem and biodiversity values into national and local planning [10]. Here is where a novel concept is emerging: ecovoltaic, the integration and co-prioritisation of PV energy production and ecosystem services [27]. Every energy system, renewable or not, exists within the land-energy-ecology nexus, which represents the interactions among energy production and its facilities or activities, the physical landscape where the energy facility is sited, and the organisms and habitats within the energy system and surrounding environment [28]. Focusing on this nexus, ecovoltaic designs are based on ecological principles to target habitat modifications, environmental heterogeneity, and maintain and enhance the ecosystem services within the land occupied by PV power plants [27].

Chapter 2
Agrivoltaic - State-of-the-Art

2.1 Installed Photovoltaic Capacity

To achieve decarbonisation in the energy sector, a shift towards increased utilisation of renewable energy sources is essential. PV energy has gained worldwide expression through the installation of centralised large-scale power plants and small-scale systems for individual buildings. This increase is mainly a result of the decrease in its associated costs, turning this energy source affordable and attractive for most applications.

According to the data published by the International Energy Agency (IEA) (see Figure 2.1), the worldwide PV power capacity has increased significantly over the past 10 years [29]. On the left chart of Figure 2.1, the yellow column for 2030 represents the PV capacity that must be achieved by 2030 to meet the goal of the Net Zero Emissions (NZE) scenario by 2050. This scenario outlines the pathway for the global energy sector to achieve net-zero carbon dioxide (CO_2) emissions by 2050 [30].

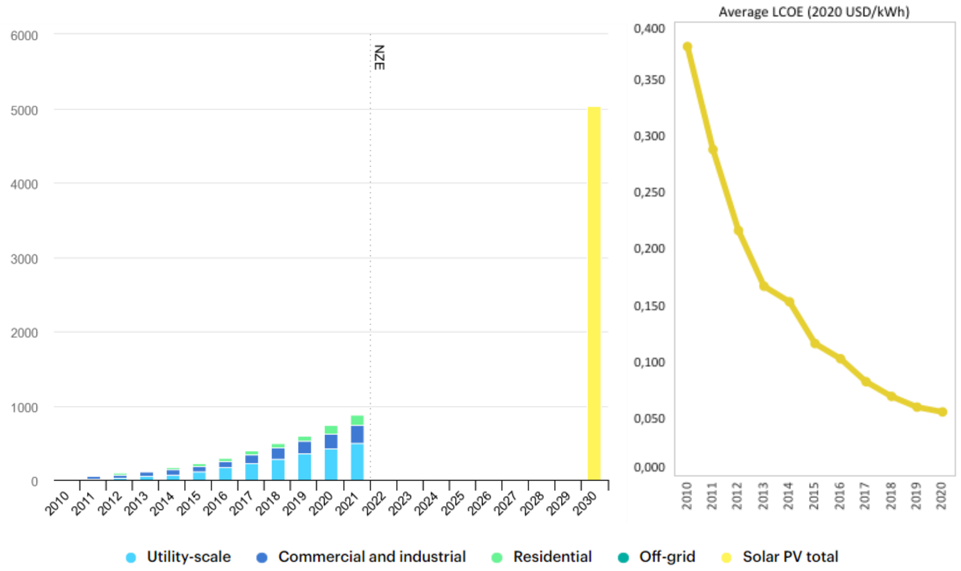

Figure 2.1: PV power capacity in the Net Zero Emissions scenario, 2010-2030, by IEA [29] (left) and average LCOE (2020 USD/kWh) of PV energy, 2010-2020, by IRENA [31] (right).

In 2021, the capacity for commercial and industrial facilities reached 238 GW, representing an increase of approximately 1,044 % since 2010. Residential PV systems surged to 145.4 GW, a growth of around 1,447 % in the same period. The most impressive increase was seen in utility-scale installations, which reached 501.1 GW, equivalent to an increment of 6,324%. Off-grid PV systems had an overall capacity of 7.4 GW, an increase of approximately 517 % in 11 years.

Nevertheless, to achieve the ambitious goal of the NZE scenario by 2030, the total PV capacity needs to experience a substantial growth from 891.9 GW installed in 2021 to nearly 5,050 GW, which translates to an increase of 465.30 %. In terms of overall power generation PV energy must contribute 7,413.9 TWh, which requires an annual growth rate of approximately 25 % from 2022 until 2030 [29]. This rapid expansion is crucial to fulfil the energy demands of a sustainable and emissions-free future.

The increase in PV power capacity is linked, among other, to the decreasing production and installation costs and so its Levelised Cost of Electricity (LCOE) (see section 2.5.1). According to the International Renewable Energy Agency (IRENA), PV had an LCOE of 0.381 $_{2020}$USD/kWh (0.334 2020 €/kWh [32]) by 2010 which decreased significantly to 0.057 $_{2020}$USD/kWh (0.050 2020 €/kWh [32]) in 2020, a decrease of almost 85 % in 10 years. The low LCOE of PV, expected to continue declining, makes it an attractive energy source.

2.2 Agricultural Practices

Agriculture can be practised in different ways and its classification has been a result of the natural resources available, farm activities and household livelihoods, kind of soil management, land use, and the main technologies used [33]. However, there is no general classification system for agricultural activities and farming systems.

According to Dastrup et al. [34] agriculture can be divided into:

- Subsistence agriculture: small-scale crop cultivation primarily for food consumption by the farmer. In case of a surplus of produced food it may be sold, although this is very uncommon. The most practised agriculture is intensive subsistence agriculture which depends on animal power and is often practised in tropical and humid regions;
- Commercial agriculture: large-scale crop cultivation for commercialisation to make profit, being more common in more developed countries that enter the global marketplace. The produced crops are generally sent to processing industries before they are sold to the consumer.

Besides these two main classifications, some agriculture subtypes were found, which can be subsistence or commercial depending on the production and land usage scale:

- Shifting cultivation: in this practice, farmers switch land every few years due to nutrient and mineral losses. It is a sub-type of subsistence agriculture [34];

- Sustainable agriculture: farming that produces food or other products without compromising the ecosystem [35];
- Urban/peri-urban agriculture: practised in (urban) or around (peri-urban) a village, town, or city, involving the cultivation, processing, and distribution of the products for the local community [35];
- Organic agriculture: cultivation that sustains the soils, ecosystems, and people's health, relying on ecological processes, biodiversity, and cycles that are adapted to the local conditions [35];
- Conservation agriculture: conserves the local environment by using the minimum of mechanical processes, minimising soil erosion, preventing water loss, maintaining organic matter levels as fertilisers, and ensuring crop rotation for insecticide and herbicide effects [35];
- Permaculture: an agricultural practice which has the diversity, stability, and resilience of natural ecosystems, integrating land, resources, people, and the environment through mutually beneficial synergies [36];
- Precision agriculture: a modern way of farming where farmers can manage specific inputs to increase the economic feasibility while enhancing the crop yield and reducing environmental impacts, using data collection through GPS, soil samplings, yield monitoring, and remote sensing [35];
- Industrial agriculture: modern farming characterised by industrialised production of livestock, poultry, fish, and crops, with technoscientific, economic, and political methods such as machinery, genetic technologies, scale production, and creation of new markets [35];
- Horticulture: practice of agriculture on the land of the cultivators, using mainly gardens smaller than fields with one or only a few different crops of perennial shrubs, herbaceous plants, and trees. Also known as house gardening [37];
- Arboriculture: growth of trees and shrubs for food, seeds, wood, and other products [37];
- Vegeculture: production of root and tuber crops through asexual reproduction by using parts of a parent plant instead of seeding [37];
- Mixed crop-livestock farming: farming of crops and livestock is done at the same place. Also known as agropastoralism [37];
- Pastoralism: a type of self-consumption farming [34] where livestock, such as cows, sheep, and goats do move temporally and spatially with their owners [37].

Regarding farmland classification, the EU's COoRdination of INformation on the Environment (CORINE) land cover program divides Europe's agricultural areas into [38]:

- Arable land: lands under a rotation system used for annually harvested plants and fallow lands, which are rain-fed or irrigated. Includes rice fields as well;

- Permanent crops: surfaces occupied by permanent crops, not under a rotation system. Includes vineyards and ligneous crops of standard cultures for fruit and nut production such as extensive orchards and groves;
- Pastures: lands that are permanently used (at least 5 years) for fodder production. Includes natural or sown herbaceous species, unimproved or lightly improved meadows and grazed or mechanically harvested meadows;
- Heterogeneous agricultural areas: includes areas of annual crops associated with permanent crops on the same parcel, annual crops cultivated under forest trees, and landscapes in which crops and pastures are intimately mixed with natural vegetation or natural areas [38].

2.3 History of Agrivoltaic

The idea of integrating PV energy with agriculture was first suggested by Prof. Adolf Goetzberger (founder of the Fraunhofer Institute for Solar Energy Systems (ISE)) and Dr. Armin Zastrow in 1981, with their article "*Kartoffeln unter dem Kollektor*" (potatoes under the collector) [39].

In the last decade, agrivoltaic technology and projects have been developed significantly. The installed capacity has increased from around 5 MWp in 2012 to around 2.8 GWp in 2020 [40] and to over 14 GWp in 2021 [39]. This advance is mainly due to government funding programs, as in Japan (2013), China (2014), France (2017), the USA (2018) and South Korea [39].

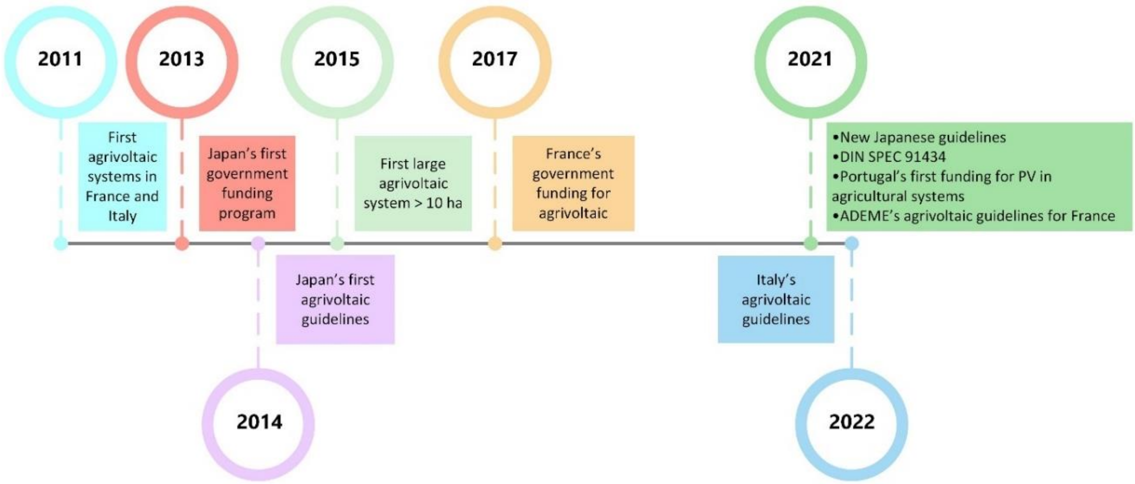

Figure 2.2: Agrivoltaic history since 2010 (adapted from [39]).

In 2004, the Italian company REM Tec [41] developed and patented the concept of an agrivoltaic system named Agrovoltaico®, a commercial large-scale system that combines sun-tracking PV modules for electricity generation and the cultivation of crops on the same land unit [42]. The first three Agrivoltaico® plants were installed between 2011 and 2012, for a total of 6.7 MW on

35 hm^2, in northern Italy [42]. The first large agrivoltaic system with an area of over 10 ha was implemented in China around 2015 [40].

In Japan, in 2013 and 2014, the Japanese Ministry of Agriculture, Forestry and Fishery (MAFF), introduced its first guidelines for agrivoltaic [21] (see section 2.11.3). Later in 2021, the New Energy and Industrial Technology Development Organization (NEDO), released new guidelines for ground-mounted agrivoltaic projects [43, 44].

Since 2021 the interest in agrivoltaic gained expression in Europe. In Germany, the *Deutsches Institut für Normung* (DIN) published in May 2021 the technical specifications for agrivoltaic systems under the DIN SPEC 91434: Agri-photovoltaic systems – Requirements for Primary Agricultural Use [45] (see section 2.11.3). From May until July of the same year, Portugal launched a €10 million call for PV systems built in combination with agricultural activities [46]. However, according to the call, the PV systems should be installed over buildings, ponds, tanks, or other water reservoirs, having not specified the possibility of building over crops. In France, the Agency for the Ecological Transition (ADEME) published a guideline document entitled "Characterising Solar PV Projects on Agricultural Land and Agrivoltaism" in July 2021 [47] (see section 2.11.3).

In June 2022, the Italian Ministry of Ecological Transition released the "Guidelines for Agrivoltaic Plants" about the design, construction and operation of agrivoltaic systems [48] (see section 2.11.3).

2.4 Proposed Classification of Agrivoltaic Systems

Agrivoltaic systems have gained a worldwide presence and are found with various configurations to suit different applications. There are different options for agrivoltaic designs, offering sometimes more than one option for the same application. The planning and design of the best agrivoltaic system for a certain application while considering the site's conditions can be one of the main challenges, as there is no general solution for every farming activity. Some of the guidelines mentioned in section 2.11.3, and some institutes doing research in agrivoltaic such as Fraunhofer ISE [39], have proposed a classification scheme for agrivoltaic designs. These are mainly based on the structure height, orientation, and farming activity.

However, based on the findings gathered during the state-of-the-art research and the agrivoltaic pilots found (see section 2.6), a new classification system for agrivoltaic designs is proposed, presented in Figure 2.3. This system, besides having the farming activity and the PV system's structure properties as categories, includes the PV module technology and density.

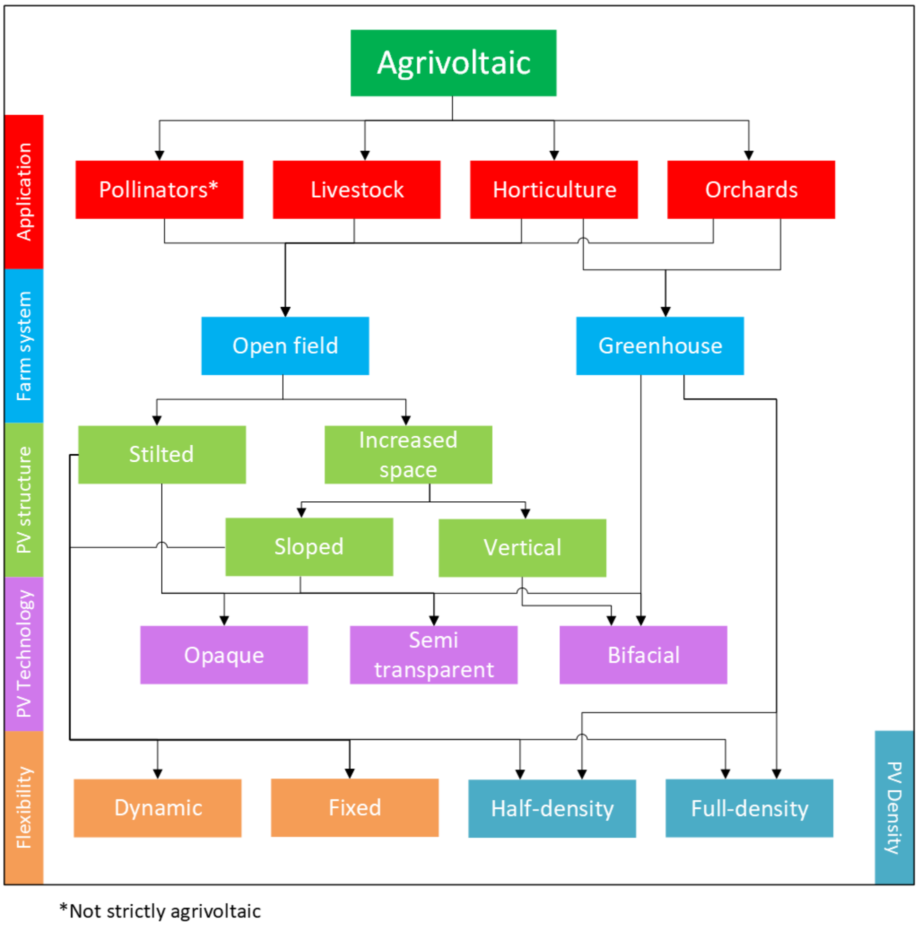

Figure 2.3: Proposed agrivoltaic system classification.

The six proposed categories are:

1. Agricultural application: the main activities used in the agrivoltaic projects found are cultivation of horticultural crops, orchards, livestock grazing and pollinator keeping (mainly bees, although it is not strictly agrivoltaic);
2. Type of farming system: agricultural activities can be practised either on open-field or in greenhouses. All agricultural activities mentioned above can take place in open-field, whereas horticulture and orchards also appear in greenhouses;
3. PV system structure: depending on the agricultural activity in an open field, the PV system's structure can be stilted (i.e., the modules are on elevated structures) or have increased interrow spacing when compared to standard PV systems. In case of the latter, the structure can be a commercial sloped system or a vertical configuration;
4. PV module technology: PV panels in agrivoltaic designs can be opaque, semi-transparent, or bifacial. Greenhouses, stilted and sloped configurations can be found with the three technologies, while vertical systems typically use bifacial modules;

5. PV system flexibility: flexibility of stilted or increased space PV systems is related to the ability (dynamic) or not (fixed) of sun tracking. It is assumed that vertical configurations and greenhouses (since they are closed and fixed environments) are always fixed;
6. PV modules density: PV modules can be arranged with full or half density. Full density is the placement of panels in a configuration that covers a large portion of available space, with little or no gaps between the modules, maximising the shaded area and the electricity generation. Half density, in turn, is when the panels have a greater spacing between them allowing more sunlight to reach the ground beneath, such as a checkered pattern, while the energy generation is lower compared to the full density arrangement.

The design of an agrivoltaic system is tailored to suit its intended application. However, it is crucial to assess which applications are feasible, as not every farming practice can be seamlessly integrated with PV systems. Regarding agricultural crops, recent research indicates that agrivoltaic projects have high potential when using aloe vera [49]; leafy greens, like lettuce [50] and spinach; and berries, fruits and fruity vegetables, like tomatoes [51, 52] which can benefit from up to 40 % of shading [53]. According to [40], all types of crops are generally suited for agrivoltaic, but different effects on the yield are to be expected due to shading. Highly shade-tolerant crops, such as leafy greens, stone fruits, berries, and soft fruits, and special crops, such as wild garlic, asparagus, and hops, show good potential. Even biomass-based energy crops or fibre production can be appropriated [54]. Higher crops, like corn and orchards, could interfere more with the panels while requiring higher structures that lead to higher costs [40]. In case of livestock, the animals can benefit from the shading provided by the PV modules, such as under a canopy. Pollinator keeping, in turn, is not strictly an agrivoltaic approach, as there is no direct benefit from the PV system for the pollinators, although it has gained popularity in some countries to be practiced on PV sites.

The optimal PV system configuration for an agrivoltaic also depends on the prevailing climate conditions. For instance, a shade-tolerant crop planted during summer in a region with intense radiation may benefit more from the shade provided by opaque PV modules with half-density than from semi-transparent modules. In coastal areas, a vertical assembly might be more advantageous in safeguarding crops from strong, salty, and moist winds.

High crops, such as orchards, will require higher stilted structures as tomatoes, or can instead be planted between vertical arrays. Higher structures are also required if agricultural machinery is intended to be used.

The best module technology, besides being dependent on the shade tolerance of the crop, is related to the structure assembly. In the case of a vertical configuration, bifacial modules are preferred for their ability to capture solar radiation on both the front and back sides, thereby maximising electricity generation compared to opaque and semi-transparent modules that only capture radiation on their front side.

Vertical modules between crop rows that are typically aligned north-south can take advantage of the apparent east-west movement of the sun. The vertical assembly of bifacial modules can be an interesting option for farmers, with much lower costs as it eliminates the need for high metallic structures. Younasa et al. [55] assessed the performance of agrivoltaic systems with north-south faced fixed tilted monofacial panels and east-west faced vertical bifacial panels. The study revealed that with a slightly lower panel density than in conventional PV power plants, the east-west vertical bifacial panels can increase land productivity by 5 %. And, for low and standard PV panel density, the vertical bifacial panels were able to distribute sunlight more evenly over the crops. However, for high densities, the fixed PV provided about 8 % higher land productivity than the vertical. Despite this, the vertical PV allowed a better crop yield. According to Khele et al. [56], vertical bifacial PV modules could be an attractive choice for agrivoltaic with lower land coverage, providing more flexibility to the farm machinery, and the ability to mitigate soiling losses.

The choice between a fixed or dynamic (sun-tracking) PV structure is not necessarily tied to the type of crop used, but rather to the desired output and available investment. A dynamic structure is beneficial for farmers with high energy consumption, as it offers a higher energy yield. The tracking algorithm may also be programmed to adjust the amount of sunlight under the panels according to the crop cycle or even protect them from harsh weather, thereby enhancing the agricultural yield and preventing yield loss. However, tracking structures come with higher CAPital EXpenditure (CAPEX) costs compared to fixed structures.

2.5 Key Performance Indicators

Every system needs to be assessed in terms of its performance through Key Performance Indicators (KPI). These metrics are crucial for measuring and quantifying performance, assessing production quality, and facilitating comparisons between two or more systems of the same type. While PV facilities and agricultural systems already have defined specific KPIs, new ones have emerged for agrivoltaic.

2.5.1 Photovoltaic Performance

The performance of a PV power plant can be assessed through the following KPI:

- System efficiency (η): ratio between the net energy output E_{AC} and the incoming solar irradiation I [57]:

$$\eta = \frac{E_{AC}}{I} \qquad \text{Eq 2.1}$$

- Final energy yield (Y_f): ratio between the net energy output during a certain time period and the maximum installed power capacity P_p of the power plant [57]:

$$Y_f = \frac{E_{AC}}{P_p} \qquad \textit{Eq 2.2}$$

- Performance Ratio (PR): ratio between the final energy yield of the system and the reference yield [58]:

$$PR = \frac{Y_f}{Y_R} \quad \text{Eq 2.3} \qquad Y_R = \frac{H_t}{1\,[kW/m^2]} \quad \textit{Eq 2.4}$$

  Where Y_R is the reference yield calculated by the ratio of the total solar radiation arriving at PV panels' surface and the reference irradiance at Standard Test Conditions (STC) (total irradiance of 1000 W/m^2, device temperature of 25 °C, and reference spectral irradiance for air mass of 1.5, as defined by IEC 60904-3 [59]).
- Capacity Factor (CF): measurement of how much energy is produced compared to the peak capacity [57]:

$$CF = \frac{E_{AC}}{8760 P_p} \qquad \textit{Eq 2.5}$$

Regarding the economic assessment, the most used indicator is the LCOE, which quantifies the average net present cost of the electricity production of an electricity production facility over its lifetime [60], considering the initial investment, the operation and maintenance costs and the costs of external electricity sources if needed.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E}{(1+i)^t}} \qquad \textit{Eq 2.6}$$

I_0 is the investment cost; A_t the annual total cost in each year t; E the amount of electricity generated; i the discount interest rate in %; and n the useful economic life in years.

2.5.2 Agricultural Performance

The most relevant KPI for farming systems in the scope of this work are:

- Agricultural yield: annual production of agricultural products measured in weight or volume per unit of land [61];
- Agricultural product quality: includes aromatic profile, colour, size, nutritional value [61];
- Water-Use Efficiency (WUE): measure of the amount of biomass produced per unit of water used by a plant [62].

In addition to these KPIs, the following indicators can be important:

- Harvesting costs;
- Livestock feed consumption;
- Energy consumption;

- Agronomic parameters: these parameters are related to the conditions and properties of the agricultural production systems related to the soil, radiation, plants and photosynthesis:
  - CO_2 concentration;
  - Leaf area index (LAI): quantifies the leaf area per unit of ground surface area, typically measured on one side, determining how effectively plants can capture light for optimal growth [63]. When below 1, some light reaches the soil. Because of the natural arrangement of leaves, LAI must be significantly higher than 1 for most of the light to be captured;
  - Leaf temperature;
  - Leaf wetness;
  - Photosynthesis;
  - Photosynthetically Active Radiation (PAR): light of wavelengths 400-700 nm which is the portion of the light spectrum utilised by plants for photosynthesis [64];
  - Soil moisture;
  - Soil nutrients;
  - Soil salinity;
  - Soil temperature;
  - Specific leaf area (SLA): represents the ratio of leaf area to leaf weight [63];
  - Specific leaf weight (SLW): is the reciprocal of SLA. Some researchers employ SLW to correlate factors like shade, age, and leaf position within the canopy [63].

2.5.3 Agrivoltaic Performance

It is important to evaluate or assess the performance and impacts of an agrivoltaic system in order to compare it with the reference situations of agriculture and PV generation separately. Besides the KPIs of each individual activity, indicators for agrivoltaic were defined to measure the impact of the integration on the agricultural and energy sides. The following KPI are commonly used in agrivoltaic:

- Energy yield: annual produced electrical energy per unit of land. It is generally lower compared to standard PV systems which are designed only for the purpose of producing electrical energy [61]. According to the Italian Guidelines [48], the agrivoltaic energy yield should not be less than 60 % of a standard PV system;

- Land Equivalent Ratio (LER): can be understood as the spatial efficiency of an agrivoltaic system by comparing the agrivoltaic PV and agricultural yields with those of separated systems [61]:

$$LER = \frac{Crop\ yield\ in\ agrivoltaic}{Crop\ yield} + \frac{PV\ yield\ in\ agrivoltaic}{PV\ yield} \qquad Eq\ 2.7$$

An LER higher than 1 indicates that the combination has a greater production than both activities on separated land units [21]. For example, an LER of 1.4 means that the same production in two separate areas would need more 40 % of area, this is, a 100 ha land of agrivoltaic produces as much as 140 ha of land with separated production. Advanced simulations of agrivoltaic projects predict LERs of up to 1.7, suggesting a high potential for the agrivoltaic concept.

- Ground Coverage Ratio - GCR: ratio between the surface area of the PV modules, A_{PV}, and the cultivated ground surface, A_{ground}. High values can provide a high energy yield whereas the crop yield can be low due to the reduced amount of light that reaches the crops [61]. In the Italian Guideline [48] (see Section 2.11.3) GCR is equivalent to Land Area Occupation Ratio (LAOR), and should have a maximum of 40 %;

$$GCR = \frac{A_{PV}}{A_{ground}} \qquad \textit{Eq 2.8}$$

- Water-Use Efficiency (WUE): influence of the PV system of the agrivoltaic system on the water balance [61];
- Economic indicators: can be measured through the price-performance ratio (ppr) [61]:

$$ppr = \frac{p}{pb} \qquad \textit{Eq 2.9}$$

Where p is the annual extra cost of an agrivoltaic system compared to the cost of a ground-mounted PV system. This extra cost is mainly dependent on the LCOE of both system types. pb are the performed benefits which are created by the annual revenues of the preservation of the agricultural land and the revenues of its products. An agrivoltaic system is economically attractive if ppr is lower than 1, indicating that the agrivoltaic performance benefits are greater than the normal revenues.

2.6 Agrivoltaic Projects

Interest in the development and research in agrivoltaic is expanding globally. France, Italy, and Germany are leading the agrivoltaic implementation and research in Europe. Agrivoltaic is currently undergoing pilot testing in numerous countries, with variations in application and design. In Europe, most pilots found are located in Belgium, France, Italy, Germany, the Netherlands, and Spain. Some of them feature entirely new designs, while others are adapted agricultural structures, such as greenhouses.

In the Netherlands, five pilot agrivoltaic projects use five different berry crops: blueberries, red currants, raspberries, strawberries, and blackberries [65]. The largest project, in Babberich, is a 2.67 MWp PV plant on a 3.3 ha raspberry farmland [66]. It uses special monocrystalline glass-glass modules supported by a structure made of wood, metal, and concrete, promoting a rapid passive heat transfer and protection from direct sunlight, rain, hail, and frost. Two pilots use PV panels with different levels of transparency, demonstrating that higher transparencies allow higher yields. Furthermore, on hot days, the temperature under the modules was about 5 ° lower than under the plastic foils, and 2 ° lower than ambient temperature. At night, the temperature under the panels was higher and humidity was more stable.

Strawberries in turn, grown in PV greenhouses since 2018 in France, had an earlier and longer harvest period than usual, accompanied by a reduction of 20-30 % in the water requirement due to the lower evapotranspiration and Mistral wind [26].

Figure 2.4: Agrivoltaic with raspberries in the Netherlands [65].

In Belgium, an agrivoltaic project initiated in 2021 combines pear orchards with 40 % transparency bifacial PV modules on fixed and dynamic stilted structures [67]. Before the agrivoltaic approach, the pear trees were protected by plastic hail nets, whose 4.6 m high structure was adapted to the PV modules allowing the use of harvesting machines. A preliminary shading simulation was conducted for the design, determining a coverage ratio of 36 % resulting in a light reduction of approximately 29 % [68]. After the implementation and monitoring, the agrivoltaic pears were identical in terms of quality and storability to the reference pears, but a decrease of 16.4 % in the total pear yield was measured linked to the individual size and numbers, and the fruits were sorted into a smaller category than those from conventional orchards [68]. In contrast, in France, an agrivoltaic project with apricots and beekeeping allowed a higher agricultural yield and 70 % water saving compared to the classic apricot farm [69, 26].

Figure 2.5: Agrivoltaic with pears orchard in Belgium [70].

In France, agrivoltaic with vineyards increased the crop resistance to heat waves and growth, reduced water demand by 12-34 %, and improved the aromatic profile of the grapes, with 13 % more anthocyanins (red pigments) and 9-14 % more acidity [71]. In this project, the PV panels were installed at a height of 4.2 m and were moved in real-time by an artificial intelligence algorithm which determined the ideal tilt based on water requirements, growth cycle, soil quality, and the weather [72].

In Heggelbach, Germany, the research project APV-RESOLA comprises an agrivoltaic system with winter wheat, potatoes, celery, and a simple grass/clover mixture using bifacial glass-glass PV modules [40]. The modules are installed on a 5 m high structure, allowing the use of standard cultivation machinery. The most highlighted result was the increased land usage rate of 160 % in 2017, after the first year. Also, potato crop yield increased from -20 % in 2017 to +11 % in 2018 compared to the reference system, noting that the summer of 2018 was hot and dry. In that year, the modules' shade improved considerably the crop yield by increasing the land use by 86 % and keeping the soil moisture levels higher than normal.

Experiments in France and Italy have shown that soybeans can be appropriated for agrivoltaic. In 2022, the French developer TSE inaugurated its first agrivoltaic demonstrator with soya, wheat, fodder rye, winter barley, and rapeseed crops, including 150 cows [73]. The project demonstrated a solid vegetative growth of the beans, with normal flowering, fertilisation, and physiological maturation. From June to mid-August, the maximum temperature under the canopy was 1.2 °C lower than in the control area, while soil temperature at a depth of 30 cm decreased by 3.5 °C. In Italy, in turn, scientists from the Università Cattolica del Sacro Cuore investigated different shade treatments (9, 16, 18 and 27 %) on soybean crops on a large agrivoltaic system of 3.2 MWp, with 11,535 polycrystalline panels placed on a 4.5 m high structure with biaxial full-sun tracking [74, 75]. Results showed an increase in the LAI and SLA with increased shading, while the chlorophyll content did not vary significantly. Average grain yield, in turn, was 8 % lower when compared to standard soybean cultivation.

Not only crop farming can be practised under PV panels. In Austria, an 11.5 MWp PV park of 12.5 ha is planned where 150 sheep will graze under the PV panels [76]. In this project, bifacial panels will be installed at a considerable height and all electrical components must be well protected to ensure the sheep and system's safety. The benefits of this approach were demonstrated by Andrew et al. [77]. According to their study, LER can increase to 1.81 for pasture production and to 2.04 for spring lamb production. The PV modules' shade increased the pasture's quality, despite lowering the yield when compared to full-sun areas. Moreover, they noted that sheep in the agrivoltaic facility tended to graze more at noon and less in the afternoon and that they had lower water intake.

Figure 2.6: Sheep under the PV modules in Austria [76].

In Spain, in Carmona, a beekeeping project is being developed at two PV power plants [78]. On the site, 250,000 PV panels are on the same land as 50 to 60 beehives [79]. The bee farm features innovative technologies and intelligent beehives to ensure the best well-being of the bees, monitor honey production and prevent theft [80]. This project aims to improve the land's potential and to protect biodiversity on the site. With the same approach in Castellet, France, a power plant of 3.8 MWp was joined with 20 beehives to prevent the collapse of the bee population [81]. The beekeepers, besides profiting from the clean energy produced by the PV facility, can protect the hives from damage and vandalism due to the power plant's fences. Beekeeping in PV facilities has also become very popular in the USA [79]. However, in this approach, it is unclear how PV panels and bees interact with each other, and whether this interaction is mutually beneficial, as in the case of crops. For this reason, beekeeping in PV parks is not strictly an agrivoltaic approach.

An interesting design is the PV park Klein Rheide, in Germany, which combines clean energy production, biodiversity protection, and extensive agriculture [69]. The project is implemented on a previous gravel extraction land which is now a fallow land, where habitats for 450 plants were created, including 17 on the Red List, as well as for native wild animals, insects, and amphibians. The land includes ponds, sandpits, stone piles, over 1,000 m² of wetland, secure corridors, 5 wild beehives, 5 bat nests, 15 birdhouses, and grazing areas for local shepherds. Indeed, PV power plants are usually devoid of people, machinery, or other kinds of human activities, being a calm and quiet place, which turns them into potential wildlife and plant sanctuaries.

To go even further regarding the application of agrivoltaic systems, China has already developed large-scale fisheries for shrimp and fish farming and PV arrays [21], while Japan is testing agrivoltaic projects with rice paddy farming [82]. According to Pringle et al. [83], combining floating PV systems with aquaculture, generating the concept of “aquavoltaics”, has advantages for both, such as the increase in water conservation by reducing water loss by 70-85 %, control of water quality by solar-powered water pumping systems, and ecosystem restoration.

Figure 2.7: Agrivoltaic fishery in China [21].

2.7 Technologies

The main difference between agrivoltaic and standard PV systems is the type and height of the structures due to the different agricultural practices. In agrivoltaic systems, higher structures tend to be used to allow the use of agricultural machinery or due to the natural plant height, as in the case of orchards. Besides the increased height, agrivoltaic designs can use wider interrow spacings. After the structure, the main difference relies on the PV module technology and density.

2.7.1 Structures

The type of support structures must be chosen considering the agricultural application and its needs, planning the adequate high and row spacing. According to [40], higher clearance heights provide easier vehicle access and better light distribution but are more expensive, whereas larger row spacings increase the land requirement and the system's cost. Clearance height is the clear vertical area between the base of the agricultural land and the lower edge of the lowest structural element under self-weight deformation [45].

Figure 2.8: Illustration of stilted agrivoltaic structures [40].

Examples of developed structures only or agrivoltaic applications are the French agrivoltaic system for hop growth which can grow up to 8 m high [84]; the German arc-shaped PV module structure Modular ARC System (Marcs), which, according to the developer Goldbeck Solar [85], could increase the yield by up to 30 % compared to standard ground-mounted structures, and up to 60 % compared to other agrivoltaic systems [86]; and the Dutch mobile array which shall improve soil quality and biodiversity on agricultural fields [87]. The developers of the latter propose the integration of an electrolyser for hydrogen production for fuel for agricultural machinery with the residual heat used for crop processing, such as drying.

Figure 2.9: Agrivoltaic structure for hop growth [84].

Figure 2.10: Arc-shaped PV modules developed by Goldbeck Solar [86].

Figure 2.11: Mobile PV array [87].

The cheapest option, in turn, are vertical PV panels, avoiding high structures and thus reducing costs [40]. This configuration uses bifacial modules. The vertical position can reduce wind intensity and speed near the ground, thus diminishing evapotranspiration and erosion. The vertical assembly can also be used as a solar fence for livestock.

Figure 2.12: Bifacial vertical photovoltaic modules [40].

Simulations and measurements have shown that a south-west or south-east orientation with 45° deviations from the south is more suitable for agrivoltaic for providing a homogenous light distribution, whereas an east-west alignment maximises the shade movement [40]. However, these simulations were made for Germany.

The more expensive option is the use of sun trackers, to optimise the crop's yield and/or PV power generation.

When designing an agrivoltaic structure, water management should be considered, since accumulated rainwater running off the modules' eaves can cause soil or splash erosion and even damage plants [88]. Narrow or tubular PV modules can be used to avoid the accumulation of large water masses, and tracking systems to distribute the precipitation [40]. Other solutions are attaching a disperser to the dripping edge of the array to promote a more homogenous distribution or a rainwater collecting system [88]. The collected and stored rainwater can later be used for irrigation and may help conserve groundwater, thus being attractive for arid regions.

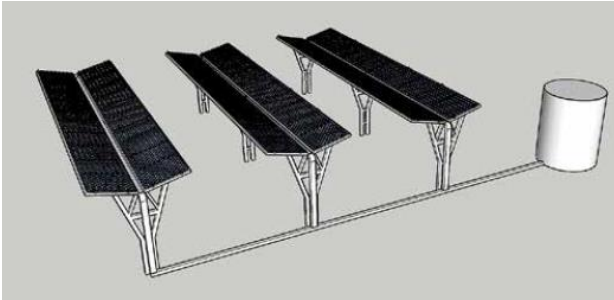

Figure 2.13: Illustration of a rainwater collection channel with storage unity [40].

2.7.2 Photovoltaic Modules

Bifacial PV modules are the most used module technology due to their ability to capture solar radiation from both sides, which makes them suitable either for silted structures or vertical. When the radiation level incident on the back side is sufficient, electricity production can increase up to 25 % [40].

The Swiss company Insolight developed a concentrated PV module technology with III-V multi-junction PV cells which can be used for agrivoltaic systems, projecting an LCOE below 0.297 €/100MWp [89]. The same company also designed its Translucency and High Efficiency in Agrivoltaic (THEIA) PV modules, which produce 30-50 % more energy than other translucent modules while including a dynamic light adjustment feature [90].

Another module technology was developed by the German company Tube Solar AG, which produces lightweight, robust, thin-film tubes, primarily for agrivoltaic [91]. The tubes can be permeated by light and water, allowing half shade which is favourable for many crops [40].

Research of the German Aerospace Center, *Deutsches Zentrum für Luft- und Raumfahrt* (DLR), developed ultra-thin PV cells based on cavity-enhanced amorphous germanium that confines the light in an ultra-thin absorber [92]. Germanium has a higher absorption coefficient for wavelengths above 500 nm than amorphous silicon, thus absorbing more green and infrared light and transmitting more blue and red light, which are used by plants for photosynthesis.

Some companies are exploring the use of organic PV modules for agrivoltaic applications, such as the Greek company Organic Electronic Technologies (OET) [93]. The company offers a complete system for cultivation in greenhouses covered with semi-transparent organic (OPV), lightweight, and flexible PV modules. According to them, the OPVs have the potential to boost crop production by as much as 30 %, decrease cooling energy consumption by up to 30 % and decrease water demand by up to 30 %.

Figure 2.14: Semi-transparent organic PV modules by OET [94].

Even though research on agrivoltaic systems and technologies has increased, there are still technical challenges to be addressed to optimise electricity generation while ensuring the lowest impact on crop yield production [95].

2.8 Scientific Research

Although agrivoltaic is being tested and implemented all around the world, there is still little scientific research and evidence about the impacts on agronomic parameters [96]. Agricultural yields are influenced by four main factors: solar radiation, temperature, evapotranspiration, and water efficiency [47]. The presence of PV panels over crops will mainly decrease the amount and intensity of solar radiation, thereby decreasing air and soil temperature. Also, the shade provided by the modules influences the spatial distribution of rainfall, depending on the PV system's height and geometry. On the other hand, according to Weselek et al. [96], the shelter of the PV could reduce the infestation of fungal diseases after persistent rainfall. The impact classification as positive or negative of the PV system on agricultural crops depends on numerous factors, such as the crop itself, climate conditions, local soil properties, and PV system configuration [47, 55]. Moreover, the diverse configurations, agricultural applications, and climatic conditions of agrivoltaic systems, difficult the comparison between the different designs. This underscores a key challenge of the agrivoltaic approach: understanding the effects of such designs on both productions. Forecasting agrivoltaic system effects is crucial for determining the optimal design for a given application, considering the desired outcomes and prevailing environmental conditions.

Besides the pilots mentioned in section 2.6, with some of them including monitoring systems, experiments at smaller scales have been conducted to study the effect of PV modules on soil and crops and their interaction. Not every experimental study found was carried out in an agrivoltaic system.

Firstly, some crops are more shade tolerant than others and are so more suitable for agrivoltaic. Based on the study case of Chae et al. [97] in South Korea, broccoli and cabbage crops had a reduced yield and a delayed harvest, despite no significant difference in quality, nutrients, and taste. However, they had an improvement in their green colour due to the longer shading periods. Identical observations were made with the pears in Belgium [68]. In Greece, a study of an agrivoltaic system with aromatic crops of thyme, oregano, rosemary, and mountain tea, showed different results of the relation between the crop cover and height in the agrivoltaic and control areas for each species [98]. In other words, the same climatic conditions and the same system design led to different effects on each species. Kim et al. [99] tested five different grain crops (sesame, mung bean, red bean, corn, and soybean) by planting them in an open-field agrivoltaic system with different shading ratios and 5.42 m high modules. For most of the crops, shade had a negative effect on the grain yield. In the case of soybeans, a grain yield reduction was also observed by Potenza et al. [75]. Tang et al. [100] used a small PV greenhouse covered with opaque modules in half-density distribution for strawberry growing in China. The results showed improved quality and yield of the fruits and even higher chlorophyll content than unshaded plants, while in the French PV greenhouse, in Eyrargues, strawberries had an earlier and longer harvest [26]. On the other side, in Italy, an agrivoltaic greenhouse with raspberries, strawberries, and blackberries, influenced the composition and increased the quality of the fruits, particularly their content of beneficial compounds [101]. After berries, lettuce appears to be one of the best crops for agrivoltaic. Marrou et al. [50] and Carreño-Ortega et al. [102] demonstrated that lettuce can maintain high yields under PV modules, noting that in an agrivoltaic system, the design should allow at least 70 % of PAR [50]. Marrou et al. [50] and Hassanien et al. [103] observed that agrivoltaic increases the total leaf area of lettuce while decreasing the number of leaves. According to Willockx et al. [104], the leaf area of potatoes also increases under PV. Tomato grown in greenhouses, in turn, seems to have a shading limit of 30 % [105], concerning that higher shading levels lead to a higher number of green fruits at the last harvesting season. According to the study of Barron-Gafford et al. [106] chiltepin and cherry tomato had greater fruit production under PV panels. Also, pepper had a higher productivity, accompanied by increased weight [107].

The integration of PV panels over agricultural crops will mainly influence the available radiation, decreasing its levels with higher shading. More important than the radiation in general are the PAR levels for photosynthesis. Chae et al. [97] and Tang et al. [100] measured lower PAR concentrations under the PV modules than in the reference plot, whereas López-Díaz et al. [105] found out that PAR reduction is proportionally higher than the shading area increase. Partial-shaded areas can receive about 75 % of solar radiation during summer when compared to full-sun areas [108]. Most of the time, half PV density configurations turn out to be more appropriate for agricultural practices. In Japan, the half-density configuration on a PV greenhouse improved the onion yield, whereas full density decreased its plant growth [109].

Air and soil temperature are the most measured parameters in agrivoltaic experiments. According to Menta et al. [110], the changes in microclimate under PV panels may be higher in the Mediterranean climate, achieving soil temperature reduction of about 2-5 °C. According to Chae et al. [97], a decrease in the soil temperature of 1.1 °C was measured when compared to the reference. The agrivoltaic project with soybeans in France [73] led to lower soil temperature and air temperature. Graham et al. [108] showed that partially shaded areas with PV panels have reduced soil temperature, elevated soil moisture, and reduced vapour pressure deficit when compared to full sun plots. Marrou et al. [111], in turn, measured no significant difference in air temperature and humidity at a height of 2 m above ground, instead, the crop temperature was affected, with a decreased day-night temperature amplitude, which was also measured in the pilot of BayWa r.e. [65] and by Barron-Gafford et. al [106]. Willockx et al. [104] observed lower temperatures under the panels during the day and night. In agrivoltaic greenhouses, the inside temperature tends to be lower than under plastic foils, as measured by Tang et al. [100] and Hassanien et al. [103].

The shading of PV panels can help increase WUE, although it depends on the crop. Barron-Gafford et. al [106], for instance, observed that agrivoltaic with jalapeño and cherry tomato increased WUE while for chiltepin the difference was negligible. However, WUE is mainly influenced by the shading level. In an experiment in the USA, soil moisture in the full-sun area was depleted more rapidly than in the partial-shade area between the panels and full-shade plot under the panels, due to the higher evapotranspiration levels caused by directly incident solar radiation [23]. This allowed soil moisture in the full-shade areas to remain available for a longer period during the growing season. According to Marrou et al. [25], plant transpiration and soil evaporation are differently affected, depending on the level of shade and type of crops, and soil evaporation is more sensitive to shading than plant transpiration. For lettuce and cucumber, transpiration has decreased in the agrivoltaic configuration, whereas evaporation was lower for lettuce and higher for cucumber, which, according to the authors, is probably a consequence of the more efficient ground cover of lettuce than of cucumber in shaded areas. Moreover, the agrivoltaic system reduced evapotranspiration by 14–29 %. In the greenhouse of Hassanien et al. [103] evapotranspiration was even decreased by 47 %. In China, an agrivoltaic system with concentrated-lighting technology and a standard module technology has shown similar results, where evaporation was reduced by 14 and 19 % which allowed saving soil water content at 33 and 51 %, respectively [22]. In this way, if water is a limiting factor, the PV system's shading can improve water efficiency due to lower evapotranspiration. The agrivoltaic project in Heggelbach [40] had an improved crop yield during the hot and dry summer of 2018, while in 2017 the crop yield was lower than in the reference field. In 2017, with a normal summer, the panels perhaps hindered the passage of enough sunlight for crop photosynthesis and growth, reducing the yield, whereas, in the hot and dry summer of 2018, the shade of PV panels helped maintain the moisture in the soil, thus enhancing crop growth.

In southern France, physical, chemical, and global soil properties were lower in a conventional PV park compared to semi-natural land cover types [112]. Furthermore, Menta et al. [110], observed that the soil under their ground-mounted PV system had modified soil fertility and decreased water-holding capacity, while electrical conductivity and pH increased. In Central Italy, measurements of soil properties were carried out on a conventional PV park 7 years after installation [113]. The results showed much lower organic matter content under the PV panels, lower soil water content, increased salinity and pH, and a higher amount of plant litter. According to the authors, the higher amount of litter may be related to the occurrence of unfavourable pedoclimatic conditions beneath the panels that have affected plant growth. In contrast, the soil between the PV arrays had a higher amount of living plant biomass which allowed a significant increase in organic matter enhancing microbial activity. Similar results were observed in the agrivoltaic studies by Adeh et al. [23], where a full-shade area had 126 % more dry biomass than the full-sun, and by Graham et al. [108], where the partially shaded area had 4 % higher floral abundance than in full sun and 4 % more than in the full-shaded areas, despite a delay in blooming. According to the observations mentioned by Moore-O'Leary et al. [28], the cover of high and medium-high grasses decreased under PV modules, being replaced by perennial herbs or invasive grass species. Despite this, in China, with a predominantly typical alpine arid desert climate, the presence of the PV panels over sandy soils in deserts lowered evapotranspiration and thus increased soil moisture, promoting vegetation recovery [24, 114]. Also in China, an agrivoltaic system with goji berries in a desertic land improved the ecosystem with an increase of small wild animals [115]. However, more experiments and research should be carried out to understand the impact of PV systems on soil properties and vegetation cover.

Moreover, PV systems with a high ground cover ratio can significantly alter the spatial distribution of rainfall, depending on the local soil properties, climate conditions and the structure height and geometry [47]. In the soil under the panels, a “bulb” of water can be formed which spreads by the mean of gravity and by diffusion to the sides. To decrease the spatial heterogeneities of rainwater distribution, Elamri et al. [116] tested an avoidance strategy which consists of an algorithm that returns the ideal module tilt angle that minimises rain interception on the modules' surface.

Regarding the performance of the PV system of an agrivoltaic facility, the presence of living vegetation under PV modules can influence energy conversion. For instance, the transpiration of plants can reduce the module temperature, as observed by Barron-Gafford et al. [106]. The PV modules' efficiency is inversely proportional to the cell temperature, meaning that a lower microclimate underneath can enhance the energy conversion. However, this effect highly depends on the modules' height. On the other side, agricultural practices can increase soiling and dust deposition on the modules' surface, thus decreasing performance. According to Jung et al. [117], even with PV panels installed at a height of more than 4 m, soiling rates were not reduced as expected, with similar levels as for ground-mounted systems in the same region during the summer months. However, soiling can increase due to agricultural fieldwork, especially when machinery is used or due to the movement of livestock. In this case, the vertical option can reduce the soiling impact and the consequent need for cleaning [55].

2.9 Potential of Agrivoltaic

Aside from assessing the mutual effects between PV and agricultural systems, it is crucial to understand the feasibility of agrivoltaic.

Concerning the location of agrivoltaic systems, a research group at the Oregon State University developed a global map of agrivoltaic potential, according to solar radiation, air temperature, wind speed, and humidity. According to the results, the western U.S., southern Africa, and the Middle East have the highest potential, while the best land classes for agrivoltaic may be croplands, grassland, and wetlands [118].

In Europe, the potential of agrivoltaic is theoretically high [26]. European territory has 32 % cropland, where 28.2 % is used as arable land and 3.8 % for permanent crops. An estimation of the Joint Research Centre shows that PV production could offset global energy demand if less than 1 % of this area were converted into agrivoltaic systems [95]. Moreover, by covering 1 % of Europe's agricultural land with PV systems, PV capacity should reach five times the total installed capacity in 2022. And, for 1 % coverage of arable land and permanent grassland and meadow, the capacities are triple and equal to the installed in 2022, respectively.

According to the methodology and assessment made by Niazi et al. [119], 16.2 % of the EU's land is suitable and eligible for agrivoltaic, corresponding to an area of 1.7 million km^2. Furthermore, by considering an agrivoltaic capacity density of 30 W/m^2, the authors estimated the agrivoltaic capacity for every NUTS-2 region. The results suggest a capacity potential of up to 400 GW in the Alentejo province, while the other regions of Portugal have slightly lower capacities. Regions in France, Lithuania, and Spain have the highest agrivoltaic capacity potential of up to 800 GW.

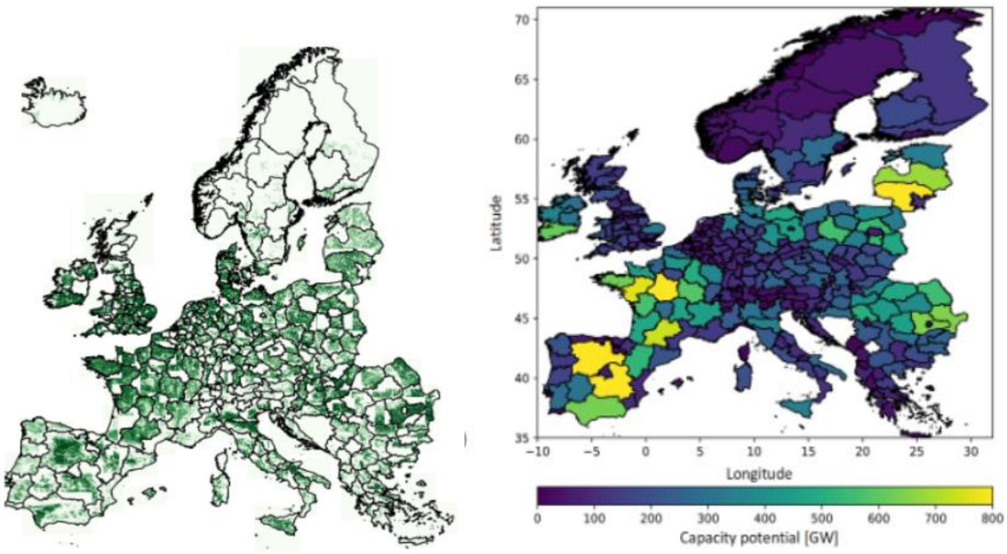

Figure 2.15: Suitable eligible land for agrivoltaic systems (left) and agrivoltaic capacity potential (right) in the NUTS-2 Regions [119].

The implementation of agrivoltaic can offer significant support in achieving various international and national commitments mentioned in section 1.6.1. Firstly, integrating PV energy generation systems on agricultural farmland allows the production of electricity for agricultural processes or the local community, thereby contributing to the decarbonisation of the sector and greater incorporation of renewable energy into the global energy mix. The PV system can provide additional energy, for households, water treatment, food cooling, and processing, with even more benefits in decentralised systems in remote and poor areas. Secondly, the configuration of the PV systems can protect crops and soil against extreme weather conditions, such as heavy rain and droughts. This safeguarding can enhance the quality of agricultural products and promote food security by preventing yield loss, while turning agricultural systems more resilient to climate change. Furthermore, the shading effect of PV panels shields the soil from excessive radiation, thereby preserving moisture levels, diminishing evapotranspiration levels, and thus improving WUE. Adapted PV structures can also easily collect rainwater, which can then be used for irrigation. The PV panels' shelter in degraded or low-value agricultural areas could reduce soil erosion and so fight desertification and soil degradation, promoting ecosystem regeneration [47]. Thus, agrivoltaic can have a beneficial effect in developed countries with arid and semi-arid regions, providing shade for plants and animals while reducing irrigation needs [40, 96]. Concerning this, agrivoltaic projects in developing and poor countries can be used as decentralised energy systems while providing food or other products, thus promoting independence to external sources while fighting energy and food poverty. Furthermore, agrivoltaic has the potential to enhance biodiversity in PV power plants if pollinator habitats, such as beehives, are included on the site [47, 108, 120, 121]. In this case, the design also falls under the concept of ecovoltaic.

Regarding the ecovoltaic approach, the limited access to the land of PV power plants could present an opportunity for it to serve as sanctuaries for small animals, reproduction areas for birds, and host habitats for pollinators, thus fostering biodiversity conservation. Additionally, PV power plant sites can create conditions for species-rich plant communities [28]. According to Sturchio et al. [27], ecological theories suggest that enhancing environmental diversity or heterogeneity, including both spatial and temporal resource variability, can boost biodiversity and modify ecosystem processes. If we consider the heterogeneity caused by PV arrays, primarily in precipitation and light distributions, and complement this with the implementation of additional strategies that aim for biodiversity conservation, ecovoltaic emerges as a promising approach for future PV parks while being aligned with international nature conservation efforts. Complementing this with the anticipated 25 to 30 years of lifespan and sustainable and extensive land management, the ecovoltaic approach could promote positive ecosystem impacts and minimise the negative impacts associated with the construction and operation phases of the facility, thus promoting net environmental gain [122, 123]. However, despite an initial definition of ecovoltaic and a vision of its strategies and potential benefits, there is still a lack of empirical evidence regarding the real impact of PV parks on biodiversity, soil quality and other ecosystem services [28, 110, 121, 122, 123].

2.10 Costs

While agrivoltaic appears to offer advantages for agricultural production, the higher installation costs, and thus the LCOE, of such systems in comparison to conventional non-PV structures may pose a barrier to adoption among farmers. The elevated investment is primarily due to the higher and more complex structures. In addition, these designs are new in the market leading to limited availability from companies.

In the German agrivoltaic power plants report [124], a technology cost analysis is made for agrivoltaic projects. According to the report, the main difference between standard PV systems and agrivoltaic systems is the tracking system, followed by the structure costs, as PV modules are generally installed slightly higher. Vertical structures, in turn, require a much simpler assembly, are lower and thus cheaper. Also, the lower soiling on their surface and the less frequent cleaning requirement can reduce substantially the costs. Regarding the module technology, as bifacial or semi-transparent modules are preferred for agrivoltaic, the same slightly increases the investment when compared to opaque technologies. Agrivoltaic projects also have more design constraints due to the different subsoil conditions. However, groundworks are usually avoided, leading to lower costs for ground preparation. Also, there is no more need for fences [39].

According to the Fraunhofer ISE report [39], costs of agrivoltaic vary and generally have a higher CAPEX compared to ground-mounted PV systems. The estimations are based on an agrivoltaic system on an area of 2 ha and for the roof systems on an installed capacity of 10 kWp. The CAPEX estimations were made for different configurations:

- Ground-mounted PV: using a capacity of 1 MWp/ha;
- Agrivoltaic on grassland: using a capacity of 300 kWp/ha;
- Agrivoltaic on arable farming: using a capacity of 600 kWp/ha and the clearance height of the project in Heggelbach of more than 4 m;
- Agrivoltaic with horticulture: using a capacity of 700 kWp/ha and a clearance height of 3m.

The estimations suggest slightly higher PV module costs for agrivoltaic facilities than for ground-mounted systems. Agrivoltaic for arable farming has much higher structure costs, followed by horticulture applications, since the first one requires much higher structures. Arable farming agrivoltaic has also the highest surface preparation and installation costs, which is a consequence of cultivation times and trafficability of the soil which must be considered in the design of the agrivoltaic facility [39].

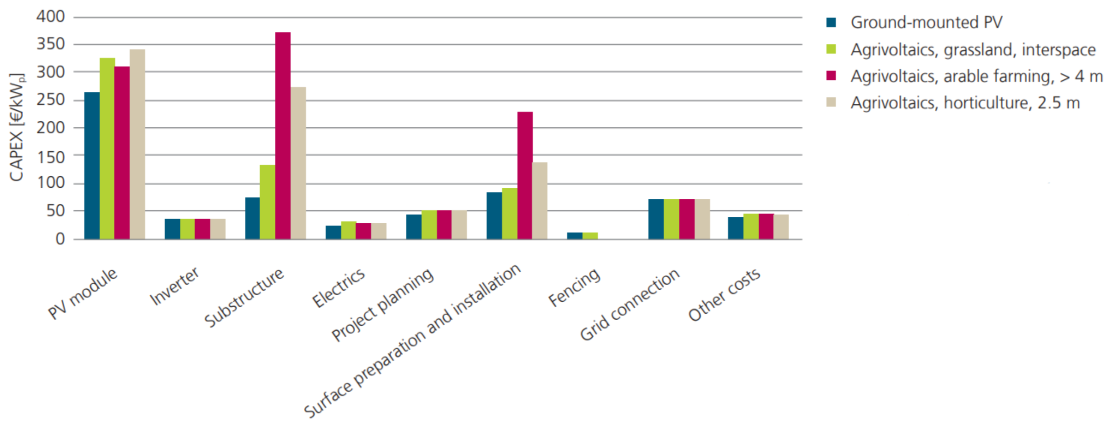

Figure 2.16: Comparison of CAPEX for agrivoltaic projects and standard ground-mounted PV systems [39].

Considering operating costs, or OPerating-EXpenditure (OPEX), agrivoltaic eliminates the usual soil maintenance costs for PV systems [124]. On the other side, higher cleaning costs are expected for high structures, due to the need for lifting platforms or other equipment, and the probability of higher soiling due to the agricultural activity.

However, instead of building an entirely new system, farmers can choose to adapt the existing structures to PV. Nets and foil support, for instance, can be used to install PV modules and cables, perhaps requiring some additional supporting elements due to the increased weight. Greenhouses can also easily be converted by replacing the glass or foil cover with rigid or flexible PV modules.

Finally, the LCOE of agrivoltaic in arable farming over a 20-year lifetime project could have an average value of 0.0815 €/kWh, which is twice the value for ground-mounted PV systems and about 30 % lower than for roof PV systems [124]. This LCOE estimation does not consider the tendency to larger agrivoltaic fields, which results in cost advantages due to scale economies. On the other side, small agrivoltaic projects have more advantages if the produced energy is directly consumed by the farm in off-grid systems, since grid connection is an important factor in investment costs.

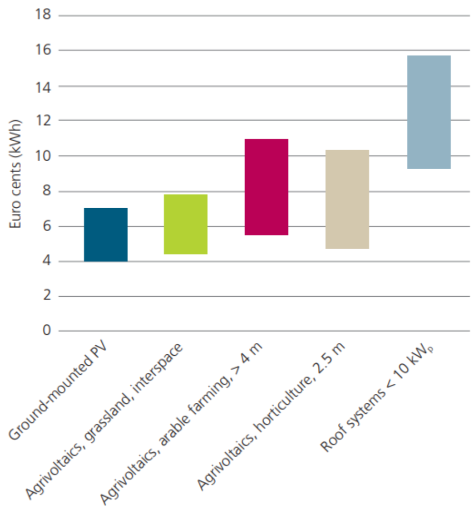

Figure 2.17: Estimated average LCOE for agrivoltaic and standard PV systems [124].

2.11 Legal Frameworks

The expansion of agrivoltaic systems is still hindered by the lack of policies, standards, and universal definitions [95]. While Germany, France, and Italy have developed guidelines and standards for agrivoltaic systems, it's important to note that each country's approach might differ based on their agricultural, environmental, and regulatory contexts. In Portugal, none of such documents have been published yet, however, the existing legal frameworks for agriculture and renewable energy production can still serve as a basis for integrating these practices. To agrivoltaic systems gain interest and traction in Portugal, guidelines and standards need to be developed to address the specific needs and national context.

2.11.1 Portuguese Legal Framework for Agriculture

Portugal's XXIII government has a department solely for agriculture and food governed by the Ministry of Agriculture and Food (*Ministério da Agricultura e Alimentação*), which is in care of policies and strategies linked to food, agriculture, and rural development [125]. Some relevant legislations for the agricultural practice are:

- Decree-Law nº 256/2009, of the 24th of September [126], modified by Decree-Law nº 37/2013, of the 13th of May [127], which approaches the integrated protection and production and organic agriculture: both integrated protection and integrated production are designed to foster environmentally responsible agricultural practices that prioritise sustainability, the environment including biodiversity, and the overall well-being of ecosystems and communities;
- Law nº 86/95, of the 1st of September [128], modified by Law nº 92/2015, of the 12th of August, about the Base Laws of Agrarian Development (*Lei de Bases do Desenvolvimento Agrário*) [129]: includes basic rules for the modernisation and development of the agrarian sector for the national interest, stating that agricultural policies shall be orientated to increase the productivity and competitiveness of agriculture, promote the rational use of natural resources, and preserve socio-economic balances. Also, fauna and flora should be preserved in and near agricultural areas;
- Dispatch nº 1230/2018 is the Guideline for Good Agricultural Practices (*Código de Boas Práticas Agrícolas* (CBPA)) [130], for the protection of waters against nitrate pollution by fertilisers.

Agrivoltaic is still an innovative concept that fits into agrarian research and could solve some of the problems faced by farmers, such as the current high energy prices and water scarcity. Furthermore, agrivoltaic could enhance the living and working conditions on farms in different ways. Firstly, the PV energy produced on-site can be used by the farmers instead of fossil fuels or other energy sources that generally are bought from an external supplier, thus presenting additional costs. Secondly, GHG emissions are reduced which helps for the decarbonisation of the sector. Thirdly, the PV modules can protect the plants and the soil from harsh weather, such as frost, hail, and rain, and from strong direct sunlight in the summer, which can reduce soil erosion and water usage, increase the final product quality, and promote climate resilience. Moreover, as mentioned in section 2.7.1, the PV structures of an agrivoltaic facility can be assembled to collect rainwater, which can further be stored and used for irrigation, thus decreasing water usage from conventional resources.

2.11.2 Portuguese Legal Framework for Renewable Energy

The main legal framework applied to energy production systems is Decree-Law nº 15/2022 [131], of the 14th of January, about the Organization and Function of the National Electric System, transposing the EU Directives 2019/944 and 2018/2001. This decree addresses the activities of production, storage, self-consumption, transport, distribution, aggregation, and marketing of electricity.

Additionally, the government published the Decree-Law nº 30-A/2020 [132] on the 18th of April 2022 about exceptional means to simplify the proceedings for electricity production by renewable sources, due to the high energy and fossil costs and so to enhance the energy transition.

2.11.3 Agrivoltaic Initiatives of other Countries

As agrivoltaic is spreading all around the world and its potential to improve agricultural productivity while producing electricity from a renewable energy source, some countries have published policies and guidelines to empower citizens and companies to develop agrivoltaic systems.

ANIE Rennovabili, Italia Solare and Elettricità Futura, three Italian renewable energy associations, have defined a paper that gathers a series of standards for agrivoltaic projects [133]. This paper defines the allowed area for PV power generation for the two most common agrivoltaic configurations, of PV arrays on elevated structures over crops, which is preferable, and PV arrays between the crop rows. For elevated PV modules, arrays can be installed either on fixed structures or on PV trackers with a minimum height of 2.1 m, to ensure normal agricultural activity and a cooler microclimate under the panels. PV modules installed between rows, classified as an inter-rows system, can also be mounted on fixed structures or on trackers and may be developed with different designs, including vertical arrays. The document defines three main requirements for agrivoltaic projects: the authorisation of agronomists or zootechnicians; the implementation of a monitoring system for the crop yield; and a limiting area for the non-agricultural activity up to 30 % of the total area.

In June 2022, the Italian Ministry of Ecological Transition published the “Guidelines for Agrivoltaic Plants” about the design, construction and operation of such systems [134]. The document also establishes the necessary criteria and requirements to classify systems as agrivoltaic. According to the guideline, two types of systems are distinguished [48]:

- Agrivoltaic system: PV systems with solutions to preserve and continue agricultural and pastoral farming activities;
- Advanced agrivoltaic system: the same as the agrivoltaic system but with innovative solutions, such as elevated PV modules, tracking systems, digital and precision farming tools, and monitoring systems to verify the impact of the PV system on the crops, water usage, crop yield, microclimate, and others.

Both classifications must fulfil specific requirements, which are [48]:

- Requirement A: the system must allow the synergy and continuity of agricultural activity with PV electricity production while enhancing both productions, ensuring that at least 70 % of the total area of the agrivoltaic system is just for agricultural activity and a LAOR of 40 %;
- Requirement B: the agrivoltaic system must not endanger the continuity of agricultural and pastoral activities by ensuring the synergistic production of electricity and agricultural

products. This can be demonstrated through the existence and yield of the crop by comparing the agrivoltaic production with previous productions without agrivoltaic or with a control area. Moreover, the specific electricity yield of the agrivoltaic system should not be less than 60 % of a standard PV system;

- Requirement C: agrivoltaic systems use elevated PV modules to optimise the performance on both energy and agricultural sides, and three types of configurations are defined:
    - Type 1: the minimum height allows the continuity of agricultural activity so that the area used for the crops or livestock coincides with the agrivoltaic system. In this case, the modules perform a synergetic function which can be expressed as the protection of the crop or livestock;
    - Type 2: the height does not allow practising agricultural activities under the PV modules, thus it is not an integration of energy with agricultural production, being more a combination of both on the same land;
    - Type 3: the PV modules are arranged in a vertical position, protecting crops from strong wind, or serving as fences for animals.

For types 1 and 3, the minimum and average height for fixed and mobile structures, respectively, are 1.3 m for livestock activity and 2.1 m for cultivation activity. Moreover, types 1 and 3 can be identified as advanced agrivoltaic systems that meet requirement C.

- Requirement D: monitoring systems must be installed to verify the effect of the PV system on the crops, water usage, productivity and the continuity of the activities on the land and other key parameters;
- Requirement E: in addition to requirement D, another monitoring system must be integrated to verify the recovery of soil fertility, microclimate, and climate resilience.

A system is then classified as “agrivoltaic” if requirements A and B are fulfilled; “advanced agrivoltaic” systems meet requirements A, B, C and D; and for National Recovery and Resilience Plan contributions requirements A, B, C, D and E must be satisfied.

In Germany, the *Deutsches Institut für Normung* (DIN) published a standard addressing agrivoltaic requirements – DIN SPEC 91434: Agri-photovoltaic systems – Requirements for Primary Agricultural Use [45]. This document reunites requirements for the main agricultural activity and the planning, operation, documentation, monitoring, and measurement of the main quality indicators. Although, it does not apply to standard ground-mounted PV systems, PV greenhouses as well as vertical farming. The document defines the different categories for agrivoltaic systems. Category I refers to installations with a clearance height of at least 2.10 m where the area under the PV modules is used for agricultural purposes. The PV modules can have different tilt angles and positions and can cover the agricultural area completely or partially. The definition of this category is similar to type 1 of requirement C of [48]. In Category

II, crops are grown between the rows of ground-mounted PV systems with a clearance height of less than 2.10 m. The norm makes a distinction between systems with permanently installed modules at a certain angle on one or two stilts, and systems with vertically or adjustably modules on a stilt. This category can be compared to types 2 and 3 of requirement C of the Italian guideline [48].

Agrivoltaic systems	Usage	Examples
Category I: **Installation with clear height** Farming under the agrivoltaic system	1A: Permanent and perennial crops	Fruit growing, soft fruit growing, viticulture, hops
	1B: Annual and multi-year crops	Arable crops, vegetable crops, temporary grassland, arable forage
	1C: Permanent grassland for mowing	Intensive farm grassland, extensively used grassland
	1D: Permanent grassland used as pasture	Permanent pasture, portion pasture (e. g. cattle, poultry, sheep, pigs and goats)
Category II: **Ground level installation** Farming between the agrivoltaic system rows	2A: Permanent and perennial crops	Fruit growing, soft fruit growing, viticulture, hops
	2B: Annual and multi-year crops	Arable crops, vegetable crops, temporary grassland, arable forage
	2C: Permanent grassland for mowing	Intensive farm grassland, extensively used grassland
	2D: Permanent grassland used as pasture	Permanent pasture, portion pasture (e. g. cattle, poultry, sheep, pigs and goats)

Figure 2.18: Classification of agrivoltaic systems by DIN SPEC 91434 (adapted from [45]).

In France, the ADEME published the guideline "Characterising solar PV projects on agricultural land and agrivoltaism" in July 2021 [47]. The document compiles evidence based on scientific research concerning the effectiveness of agrivoltaic systems, categorises various configurations, enumerates best practices, and offers guidance concerning the supervision, implementation, and operation of these systems. According to the document, a PV system can be considered agrivoltaic when the modules are located in the same area as the agricultural production, and when they impact the agricultural production by providing climate change adaptation, hazard protection, animal welfare, and specific agronomic services, without any significant degradation of the agricultural production or income loss. Furthermore, the three criteria evaluated for the characterisation of an agrivoltaic project are:

- Criteria 1 - Contribution to agricultural production: the PV systems must have a direct contribution to agricultural production, e.g. protection of crops and welfare of animals;
- Criteria 2 - Incidence on agricultural yields: the PV system must increase, maintain or decrease within acceptable proportions the agricultural yield;

- Criteria 3 - Incidence in the revenues of the farm owner: the PV system must maintain or improve the farmer's income.

Moreover, the agrivoltaic installation must be adaptable and flexible to be adjusted according to the agricultural activity which can change during the project's lifetime. This French guideline does not specify quantitative criteria as the other guidelines and proposals, which define minimum ensured crop yield, maximum coverage, or minimum electricity production.

In Japan, the Japanese MAFF introduced its first guidelines for agrivoltaic in 2013 and 2014 [21]. These guidelines approved the installation of PV systems on already existing farmland with the requirement that the potential reduction of the crop yield through the shading stays below 20 %. Later, the NEDO released new guidelines for ground-mounted agrivoltaic projects [43]. This document states that agrivoltaic projects are not allowed to exceed a module height of 9 m and it excludes arrangements with trackers or on greenhouses. Also, the holding of livestock or crop growth on already existing PV plants might not be classified as agrivoltaic. Additionally, agrivoltaic land is considered farmland which has tax benefits, and the Ministry of Economy, Trade and Industry (METI) provides a rebate covering of 50 % of the project's cost. The document also incentives for self-consumption or projects with Power Purchase Agreements (PPA).

Chapter 3
Photovoltaic Power Plant at Cercal do Alentejo

Recognising the potential of agrivoltaic and ecovoltaic approaches for PV power plants and aiming to define initiatives that embrace these methods, the upcoming PV power plant of Cercal Power in Cercal do Alentejo was chosen as a case study. This chapter encompasses all the information collected to characterise both the PV power plant and the project site.

3.1 Location

Cercal do Alentejo (37.8033° N 8.6708° W) is a parish located in the province of Alentejo, near the Alentejo Coast (*Alentejo Litoral*), Portugal. In the district of Setúbal, it is in the municipality and county of Santiago do Cacém [135].

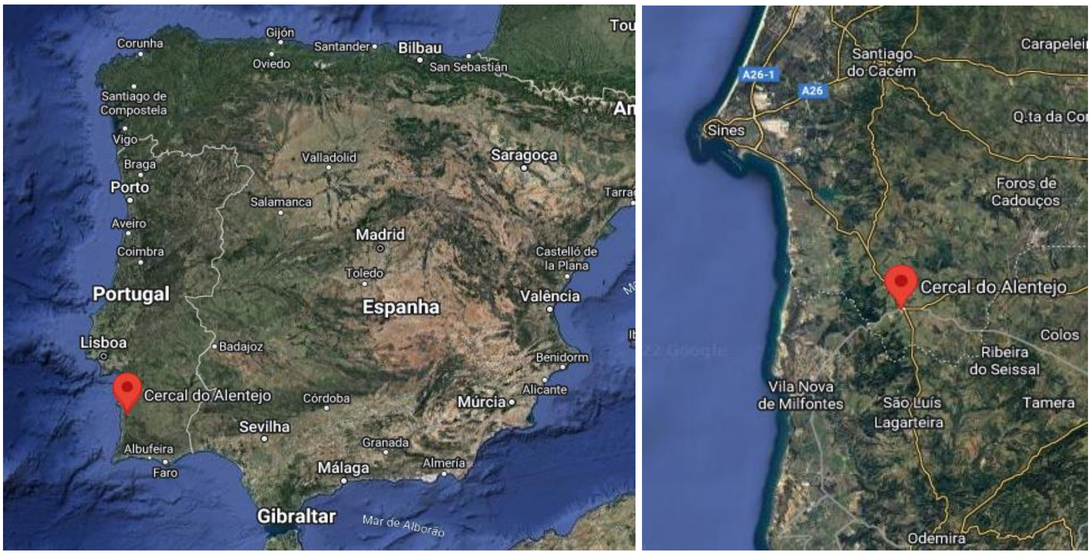

Figure 3.1: Location of Cercal do Alentejo [136].

3.2 Climatic Conditions

Generally, the Alentejo is characterised by hot summers to very hot and fresh to moderate winters, with irregular and relatively low precipitation levels [137], especially in the last years due to climate change. The extreme temperatures during summer, which can reach 40 °C or more, and the null precipitation levels lead to high evapotranspiration of the ground. Additionally, the anthropic pressure, mainly due to farming activities, has been depleting the nutrients of the soil. For this reason, according to the Land Use Capacity Map of Portugal, most of the land in the Alentejo is not suitable for agricultural use [137].

Regarding Cercal do Alentejo, as the village is 15 km from the ocean, it has a temperate climate that allows one of the most diversified fauna and flora of all the southwest of the Alentejo [135]. The Koppen classification of the Alentejo region is Csa - temperate climate with rainy winters and hot, dry summers [138].

Through the Photovoltaic Geographical Information System (PVGIS) [139] tool from the EC, the climate data of the Typical Meteorological Year (TMY) was analysed for the location of the PV plant in Cercal do Alentejo. The average monthly air temperature and relative humidity were calculated based on the hourly data (day and nighttime) of the TMY.

According to the hourly data of the TMY, the lowest temperature can be about 3.00 °C in the morning of February, and the highest is around 33.0 °C during July. In terms of average values, summer months have around 20 °C while during winter the temperature is about 12 °C in February.

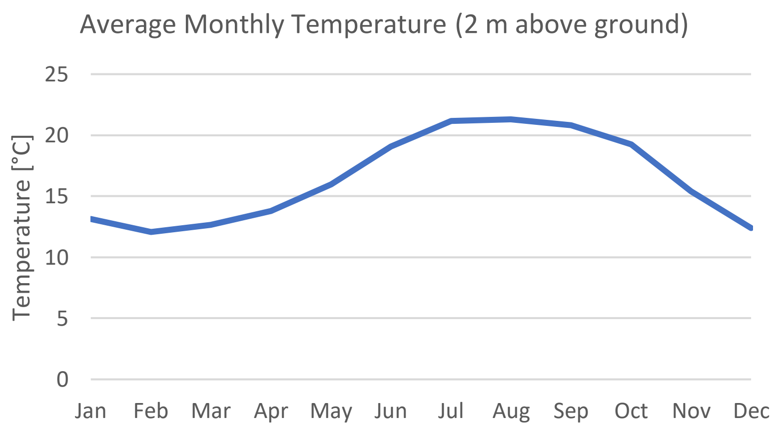

Figure 3.2: Average monthly air temperature 2 meters above ground in Cercal do Alentejo.

Relative humidity is lower in the summer months (with a minimum value of about 20% in June at 14:00) and higher in winter, as it is temperature dependent. Higher air temperatures increase the air's capacity to hold moisture, thus decreasing relative humidity, while lower temperatures lead to the opposite effect. On a yearly basis, considering both day and night values, humidity varies between 70% and 80%, which is a consequence of the proximity to the coast and the influence of incoming breezes and fogs.

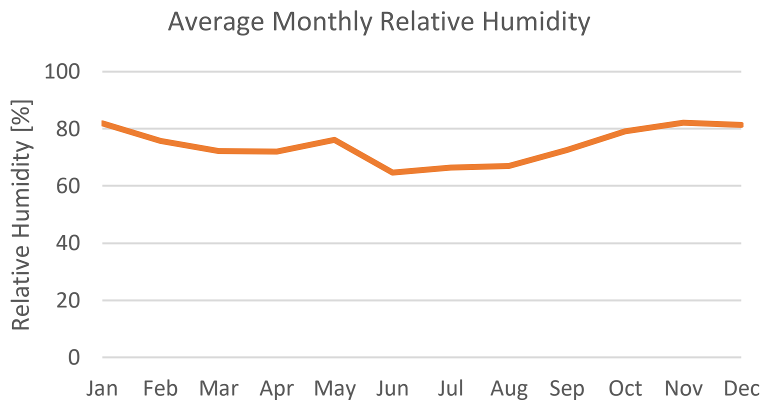

Figure 3.3: Average monthly relative humidity in Cercal do Alentejo.

Direct irradiance can reach about 1,000 W/m^2, while diffuse irradiance on a horizontal plane reaches around 500 W/m^2. Direct and diffuse irradiance depend highly on the local meteorological conditions, such as cloud density and composition and aerosol types and concentration. The TMY suggests that direct irradiance is almost constant over the year, with a peak during mid-April and more frequently higher values during summer. Diffuse irradiance seems to be more intense from the end of March until the beginning of July.

The two gaps of direct and diffuse irradiance near the 15th of April 2009 at 04:00 and the 16th of May 2008 at 10:00 are due to missing values from the 16th of April of 2009 at 16:00 until the 19th of April 2009 at 7:00 and the 17th of May 2008 at 13:00 and the 20th of May 2008 at 9:00, respectively.

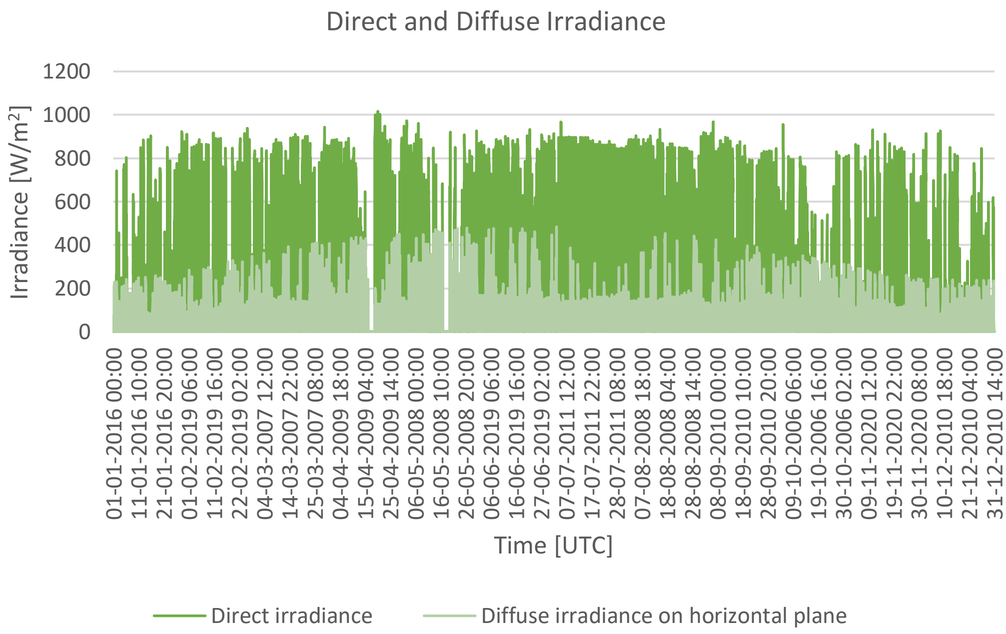

Figure 3.4: Typical Meteorological Year for direct and diffuse irradiance on a horizontal plane in Cercal do Alentejo.

Global irradiance is the sum of direct and diffuse irradiance, with higher intensity during June and mid-July. Lower global irradiances are more frequent from the beginning of December to mid-January. Again, the two gaps near the 15th of April 2009 at 04:00 and the 16th of May 2008 at 10:00 are due to the unavailable data in the same periods as for the direct and diffuse irradiance.

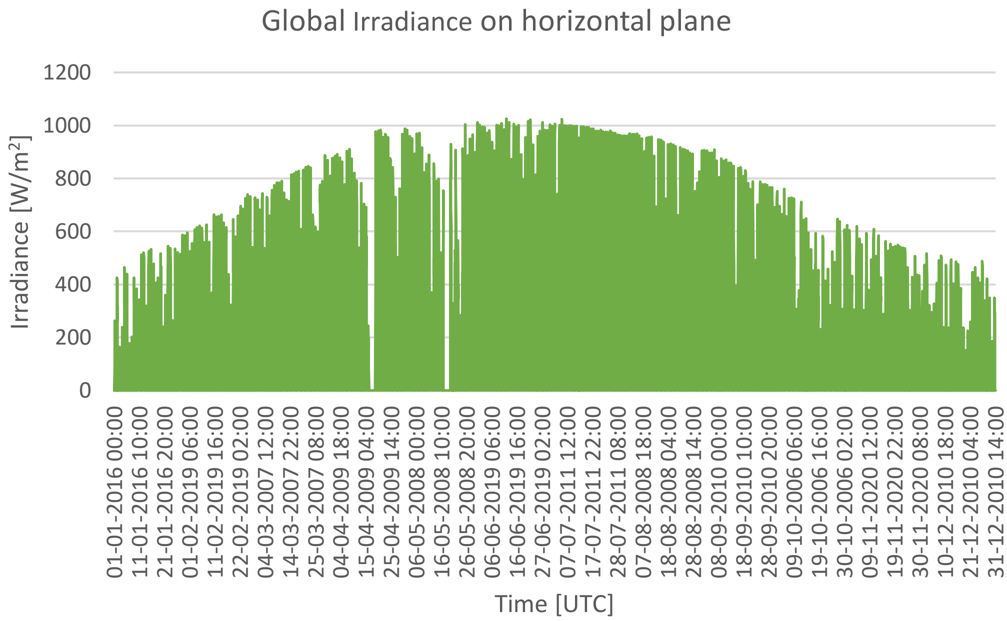

Figure 3.5: Typical Meteorological Year for global irradiance on a horizontal plane in Cercal do Alentejo.

Finally, surface infrared irradiance on a horizontal plane is the thermal irradiance emitted by the Earth's surface, being an upward irradiance, unlike global, direct, and diffuse irradiance which are downward. Surface infrared irradiance varies between about 225 and 420 W/m^2, in December and August, respectively. This upward irradiance will influence humidity and increase air temperature near the soil, which at a PV power plant can heat the direct environment of the modules thus reducing the energy conversion efficiency.

Surface infrared irradiance is related to the surface emissivity for infrared radiation, which depends on the surface's properties, such as colour, texture, composition, temperature, and the emitted wavelengths. In open fields, the surface's emissivity depends on vegetation type and cover density. According to [140], green foliage usually has a higher emissivity than dry grass. Regarding soils in general, organic matter decreases the emissivity while moisture increases it.

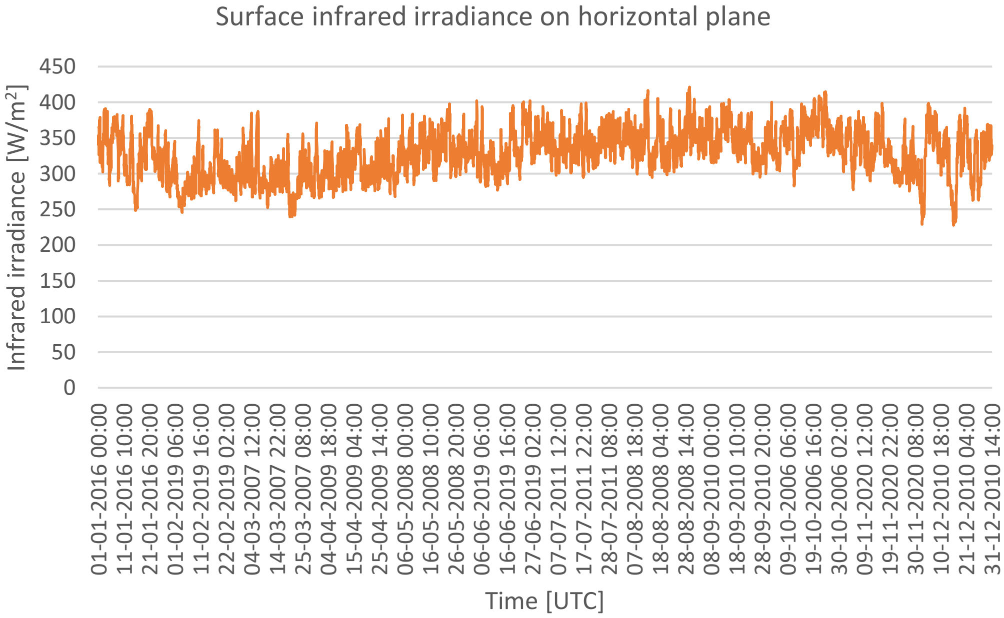

Figure 3.6: Typical Meteorological Year for surface infrared irradiance on a horizontal plane in Cercal do Alentejo.

Days with precipitation are defined as days when the minimum liquid precipitation or equivalent as liquid is 1 mm [141]. The values in Figure 3.7 are the accumulated precipitation levels of 31 days around every day of the year [141]. November has the highest precipitation levels, of almost 80 mm, whereas the usual rainy period, with precipitation levels over 13mm, is from September until June.

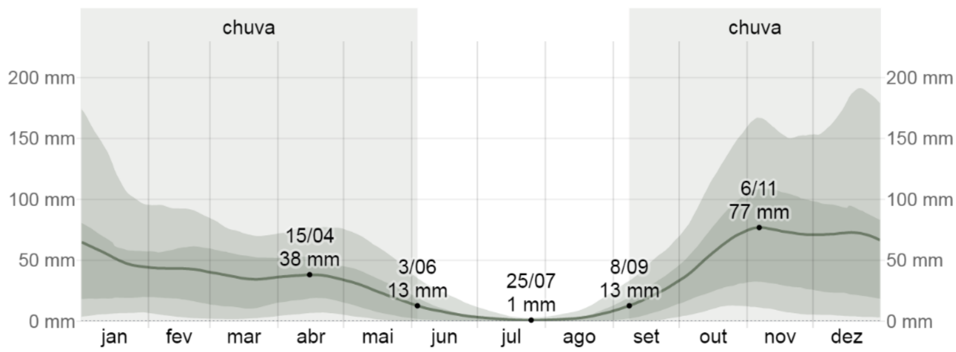

Figure 3.7: Monthly precipitation levels at Cercal do Alentejo, indicating the periods with rain (chuva) [141].

3.3 Technical Characterisation of the Cercal Power PV Plant

The Cercal Power PV plant will be located about 1.0 km from Cercal do Alentejo and 24.0 km from Santiago do Cacém, resulting from the junction of five PV plants: Alvalade, Borreiro, Cercal, Freixo and Vale das Éguas [142]. The project is still in the planning stage and is envisioned to have a nominal installed power of 263.8 MWp [143] with an estimated production of almost 600,000 MWh/year, avoiding about 480,000 tons of CO_2 per year [142].

Since the energy produced is at a voltage level of 30 kV, the project will include a substation to upgrade the connection voltage to the national electricity grid voltage of 400 kV [143].

The area that has been studied for the implementation of the PV plant is about 816 ha, whereas the area excluded from the various constraints is about 632 ha [142]. The area of the panels and the interrows is about 312.80 ha, of which the panels occupy around 125.79 ha [144].

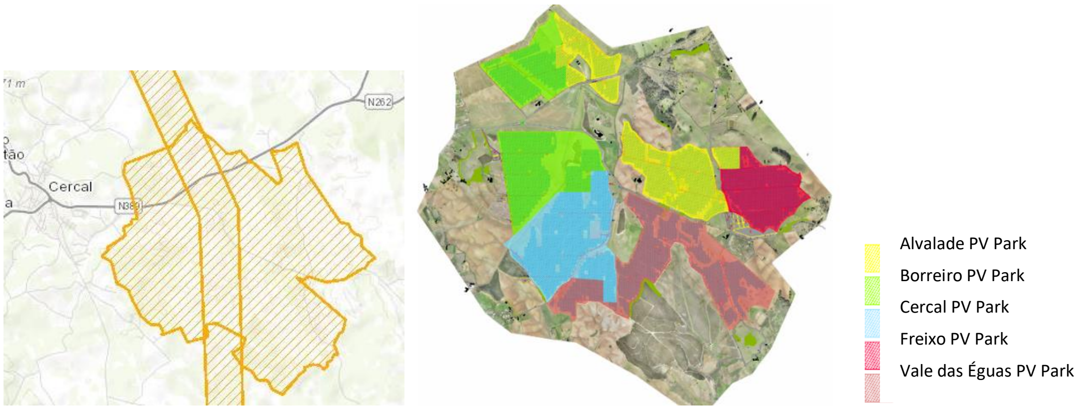

Figure 3.8: Total area of the Cercal Power PV plant and Very High Voltage transmission line [145] (left), and location of the five PV plants [144] (right).

The set of the five PV plants that make up the Cercal Power plant will have about 405,840 modules of 650 Wp each, 60 central inverters, 60 transformer stations, and 5 sectioning stations [143].

The envisaged modules are of bifacial technology, supported by single axis tracking structures (rotation amplitude of 55° and 0° azimuth) fixed to the ground through directly driven metal piles, eliminating the need for concrete for foundations [143] (Figure 3.9). The metal piles reach a height of approximately 2.4 m, indicating a minimum and maximum module height relative to the ground of 0.3 m and 4.3 m when the module is at its maximum inclination.

The chosen structure is also characterised by its adaptability to the terrain, being able to be installed on terrains with north-south slopes of up to 36 %, thus avoiding extensive earthmoving. The east-west distance between the structure rows will be 10.0 m, providing sufficient space for operation and maintenance works, as well as for the renaturation of these spaces [144].

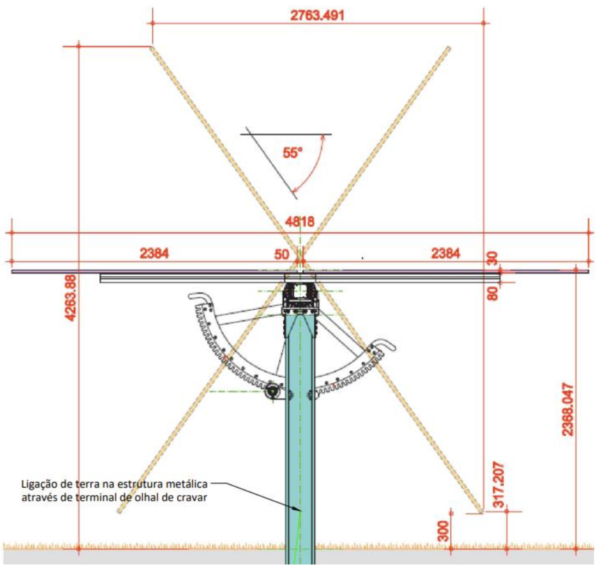

Figure 3.9: Illustration of the single-axis tracking structures of the Cercal Power PV plant [143].

Another significant aspect of the PV project, pertinent to this work for the ecovoltaic approach presented in Chapter 4, is the use of fences to limit specific areas within the project site. The proposed layout for the PV power plant entails utilising the existing agricultural fences whenever possible. Should new fences be required, the same will follow the agricultural fence design illustrated in Figure 3.10 [144].

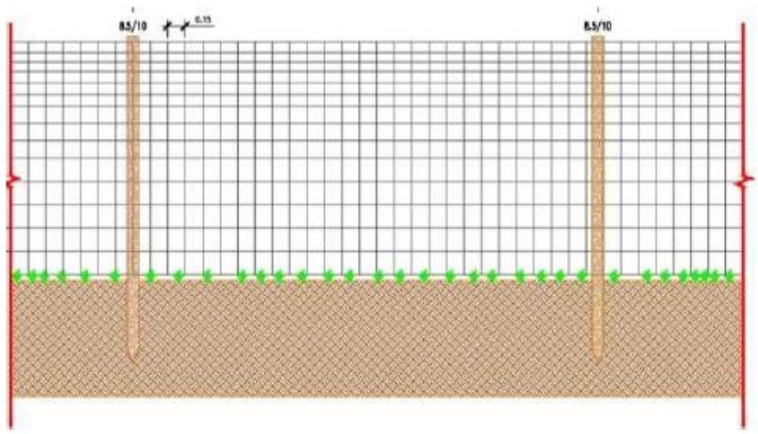

Figure 3.10: Agricultural fences for the Cercal Power power plant [144].

3.4 Characterisation of the Land

The following description of the project implementation area is based on the information given in the Environmental Impact Assessment (EIA) report [146]. The assessment was conducted between November 2019 and August 2020 and was re-edited in March 2021. The studied area is located in the Mariânico-Monchiquense Sector, which is a mountainous region primarily composed of schist with a climate that ranges from sub-humid to humid [146].

Figure 3.11: Environmental constraints at the Cercal Power PV plant implementation area identified through the environmental impact assessment [144].

On the 15th of July 2023, a field visit to the implementation area was carried out, where the following photos were taken:

Figure 3.12: Photos of the Cercal Power PV plant implementation area: a) at Cercal PV park, b) and d) at Alvalade PV park, c) at Vale das Éguas PV park.

3.4.1 Soil

The project area evidences some soils with good agricultural suitability integrated into the National Agricultural Reserve (*Reserva Agrícola Nacional* (RAN)), although they have little significance [142]. These soils are associated with the main water lines and were excluded from the PV area.

Regarding the soil taxonomy, the most representative soil orders in the study area are Luvisols [146] (*Solos Argiluviados Pouco Insaturados*, according to the *Serviço de Reconhecimento e Ordenamento Agrário* (SROA) classification), characteristic of temperate regions with a Mediterranean climate [147]. The presence of Fluvisols (*Aluviossolos,* SROA), which are young soils in alluvial, deltaic, lacustrine, or marine deposits [148]; Leptosols (*Litossolos,* SROA), which are found in mountainous regions and in areas where the soil has been eroded to the extent that hard rock comes near to the surface [149]; and, Gleysols (*Solos Hidromórficos Sem Horizonte Eluvial,* SROA), originated by groundwater that wets the soil during a prolonged part of the year [150], were also identified.

Regarding the Land Use Capacity of the soils, all classes (A, B, C, D and E) are present, with a predominance of class E followed by class D [146]. According to the definitions in [151], soils of class E are characterised by having very severe limitations, including for grazing, scrubland, and forest exploitation, and very high erosion risks, and are not suitable for agricultural purposes, but can be used for natural vegetation, protection or forest restoration. Soils D in turn, do have severe limitations, with few or moderate limitations for grazing, scrubland, and forestry, have high to very high erosion risk, and are generally not suitable for agriculture except in very special cases.

Therefore, it can be deduced that the soil at the project site is unsuitable for any form of agricultural activity without any effort to improve the existing conditions.

3.4.2 Water

The project area is located in the south Portuguese Zone of the Sado Basin and Mira Basin, with insignificant aquifers whose water masses are classified as "Quantitively and Qualitatively Good" [146]. Through a hydrological study, seven main water lines were identified in the project area, which are limited by the hydrographic basins. Most of these watercourses have a markedly torrential regime and remain dry for much of the year.

According to the information provided by the *Agência Portuguesa do Ambiente* (APA) in 2019, the area has five groundwater abstractions, three wells and two vertical boreholes, with some more wells identified through the military maps [146].

3.4.3 Areas

The predominant class on the land is "Agricultural Areas", covering approximately 656.74 ha which corresponds to about 80.50 %, followed by the "Forest Areas" class with an approximate representation of 12.79 % [146]. Within the agricultural areas, the subclasses "Arable Crops" and "Olive Groves" were identified. The subclass "Arable Crops" covers most of the study area, accounting for 80.14 %, and includes annual dryland crops. These areas are also used for pasture.

Within the forest class, four subclasses were identified: "Eucalyptus Stands," "Acacia Stands," "Stone Pine Stands," and "Stone Pine Stands with Cork Oaks". These agglomerates are of anthropogenic origin and are scattered. There is a significant area of "Eucalyptus Stands" in the southern part of the study area, covering 12.63 % of the area. Overall, both agricultural and forested areas are largely of anthropogenic origin.

"Artificialised Areas" have limited representation, as do "Natural and Semi-Natural Areas", occupying 2.81 % and 3.90 % of the study area, respectively.

3.4.4 Biodiversity

The project area is not located in a "Sensitive Area," according to the definition in Article 2 of Decree-Law Nº 151-B/2013 of the 31st of October, in its current version (republished in Annex II of 152-B/2017, of the 11th of December) [146]. However, the nearest sensitive areas are [146]:

- Special Conservation Zone Southwest Coast (*Zona Especial de Conservação Costa Sudoeste*) (PTZEC0012) – the power plant is located about 0.5 km away;
- Southwest Alentejo and Vicentina Coast Natural Park (*Parque Natural do Sudoeste Alentejano e Costa Vicentina*) (PNSACV) – the power plant is about 6.5 km away;
- Southwest Coast Special Protection Zone (*Zona de Proteção Especial Costa Sudoeste*) (PTZPE0015) – about 9.2 km away from the project.

Furthermore, some of the main water lines belong to the National Ecological Reserve (*Reserva Ecológica Nacional* (REN)) [142].

3.4.4.1 Flora and Habitats

The designated area for the implementation of the Cercal Power PV plant is not situated within areas of high conservation interest classified under the Habitats Directive [146]. Although, there are various scattered *montado* areas, which are human-created oak forests, considered habitats with protective status. Unfortunately, most *montados* are in a poor conservation status [146].

Based on the analysis conducted in the study area, the following habitats were identified: 1) cork oak *montado* units - Habitat 6310 - Evergreen *Quercus spp.*; and 2) units related to riparian vegetation that develops along the banks of existing watercourses: 2a) reedbeds - Habitat 6420 - Mediterranean tall herbaceous *Molinio-Holoschoenion* wet meadows, and 2b) willow stands - Habitat 92A0pt3 - *Psammophilous* wooded *Salix Atrocinerea* stands.

Regarding the floral biodiversity, data collected in the field in October 2019 for floristic inventory allowed the identification of 49 species distributed across 27 families, among which the *Poaceae*, *Fabaceae*, *Asteraceae*, *Apiaceae*, and *Lamiaceae* families are the most represented. However, given the size of the study area, it can be considered to have a limited floral diversity. In an overall analysis, the studied area is profoundly marked by human activity, with notable impacts resulting from agricultural exploitation and pasture.

Moreover, according to the Red List of Vascular Flora of Continental Portugal, published on the 24th of October 2020 [152], the region of Baixo Alentejo has most of the endangered plants. Only in the Baixo Alentejo, 86 plant species are threatened and more than 20 are linked to the disappearance of the traditional dryland olive groves. This is mainly due to the intensive agricultural activities on large scale [153]. One species that is probably extinct, once the last observation was made in the mid-90s, is the *Linum Maritimum* which grows in meadows and wet soils. *Armeria arcuate* in turn is already extinct [154]. Other endangered species are *Apiu* *repens*, *Plantago almogravensis* (in danger), *Ononis hackell* (vulnerable), *Bupleurum acutifolium* (vulnerable) which is mainly endangered by the large eucalyptus forest in the mountains of Cercal, and the *Senecio lopezii* whose population has diminished due to the intensive forest cleaning [153]. According to the Red List of Vascular Flora, the endemic plant *Chaenorhinum serpyllifoliu* (in danger) of the Portuguese southwest coastline, *Klasea algarbiensis* (vulnerable) which grows in bushes of sandy areas, *Scorzonera hispanica* (in danger), a perennial herb which grows in clearings of bushes, and *Doronicum plantagineum* (vulnerable), an endemic plant of the south Portugal which occurs on edges and in the undergrowth of evergreen or marcescent scrub and woodland, are some of the species listed with registrations near to Cercal do Alentejo [155].

3.4.4.2 Fauna

A total of 138 species of fauna were inventoried in the implementation area [146]. The faunal group with the highest number of identified species is birds, with 96 species, followed by mammals with 23 species, amphibians with 13 species, and reptiles with six species. Out of the total inventoried species, 30 were found on the site and 18 are considered concerning from a conservation standpoint. The following species stand out due to their high conservation status and high likelihood of occurrence: Red Kite (*Milvus milvus*), Bonelli's Eagle (*Aquila fasciata*), Montagu's Harrier (*Cyrcus pygargus*), Stone Curlew (*Burhinus oedicnemus*), Rufous-necked Nightjar (*Caprimulgus ruficollis*), Greater Mouse-eared Bat (*Myotis myotis*), and Lesser Mouse-eared Bat (*Myotis blythii*).

Regarding the birds, 37 species are very likely to occur, 17 species likely and 15 unlikely to occur in the study area, whereas 26 were observed on the site. From the total of the 96 species inventoried, nine are critically endangered and eight endangered. Also noteworthy is the occurrence of critical and very critical areas for birds around the study area, mainly for nidification. Furthermore, the surroundings have zones that serve as bat shelters with national importance.

Chapter 4
Agrivoltaic and Ecovoltaic Compatibility Strategies

This chapter contains the definition of suitable agrivoltaic and ecovoltaic compatibility strategies using the Cercal Power PV power plant at Cercal do Alentejo as case scenario. In this dissertation, compatibility strategies are defined as agrivoltaic and ecovoltaic initiatives that align with a given PV project site, considering the PV system's commercial layout and the land's environmental and climatic properties.

Agrivoltaic compatibility strategies include agricultural activities that are compatible with either an existing PV system or an agricultural production land, without significantly modifying the initial system and compromising the energy production. In other words, they are agricultural activities, such as crop cultivation and livestock holding that are adapted to an existing PV or agricultural system following the agrivoltaic concept. In this approach, PV facilities, besides supplying energy, offer an agricultural product, such as crops, animals, or its by-products.

Traditional PV parks and most agrivoltaic systems are primarily designed for energy and agricultural production, with a secondary consideration for additional ecosystem services [27]. PV infrastructures may alter populations and movement of pollinators, reduce predation by birds on insects, affect plant nutritional composition due to the panels' shade, and habitat fragmentation [28]. Ecovoltaic, in turn, relies on an ecological understanding of the abiotic and biotic consequences of PV system configurations and their impact and effect on ecosystems [27]. For instance, PV parks are typically closed through fences to prevent theft and vandalism and for safeguard purposes, which also hinder the mobility of wildlife in the area, thereby diminishing habitat connectivity [121]. In an ecovoltaic design, it is possible to mitigate this issue by introducing well-sized gaps in the fence or by using permeable hedgerows that allow the passage of small animals [121].

Following this, ecovoltaic compatibility strategies are defined as initiatives designed to safeguard and enrich the natural spaces within the PV power plant, while mitigating the environmental impact caused by the facility's construction and operation. It is fundamentally based on three principles: the protection of biodiversity, the responsible use of resources and the circular economy and local socioeconomic development. Moreover, with these strategies, it is intended to create new habitats and promote greater biodiversity in the project site.

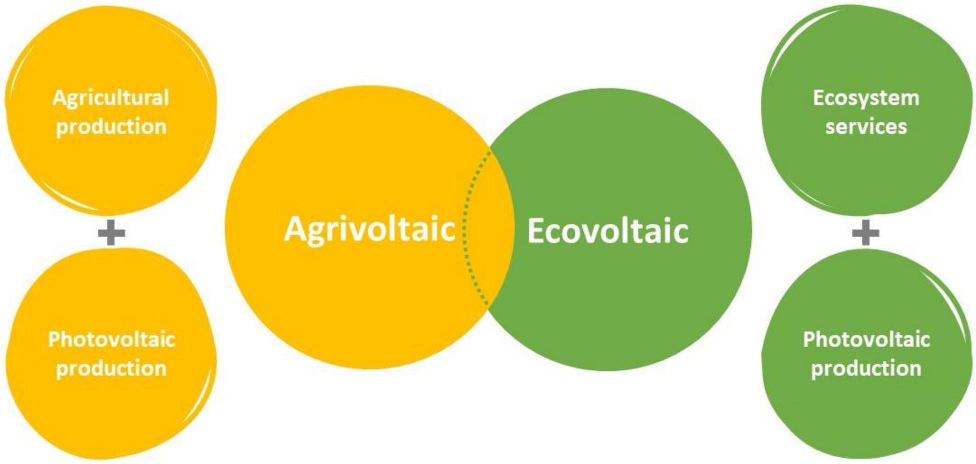

Figure 4.1: Illustration of agrivoltaic and ecovoltaic definitions.

However, some strategies can be simultaneously considered agrivoltaic and ecovoltaic. Grazing sheep, for instance, falls under both concepts once the animals or their wool can be used for further products while they ensure sustainable and natural vegetation control on PV sites. Also, beekeeping in agrivoltaic facilities with crop production can be considered ecovoltaic, once bees will support the local floral diversity. Moreover, farming practises based on conservation, organic, permaculture or sustainable agriculture, as they are focused on preserving the ecosystem services on the agricultural land, can be considered ecovoltaic.

4.1 Agrivoltaic Compatibility Strategies

For the case study at Cercal do Alentejo, the following agricultural activities were explored:

1. Crop cultivation;
2. Livestock holding;
3. Beekeeping.

4.1.1 Crop Cultivation

For a given PV project site, the following three base cases covering all possibilities can be found:

i. Retrofit of an existing PV power plant;
ii. Installing an agrivoltaic system on land with agricultural potential but not currently in use;
iii. Adapting agricultural land with productive use with an agrivoltaic system.

In the scope of this dissertation, the two first cases are proposed for the Cercal Power case study.

The first agricultural strategy to be explored is the incorporation of crops into the PV area of the commercial layout. In other words, these strategies are forecasted to be integrated into the same area as the PV arrays without modifying their configuration (height, row distance, tracker, module technology, etc). This strategy can be understood as a retrofitting of the commercial PV layout, where only some minor adjustments may be needed to ensure an adequate environment for the agricultural activity.

The second crop cultivation strategy is based on a purely agrivoltaic design, i.e., a new PV facility whose design already considers the integration of an agricultural application.

Crop cultivation should follow the principles of organic, conservation and sustainable farming, to preserve the ecosystem and soil quality. Given the site's existing limitations in terms of biodiversity and the poor soil conditions, it is avoided proposing any intensive agricultural practice that might worsen these conditions.

The proposed strategies may be implemented near the RAN areas and on land that has previously been used for crop cultivation.

4.1.1.1 Retrofitting of the Commercial PV Power Plant

For the definition of the strategies for crop cultivation, the first step was finding suitable crops for the PV plant and site under study. This involved researching various crops, mainly horticultural and herbaceous, typically cultivated in Portugal and the Mediterranean climate, i.e., adapted to the local climatic conditions. It was tried to characterise each crop by:

- Cardinal temperatures;
- Frost tolerance;
- Solar radiation needs and shade tolerance;
- Hydric needs;
- Soil movement and mechanisation needs;
- Maximal plant height;
- Implantation method and compass;
- Rotation and association with other crops.

The second step consisted of selecting crops with shade-tolerant characteristics, once in the PV park the plants will experience higher shading levels due to the PV modules.

As the aim is to identify one or more crops that can be effectively integrated into the PV park, which already has a predefined layout concerning the height of structures and interrow spacing, the third step was selecting crops whose maximal height is lower than the minimum height of the modules. It must be ensured that the selected crops do not create any shading on the PV modules that affects energy production. Furthermore, it was tried to find crops which can be integrated into a rotational crop cycle covering about one year.

In the case where multiple crops and rotational plans seem suitable, the final selection should be based on prioritising the crops with the highest economic value.

The following chart illustrates the mentioned steps:

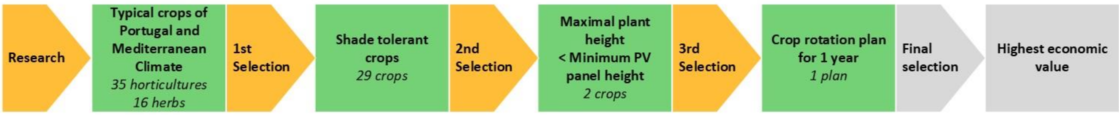

Figure 4.2: Chart of the procedure of finding suitable crops for the Cercal Power PV power plant.

During the research of crops, due to time available, limitations in both the University's and the city's public library resources, as well as the credible sources available on the internet, it was not possible to thoroughly characterise all selected crops by the parameters mentioned above. All crops and the respective properties gathered are organised in the table ANNEX 1 – Agricultural Crops and Herbs Characterisation. As various sources provide different implantation compasses and durations for the crop cycles, the range of values presented in the table results from the minimum and maximum values found. It is important to mention that these values of compass and crop cycle duration are merely indicative since the same depend on the specific crop variety and desired product to harvest (e.g., seeds or leaves). Regarding the solar irradiation needs, every time the terms "full sun", "high luminosity demand", "direct sunlight", and "good solar exposure" were found, the same were encountered as "sunny".

After the research, a total of 35 horticultures and 16 herbs typical from Portugal and the Mediterranean climate were found. From these, Table 4.1 has listed the crops with shade-tolerant characteristics and/or that have demonstrated promising results in the agrivoltaic experiments mentioned in the state-of-the-art of this dissertation:

Table 4.1: Shade-tolerant crops typical from Portugal and the Mediterranean Climate.

Shade tolerant	Partial shade tolerant	Light shade tolerant	Low luminosity
Barley [156]	Arugula [157]	Lettuce [50, 102, 158, 159]	Chard [160]
Eggplant [160]	Beetroot [158]	Mustard [157]	Radish [160]
Grapes [71]	Broccoli [97]	Tomato [106, 105, 161]	Turnip [160]
Pepper [107, 158]	Cabbage [158]	Spinach [162]	
Potato [39, 104]	Carrots [163]		
Rosemary [98]	Cauliflower [158, 160, 164]		
Strawberry [26, 100]	Coriander [165]		
	Lemon Balm [164, 165, 166]		
	Mint [165, 166]		
	Onion [109]		
	Parsley [163, 165, 166]		

	Peas [158]		
	Pennyroyal [165]		
	St. John's Wort [165]		
	Thyme [166]		

Given that the modules have a minimum height of 0.30 m at their maximum inclination [143], the selected crops should have maximum heights of 0.30 m or less. Among the identified crops, and considering that many horticultural varieties exceed this height, only carrots and lettuce turn out as suitable options for the PV park, as both have a maximum plant height of 0.30 m. Furthermore, both carrots and lettuce can be sown and harvested throughout most of the year. This facilitated the development of a practical crop rotation plan for these crops.

Table 4.2: Relevant agricultural properties of carrot and lettuce.

	Carrots	**Lettuce**
Family	*Apiaceae* [157, 160, 164, 167, 168]	*Asteraceae* [157, 159, 160, 164, 167]
Cardinal Temperatures [˚C]	Minimum lethal temperature: -3 for leaves and -5 for roots Germination: Min: 2.3-7 Opt: 20-25 Max: 30-35 Optimum root growth: 16-21 Vegetation: Min: 6 Opt: 15-21 Max: 30-35 [164] Frost tolerance: -3 for superficial plant and -5 for root [160]	Germination: Min: 2-5 Opt: 15-25 Max: 30 Optimum monthly average: 15-20 Leaf production: Day: 12-15 Night: 10-12 Head formation: Day: 10-12 Night: 2-6 Optimum soil temperature: 13-15 [164] Frost tolerance: -6 [160], avoid frost [159]
Solar radiation	- Long-day plant [160, 168] - Grows when daytime is over 12 h [160] - Sunny [163] - Partial shade tolerant [163]	- Long-day plant [160] - More than 10 h per day [157, 159, 160] - Sunny [158, 163] - Light shade tolerant [158, 159]
Hydric needs	- Spray or central pivot irrigation [167] - 30-50 mm/week [157, 164] - Frequent irrigation and with low rotation [168] - Avoid water excess [167, 168]	- Drop [159] and hydroponic [167] - Periods of high demand every 5-7 days [160] - Periods of low demand every 15-20 days [160] - High water demand [164]
Soil movement and mechanisation needs	- First 4 cm should be well crushed [157] - Tillage 25-30 cm deep [164] - Ridges and grooves [157, 164] - Harvest can be mechanical [164, 167]	- Loamy-sandy texture at 40-50 cm depth [157] - Levelled ground [159] - Superficial soil mobilisation [159] - Ridges and grooves [159] - Tillage [159] - Minimise mobilisation [159] - Planting can be mechanical [164]
Maximal height [m]	0.3 [164]	0.3 [164]

Crop cycle	- Biennial plant [160] cultivated as annual [164] - Cycle can vary between 75-220 days [164, 167] - Sowing from February [168] until November [164] - In hot climate, sowing during February-October [160] - In extreme climate, sowing during April-August [160] - Harvest in 100-200 days after sowing [160]	- Biennial plant [160] cultivated as annual [164] - 45-90 days cycle [159] - In hot climates can be sowed all year [159, 160] - In extreme climates can be sowed during March-April [160] and September-October [159, 160] - Harvest in 60-150 days [160]
Implantation method	Direct sowing [157, 168]	Direct sowing [157, 162] or transplanting [157, 164]
Compass [m]	Ridges 0.2-0.25 high and 1.1-1.2 wide [157, 168] 4-8 rows [157, 168] Rows: 0.17 [157, 167, 168] - 0.45 [164] Plants: 0.05 [164, 167] - 0.15 [157, 164, 168]	Ridges 0.25-0.3 high with one or more rows [159] Direct sowing in 0.5 x 0.15 [159] 4 rows [159] Rows: 0.25 [159, 167] - 1 [164] Plants: 0.2 [159, 164] - 0.5 [160]
Rotation	- Minimum recurrence period of 3 years [157, 164] - Plant before fall/winter Brassicas [162] - Plant after *Alliaceae*, Cucurbits, potato, cauliflower, broccoli, or maize [169] - Do not plant after other *Apiaceae* or *Gramineae* [164] - Associate with lettuce, rosemary, peas, garlic, radish, tomato, broad beans, coriander, beans, onion, sage, pepper, leek [170] - Do not associate with chard or maize [170]	- Can be used as main crop for rotation [157, 164] - Plant before cabbage, beetroot, and beans [157] - Plant after *Alliaceae*, Cucurbits, potato [169], *Solanaceae*, Cucurbits and *Apiaceae* [164] - Avoid planting after *Brassica* or *Fabaceae* [164] - Can be associated with cabbage, beetroot, radish [157], tomato, cucumber, peas, garlic, leek, beans and broad beans [170] - Do not plant with celery or parsley [170]

As only two appropriate crops were identified, which also can be integrated into one crop rotation plan, there was no need for a final selection based on the economic value.

Considering the information in Table 4.2, it is advisable to schedule the planting of lettuce after the cultivation of *Apiaceae*. Consequently, the crop cycle should start with the cultivation of carrots. Lettuce exhibits a lower optimal germination temperature range (15-20 °C) compared to carrots (20-25 °C). Similarly, the optimal temperature range for the lettuce's head and leaf formation (between 10-15 °C during the day) is lower than that required for the root formation of carrots (16-21 °C). Additionally, carrots require longer daylight periods compared to lettuce. Thus, carrots are better suited for cultivation during the summer, while lettuce is more favourable for winter growth. Even though lettuce typically requires more than 10 hours of daylight, considering that the day length in Portugal is approximately 9 hours during the winter solstice [139], it is assumed that this one-hour disparity in daylight duration will not significantly affect crop growth. In addition, before every new crop cycle, it is recommended to conduct soil quality analyses and, if necessary, a fertilisation process to enhance productivity. Consequently, the proposed crop rotation calendar is the following:

Table 4.3: Proposed crop rotation activities of the carrot-lettuce cycle for the Cercal Power PV park.

Months	**Activities**
April	Fieldwork: fertilisation, tillage, ridges, and groves for carrots
May	Direct sowing of carrots
June	Growing period of carrots
July-August	Harvest period of carrots

September	Fieldwork: fertilisation, removal of remaining carrots, soil mobilisation and levelling for lettuce
October	Direct sowing of lettuce
November	Growing period of lettuce
December-February	Harvest period of lettuce
March	Pause

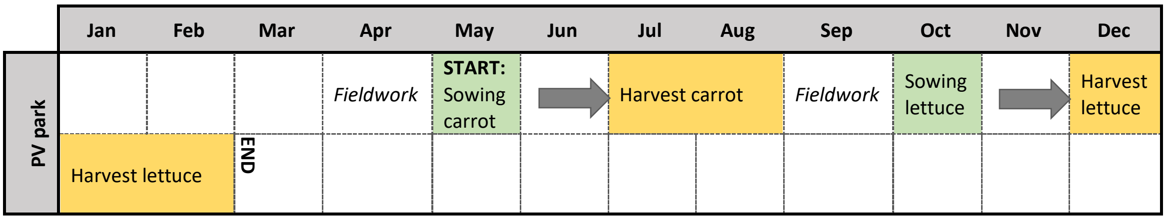

Figure 4.3: Proposed crop rotation calendar of the carrot-lettuce cycle for the Cercal Power PV power plant.

To guarantee enough space for the machinery while maximising the cultivated area, the latter will be delimited by the modules' lower edge at their maximum inclination, suggesting a safety distance to the middle axis of the arrays of 1.40 m.

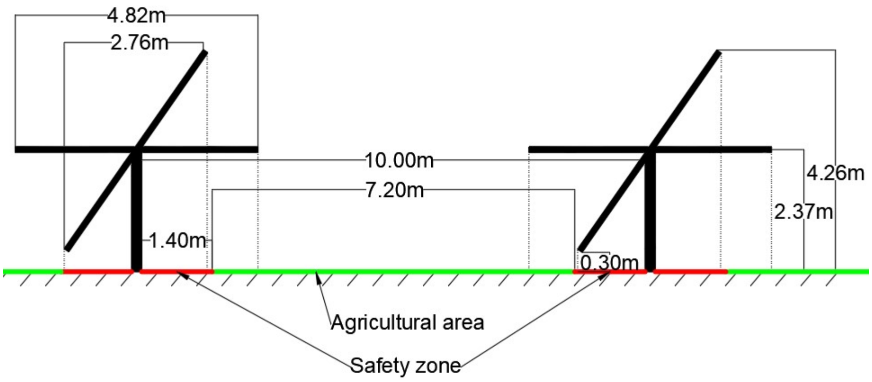

Figure 4.4: Proposed agricultural area between the PV arrays of the Cercal Power PV plant.

Therefore, as the trackers are spaced 10.0 m between rows, the proposed agricultural area between the arrays will be 7.20 m wide. In this design, fieldwork only can be carried out when the PV arrays are at their maximum inclination. Moreover, to facilitate the movement of workers or machinery for maintenance purposes of the PV system, which can occur during the growing periods of the crops, the agricultural area should feature two uncultivated rows. These rows should have a width matching the machinery's tyre dimensions and be separated by a distance equivalent to the axle length.

Further, an appropriate irrigation system must be designed to satisfy the water requirements of the crops. Since it is preferable to irrigate carrots through spray mechanisation and lettuce through drip irrigation, it is necessary to develop two distinct irrigation systems. These systems should be designed to facilitate switching when transitioning between crops. One possibility could be using the same irrigation infrastructure with exchangeable nozzles, using a drop nozzle for lettuce and a spray nozzle for carrots. The nozzles would then be changed during the fieldwork before the sowing period of each crop. The design of the infrastructure, i.e., the diameter and of the tubes, the number and size of the nozzles, should be designed according to the water requirements of each crop. The irrigation could be regulated and controlled by an automatic and intelligent irrigation system.

Focusing on safety means, since agrivoltaic systems have a higher risk of damaged wiring and equipment [26] due to the agricultural activity itself and the fieldwork, it must be ensured that all components are well protected. The main safety means in this case are the protection of cables, which can be done by installing them at an appropriate height (2 m or more [26]) or burying at a safe depth. In this case, it is considered to fix the cables along the structure to avoid additional soil movements.

4.1.1.2 Agrivoltaic Pilot

The purely new agrivoltaic installation, along with a reference plot characterised by the absence of a PV system, will initially serve as an experimental test field. The aim is to investigate the impact of the PV system on the crop yield and other agricultural parameters.

Moreover, it would be interesting to compare the agricultural performance between the agrivoltaic pilot, the reference plot, and the retrofitting case. This approach would allow a comparative assessment of the crop yields across three distinct scenarios:

1. The agrivoltaic approach;
2. Integration in preexisting commercial PV system;
3. The reference situation with full sun exposure.

Given that the suggested crops for the commercial PV arrays of the Cercal Power plant are carrots and lettuce, these will also be proposed for the initial studies with the agrivoltaic pilot. Also, the agrivoltaic pilot must have the same cultivated area as within the PV arrays to allow a proper comparison.

Within the agrivoltaic pilot, three different shade patterns are proposed, which result from different module technologies and arrangements. The aim of the proposed areas, the comparison of agricultural parameters between the three plots, and the different shading levels in the agrivoltaic pilot, is to answer the following questions:

i. Can we integrate agricultural activities in PV power plants without modifying their design, i.e., is retrofitting feasible?
ii. On stilted agrivoltaic structures, how do the shade patterns resulting from different PV module configurations and technologies influence agricultural parameters?
iii. Is agrivoltaic feasible in the Alentejo province?

After the comparison between the two PV configurations, other crops and a different cultivated area can be used for the agrivoltaic pilot for further studies only with this design, i.e., without considering the retrofitting case.

For the agrivoltaic system, a suitable area had to be identified in the project area. To compare the results of the pilot with the observations made in the commercial PV arrays and reference areas, the three plots should be relatively close, so they experience similar environmental conditions. The selection of the area for implementing these three plots was based on the following criteria:

1. Proximity to a water source;
2. Gently sloping topography;
3. Easy access by agricultural machinery;
4. Representative size;
5. Proximity to farming neighbours with potential for collaboration.

After analysing the project layout and environmental constraints of the site, an area that meets the mentioned criteria was identified on the west side of the PV power plant (see Figure 4.5).

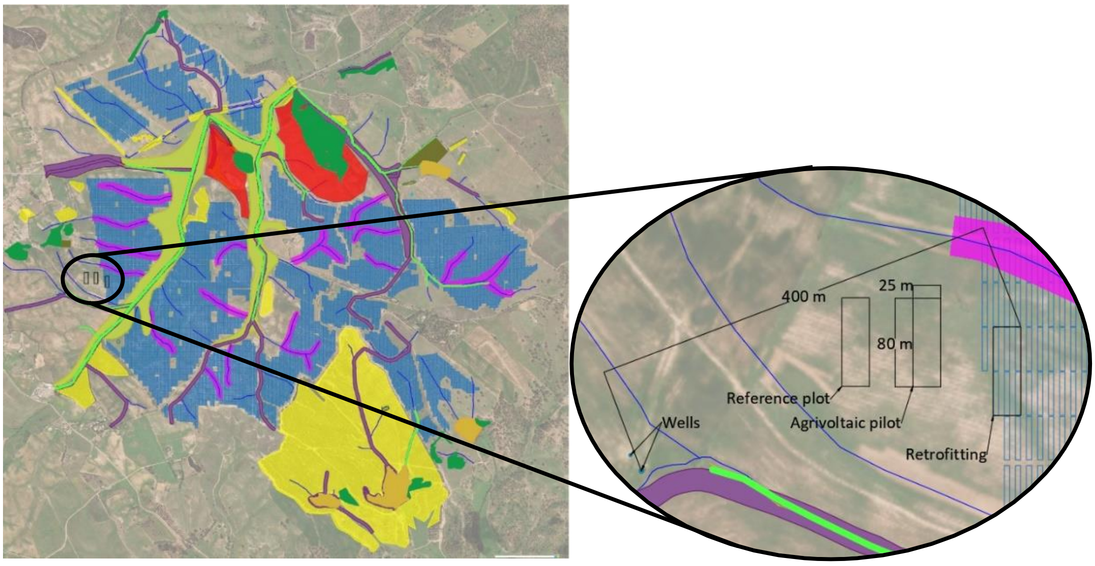

Figure 4.5: Proposed locations and areas for the agrivoltaic, retrofitting, and reference experimental plots in the Cercal Power PV power plant.

The chosen areas were selected since, firstly, the nearest well is at a maximum distance of about 400 m, and secondly, the same land had been previously used for agricultural purposes. Each area will have dimensions of approximately 25 m x 80 m, totalling 2000 m^2. Therefore, the selected areas are sufficiently representative to investigate the reciprocal effects of PV modules on agricultural activities. In the case of the retrofitting plot, the area will cover three PV module rows.

4.1.1.2.1 Structure

In the design of an agrivoltaic project, the maximum plant height and/or the utilisation of agricultural machinery determines the minimum required structure height. Nowadays, most agricultural practices rely heavily on mechanisation involving large equipment for tillage, sowing, and harvesting, which implies significantly higher structures, thereby increasing the CAPEX of the PV system. Following the recommendations of Fraunhofer ISE [39] and Weselek et al. [96], the structure should be at least 5 m high to allow agricultural machinery to work safely. Therefore, this height is proposed for the agrivoltaic pilot at Cercal do Alentejo.

Concerning flexibility, fixed structures with 0° azimuth for PV panels were selected for being economically more attractive, with a module inclination of 33° which is the optimal angle for Cercal do Alentejo [139]. 3 m of interrow spacing is assumed to be adequate to allow enough light to reach the crop while still achieving satisfactory energy yields [96]. In this way, a possible design for the agrivoltaic pilot structure could be as the following:

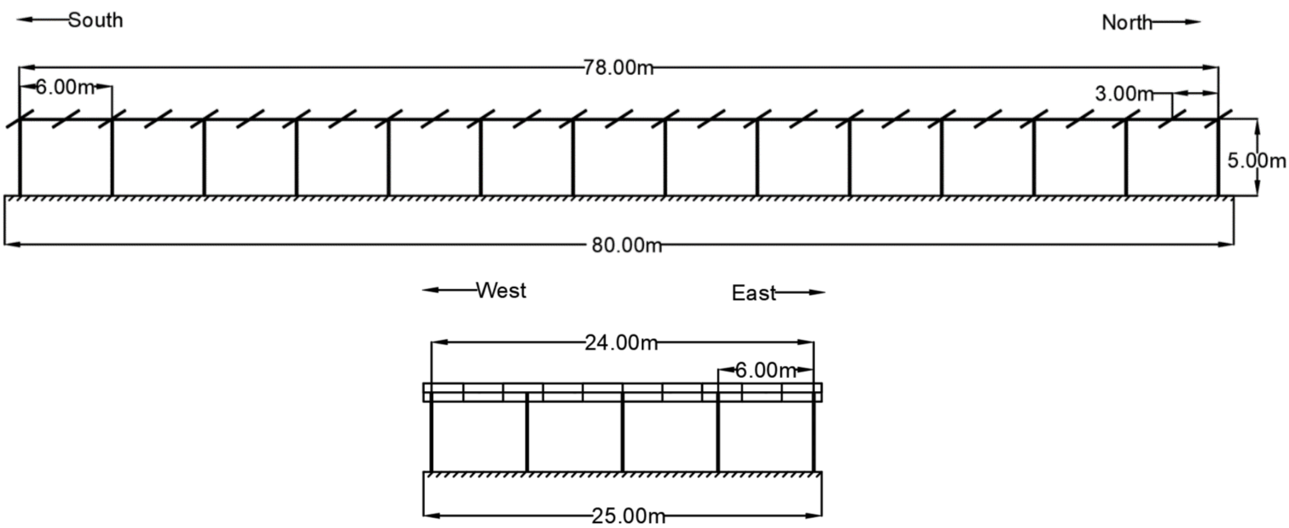

Figure 4.6: Side and front views of the proposed structure for the agrivoltaic pilot.

The approximately 80 m x 25 m field provides sufficient space for 27 rows of modules, with a 3 m separation between each row. It is important to note that Figure 4.6 represents only a conceptual design. In this representation, 70 masts are separated by 6 m. However, the number and distance between masts will depend on the chosen PV modules and the outcomes of mechanical load studies, such as structural analysis. Additionally, the quantity of modules in each row will also vary based on the selected module technology and density.

However, the structure should be anchored using driven metal piles, as in the commercial PV park. This avoids the use of concrete or other foundation types, thereby minimising the impact on the soil.

4.1.1.2.2 Photovoltaic Modules

Once it is intended to study the impact of different shading levels or patterns, three different zones are suggested which are provided by different PV technologies with different densities:

- High shade: opaque modules with full density;
- Partial shade: opaque modules with half density;
- Light shade: semi-transparent modules with half density.

For the partially shaded zone, opaque modules are proposed to allow the comparison of results between this area and the high-shaded plot, once the only difference between the two plots is the panel density. The difference between the partially shaded area and the light-shaded area relies on the transparency of the module technology. Consequently, the following comparisons can be made:

1. Influence of opaque module density shading on the crop yield;
2. Influence of transparency level in a half module density configuration on the crop yield.

In order to reduce the CAPEX expenses associated with the pilot project's higher structure, the option of using second-life opaque modules could be explored, which come with significantly reduced costs compared to new ones. Besides the cost reduction, this approach promotes the reuse of PV modules from other PV energy facilities. Although, the selection of second-life modules is only recommended for agrivoltaic systems that are mainly agricultural centric, once these modules have a reduced energy conversion efficiency due to their degradation over time.

Considering the total area for the agrivoltaic design, each module technology will occupy an area of about 25 m x 26. 7 m, equal to 667.5 m^2, encompassing 9 module rows. Regarding the densities, the full density zone will have rows completely full of modules, whereas the half density will be achieved through a checkered pattern obtained by taking out every second module from the full density design.

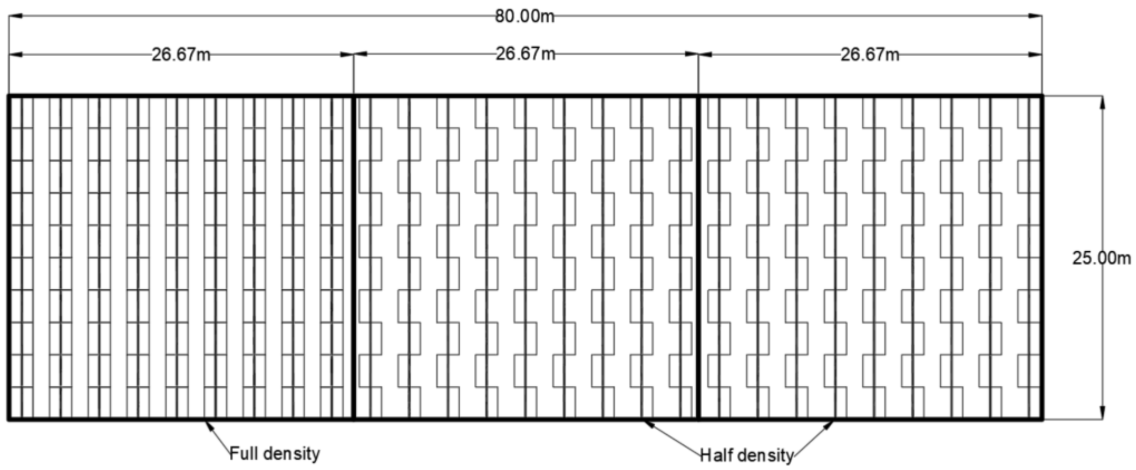

Figure 4.7: Proposed arrangements for the full and half PV module densities for the agrivoltaic pilot.

ANNEX 2 - Conceptual Design of the Agrivoltaic Pilot for Cercal Power contains the technical drawing of the proposed design.

As for the agricultural area integrated into the PV park, the wiring of the agrivoltaic pilot must be protected from workers and machinery. To avoid additional land movements to bury the cables at a safe depth, the same must be fixed on the structure as in the retrofitting case. Inverters and other electrical equipment should be positioned at a safe distance from the agricultural area. This is to prevent any potential contact between agricultural workers and the equipment during fieldwork, and it also ensures that PV professionals are away from the agricultural area during the maintenance of the electrical equipment.

4.1.1.2.3 Design of the Agricultural System

To enable a meaningful comparison, the cultivated area in all three plots needs to be consistent. Given that the PV park and its layout impose restrictions on the available cultivated space, both the reference and agrivoltaic plots must have the same cultivated area as the retrofitting plot. Thus, the area effectively cultivated in each plot will be of 2 x 7.2 m x 80 m, equivalent to 1152 m^2 (see Figure 4.8).

The irrigation systems must also be the same in the three plots. The water needed for irrigation could potentially be supplied by the two wells located near the chosen areas, identified on Figure 4.5, but only if the available groundwater is sufficient. If groundwater levels are low, an alternative water source may be necessary. For example, additional water reservoirs could be installed near the area to meet the irrigation needs.

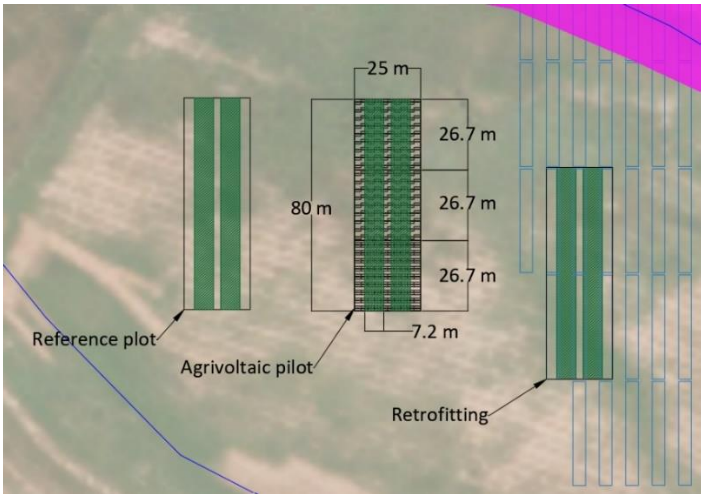

Figure 4.8: Effective cultivated area on the agrivoltaic, retrofitting, and reference plots.

By setting the carrot-lettuce cycle as the initial experiment for the agrivoltaic pilot, including an equal area on the commercial PV arrays to investigate the retrofitting strategy, the three experimental plots will have the following technical specifications:

Table 4.4: Technical specifications of the agrivoltaic pilot, retrofitting of the commercial PV park, and reference plots.

	Agrivoltaic Pilot			Retrofitting of commercial PV park	Reference
	High shade	**Partial shade**	**Light shade**		
Plot dimensions	25 m x 80 m; 2000 m^2				
PV system					
Height	5.0 m			2.4 m (trackers)	-
Interrow spacing	3.0 m			10.0 m	-
Structure orientation	W-E			N-S	-
Flexibility	Fixed, 33°			Single-axis tracking	-
Foundation	Driven metal piles			Driven metal piles	-
PV module technology	Opaque 2nd life	Opaque 2nd life	Semi-transparent	Bifacial	-
PV module density	Full density	Half density	Half density	-	-
Agricultural activity	Carrots-Lettuce cycle				
Agricultural area	2 x 7.2 m x 80 m; 1152 m^2				

4.1.1.2.4 Monitoring

To understand the impact that different PV configurations have on agricultural conditions and yields, it is necessary to define an appropriate monitoring system which is installed in each study area. The parameters that should be considered for monitoring are:

- Environmental conditions, with one measurement station close to the three plots to measure:
    - Air temperature;
    - Precipitation levels;
    - Relative air humidity;
    - Solar irradiance;
    - Wind speed and direction;
- Agricultural parameters, through multiple measurements at each experimental plot:
    - Agricultural yield;
    - Air temperature;
    - Evapotranspiration;
    - LAI;
    - Photosynthesis;
    - PAR;
    - Product quality;
    - Relative air humidity;
    - Soil moisture;
    - Soil quality through point demonstrations over time;
    - Soil temperature;

- Rainwater distribution: measurement of the rainwater dispersion in the soil. This is aims to study the influence of the PV modules of the agrivoltaic and retrofitting plots on the rainwater dispersion.

The following table has some examples of sensors recommended for monitoring agronomic parameters in agrivoltaic systems:

Table 4.5: Recommended sensors for monitoring in agrivoltaic systems [171].

Parameter	Measurement	Sensor
Soil temperature, moisture, and salinity	Measurements across multiple depth points to monitor soil conditions along a depth profile	Sentek Drill & Drop [172] Earth Science GroPoint (moisture only) [173] Seeed Studio S-Soil MTEC-02A [174] Seeed Studio S-Soil MTEC-02B [175] Campbell Scientific SoilVUE10 [176]
Soil NPK	Soil nutrient monitoring, nitrogen, phosphorous, potassium; Delivers information regarding plant nutrient uptake and seepage;	EIC soil NPK sensor [177]
PAR	Measures light spectrum with higher sensitivity in photosynthetic range compared to pyranometers; Can be installed flexibly at plant height; Important performance indicator due to radiation absorption by PV systems;	LI-COR LI-190R [178]; Seeed Studio S-PAR-02A [179] Apogee Quantum [180] TSL2561 Luminosity Sensor (NDVI spectroscopy sensor) [181] AS7265x Smart Spectral Sensor (NDVI spectroscopy sensor) [182]
Leaf temperature and wetness sensor	Should be installed in the same conditions as the plant, underneath the module, and with different orientations; Additional sensors should be included in a weather station as a reference;	INFWIN LWS10 (leaf wetness sensor) [183] Rika RK300-04 (leaf wetness and humidity) [184] Seeed studio S-YM-01 (leaf temperature and wetness) [185]
Photosynthesis	A handheld system with modular chambers for enclosing plant leaves in a clamped, airtight chamber; CO_2 flux is measured within the airtight chamber under the influence of different radiation profiles to ascertain plants' light sensitivity profiles;	LI-COR LI-6800 [186] CID CI-340 [187]
CO_2 concentration		Vaisala GMP252 [188] Vaisala GMP343 [189]

As the purpose of the agrivoltaic pilot is to carry out experiments to study the effect of the design on the agricultural yield of crops, the locations of the different sensors of the monitoring system were defined based on its design. Each shading area was divided into five rows and five columns, totalling 25 squares of 5 m x 5.33 m, equivalent to 26.65 m^2 (see Figure 4.9). Around the centre of each square, a set of sensors for measuring evapotranspiration, photosynthesis, PAR, soil quality, moisture, and temperature, as well as air temperature and relative humidity could be installed. Following this design, each shading zone, of almost 666.67 m^2 will have 25 measurement points, equivalent to 26.67 m^2/sensor. The same kind of sensors with the same distribution as in one shading area of the agrivoltaic pilot should also be installed in the retrofitting plot. Finally, one sensor of each must be installed in the reference area.

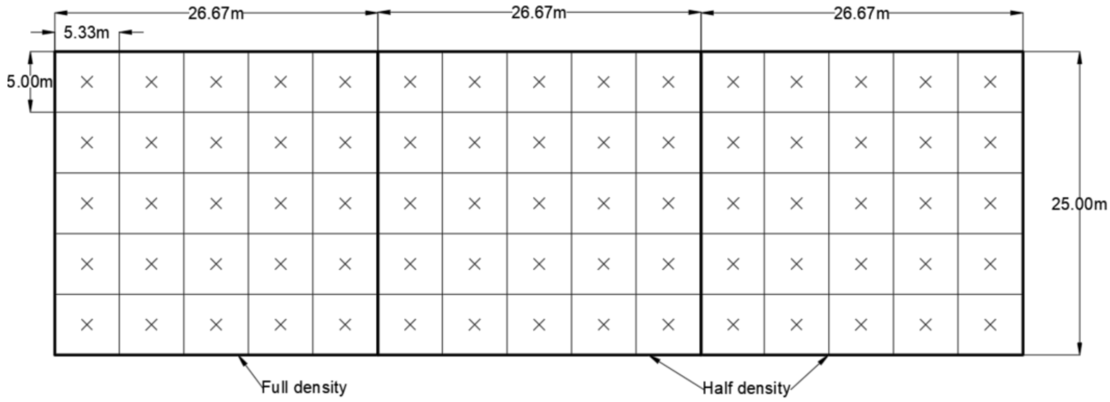

Figure 4.9: Proposed sensor grid for the agrivoltaic pilot.

Rainwater distribution measurements should be carried out through sensors installed on three different positions relative to the PV module rows: directly under the modules, under the modules' edge, and between rows. The exact location of these sensor will depend on the chosen modules and its dimensions. Also, these sensors should be installed in the retrofitting and reference areas. These devices could rely on simple soil moisture or water content sensors, such as the SoilVUE10, which measures the volumetric water content along a depth profile.

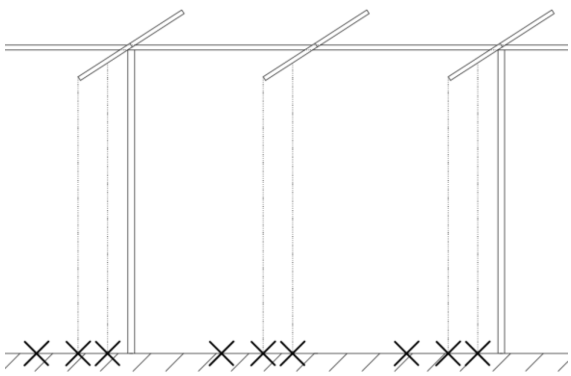

Figure 4.10: Proposed rainwater distribution measurement points.

The agricultural parameters agricultural yield, LAI, and product quality are assessed after harvesting.

With this monitoring system, it is forecasted to observe variations between the distinct study areas once different shading conditions and potentially diverse microclimatic conditions are generated by each PV system configuration. It is expected to have an enhanced crop quality, especially for carrots, in the agrivoltaic and PV areas, as during summer the modules will protect the crops from the intense solar radiation. Additionally, the shade probably helps maintaining the moisture levels in the soil. The aim of measuring all these parameters in the agrivoltaic plot and in the PV park is to understand whether the integration of agricultural activities with PV energy generation, without compromising the respective yields, demands the development of an entirely new system. Simultaneously, the investigation seeks to determine the feasibility of incorporating such activities into existing commercial PV facilities.

4.1.1.2.5 Procedures

After the engineering and procurement of all elements of the agrivoltaic pilot and irrigation and monitoring systems, the construction phase should proceed with the following steps:

1. Soil levelling, if required;
2. Installation of the structure, avoiding soil compaction and preferably during a dry period;
3. Installation of the modules and inverter.

The next actions, besides being for the agrivoltaic system, are also applicable to the retrofitting pilot:

4. Installation of all cables under the modules and along the mounting structures using additional protection elements;
5. Installation of the irrigation system according to the hydric needs of the crops;
6. Installation of the monitoring systems;
7. Commissioning;

Only after installing all components and the commissioning period the preparations for crop cultivation can start, once the previous steps involve the movement of workers and machinery on the field.

Before initiating the fieldwork and sowing the crops on unfamiliar land with unknown nutrient levels, it is recommended to conduct soil quality analysis. This analysis aims to evaluate the soil's composition, nutrient content, and overall health, indicating if fertilisation is necessary. Thus, for the initial studies with a carrot-lettuce cycle, the following steps are recommended:

8. Soil quality analysis;
9. Soil fertilisation according to the previous analysis and aligned with the crop's requirements;
10. Fieldworks according to the crop's requirements, such as tillage, soil mobilisation, and seedbed preparation;
11. Start of the proposed carrot-lettuce cycle (see Figure 4.3), adding the following steps:
    - 11.1. Data collection of the different parameters monitored during the crop cycle;
    - 11.2. Final crop product quality evaluation after harvest;
    - 11.3. Data analyses and comparison between plots;
    - 11.4. Assessment of each setup and identification of improvements.

Should any step result in significant soiling on the modules' surfaces, it is advisable to clean them.

All mentioned steps are presented in the following Gantt:

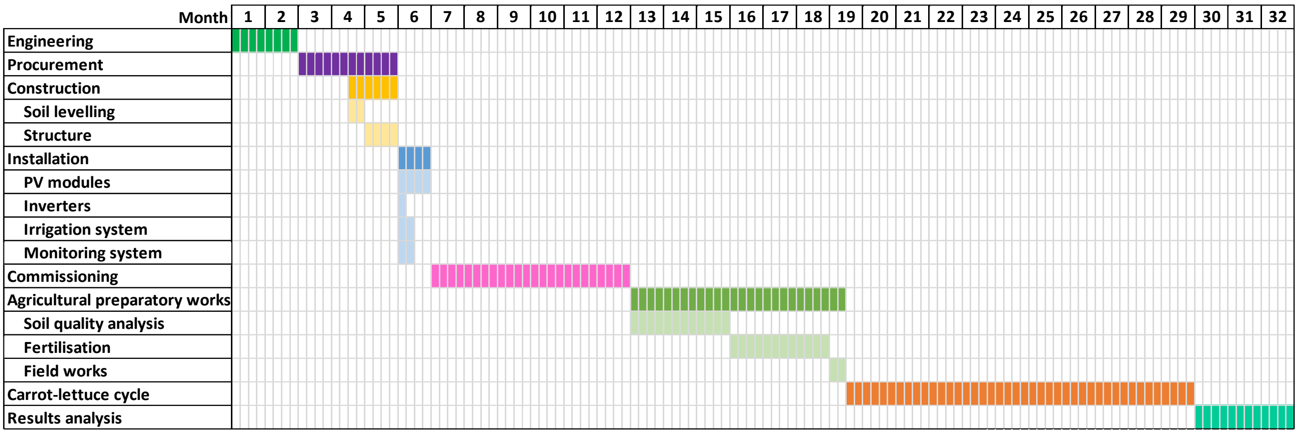

Figure 4.11: Proposed Gantt for the agrivoltaic pilot EPC phases and first experimental study.

According to the suggested Gantt, the execution of the agrivoltaic project from EPC until the result analysis is forecasted to have a duration of about 2 years and 8 months.

4.1.2 Livestock Grazing

4.1.2.1 Sheep Grazing

During the field visit some landowners were met who lease their land to the company for the PV project. Among them, some currently use the land for their sheep and cows to graze.

According to the Italian guideline [48], the average height of the modules on flexible structures of a PV system should be at least of 1.3 m to allow livestock activity. As the Cercal Power PV plant predicts a minimum clearance height of 0.3 m and a maximum of 4.26 m, with an average of 2.28 m, the PV facility allows livestock grazing. However, given the substantial size and weight of cows, it is not advisable to continue their grazing in the area after the installation of the PV park. This precaution is taken to mitigate the potential damage to the PV infrastructure and to ensure the safety of the animals, considering the presence of electrical equipment.

However, sheep can safely continue their grazing practices, once it has been successfully done in other sites ([77, 190, 191]). In this approach, sheep will profit from the modules' shade, especially during summer. Additionally, the modules' shade may enhance the ground coverage between the rows, promoting more food for the animals. Therefore, it is proposed to allow sheep to graze across the entire PV park. This offers the additional advantage of eliminating the need for vegetation control by providing sustainable land management. To ensure effective vegetation control by sheep, the latter should follow a rotational plan between the different areas of the PV plant, in order to avoid overgrazing and consequently the appearance of bare ground. Nevertheless, all PV areas occupied by sheep must fulfil special safety requirements, thus, as in the agricultural area, all cables must be well protected by fixing them at the structure to avoid any potential contact with the animals.

4.1.2.2 Black Pig Rearing

Besides sheep and considering that the project area has several *montado* zones, the option of including black or Alentejo pigs is explored. The black pig-*montado* binomial is the key to the sustainable development of this autochthonous species and is important for the equilibrium of the *montado*'s biodiversity [192]. In traditional production, the *montado* is important during the fatting period of the pigs [193]. Given that the pigs will primarily remain in the vicinity of the oak trees to consume acorns, their presence in the PV arrays area will likely be minimal. Consequently, it is anticipated that pigs will not interfere much with the PV system. As a result, this approach would not be categorised as agrivoltaic, as there is no interaction and mutual benefit between the PV system and the pigs. It is suggested that black pigs should be held in the zones with higher *montado* density, which are marked in red on Figure 4.20.

4.1.3 Beekeeping

Beekeeping is not considered agrivoltaic in the strict sense, however, it should be explored for the Cercal Power PV plant to enhance the natural propagation of plant species, while preventing the collapse of the bee populations. This practice allows the production of beekeeping products, such as honey, pollen, and propolis, among others. Therefore, beehives can be installed throughout the project implementation area, giving special emphasis to locations sheltered from the prevailing winds and exposed to the east or south.

The following table summarises the proposed agrivoltaic compatibility strategies:

Table 4.6: Summary of the proposed agrivoltaic compatibility strategies for Cercal Power.

Strategy	Main objective	Target area
Retrofitting of the commercial layout	Enhance the land's potential	PV area
Agrivoltaic design	Research	see Figure 4.5
Sheep grazing	Vegetation control	PV area
Black pig rearing*	Management of the *montados*	*Montados*
Beekeeping*	Production of local beekeeping products, enhance pollination and prevent bee population collapse	Entire project area

*Not strictly agrivoltaic

4.2 Ecovoltaic Compatibility Strategies

The following ecovoltaic approaches are an initial study of possible initiatives for the PV plant under study with some inputs from experts of the fauna and flora fields from the Mediterranean Institute for Agriculture, Environment and Development, and Institute of Earth Sciences, both from the University of Évora. The here presented strategies, such as the agrivoltaic strategies, will be evaluated by the company and adjusted after receiving the final biodiversity reports of the site.

4.2.1 Renaturation and Habitat Restoration

The easiest zones to undertake renaturation efforts are the REN areas, ponds, and the areas surrounding the main watercourses. Some of these zones remain untouched during the operation and maintenance of the PV park, being devoid of human interference. This allows the creation of small natural sanctuaries. The process of renaturing these areas will involve enhancing the existing habitats by promoting the growth of the existing flora and establishing shelters for the associated faunal species. A special focus should be considered on Habitat 6310 of *Quercus spp.* and the two units of riparian vegetation, Habitat 6420 and Habitat 92A0pt3, identified during the EIA. According to the input of faunal and floral experts, Habitat 92A0 can be enhanced through the restoration of the main water lines using willow cuttings (*Salix atrocinerea Brot.*). The restoration of this habitat is essential to reduce water erosion, as well as to promote local biodiversity, such as birdlife. The promotion of Habitat 6310 must be based on soil conservation, allowing the regeneration of lively herbaceous cover, control of shrub cover, and a dispersed tree cover of different ages.

In addition to enhancing the existing habitats, considering the limited floral diversity, and recognising that the Alentejo has numerous floral species under conservation status [194], it is worth considering the incorporation of some endangered species native to the Cercal do Alentejo region within the PV plant. The inclusion of endangered species could contribute to the restoration of floral habitats and subsequently lead to an enriched faunal biodiversity. Following the Red List of Vascular Flora [155], the following species occur in the region of Cercal do Alentejo:

- *Bupleurum acutifolium*: classified as vulnerable, living in dry and open scrubland and rocky areas, that only exists in the Cercal do Alentejo. Height of 0.30–1.00 m [195];
- *Chaenorhinum serpyllifolium*: classified as in danger, a plant endemic to the southwest coast of Portugal, which colonises crevices in calcarenite rock outcrops and human buildings made of this rock. Height of 0.20–0.30 m [196];

- *Doronicum plantagineum*: classified as vulnerable, an endemic plant of south Portugal which occurs on edges and in the undergrowth of evergreen or marcescent scrub and woodland. Reaches heights up to 0.90 m [197];
- *Klasea algarbiensis*: classified as vulnerable, occurs in clearings of scrubland on sandy soils. Generally stemless, i.e., its floral buds grow close to the ground [198];
- *Scorzonera hispanica*: classified as in danger, the herbaceous perennial that inhabits forest clearings. Height of about 0.60–0.90 m [199].

A blend of the listed species could be planted across different zones within the project implementation area. However, since each species is linked to a distinct habitat with unique properties, it might be necessary to establish specific environments, e.g. incorporation of calcarenite rocks for *Chaenorhinum serpyllifolium*.

Furthermore, the presence of the endemic *Juniperus navicularis* Grand., a juniper that occurs practically only in the southwest of Portugal, should be highlighted. The main conservation measures for juniper in the study area include soil conservation, as well as the control of exotic species. Nonetheless, to determine if these species can be effectively introduced in the project area, and if so, to establish the precise locations and procedures for the introduction, it is necessary to gather more detailed information of the site through field visits.

Figure 4.12: Bupleurum acutifolium [200].

Figure 4.14: Doronicum plantagineum [202]

Figure 4.13: Chaenorhinum serpyllifolium [201].

Figure 4.15: Scorzonera hispanica [203].

Figure 4.16: Klasea algarbiensis [204].

Besides the ponds, REN and watercourses, which are areas without PV arrays, given that some studies highlighted increased ground coverage in the partially shaded areas between module rows in PV parks [23, 108, 113], it is reasonable to consider implementing such initiatives in the interrows of the PV park. Furthermore, the landscape features valleys coincident with some watercourses that, when shaded by the PV arrays, might exhibit higher soil moisture levels than in the surroundings, consequently enhancing the expansion of ground coverage. Hence, valleys within the interrows of the PV park may be favourable sites for renaturation and the reintroduction of local endangered floral species. Some of the more pronounced valleys are highlighted in pink in

Figure 4.20. Nevertheless, renaturing the valleys within the PV areas is challenging. On one hand, these areas should ideally be kept as undisturbed as possible to reestablish the fauna and wildlife populations. On the other hand, in the case of floral species, specially near to the arrays, it must be ensured that they do not grow over the modules to avoid any shading on the PV modules. In the case study, plants must be lower than 0.30 m near the modules. This results in increased maintenance requirements for grass cutting, leading to increased disturbances besides interrupting the natural development of the species. Concerning this, two options are proposed:

1. Incorporation of sheep grazing into the renaturation area for sustainable land management, according to a rotational plan. This implies introducing plant species consumed by the animals, so the same are effectively controlled;
2. Incorporation of floral species with maximal plant heights of 0.30 m, thereby diminishing the need for vegetation control. From the endangered species, e.g., only *Chaenorhinum serpyllifolium* and *Klasea algarbiensis* could be reintroduced. In the centre of the interrow spacings slightly taller floral species can be planted.

Furthermore, it is important to control the presence of invasive exotic species in places where they have already been detected, as they gain expression with the disturbance of ecosystems and threaten habitats. The list of invasive exotic species can be found on Decreet-Law n.º 92/2019 of 10th of July [205].

4.2.2 Green Curtains

Additionally, based on a visual impact assessment of the PV park specific zones require obstruction. The obstruction can be created using "green curtains" of indigenous trees, such as the *Arbutus unedo* L. [206, 207].

The *Arbutus unedo L.* has multiple uses, including leather tanning, traditional medicine, and the production of the renowned *medronho* brandy, making it economically attractive. Additionally, it acts as a pioneer species, thriving on nutrient-poor soils and exhibiting fire resistance. Its blossoms provide bees with abundant nectar and pollen, while its fruits serve as sustenance for birds. The dense foliage offers shelter to insects and small animals in winter, and the extensive root system promotes soil stabilisation. It can achieve height of up to 15 m [208]. In the area of Cercal, it often reaches 4 or 5 m in height and can reach larger dimensions in gardens.

Figure 4.17: Arbutus unedo L., an indigenous tree which can achieve heights up to 15 m [206].

Following the information given in [208] and [209], the following shrubs and trees may be suitable for green curtains around the PV park, as they are native to the region:

- *Crataegus monogyna* Jacq.;
- *Erica arborea* L.;
- *Erica lusitanica* Rudolphi;
- *Fraxinus angustifolia* Vahl;
- *Myrtus communis* L.;
- *Nerium oleander* L.;
- *Pistacia lentiscus* L.;
- *Populus nigra* L.;
- *Pyrus bourgaeana* Decne.;
- *Rhamnus alaternus* L.;
- *Salix atrocinerea* Brot.:

- *Salix neotricha* Goerz;
- *Salix salviifolia* subsp. *australis* Franco;
- *Sambucus nigra* L.;
- *Tamarix africana* Poir.;
- *Viburnum tinus* L..

According to [208], *Salix atrocinerea* can achieve height up to 15 m, and is important for the protection and conservation of water lines and moist zones, a noteworthy aspect given the current conditions on the site.

4.2.3 Nidification and Breeding Spots for Birds and Mammals

Actions aimed at enhancing floral biodiversity will consequently enhance faunal biodiversity, once a healthy and diverse plant community can provide a wide array of food, shelter, and other resources that faunal species depend on, resulting in an overall increase in faunal biodiversity.

Nevertheless, it is advised to introduce supplementary wildlife measures, especially for birds since the same are the predominant faunal group at the project site with 17 endangered species. In the project area, the Great Bustard (*Otis tarda*) and the Little Bustard (*Tetrax tetrax*) are confirmed [146]. According to the input of faunal experts, these steppe species depend on the traditional extensive cereal crops system and big continuous habitat areas, leading to a need for habitat conservation and habitat management measures.

Furthermore, the incorporation of shelters for birds within the forest areas could be considered, including birdhouses and hidden nidification spots on trees or on artificial structures across the project site. Also bat houses to promote arboreous bats shelters in the forest areas should be distributed.

For some mammals such as rabbits, classified as in danger, naturalised shelters made by a mix of piles of wood, branches, stones, and soil, can be improvised. These kinds of spots are also used by reptiles.

4.2.4 Hedgerows as Passages for Wildlife

The defined layout has included fences around the different PV array areas, which hinders the passage of wildlife to and from the PV park to the surroundings. This can be overcome by replacing the traditional fences with green fences made of shrubs, such as hedgerows. These structures provide shelter and shade for animals, control erosion and act as windbreaks or firebreaks [210] with the proper species, while allowing the passage of wildlife.

Figure 4.18: Example of a hedgerow as fence [210].

Table 4.7 summarises the proposed nature conservation strategies for the Cercal Power PV plant, their main objective and target areas.

Table 4.7: Summary of the proposed ecovoltaic compatibility strategies for the Cercal Power PV Power Plant.

Strategy	Main objective	Target area
Enhancement of the existing habitats	Renaturation and biodiversity enhancement	REN, ponds, watercourses
Introduction of endangered floral species	Renaturation and biodiversity enhancement	REN, ponds, watercourses, PV arrays
Indigenous trees and shrubs as green curtains	Visual obstruction required by the Visual Impact Assessment Shelter for wildlife	Main roads and around the project area
Shelter and nidification spots for birds	Improve natural conditions for local bird species	Forests
Shelter spots for mammals and reptiles	Improve shelters for mammal and reptile species	Grassland and pastures, PV arrays
Hedgerows	Green fences to allow the passage of wildlife while providing shelter and food	Replacement of the conventional agricultural fences

Figure 4.19 is an attempt to illustrate the difference between a conventional PV power plant and one incorporating the proposed actions using the Artificial Intelligence (AI) image generators Imagen [211] from Google and Dall-E [212] from OpenAI, available on Canva [213].

As previously mentioned, these approaches are an initial study of possibilities for the forthcoming PV power plant at Cercal do Alentejo. Additionally, the final report concerning floral and faunal species is still being developed, gathering more detailed information about the exact species present in the implementation area, their distribution, and exact occurrence locations. With this information, the nature compatibility strategies can be more targeted at specific species and habitats.

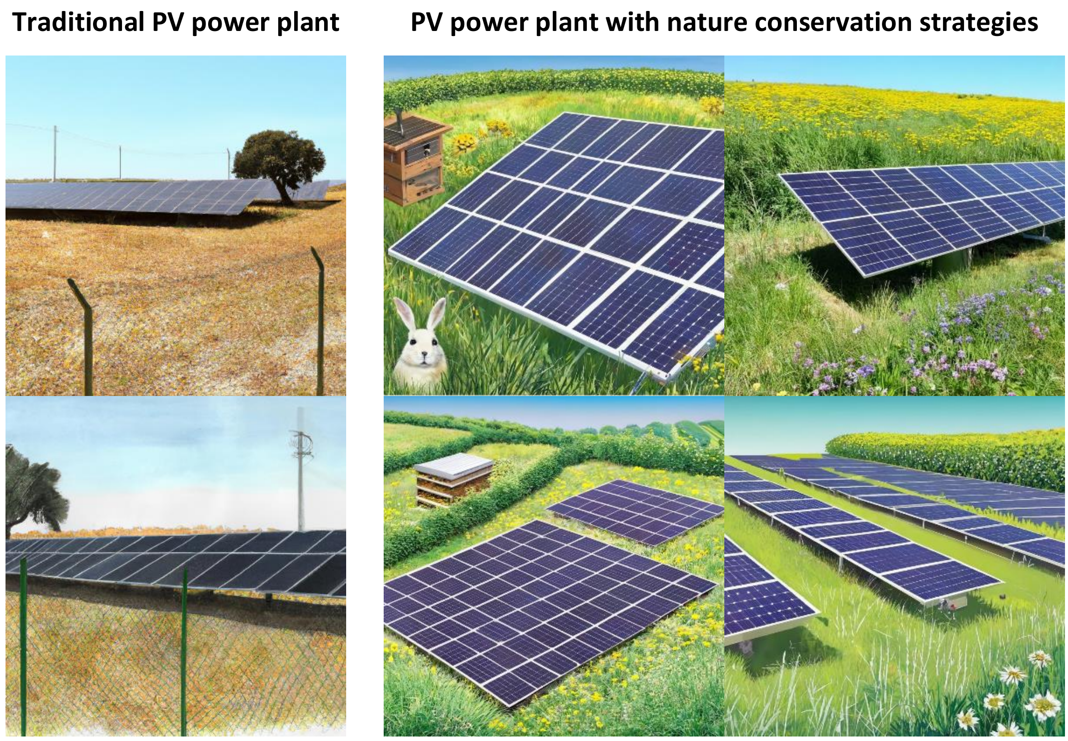

Figure 4.19: Illustration of the differences between a traditional PV power plant (left) and with the proposed nature conservation strategies (right).

Although the designated zones for nature conservation and biodiversity improvement are intended to remain undisturbed, certain actions are proposed to examine their progress, i.e., to measure their effectiveness by comparing the measurements taken over a certain period with the conditions before the installation of the PV park. Some of the recommended measurements are:

- Conducting on-site assessments of floral density and ground coverage;
- Counting and documenting insect populations;
- Measurement of soil properties:
    - Temperature;
    - Moisture;
    - Organic matter;
    - Biological indicators;
    - Microbial communities.

As the project site is characterised by poor and dry soils, especially during summer, it is expected to have similar results as obtained in the deserts in China ([24, 114, 115]), i.e., a cooler microclimate and a ground cover recovery. However, there is still missing research about the impacts of PV parks on the natural environment, which makes the definition of appropriate nature conservation strategies more difficult.

By implementing these strategies and measures, the primary goal is to investigate the feasibility of renaturing PV parks and to demonstrate the possibility of creating a positive environmental impact on big PV power plants. If the results are promising, best practices can be identified and listed to be applied to other commercial PV parks, fostering a positive environmental impact on both the renewable energy sector and the natural conditions on site.

To conclude, and provide an overview,

Figure 4.20 has identified some possible and approximated locations for the proposed compatibility strategies for the Cercal Power PV plant.

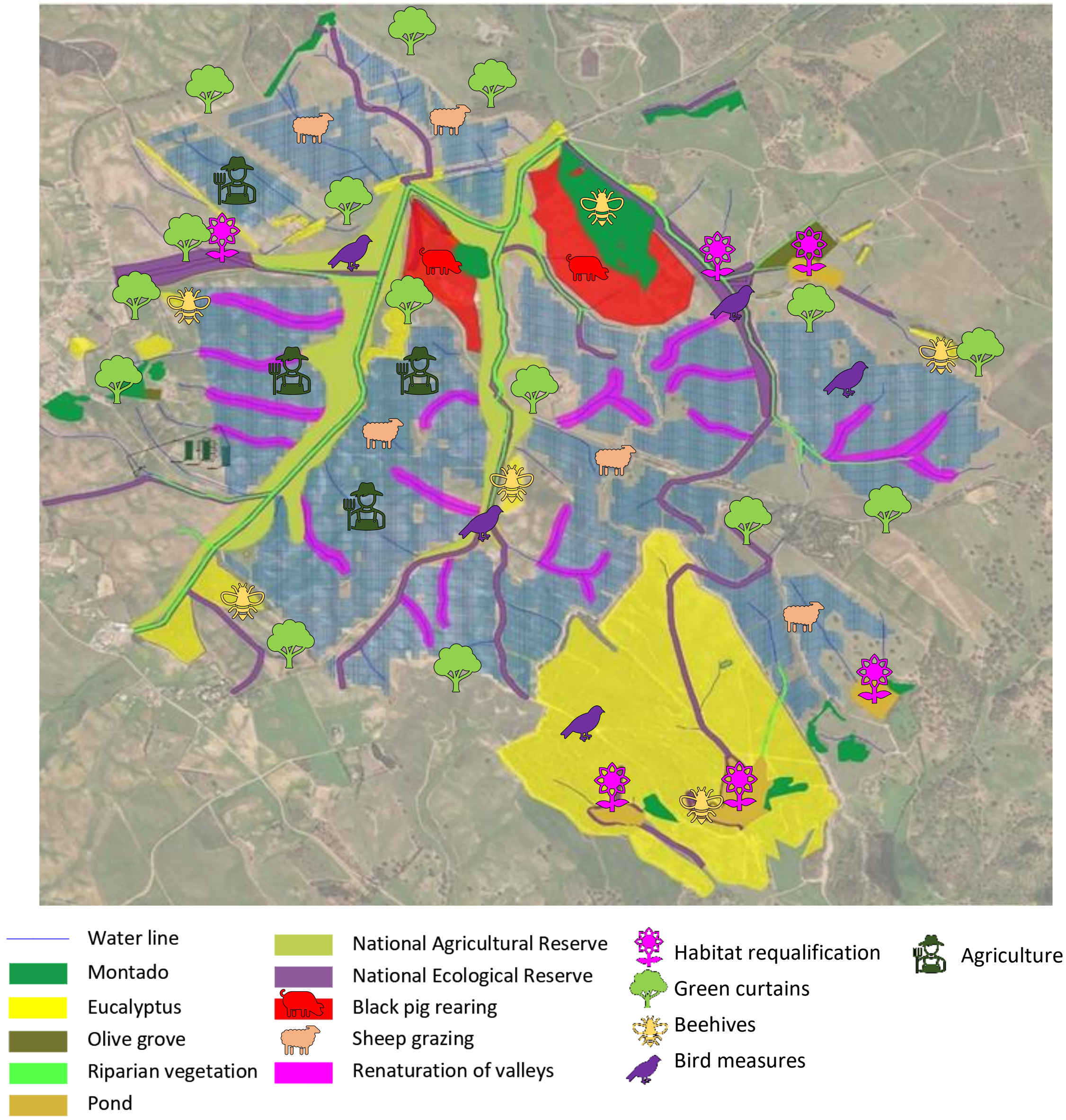

Figure 4.20: Proposed areas for agricultural and nature conservation compatibility strategies for the Cercal Power PV power plant.

Regarding the beehives, bird measures, habitat requalification, and agriculture, the respective icons do not pinpoint the precise location or number of actions, but rather indicate proposed areas. Nevertheless, it is recommended to maintain a separation of 1 km between beehives, given that bees operate within a 3 km radius.

ANNEX 3 - Agrivoltaic and Ecovoltaic Compatibility Strategies for the Cercal Power PV Power Plant contains the project site's environmental constraints, PV array locations, black pig rearing areas near the identified *montados*, and a zoom-in of the agrivoltaic, retrofitting and reference areas, with the respective scaling factors.

4.3 Agrivoltaic and Ecovoltaic Compatibility Strategies Tool

Parallel to the definition of the previous strategies for the specific case of the Cercal Power plant, but within the study for Aquila Capital, a tool to find the best agrivoltaic and ecovoltaic strategies for any other PV power plant was developed. In the case of the Cercal Power plant, the company has already defined the layout and established specific goals, including incorporating crops and renaturation. From these statements, the previous strategies were defined and proposed. In contrast, the aforementioned tool is intended for future projects where a predefined layout is not yet established. No document or tool like this has been developed yet. However, farmers and PV project planners should be provided with informed guidance for agrivoltaic and ecovoltaic initiatives. Such a tool can foster the adoption of these approaches. Selecting the optimal design for agrivoltaic systems, and recognising the variety of possible configurations and applications, may pose a challenge for farmers and PV project planners. Similarly, the choice of ecovoltaic strategies presents a comparable complexity. Furthermore, every PV facility should implement actions aimed at conserving and enhancing ecosystems and their services and biodiversity. Incorporating such measures not only aligns with the principles of sustainable development but also contributes significantly to global targets for biodiversity preservation.

The proposed tool is based on a matrix database to select the most suitable agrivoltaic and/or ecovoltaic strategies for a given PV project considering a set of key indicators, aiming to improve the environmental conditions of the site and/or enhance the land's potential. The referred matrix can be consulted on ANNEX 4 – Matrix Database of the Agrivoltaic and Ecovoltaic Compatibility Strategies Tool.

Given a certain implementation area or a conventional commercial PV power plant, the user should choose the most relevant key indicators according to the expectations, priorities, or business model for the project. To each indicator, the user must assign a relative weight according to its priorities. Based on these weights, the matrix offers a systematic approach to identifying and rank the most effective strategies through a final merit factor, enabling a comparison of all strategies. Strategies with the highest scores are deemed the most suitable for the project and context in case. Further analysis by the user could include sensitivity analysis for any given indicator and relative weights.

This tool was elaborated in collaboration with experts in fauna and flora fields from the Mediterranean Institute for Agriculture, Environment and Development, and Institute of Earth Sciences, both from the University of Évora.

4.3.1 Methodology

The matrix has agrivoltaic and ecovoltaic strategies in its rows and relevant key indicators in its columns. For each strategy, their potential impact on every key indicator was identified with values between -2 and 2, with the following classification:

- -2: very negative impact;
- -1: negative impact;
- 0: neutral impact;
- 1: positive impact;
- 2: very positive impact.

Not all indicators are applicable to every strategy, e.g., agricultural indicators do not apply to ecovoltaic strategies. Consequently, they have been assigned with NA – Not Applicable.

The classification of the potential impact of the strategies on each indicator was based on a comparison with the reference situation of a conventional commercial PV power plant. In the case of aquaculture as an agrivoltaic strategy, the reference system can be a silted or a floating PV system. The implementation of the strategies may imply modifications of the commercial PV design, such as, for example, elevated structures to allow the operations of agricultural machinery.

The evaluation of the impacts involved diverse group discussions with experts in faunal, floral, and PV systems fields. This approach was chosen to incorporate a wide range of perspectives and inputs. During the analysis of each strategy, each indicator was discussed to reach a final consensus among all three parties. Furthermore, the following general considerations were taken into account:

- Conservative scenario for the financial parameters;
- Financing costs were not considered in this analysis, given their variability related to the source of investment;
- The remuneration for the generated electricity is not considered given the variability of available remuneration schemes;

- The methodology and formulation for the various economic indicators follow the standard used by the PV industry in its technical and economic analysis, allowing a comparative analysis with projects of a similar nature;
- To the best of current knowledge, the estimated costs for the agrivoltaic systems were based on market values with a relative safety margin. However, the evolution of the international market for raw materials and logistics goods is particularly unstable, so the costs considered may vary when the investment is made, affecting the undertaken comparisons;
- Given the innovative nature of these topics, the concepts of agrivoltaic and ecovoltaic and their respective compatibility strategies and key performance indicators are the subject of ongoing research and innovation. Therefore, based on extensive research into the state-of-the-art, information was gathered on applicable compatibility strategies, ongoing pilot projects and quantifiable and qualifiable results. From this analysis comes the comparative score assigned in the matrix, which should naturally be seen as a dynamic and updatable document;
- Specific country contexts, for example, regulatory or legislative restrictions, are not reflected in this matrix scoring and should always be subject to ad-hoc analysis at the project design and engineering stage.

The following sections list and describe the proposed agrivoltaic and ecovoltaic strategies and the selected key indicators.

4.3.1.1 Agrivoltaic Strategies

These strategies are based on existing agrivoltaic projects found during the state-of-the-art research:

- Livestock grazing: grazing of cows, sheep, pork, and goats;
- Poultry: free-range chicken, turkeys or other birds farming;
- Beekeeping: incorporation of beehives and beekeeping goods production. Despite not being agrivoltaic in the strict sense, it is considered due to the ability to improve floral biodiversity at PV sites while producing beekeeping products;
- Forage: cultivation of forage crops;
- Permanent crops: cultivation of permanent crops;
- Rotational crops: cultivation of rotational crops, such as most vegetables;
- Vineyard;
- Orchards;
- Permaculture;
- Aquaculture: farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants [214];

- Greenhouse: greenhouse with integrated PV modules.

4.3.1.2 Ecovoltaic Strategies

As ecovoltaic strategies, the following actions were defined:

- Nature conservation: conservation of existing natural areas and their biodiversity and ecosystems in areas occupied by PV power plants and close surroundings, such as maintenance of the existing natural vegetation, no soil movements, no concrete foundation;
- Reforestation: reforestation of areas occupied by PV power plants and close surroundings;
- Habitat restoration: recovery and creation of habitats in areas occupied by PV power plants and close surroundings;
- Riparian restoration: recovery of riparian vegetation in areas occupied by PV power plants and close surroundings;
- Soil requalification: improving soil conditions at PV power plants, including the recovery of industrial soils, mining areas, brownfields, and infertile agricultural soils.

4.3.1.3 Key Indicators

The selected key indicators were grouped into five categories:

1) **Performance** - related to the productivity of an agrivoltaic system compared to the separated agricultural and energy productions:
    - Land Equivalent Ratio – LER;
2) **Agriculture**: related to the agricultural production:
    - Water-Use Efficiency – WUE;
    - Yield;
3) **Photovoltaic** - related to the PV energy production:
    - Soiling: impact on soiling levels on the modules' surface, which affects the energy conversion efficiency;
    - Efficiency: measures the impact of the implemented strategy on the modules' energy conversion efficiency, for instance, due to temperature changes;
    - Energy yield;
4) **Environment** - related to ecosystem services, including environmental conditions and biodiversity:
    - Landscape visual impact: visual changes to the landscape resulting from the implementation of the strategy;
    - Herbaceous: changes in the herbaceous cover. This criterion is based on the characterisation of herbaceous vegetation before and after the installation and during operation;

- Shrubs: changes to the shrub cover. This criterion is based on the characterisation of the shrub vegetation before and after the installation and during operation;
- Trees: changes in tree cover. This criterion is based on the characterisation of the tree vegetation before and after the installation and during operation;
- Macrovertebrates: changes in the macrovertebrates' communities. This criterion is based on the characterisation of these communities before and after the installation and during operation. A specific species or group may be highlighted whenever appropriate;
- Microvertebrates: changes in the microvertebrates' communities. This criterion is based on the characterisation of these communities before and after the installation and during operation. A specific species or group may be highlighted whenever appropriate;
- Invertebrates: changes in the invertebrates' communities. This criterion is based on the characterisation of these communities before and after the installation and during operations. A specific species or group may be highlighted whenever appropriate;
- Climate resilience: capacity of social, economic and ecosystems to handle with hazardous events, trends or disturbances, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in the case of ecosystems while also maintaining the capacity for adaptation, learning and transformation [215]. This indicator assesses the impact of the strategy on the climate resilience of the system and environment;
- Carbon balance: for the given 25-year lifespan of the PV power plant, the carbon balance can be: 0 for net-zero carbon emissions, <0 for overall positive carbon emissions, and >0 for overall carbon sequestration;
- Water: impact of the strategy on the soil's water retention capacity;
- Soil quality: impact on the organic matter levels in the soil. This criterion is based on the characterisation of the soil quality before and after the installation and during operation;
- Erosion: defined as the removal or detachment of the top layer of soil by water (hydraulic) and wind (aeolian), reducing levels of organic matter and nutrients, leading to a consequent decrease in its productivity [216]. This criterion is based on the characterisation of the soil erosion levels before and after the installation and during operation.

5) **Socioeconomic** - social and economic factors:
    - Jobs: refers to the number of jobs created for the management and operation of the installations, including the PV system, agricultural works, and forest management;
    - Levelised Cost of Electricity – LCOE;
    - CAPital EXpenditures – CAPEX;

- OPerational EXpenditures - OPEX: operation and maintenance costs of the installation, including vegetation control, module cleaning, equipment replacement, agricultural fieldwork, etc;
- Cultural ecosystem services: socioeconomic aspects of ecosystem services, such as public health, education, and leisure, once environmental aspects of ecosystem services are more explored in the environmental category;
- Revenue: refers to the profit of the installation, including the profit of the produced PV energy and agricultural products.

4.3.2 Example of Application

The proposed tool should be applied during the early stages of defining a new PV project. Following the life-cycle of a PV power plant, illustrated in Figure 4.21, the first step of a PV power plant is its pre-planning.

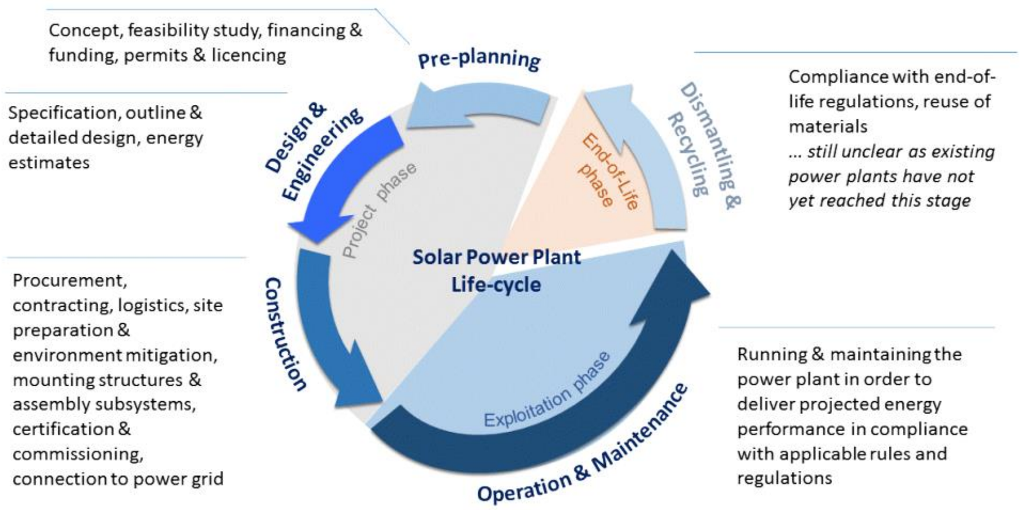

Figure 4.21: The different phases of a PV power plant life-cycle [217].

During the pre-planning phase, the business model of the project is drafted. The project planner must have a comprehensive understanding of both agrivoltaic and ecovoltaic concepts, including the possible compatibility strategies for a PV power plant. After understanding both approaches, the business model can be defined. This business model covers the project's desired return or output, values, available investments, and resources, aligning with economic returns and/or ecosystem services. By knowing the project site's characteristics, including the climatic and environmental conditions, obtained through the EIA, for instance, and considering the previously defined business model, the project planner identifies the most relevant key indicators. Each key indicator is assigned a relative weight based on its importance within the defined business model. The developed tool returns then the most suitable strategy based on a final merit factor and following a systematic approach. From the results, the project planner and the company can choose one or more of the strategies with the highest score.

The assessment tool was created in Excel and contains two sheets: one with the database matrix (ANNEX 4) and one with the user interface and calculator (Figure 4.22).

						Version	Date
	Agrivoltaic and Ecovoltaic Strategies Selector Tool					V1	22/11/2023

Instructions - How to use this tool ?

1st STEP-> Select the Key Indicators more suitable for your business model for a given PV project (up to five KPIs)	**Key indicator**	WUE	Herbaceous	Shrubs	CAPEX		
2nd STEP-> Assign the relative weight to each of these for the final merit formula, on a scale of 0 to 1. (their sum must equal 1)	**Relative weight**	0,4	0,2	0,2	0,2		OK

3rd STEP -> Check your results regarding weighted Merit Factor for each strategy and their corresponding Merit Factor ranking.

	Strategy	Merit Factor	Strategy	Ranking result
Agrivoltaic	Livestock grazing	0,6	Beekeeping	1,2
	Poultry	0,2	Habitat restoration	0,8
	Beekeeping	1,2	Livestock grazing	0,6
	Forage	-0,2	Nature Conservation	0,4
	Permanent crops	-0,6	Poultry	0,2
	Rotational crops	-0,4	Permaculture	0,2
	Vineyard	-0,6	Aquaculture	0,2
	Orchard	-0,6	Reforestation	0,2
	Permaculture	0,2	Riparian restoration	0,2
	Aquaculture	0,2	Soil requalification	0,2
	Greenhouse	-0,4	Forage	-0,2
Ecovoltaic	Nature Conservation	0,4	Rotational crops	-0,4
	Reforestation	0,2	Greenhouse	-0,4
	Habitat restoration	0,8	Permanent crops	-0,6
	Riparian restoration	0,2	Vineyard	-0,6
	Soil requalification	0,2	Orchard	-0,6

Figure 4.22: User interface and calculator.

To demonstrate an application case of the selector tool, the following example with numeric values is used:

The main objective of a PV power plant is to integrate agricultural activity, concerning that the target site presents limited water availability. Besides the agricultural practice, it is intended to increase the herbaceous and shrub communities in the surroundings to enhance the floral biodiversity. However, the available initial investment budget is also of strategic importance for the promotor.

For these objectives, the following key indicators and weights may be selected:

- WUE – 0.4;
- Herbaceous – 0.2;
- Shrubs – 0.2;
- CAPEX – 0.2.

Key indicator	WUE	Herbaceous	Shrubs	CAPEX		
Relative weight	0.4	0.2	0.2	0.2		OK

Figure 4.23: Introduction of the indicators and relative weights in the calculator tool.

The sum of the relative weights must always be equal to 1.0, otherwise, the calculator returns an error message.

Key indicator	WUE	Herbaceous	Shrubs	CAPEX	
Relative weight	0,4	0,2	0,2	0,3	

Relative Weight Sum is different than 1, please check your input values

Figure 4.24: Error message when the sum of relative weights is different than 0.

With the assigned weights and the potential impact classification values in the matrix, the tool calculates the final merit factor. This factor is calculated for each strategy through the sum of the multiplications of the assigned weights w_i by the impact classification I_i of each considered key indicator i, i.e.:

$$F = \sum_{i=1}^{n} w_i I_i, \text{ where } \sum_{i=1}^{n} w_i = 1.0 \qquad \textit{Eq 4.1}$$

On the interface, the merit factors are presented following a colour scale, with green standing for the best scores and red for the worst.

	Strategy	Merit Factor
Agrivoltaic	Livestock grazing	0.6
	Poultry	0.2
	Beekeeping	1.2
	Forage	-0.2
	Permanent crops	-0.6
	Rotational crops	-0.4
	Vineyard	-0.6
	Orchard	-0.6
	Permaculture	0.2
	Aquaculture	0.2
	Greenhouse	-0.4
Ecovoltaic	Nature Conservation	0.4
	Reforestation	0.2
	Habitat restoration	0.8
	Riparian restoration	0.2
	Soil requalification	0.2

Strategy	Ranking result
Beekeeping	1.2
Habitat restoration	0.8
Livestock grazing	0.6
Nature Conservation	0.4
Poultry	0.2
Permaculture	0.2
Aquaculture	0.2
Reforestation	0.2
Riparian restoration	0.2
Soil requalification	0.2
Forage	-0.2
Rotational crops	-0.4
Greenhouse	-0.4
Permanent crops	-0.6
Vineyard	-0.6
Orchard	-0.6

Figure 4.25: Final merit values for all strategies and corresponding ranking.

In the example, the highest final merit factor is of 1.2 for beekeeping, followed by habitat restoration (score of 0.8) and livestock grazing with a final score of 0.6. Consequently, beekeeping seems to be the most suitable agricultural practise for the project site. In any case, multiple strategies can be selected, for example, the first three strategies in the ranking can be integrated into the project.

Chapter 5
Conclusions

5.1 Conclusions

This dissertation has made it possible to provide answers to the research questions raised and to contextualise this recent application of coexistence of PV systems and agricultural production. The main questions were addressed (section 1.3) and it is possible to draw the following conclusions:

1. Agrivoltaic is a relatively recent concept where PV systems and agricultural activities coexist on the same land unit. In this approach, the PV panels provide shade and shelter to the crops underneath, protecting them from intense solar radiation and harsh weather, while decreasing evapotranspiration and thus irrigation needs. The panels, in turn, can benefit from the cooler microclimate created by the plants. Furthermore, and considering the global climate situation we are facing, agrivoltaic can support rural areas by minimising environmental pressure and offering solutions against extreme weather conditions, such as the droughts and heat waves in the Alentejo. If the PV system is designed in accordance with the crop's needs and the local climatic conditions, the design can promote climate resilience to the agricultural system. On the other hand, the PV system allows the generation of clean and cheap electricity, promoting the decarbonisation of the agricultural sector.
2. Agrivoltaic is defined as a dual-land use concept wherein energy generation through PV systems and agricultural production take place on the same unit. However, this integration needs to foster benefits for both through a synergetic relationship. In other words, PV generation shall profit from plants underneath through their transpiration and the generated cooler microclimate, increasing their efficiency, while crops benefit from the shelter provided by PV modules above. Besides crops, livestock can also benefit from the shading provided by the PV modules. Agrivoltaic designs vary widely, ranging from ground-mounted installations to stilted structures and even modules positioned vertically. However, there is no one-size-fits-all agrivoltaic solution, as the design depends on the specific activity and climatic conditions of the site. In any case, the facility has two outcomes: electricity and agricultural products.
3. While agrivoltaic designs are mainly focused on agricultural performance and production, ecovoltaic, in turn, is defined as the integration and co-prioritisation of PV energy generation and ecosystem services, where the PV system design is based on ecological principles. Ecovoltaic is even more recent than agrivoltaic and is based on strategies focused on the

enhancement of the environmental conditions and ecosystem services at PV power plants, being targeted to the soil and the faunal and floral biodiversity. But also here, and even more than for agrivoltaic, is no clear understanding of the PV system's impact on biodiversity and ecosystems. However, both approaches could help in the achievement of the ambitious international and national targets regarding GHG emissions and the consequent climate change, and biodiversity loss in the case of ecovoltaic. Furthermore, both agrivoltaic and ecovoltaic actions, if properly designed, can reduce the environmental impact caused by the construction and operation of PV power plants.

4. Are there international and national legal frameworks for agrivoltaic? Portugal has initiatives aimed at integrating renewable energy sources, such as PV, into the agricultural sector, alongside measures to conserve and enhance ecosystems and biodiversity. However, no legal framework, guidelines, or similar documents at the national level addressing agrivoltaic or ecovoltaic have been published yet. In Europe, only Germany, France, and Italy have established national guidelines and standards for agrivoltaic systems. Nonetheless, such documentation is crucial to provide clarity on agrivoltaic and ecovoltaic approaches, thereby promoting the adoption of such designs. Particularly for ecovoltaic, measures aimed at preserving and enhancing the natural environment of PV sites should be mandatory.

5. Agrivoltaic is becoming a popular topic between companies and scientific companies. Agrivoltaic technology and projects have been developed more significantly in the last decade. In Europe, agrivoltaic applications can be found in Belgium, France, Italy, Germany, the Netherlands, and Spain. Berries seem to be a very popular crop for agrivoltaic, once these crops are generally sensitive. In Belgium and Germany, agrivoltaic is even being tested with orchards. Also, beekeeping and sheep grazing seem to be famous for being integrated into PV facilities. Moreover, companies developed proper structures and PV modules for agrivoltaic applications. However, there remains a need for more scientific research to fully understand the impact of agrivoltaic on both PV and agricultural production. Agricultural output is heavily influenced by factors such as solar radiation, temperature, evapotranspiration, and water availability, all of which can be affected by the presence of PV systems above or between crops. Scientific experiments demonstrated lower PAR radiation levels, lower air and soil temperature under PV modules with lower day-night amplitudes, and lower evapotranspiration, and thus higher moisture levels. These observations turn agrivoltaic into a promising solution to increase the agricultural sector's climate resilience. Understanding this relationship is crucial for optimising agrivoltaic designs and procedures. Such knowledge can encourage the adoption of agrivoltaic among farmers, thereby promoting the decarbonisation of the agricultural sector.

6. Agrivoltaic systems are generally classified according to the agricultural activity and the type of structure used. However, the designs also vary according to the module technology and

density. Considering the different pilots found, a classification system for agrivoltaic design is proposed, based on six categories: agricultural activity, farming system type, PV structure and its flexibility, PV module technology and density. The proposed classification illustrates the possibility of agrivoltaic designs for different agricultural activities and serves as an overview of the actual existing projects.

7. What agricultural and nature conservation actions can be integrated into the forthcoming photovoltaic power plant in Cercal do Alentejo? The Cercal Power PV power plant of the Aquila Capital Group is designed for 264 MWp on 816 ha land near Cercal do Alentejo, in the south of Portugal. This PV power plant already has a defined configuration in terms of module technology, interrow spacing and tracking structure, based on a typical design of a standard commercial PV power plant. The EIA of the project area suggests poor soil conditions making it inappropriate for any kind of agricultural activity, as well as limited floral and faunal biodiversity, having some species with concerning conservation status, especially birds. In addition, the province of Alentejo is known for its hot to very hot summers and low precipitation levels, which have been even more reduced due to climate change. In this way, it was attempted to define strategies that can diminish the additional environmental impact caused by the power plant and even have the potential to enhance the prevailing conditions, following the agrivoltaic and ecovoltaic concepts.

   The proposed agrivoltaic compatibility strategies rely on the cultivation of crops and livestock grazing activities that are aligned with the project area. For the cultivation of crops, two different approaches were explored, both based on a commercial agricultural practice focused on sustainable and organic farming on arable land. The first one consists of the cultivation of a carrot-lettuce cycle in the commercial PV power plant, being a retrofitting action of the latter. An already installed PV system can be turned into an agrivoltaic system with few or no modifications, with shade-tolerant and small crops growing under and between the PV panel rows, benefiting from their shelter and partial shade. Carrots and lettuce were chosen due to their low plant height, avoiding any shading on the PV modules. Both cultures are proposed for the area between the tracker rows, occupying about 7.2 m x 10.0 m. The second proposal is an additional purely agrivoltaic pilot, with stilted structures and three different shade patterns. This agrivoltaic system will initially be used for experimental studies to understand the impact of different PV system designs on agricultural parameters. Adding three different shading levels to the agrivoltaic pilot enables the assessment of the same crop performance under different environmental conditions. Such an amount of data has the potential to significantly contribute to scientific research on agrivoltaic practices and their impact on agricultural production. Still, within the agrivoltaic strategies, the integration of sheep grazing following a rotational plan throughout the entire project site for vegetation control is suggested, where sheep can profit from the PV modules' shade while ensuring sustainable land management. Once the project area has two *montado* zones, the integration of black pigs is proposed, promoting the health and management of these ecosystems. Furthermore, the installation of beehives to promote the propagation of plants should be explored on the project site, while supporting the bee population in general, with the additional benefit of producing local beekeeping products.

Regarding the ecovoltaic approach, the proposed strategies are divided into four main actions. The first action is based on the renaturation and biodiversity enhancement through the restoration and recovery of existing habitats, the introduction of endangered floral species on the main waterlines, ponds, REN areas and some valleys within the PV area, and the control of invasive exotic species. The second action is based on the plantation of native trees and shrubs as green curtains for visual obstruction to the PV park, an aspect required after the visual impact assessment of the power plant. One potential identified tree is the *Arbutus unedo* L., which has attractive properties such as fire resistance and the capability of enhancing poor soils while providing shelter and food for birds, bees, and other small animals. The third initiative is focused on faunal species, particularly birds, which are the faunal group with the highest number of endangered species at the project site. To support faunal species, structures for shelters, nesting, and breeding can be strategically implemented on the project site. Finally, the fourth measure involves introducing hedgerows to replace traditional fences, once the first facilitates the movement of small animals while providing both food and shelter.

8. The identification of agrivoltaic and ecovoltaic strategies for a certain site can be challenging. During the state-of-the-art research, no general guideline or similar for the implementation or application of agrivoltaic and/or ecovoltaic actions was found. There is a lack of comprehensive documentation about the steps to define and integrate such strategies during the planning process of a new PV project. Nonetheless, the current challenges of climate change affecting agricultural production and biodiversity, along with the urgent need for decarbonisation of the economic sectors and the development of climate-resilient systems, underscores the potential benefits of adopting agrivoltaic and ecovoltaic strategies. Considering this, the creation of a comprehensive document accessible to any conventional PV power plant project planner becomes crucial. In order to contribute to such a guideline, a tool for selecting the best agrivoltaic and/or ecovoltaic strategy, according to specific key indicators, for any future PV power plant was created. This tool is based on a database matrix of indicators and the potential impact that different agrivoltaic and ecovoltaic strategies may have on them. The proposed database must be seen as a dynamic and updatable document, as both agrivoltaic and ecovoltaic are recent concepts with few quantitative results published yet.

Once the strategy or strategies are selected during the initial phase of planning a PV system, the project continues with its EPC. In the case of an agrivoltaic compatibility strategy involving crop cultivation, engineering can start with defining the cultivated area and preferred crops, especially if no layout for PV system has been designed. Otherwise, based on the structure's height, interrow distance and flexibility (i.e., the presence of a sun tracker), a suitable area and/or compatible crops need to be selected. In this case, for small heights under 3 m, it is recommended to use the interrow spacings rather than the area under the PV modules. In any agrivoltaic system, it must be ensured that the structure does not interfere with the agricultural activity, including all fieldworks from tillage until harvest. It is also recommended to draw a crop cultivation calendar, to avoid that agricultural fieldworks coincide with major maintenance procedures of the PV system. Another safety measure is that no fieldwork should be carried out during extreme weather conditions, such as extreme wind and heavy rain. Since at agrivoltaic systems more frequent fieldworks are carried out due to the agricultural activity, all cables must be protected at an appropriate safe height or depth. Also, electrical equipment must be well protected. This is especially important when integrating livestock activities in the PV area.

For ecovoltaic strategies, in turn, the design and implementation of the strategies consider the specific environmental conditions of the site and the potential environmental impacts arising from the construction and operation of the planned PV facility. These strategies may also extend beyond the immediate project site to encompass surrounding areas, such as nearby forests. Given a certain ecovoltaic strategy returned from the tool, and considering the project site in case, the two main questions that arise are: where and how should the action be implemented? The implementation of these strategies highly depends on the nature of the strategy, project-specific conditions, and local variables, as well as the available investments and resources for such efforts that may not yield direct economic returns. Nevertheless, the initial step involves an exhaustive in-depth assessment of the existing natural conditions. After studying and assessing the environmental conditions at the project site and the identification of pertinent environmental challenges, a set of actions targeting the identified issues or vulnerable areas should be defined. These actions may either be punctual, focusing on specific areas, or expansive, covering multiple points across the project site and its surroundings. The foremost consideration for ecovoltaic efforts should be the preservation and enhancement of already existing and identified habitats, irrespective of their condition during the initial assessment. Each existing habitat should be safeguarded and, where feasible, improved. For an increased impact, additional areas for renaturation actions can be identified. Selection criteria for such areas may be based on topographical features, with valleys, watercourses, and ponds being particularly attractive due to their potential for water and moisture accumulation. Actions directed at specific floral and faunal species must be carefully chosen based on the inventory of species, their occurrence, and distribution across the entire project area. Following the identification of local species, research should be conducted into their natural habitats and the preferred environment for each stage of their life cycle.

In conclusion, the agrivoltaic application presents itself as an option for a just transition, ensuring that the possible environmental, social, and economic impacts of this transition to decarbonised electricity production systems are more appropriately addressed. This application has great potential in Europe, making a clear contribution to the objectives set by the EU and allowing sectors such as agriculture to be actively involved in solving the challenges we face today.

5.2 Future Work

Within the service provision for Aquila Capital, after the acceptance of the conceptual agrivoltaic pilot and compatibility strategies, the definition of the detailed agrivoltaic pilot will proceed. This will involve the EPC of the entire project, as well as the execution of the previously mentioned experiment with a carrot-lettuce cycle.

After the elaboration of this dissertation, further research questions emerged, which should be addressed in future work:

1. Is the agrivoltaic retrofitting of commercial PV power plants feasible?

The aim of the Cercal Power agrivoltaic pilot, by comparing the obtained results of the agrivoltaic and retrofitting pilots, is to understand whether the integration of agricultural activities with PV energy generation, without compromising the respective yields, demands the development of an entirely new system. Simultaneously, the investigation seeks to determine the feasibility of incorporating such activities into existing commercial PV facilities. Should this conjecture hold true, technical guidelines and practices can be defined for the incorporation of agricultural activities at pre-existing PV power plants.

2. Is agrivoltaic feasible for the Alentejo province?

This study would be the first implemented in the Alentejo region on a large scale. If the results are promising, this approach may present a solution to local farmers who are tackling the higher temperatures and lower precipitation levels due to climate change, while profiting from cheap and clean energy.

3. Given the environmental conditions of a PV power plant, how to define and implement targeted ecovoltaic strategies?

In this dissertation, once information about the exact species and their location at the project site was missing, no actions targeted to specific habitats and species were defined. However, having this information, in addition to more field visits, it is planned to identify more targeted ecovoltaic actions. The aim is to design an ecovoltaic pilot to measure and investigate the mutual impact of PV systems on environmental conditions, biodiversity, and ecosystem services. Additionally, as well as for the agrivoltaic approach, it is foreseen to prepare a set of best ecovoltaic practices and guidelines for preexisting commercial PV parks, with the goal of improving the local ecosystem services.

The outcomes from these pilots, coupled with a systematic review of agrivoltaic and ecovoltaic literature, can contribute to the refinement of the database matrix of the agrivoltaic and ecovoltaic strategies tool. Nevertheless, this undertaking may become exhaustive given the numerous selected key indicators. The feasibility of this effort also depends on the existence of a significant number of studies with quantitative results of the real impact of agrivoltaic and ecovoltaic actions.

Lastly, in addition to the Aquila Capital project, other agrivoltaic pilots are currently being designed for various locations: Herdade da Mitra, Alqueva and Graça do Divor, in Portugal, and Arroyo de la Luz, in Spain. Future experiments and their results at these pilots will also contribute to the refinement of the presented database.

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ANNEX 1 – Agricultural Crops and Herbs Characterisation

Crop	Family	Region and Climate	Cardinal Temperatures [ºC]	Solar radiation	Hydric needs	Soil movement and mechanisation needs	Maximal plant height [m]	Crop Cycle	Implantation method	Compass [m]	Rotation and Association
HORTICULTURE											
Arugula	*Brassicaceae* [1, 2, 3, 4]	South Europe [4] Mediterranean [4] Cool climate [4] Mild climate [1, 3]	Min: 0 [1] Opt: 15-20 [1, 2, 3] Max: 22 [1]	- Partial shade during summer [1] - Sunny during winter [1]	- Spray irrigation [4] or hydroponic [3] - Avoid water excess [1, 3] - Avoid soggy soils [3]	- Ridges and grooves [1, 2]	1 [1]	- Annual cycle [4] - 30-90 days cycle [3, 4] - Sowing during the end of winter and beginning of spring [4] - Harvest 20-30 days after sowing [4]	Direct sowing or transplanting [3, 4]	Low ridges 1-1.2 wide [1, 2] Rows: 0.1 [2, 3] - 0.6 [1] Plants: 0.05 [3] - 0.3 [1]	Rotation with species of other families [3]
Barley	*Gramineae* [5]	Alentejo [6]	Vegetation Opt: 15-18 After tillering: 17-18 [5]	Shade tolerant [7]	Rainfed crop [5]	- Seedbed preparation - Sowing is generally mechanical [8] - Harvesting is mechanical with a thresher [8]		- Winter cereal [5] - As forage crop, sowing during October-November [5] - For grains, sowing during February-March [5] - Harvest during June-July [8]	Direct sowing [5, 8]	Rows: 0.15-0.17 [8]	- Recurrence period of 4 years [5] - Rotation with other rainfed crops [5] - Can be rotated with sunflower, wheat, and Fabaceae [5]
Beetroot	*Chenopodiaceae* [9, 1, 3, 4, 10]	Alentejo [11] Mediterranean [4] Europe [4] Latitudes of 30-60 ºN [4] Mild climate [3] Temperate and moist climate [10]	Germination Min:5-8 Opt:18-20 Max:30 Vegetation Min: 5 Opt: 16-20 Max: 30-35 [4] Frost tolerance: -7 [9]	- Sunny [1, 12] - Long-day plant [9] - Partial shade tolerant [13]	- Spray or central pivot irrigation [3] - Periods of high demand every 7-10 days [9] - Periods of low demand every 15-25 days [9] - High water demand [4]	- Seedbed preparation [4] - Tillage [4] - Planting can be mechanical [3]	0.4 [4]	- Biennial plant [9] cultivated as annual [4] - Direct sowing in February-May [9] for early varieties and September for late varieties [10] - Harvest in 2-7 months depending on variety [3, 9, 10]	Direct sowing or transplanting [1]	Rows: 0.2 [3] - 0.6 [1, 4] Plants: 0.05 [1] - 0.3 [9] Low ridges 1-1.2 wide with 0.35-0.5 between plants [10]	- Rotation with cabbage, lettuce, carrot and beetroot [1] - Do not repeat on the same area [9] - In a rotational cycle of 3 years, plant on areas that were fertilised the year before for Fabaceae or onions, [14] - Plant before broad bean, pea, beans and cereals [9] - Do not plant after other Chenopodiaceae [4] - Associate with lettuce, onion, cabbage, beans, cauliflower, celery, and garlic [15] - Do not associate with chard [3], potato, carrot, tomato, leek, or beans [15]
Broad Beans	*Fabaceae* [9, 16]	Algarve [17, 18] Temperate and cool climate [16]	Development stop: 6-8 Germination Min: 7 Opt:12-20 Max: 30 Vegetation Min:8-10 Opt: 18-22 Max: 35 [9]	- Short-day plant [9, 16], with daytime under 13 h [9] - Sunny [12, 13]	Low water demand [9, 16]			- Annual cycle [9] - In temperate climates sowing during October-November [9] - Direct sowing in fall/winter in Portugal [16] - Harvest in 70-150 days after germination [9]	Direct sowing [9]	Rows: 0.35 [9] - 0.8 [16] Plants/Seeds: 0.15-0.30 [9, 16]	- Associate with cabbage, lettuce, potato, maize, and celery [15] - Do not associate with onion or garlic [15]

			Frost tolerance: -5 for the plant and -1 for flowers [9]								
Broccoli	*Brassicaceae* [2, 3, 4]	Mediterranean [4] West Portugal and Ribatejo [4]	Min: 5 Opt: 13-20 Max: 25 [4] Frost tolerant [4]	Sunny [12]	- Spray or drop irrigation [3] - High water demand [4] - Avoid water excess [3]		0.8 [12]	- Biennial cycle [4] - 90-120 days cycle [3] - Planting in summer or winter [2]	Transplanting [3, 4]	- Ridges separated by 1.5 [4] Double rows: 0.5-0.55 Plants: 0.5 - Single rows [4]: 0.4 [4] - 1.2 [3] Plants: 0.3 [4] - 0.7 [3, 9]	- Rotation with species of other families [3] - Do not associated with other Brassicaceae [3] - Associate with beetroot, celery, lettuce, potato, beans, peas, cucumber, spinach, oregano, onion, sage, rosemary, mint, tomato, camomile, and thyme [15] - Do not associate with strawberry, radish, zucchini, lettuce, maize, or leek [15]
Cabbage	*Brassicaceae* [1, 2, 3, 4, 9]	Portugal [1] Algarve [4] Ribatejo and west Portugal [4] Mediterranean climate [4] Mild and cool climate [1] Moist climate [2]	Germination Min: 4.5 Opt: 29 Max: 38 Vegetation Min:7 Opt Day: 16-18 Opt Night: 10-12 Max: 35 Vernalisation: 4-10 [4] Some species tolerate up to -10 ºC [1]	- Long-day plant [9], with daytime over 12 h [9] - Sunny [1, 12] - Partial shade tolerant [13]	- Spray [2] (not recommended [4]) or drop irrigation [3] - Irrigation need depends on the season: Spring: every 8-12 days Summer: 8-10 days Fall: 10-15 days Winter: 15-20 days [9] - Avoid soggy soil [3] - Drought tolerant [4] - Higher water demand with higher wind speeds [4]	- Ridges and grooves [2] - Tillage [4]	1.5 [4]	- Biennial cycle [1] planted as annual [4, 9] - 5-6 months cycle [9] - Can be planted all the year [1, 2, 4] - Leaf cabbage can be planted all the year [2] but is generally planted during July-August for harvest during winter [4] - Head cabbage can be planted in summer and winter [2] - 80-120 days for harvest begin [3]	Direct sowing or sprouts transplanting [1, 3]	Rows: 0.5 [1, 2, 9, 4] - 1 [1] Plants: 0.25 [1, 4] - 0.7 [9]	- Recurrence period of 5 years [4] - Rotation with species of other families [3] - Plant after Alliaceae, Cucurbits, Chenopodiaceae, Solanaceae [4], and sweet potato [27] - Do not plant after other Brassicaceae [4] - Associate with beetroot, celery, lettuce, potato, beans, peas, cucumber, spinach, oregano, onion, sage, rosemary, mint, tomato, camomile, and thyme [15] - Do not associate with strawberry, radish, zucchini, lettuce, maize, or leek [15]
Carrots	*Apiaceae* [1, 3, 4, 9, 19]	Alentejo [17] Ribatejo and west Portugal [4] Mediterranean [4] Temperate climate [4]	Min lethal temperature: -3 for leaves and -5 for roots Germination Min: 2.3-7 Opt: 20-25 Max: 30-35 Root grow Opt: 16-21 Vegetation Min: 6 Opt: 15-21 Max: 30-35 [4] Frost tolerance: -3 for superficial plant and -5 for root [9]	- Long-day plant [9, 19] - Grows when daytime is over 12 h [9] - Sunny [12] - Partial shade tolerant [12]	- Spray or central pivot irrigation [3] - 30-50 mm/week [1, 4] - Frequent irrigation and with low rotation [19] - Avoid water excess [3, 19]	- First 4 cm should be well crushed [1] - Tillage 25-30 cm deep [4] - Ridges and grooves [1, 4] - Harvest can be mechanical [3, 4]	1.5 [4]	- Biennial plant [9] cultivated as annual [4] - Cycle can vary between 75-220 days [3, 4] - Sowing from February [19] until November [4] - In hot climate, sowing during February-October [9] - In extreme climate, sowing during April-August [9] - Harvest in 100-200 days after sowing [9]	Direct sowing [1, 19]	Rows: 0.17 [1, 3, 19] - 0.45 [4] Plants: 0.05 [3, 4] - 0.15 [1, 4, 19] Ridges 0.2-0.25 high and 1.1-1.2 wide [1, 19] 4-8 rows [1, 19]	- Minimum recurrence period of 3 years [1, 4] - Plant before fall/winter Brassicas [14] - Plant after Alliaceae, Cucurbits, potato, cauliflower, broccoli, and maize [27] - Do not plant after other Apiaceae or Gramineae [4] - Associate with lettuce, rosemary, peas, garlic, radish, tomato, broad beans, coriander, beans, onion, sage, pepper, and leek [15] - Do not associate with chard or maize [15]

Cauliflower	*Brassicaceae* [2, 3, 4, 9]	West Portugal and Algarve [4] Moist and cold climates [4]	Min lethal temperature: -8 - -10 Germination Min: 6-8 Opt: 18-25 Max: 30-35 Vegetation Min: 3-5 Opt: 16-18 Max: 30 [4]	- Sunny [12] - Partial shade tolerant [4, 9, 13]	- Spray or drop irrigation [3] - High water demand [4] - During summer: every 8-12 days Fall: 15-20 days Winter: 20-25 days [9] - Avoid water excess [3]			- Biennial crop [9] planted as annual [4] - 90-140 days cycle [3] - Plant during spring-fall, depending on variety [2] - Harvest from end of summer until winter [4, 9]	Direct sowing [4] or transplanting [3, 4]	Rows: 0.6 [9]-1.2 [3] Plants: 0.4 [2, 3, 9] - 0.7 [3]	- Rotation with species of other families [3] - Do not associated with other Brassicaceae [3] - Associate with beetroot, celery, lettuce, potato, beans, peas, cucumber, spinach, oregano, onion, sage, rosemary, mint, tomato, camomile, and thyme [15] - Do not associate with strawberry, radish, zucchini, lettuce, maize, or leek [15]
Celery	*Apiaceae* [3, 4, 9, 19]	Temperate and subtropical climate [4] Mild climate [3]	Min lethal temperature: -2 Germination Min: 5 Opt: 15-20 Max: 25 Max liquid assimilation rate: 26 Vegetation Min: 5 Opt: 16-21 Max: 35 [4] Frost tolerance: 0 [9]	- Long-day plant [9, 19] - Blooms when daytime is over 12 h [9]	- Spray or drop irrigation [3, 4] - High water demand [9] - Season with maximal demand every 2-7 days [9] - Season with minimal demand every 20-25 days [9] - Constant moist level in the soil [19] - Avoid water excess [3]		0.6 [4]	- Biennial plant [9] cultivated as annual [4] - 100-160 days cycle [3, 4] - 4-5 months cycle during winter [4] - More than 3 months cycle during summer [4] - Sowing during summer [4] - Transplanting during September-November [4] - Harvest during December-April [4]	Transplanting [3, 19]	Ridges 0.7-1 wide with double rows Grooves 0.25 deep separated by 0.4-0.8 [19] Rows: 0.3 [3, 9] - 0.9 [9] Plants: 0.15 [4] - 0.4 [3]	- Recurrence period of 3 years without other Apiaceae [4] - Plant after Fabaceae, Aliaceae, Brassicas, and Solanaceae [4] - Rotation with species of other families [3] - Associate with spinach, garlic, leek, cabbage, cauliflower, onion, beans, tomato, beetroot, cucumber, broads beans, and peas [15] - Do not plant with lettuce, maize, parsley or potato [15]
Chard	*Chenopodiaceae* [3, 4, 9, 10]	Mediterranean [4] Europe [4] Latitudes of 30-60 ºN [4] Low latitude [3] Mild climate [3] Temperate and moist climate [10]	Germination Min:5-8 Opt:18-20 Max:30 Vegetation Min: 5 Opt: 16-20 Max: 30-35 [4] Frost tolerance: -5 [9]	- Long-day plant [9, 10] - Does not bloom when daytime is under 12 h [10, 14] - Does not like intense luminosity [9] - Sunny [12]	- Spray or drop irrigation [3] - Requires damp soil [4]		2.5 [12]	- Biennial plant [9] - 60-80 days cycle [3] - Lifespan of 2-3 months [4] - Sowing in open field during February-March and August-October [9] - Harvest in 2-4 months - Harvest during summer, winter, and spring [14]	Direct sowing [1], sowing in growers and transplanting [3, 9]	Rows: 0.3 [3] - 0.9 [9] Plants: 0.2 [3, 4, 10] - 0.5 [9] Low ridges 1-1.2 wide, 8-10 lines, sowing 0.4-0.45 between plants [10]	- Do not plant with beetroot [3] or leek [15] - Associate with carrot, cabbage, onion, and beans [15]
Cucumber	*Cucurbitaceae* [3, 9, 20]	Algarve [17]	Development stop: 10-12 Germination Min: 12 Opt: 30 Max: 35 Fecundation Opt: 18-21 Development Opt Day: 20-25 Night: 18-22 Soil Min: 12 Opt: 18-20 [9] Frost tolerance: -1 [9]	- Neutral-day plant [9], with minimum of 8 h of sun per day [13] - Sunny [12, 20]	- Spray, furrow or drop irrigation [3, 20] - Regular irrigation during the entire cycle [14] - Irrigation every 2-4 days [9] - Higer water demand during spring/summer [20] - Keep soil moist [20]	Planting can be mechanical [3]		- Annual cycle [9] - Can be sowed (in growers) and planted during all the year [20] - In the Algarve, the planting is made in August-September or December-February [20] - 50-80 days for harvest begin [3] - Harvest in 60-90 days [9]	Direct sowing or transplanting [3]	Rows: 0.8 [3] - 1.5 [3, 20] Plants: 0.2 [20] - 0.5 [9] Ridges 1.2-1.4 wide or corridors 1.6-1.8 wide [9]	- Recurrence period of 3 years [9] - Plant after beans and tomato [9] - Associate with beans, lettuce, beetroot, celery, broad beans, radish, spinach, peas, maize, onion, cabbage, marjoram, and camomile [15] - Do not associate with tomato, potato, or melon [15]

			Frost sensitive [20]								
Eggplant	*Solanaceae* [3, 9, 21]	Hot climate [21]	Development stop: 10-12 Germination Min: 15 Opt: 20-25 Max: 35 Vegetation Min: 13-15 Opt day: 22-27 Opt night: 17-22 Máx: 40-50 Blooming: 20-30 [9] Frost tolerance: 0 [9] Frost sensitive [21]	- Neutral-day plant [9] - Sufficient luminosity [9] - Sunny [12, 13, 21] - Shade tolerant [9]	- Spray, furrow or drop irrigation [3] - Avoid soggy soil [3]			- Annual plant [9] - 90-120 days cycle [3] - Planting during February/March-August/September [21] - Harvest in 60-125 days [9, 21]	Transplanting [3]	Rows: 0.8 [21] - 1.5 [3, 21] Plants: 0.55 [21] - 0.9 [3] Ridges 0.15-0.2 high [21]	- Associate with beans, peas, thyme, and pepper [15] - Do not associate with tomato, onion, or potato [15]
Garden cress	*Brassicaceae* [2, 3, 4]	Europe [4] Temperate climate [4] Mild climate [3]	Opt: 15-20 [2, 3] Frost tolerant [4]	- Photoperiod of 12 h [2] - Sunny [12]	- Spray or flood irrigation [3] - Keep soil moist [4]			- Biennial plant [4] - 50-80 days cycle [3] - Direct sowing in March [2] - October [4] - Transplanting during summer [2] - Harvest in January-March [4]	Direct sowing [4] or transplanting [2, 3]	Sowing in rows separated by 0.1-0.15 m [2] Rows: 0.1 [2] - 0.3 [2, 3, 4] Plants: 0.08 [4] - 0.25 [3]	
Garlic	*Alliaceae* [9, 3, 4, 22]	Alentejo [11] Mediterranean [4] West and north Portugal, Montijo [4] Temperate and cool climates [22]	Min lethal temperature: -5 Root emergence Opt: 15 Emergence [9] Min: 5 Opt: 20-22 Max: 30 Vegetation Min: 0-5 Opt: 20 Max: 40 [4] Frost tolerance: -5 [9]	- Daytime more than 15 h for bulb development [4, 9] - The bulb does not develop with daytime less than 10-11 h [9] - Faster bulb development with long-red wavelength radiation [4] - Sunny [12]	- Spray, central pivot, or drop irrigation [3] - Stop irrigation 2-3 weeks before harvest [4] - Critical period during bulb growing [4] - Frequent irrigation and with low rotation [4]	- Ridges and grooves [22] - Planting can be mechanical [3, 4]	0.8 [4]	- 4 [3] - 8 months cycle [4] - Planting during October-January depending on the variety [22] - Germination 10-12 days after sowing [9] - Harvest during June-July [4, 9] - Harvest in 7-8 months after sowing during fall [9] - Harvest in 4-5 months after sowing during spring [9]		0.15 x 0.1 in double rows separated by 0.3-0.4 [3] Rows for little bulbs production: 0.2-0.4 [4] Rows in mechanical planting: 0.5-0.8 [4] Ridges 1.5-2 wide and 0.15 high [22] Rows: 0.2 [22] - 0.7 [9] Plants: 0.05 [4] - 0.15 [4, 9, 22]	- Long rotations, preferable more than 5 years, without Aliaceae [4] - Plant after potato, cabbage, and spinach [9] - Associate with lettuce, beetroot, carrot, tomato, spinach, and strawberry [15] - Do not associate with beans, peas, broad beans, cabbage, or potato [15]
Grapes		Alentejo [6] Mediterranean and temperate climates [23]	Temperature tolerance of -15 and -2.5 for young plants [23]	Sunny [23]	- Drop irrigation [23, 24] - Irrigation during hydric stress [23] - Generally, irrigation starts in mid-July [23]	- Deep soil [23, 24] - Levelled soil [23, 24] - Tillage [23] - Several steps of the cultivation can be done mechanically [23] - Grapes for fresh		- Pluriannual plant [23] - Planting during January until March [24]		Rows: 2.5-4.5 Plants: 1-3 Rows are aligned N-S [24]	- Recurrence period of 4-7 years [23]

						consumption are harvested manually while for wine mechanically [23]					
Green Beans	*Fabaceae* [1, 3, 9, 16]	Algarve [17, 18] Mild climate [3]	Development stop: 8-10 Germination Min: 12 Opt: 15-25 Max: 30 Vegetation Min: 10-12 Opt: 18-30 Max: 35-40 Blooming Min:12-15 Opt: 15-25 Max: 30-40 [9]	- Sunny [1, 12] - Neutral-day plant [9]	- Drop irrigation [16] - High water demand [14, 16] - Avoid water excess [16]	- Ridges and grooves [16] - Planting [3] and harvest [16] can be mechanical		- 50-70 days cycle [3] - Generally sowing February onward [16] - Plantation during May-July [16] - Harvest in 90-160 days [9]	Direct sowing (more common) [9] or transplanting [16]	2 seeds per pit Ridges 0.4-0.6 wide [16] Rows: 0.4 [16] - 1 [1, 9] Plants: 0.1 [3] - 0.65 [9]	- Recurrence period of 3 years [9] - Rotation with species of other families [3] - Plant after Alliaceae, carrot, cabbage, pepper [27] - Do not plant after peas, broad beans, spinach, beetroot, or maize [9]
Leek	*Alliaceae* [1, 3, 4, 9, 22]	Portugal [1] Mediterranean [4] Entre-Douro-e-Minho, Ribatejo and West Portugal [4] Temperate and moist climates [22] Mild climate [3]	Germination Min: 2 Opt: 11-23 Max: 30 Vernalisation: < 15 Vegetation Min: 5 Opt: 13-24 Max: 30 [4] Frost tolerance: -7 [1]	- Long-day plant [9] - More than 10 hours of sun per day [13] - Sunny [12]	Spray [1, 3, 4] or drop irrigation [22]	- Uniform soil preparation at 20 or 25 cm depth [4] - Ridges and grooves of 15 cm [4] - Planting can be mechanical [4]	1 [4]	- Winter and summer varieties [1, 4] - Biennial crop [1, 9] cultivated as annual [1, 4] - 110-140 days cycle [3] - Can be planted all the year in temperate climates, but generally during August-September and harvested during winter [22] - Harvest in 4 months after germination [9] - Harvest in 3 [4] - 8 [22] months	Sowing in growers followed by transplanting [1] or direct sowing [4]	Rows: 0.3 [1, 3, 4, 9, 22] - 0.75 [4] Plants: 0.1 [9, 4, 22] - 0.25 [4]	- Recurrence period of 3-4 years [4] - Rotation with maize, tomato, and cabbage [1] - Avoid Allium precedents [4] - Associate with carrot, strawberry, celery, tomato [1], fennel, lettuce, and garden cress [15] - Do not associate with beetroot, green beans, pea, parsley, lettuce [1], cabbage, chard, or broad beans [15]
Lettuce	*Asteraceae* [1, 3, 4, 9, 25]	Near East [4] west Portugal, Coastline and Entre-Douro-e-Minho [4] Mediterranean climate [4] Mild climate [3]	Germination Min: 2-5 Opt: 15-25 Max: 30 Opt mean monthly: 15-20 Leaf production Day: 12-15 Night: 10-12 Head formation Day: 10-12 Night: 2-6 Opt soil: 13-15 [4] Frost tolerance: -6 [9] Avoid frost [25]	- Long-day plant [9] - More than 10 h per day [1, 9, 25] - Sunny [12, 13] - Light shade tolerant [13, 25]	- Drop [25], spray (not recommended [25]) and hydroponic [3] - Periods of high demand every 5-7 days [9] - Periods of low demand every 15-20 days [9] - High water demand [4]	- Loamy-sandy texture at 40-50 cm depth [1] - Levelled ground [25] - Superficial soil mobilisation [25] - Ridges and grooves [25] - Tillage [25] - Minimise mobilisation [25] - Can be planted mechanically [4]	1 [4]	- Biennial cycle [9] - Annual herb [4] - 45-90 days cycle [25] - In hot climates can be sowed all year [9, 25] - In extreme climates can be sowed during March-April [9] and September-October [9, 25] - Harvest in 60-150 days [9]	Direct sowing [1, 14] or transplanting [1, 4]	Ridges 0.25-0.3 high with one or more rows [25] Direct sowing in 0.5 x 0.15 [25] 4 rows Rows: 0.25 [3, 25] - 1 [4] Plants: 0.2 [4, 25] - 0.5 [9]	- Can be used as main crop for rotation [1, 4] - Plant before cabbage, carrot, beetroot, and beans [1] - Plant after Alliaceae, Cucurbits, potato [27], Solanaceae, Cucurbits, and Apiaceae [4] - Avoid planting after Brassica or Fabaceae [4] - Can be associated with cabbage, beetroot, radish [1], tomato, cucumber, peas, garlic, leek, beans, and broad beans [15] - Do not plant with celery or parsley [15]
Maize	*Poaceae* [3, 26]	Alentejo [6] A mild and hot climate [3]	Min: 8-10 [26] Max: 30-32 [26]	- Minimum 8 hours of sun per day [13] - Sunny [12]	- Spray, central pivot, furrow or drop irrigation [3]	- Deep soil [26] - Tillage [26] - Seedbed		- 80-120 days cycle [3] - Sowing when the soil temperature is above 12-13 ºC [26]	Direct sowing [3, 26]	Rows: 0.8-1.1 [3] Plants: 0.14 [26] - 0.3 [3]	- Do not repeat the following year [26] - Associate with beetroot,

		Moderate climate [26]			- Good irrigation during floriation and dry periods [14] - Critical periods before and after blooming [26]	preparation [26] - Sowing can be mechanical [3, 26]					pumpkin, beans, peas, and tomato [15] - Do not associate with lettuce or onion [15]
Melon	*Cucurbitaceae* [1, 3, 9, 20]	Alentejo [18] Algarve [18]	Development stop: Air:13-15 Soil: 8-10 Germination Min: 13 Opt: 28-30 Max: 45 Blooming Opt: 20-23 Vegetation Opt: 25-30 [9] Frost tolerance: 1 [9] Frost sensitive [20]	- Neutral-day plant [9] - Sunny [1, 9, 13]	- Furrow, spray or drop irrigation [1, 3] - 4000 m3/ha [1] - Avoid water excess [20] - Drought resistance [20]	- Tillage [1] - Ridges and grooves [1] - Planting can be mechanical [3]		- 55-90 days cycle [3] - Planting during April-May [20] - Harvest in 101 days after germination [9] - Harvest lasts 60 days [9]	Direct sowing or transplanting [1]	Double rows separated by 1.5-1.6 [20] Rows: 1.5 [1, 9] - 2.5 [1, 3, 9] Plants: 0.2 [3] - 1.5 [9]	- Recurrence period of 3 years [9] - Do not plant immediately before or after other Cucurbit [1, 9] - Plant Alliaceae, Brassicas, Poaceae, and Fabeaceae [1, 27] - Associate with maize, radish, spinach, beans, and marjoram [15]
Mustard	*Brassicaceae* [1, 2, 3]	Portugal [1] Mild climate [1, 3]	Opt: 15-20 [1, 2, 3] Max: 27 [1] Not frost tolerant [2]	- Sunny [12] - Partial shade during summer [1] - Requires shadow until germination [14]	- Spray or drop irrigation [3] - Avoid water excess [3]	- Ridges and grooves [2]		60 [3] - 110 [9] days cycle	Direct sowing [1]	Low ridges 1-1.2 wide [2] Rows: 0.1 [1, 2] - 0.35 [3] Plants: 0.25-0.35 [3]	Rotation with species of other families [3]
Onion	*Alliaceae* [3, 4, 9, 22]	Alentejo [17] Short-day: latitudes below 35 º [4] Medium-day: latitudes 32-38 º [4] Long-day: latitude over 38 º [4] All around the world [4] Ribatejo, West Portugal and Entre-Douro-e-Minho [4] Temperate and moist climate [22]	Germination Min: 1.4-3.5 Opt: 20-25 Max: 40 T0 for seedling growth: 6 T0 for leaf production: 2 Vegetation Min: 5 Opt: 13-24 Max: 45 [4] frost tolerance: -3 [9]	- Short-day varieties: 11 or more hours of sunlight for bulb development [4] - Medium-day varieties: 13 hours of sunlight for bulb development [4] - Long-day varieties: 14-16 hours of sunlight for bulb development [4, 9] - Sunny [12, 13]	- Spray [22], central pivot or furrow irrigation [3] - Periods of high demand every 10-15 days [9] - Periods with low demand every 20-25 days [9] - Regular irrigation until mid-summer [14] - Stop irrigation 2-3 weeks before harvest [4] - Critical period during bulb growth [22] - Water excess can delay the cycle and rot the bulb [3] - Avoid soggy soil [3]	- Tillage that leaves the soil with an unformed structure up to 25 cm deep [4] - Ridges and grooves [22] - Planting can be mechanical [3, 22]	0.4 [4]	- Biennial cycle [4, 9] - 90-160 days cycle [3] - Sowing of fall/winter varieties: August-September [9] - Sowing of spring/summer varieties: February-May [9] - Harvest during spring-summer [4]	Direct sowing, transplanting, or transplanting of bulbs [3, 4]	Ridges with 2-8 lines [22] Rows: 0.17 [3] - 0.4 [4] Plants: 0.05 [3] - 0.2 [9]	- Plant after Fabaceae, Poaceae, Brassicas, Solanaceae, and Cucurbits [4, 9, 27] - Do not plant after cabbage or beetroot [9] - Avoid other Aliaceae during short rotations [4] - Associate with lettuce, beetroot, carrot, tomato, camomile, cabbage, strawberry, and radish [15] - Do not associate with peas, broad beans, or beans [15]
Peas	*Fabaceae* [3, 9, 16]	Algarve [17] Mild and cold climate [3] Temperate and cool climate [16]	Development stop: 5-7 Germination Min: 6 Opt: 14-25	- Neutral-day plant [9] - Sunny [9, 12, 13] - Partial shade	- Spray [16] or central pivot [3] - Moderate irrigation [16]	Planting can be mechanical [3]		- 85-110 days cycle [3] - In temperate climates sowing from October-November [9] - In cool climates sowing during	Direct sowing [3]	12-16 seeds in 1 m row [3] Rows: 0.2 [3, 16] - 1.3 [3]	- Rotation with species of other families [3] - Plant after tomato [3] - Associate with carrot, turnip,

			Max: 30 Vegetation Min: 6-10 Ppt: 16-20 Max: 35 [9] Frost tolerance: -4 [9]	tolerant [13]	- Avoid soggy soils [3, 16]			February-March [9] - Harvest in 2-4 months after sowing [9] - Harvest can last 20-30 days [9]		Plants: 0.3 [3] - 1.2 [9]	lettuce, fennel, cabbage, celery, cucumber, maize, beetroot, spinach, potato, and radish [15] - Do not associate with garlic, leek, onion, beans, or parsley [15]
Pepper	*Solanaceae* [1, 3, 9, 21]	Alentejo [17] Algarve [17, 18] Tropical climate [3] Mild climate [3]	Development stop: 10 [9] Poor development: 15 [9] Germination [9] Min: 13 Opt: 25 Max: 40 Development Opt [9] Day: 20-25 Night: 16-18 Flower formation [9] Min: 18-20 Opt: 25 Max: 35 [1, 3, 9] Frost tolerance: -1 [9] Frost sensitive [21]	- Neutral-day plant [9] - Sunny [9, 12] - Shade tolerant [13]	- Spray, furrow [3] or drop irrigation [1, 3, 21] - Avoid water excess [3, 21] - Seasons with maximal demand every 8-10 days [9] - Seasons with minimum demand every 20-30 days [9] - Frequent irrigation with low rotation [21]	- Ridges and grooves [21]		- 80-100 days for harvest begin [3] - Pepper for fresh consumption is generally cultivated in growers and for industrial applications in open-field [21] - In open field, planting during April-May [21] - Harvest in 2-4 months [9] - Harvest lasts 3-4 months [9]	Direct sowing or transplanting (most common) [1]	Double rows separated by 1.1 [1] - 1.6 [21] Rows: 0.35 [21] - 1.5 [3] Plants: 0.3 [9] - 0.7 [3]	- Recurrence period of f 3-5 years [1] - Rotation with Poaceae, Fabaceae, Gramineae, Apiaceae, Alliaceae, Brassicaceae, and Asteraceae [1] - Do not rotate with other Solanaceae [3], Cucurbits, or Convolvulaceae [1] - Associate with eggplant, tomato, peas, basil, carrot, marjoram, oregano, onion, and strawberry [15] - Do not associate with fennel [15]
Potato	*Solanaceae* [1, 3, 21]	Alentejo [6] Can be adapted to tropical climates [3] Cool climate [21]	Development stop: 10 [21] Opt: 16-25 [21] Max: 27-30 [1, 21] Not frost tolerant [14]	Sunny [1, 13]	- Central pivot [3] or spray irrigation [1, 21] - Irrigation during dry days, especially 15 days before harvest [14] - Avoid water excess [21] - Uniform irrigation [21]	- Tillage 30 cm deep [1] - Ridges about 20 cm high [1] - Planting can be mechanical [3]		- Annual cycle [1] - 90-110 days cycle [3] - Industrial varieties are planted during January-March and harvested in May, or planted during April-July and harvested in August [21]	Potato seed [1]	Open grooves Ridges separated by 0.75 [21] Rows: 0.7 [3, 21] - 0.9 [3] Plants: 0.22 [21] - 0.4 [3]	- Plant after Cucurbits, Fabaceae, cauliflower, and broccoli [27] - Associate with celery, beans, cabbage, spinach, garlic, broad beans, lettuce, onion, peas, radish, turnip, eggplant, and thyme [15] - Do not associate with beetroot, cucumber, pumpkin, tomato or leek [15]
Pumpkin	*Cucurbitaceae* [1, 3, 20]	Alentejo [11]	Min: 10-14 Opt: 25-30 Max: 35 [1] Frost sensitive [20]	Sunny [12, 13, 20]	- Drop irrigation [1, 20] - High water demand [14]	Plough soil about 25 cm deep [1]		- Sowing in April-May in the south of Portugal and April-June in the north [20] - Direct sowing from the end of spring onwards [14] - Transplanting about 4 weeks after sowing in pits [14]	Direct sowing or transplanting [1] Growers or pits [1]	1-2 plants per hole of 4-5 x 4 m for varieties with long rods and 4 x 3 m with short rods [1] 3-5 seeds per hole [20] Rows: 2-3 [20] Plants: 1-1.5 [20]	- Do not plant with other Cucurbits [1] - Sow radish around the pumpkins after transplanting [1, 14] - Associate with beans, maize [1], lettuce, broad beans, peas, onion, mint, marjoram, and camomile [15] - Do not associate with radish, fennel, pumpkin [15]
Radish	*Brassicaceae* [2, 3, 4, 9]	Mediterranean [4] Mild climate [3]	Development stop: 6 [9] Germination Min: 8 Opt: 20-25 Max: 30-35 Vegetation	- Long-day plant [9] - Low luminosity demand [9] - Sunny [12, 13]	- Spray irrigation [3] - Constant soil moist content [2, 3] - High water demand [4] - Avoid water excess	- Preparation of seed bed [4] - Soil should be crushed [4] - Ridges and grooves [4]	1 [4]	- Annual plant [4] - 20 [9] - 70 days cycle [4] - Sowing in February until November [2]	Direct sowing [2, 4]	Rows: 0.15 [3, 4, 9] - 0.3 [2] Plants: 0.05 [3, 4] - 0.15 [2]	- Rotation with species of other families [3] - Associate with garden cress, lettuce, spinach, carrot, peas, pepper, tomato, beans, onions, broad beans, pumpkin, beetroot,

			Min: 6 Opt: 18-22 Max: 30 [4] Frost tolerance: -2 [9]		[3]	- Planting [3] and harvest [4] can be mechanical					and mint [15]
Spinach	*Chenopodiaceae* [3, 4, 10, 9]	Europe [4] Cool climate [4] Temperate climate [10]	Germination Min: 2-5 Opt: 20-25 Max: 30 Vegetation Min: 5 Opt: 15-20 Max: 32 [4] Frost tolerance: -5 [9]	- Long-day plant [9] - Does not bloom when daytime is under 12 h [9] - Sunny [12, 13] - Light shade tolerant [14]	- Drop, spray [10] or hydroponic [3] - Periods with high demand every 6-8 days [9] - Periods with low demand every 20-30 days [9] - Constant water supply [4] - Short irrigation [10] - Avoid water excess and soggy soils [3, 10]	- Seedbed preparation [4, 10] - Ridges and grooves [4, 10] - Sowing can be mechanical [10]	0.8 [4]	- Biennial cycle [9] - Annual herb [4] - 30 [4] - 90 days cycle [3] - Sowing during the end of winter or summer [14] - Harvest 30 [10] - 90 days [9]	Direct sowing [10] or transplanting [3]	Low ridges 1-1.2 wide Rows: 0.17 [4] - 0.4 [3, 10] Plants: 0.05 [4] - 0.25 [3]	- Rotation with species of other families [3] - Do not repeat on the same area [9] - Plant before Fabaceae [9] - Do not plant after beetroot [4], or chard [9] - Associate with carrot, cabbage, lettuce [4], eggplant, celery, onion, peas, beans, beetroot, radish, tomato, turnip, cucumber, leek, and strawberry [15] - Do not associate with potato [15]
Strawberry	*Rosaceae* [1, 3, 28]	Alentejo [18] Algarve [18]	Development stop: 2-5 Rooting Min: 10 Opt: 18 Max: 35 Day: 15 Night: 8-10 Maturation Day: 18-27 [1] Night: 10-13 [9] Frost tolerance: -3 - -5 [9] Flowers are very frost sensitive [28]	- Sunny [1] - Short-day plant, with daytime less than 14 h [1] - Blooms when daytime is about 8-10 h [9]	- Drop, spray or manual irrigation [1] - Seasons of maximal demand every 4-6 days [9] - Seasons of minimal demand every 20-25 days [9] - Low water demand [9]	- Ridges and grooves [28] - Tillage [28] - Superficial soil mobilisation [28]		- Perennial plant [9] - 3-4 years [1] - Planting during fall [9] and harvest during spring/summer [28] - 60 [3] - 90 days for harvest to begin [9] - Harvest lasts 30-90 days [9]	Runners (most common) [3] or direct sowing [1]	Ridges 0.5 wide, 0.25 high and separated by 1.2 [1]: Double row on the same ridge [1] Ridges 0.5-0.6 wide and 0.4-0.5 high and separated by 1.1-1.2 [28] Rows: 0.25 [3, 9, 28] - 0.6 [9] Plants: 0.2 - 0.4 [9]	- Associate with spinach, tomato, garlic, leek, lettuce, beans, onion, and radish [15] - Do not associate with cabbage [15]
Sweet potato	*Convolvulaceae* [1, 3, 9]	Alentejo [17] Algarve [17]	Development stop: 10 [1, 9] Vegetation [9] Min: 12-14 Opt: 21-24 Planting [9] Night: 10 Day: 16-18 Frost tolerance: 0 [9]	- Sunny [1, 12] - Short-day plant, with daytime of 10-12 h [9]	Spray irrigation [3]	- Ridges and grooves [1] - Tillage [1] - Planting can be mechanical [3]		- Perennial crop [1] planted as annual [1, 9] - 100-150 days cycle [3] - Planting in May [9] - Harvest in 150-190 days [9] - Harvest in September-October [9]	Branches of an adult plant, tuber germination or direct sowing [1]	Open grooves 0.3 wide [1] Rows: 0.8 [3, 9] - 1.2 [3] Plants: 0.2 [3] - 0.6 [9]	- Rotation of crops is important [1] - Rotation with Fabaceae [1]
Tomato	*Solanaceae* [1, 3, 9]	Alentejo [6] Algarve [17, 18] Mild climate [3]	Development stop: 10-12 [3] Highest development: 20-24 Monthly mean for	- Neutral-day plant [9] - Sunny [12, 1, 21]	- Drop irrigation [1] - 400-500 m3/ha [9] - Periods with high demand every 6-10 days [9]			- 90 [9, 21] - 125 days cycle [9] - Sowing during spring in pits in growers [14] - Transplanting to open field from early summer onwards [14, 21]	Direct sowing or transplanting [1, 21]	Single rows or double rows on ridges [1] Rows: 0.3 [3] - 2 [1]	- Do not rotate with other Solanaceae [3] - Do not repeat on the same area for the next 3-5 years [9] - Plant before maize, leek, onion,

			development: 16-27 Germination Min: 10 Opt: 25-30 Max: 35 Birth: 18 First leafs: 12 Development Day: 18-21 Night: 13-16 Blooming Day: 23-26 Night: 15-18 Maturation Red fruit: 15-22 Yellow fruit: 12 Soil Min: 12 Opt: 20-24 Max: 34 [9] Frost tolerance: -2 [9]		- Periods with low demand every 20-30 days [9] - Regular irrigation during dry periods [14] - Avoid water excess [3]			- 90-120 days for harvest begin [3]		Plants: 0.25 [1, 9] - 0.6 [9]	garlic, and winter cereals [9] - Plant after Alliaceae, Brassicas, and carrot [9] - Do not plant before pepper, eggplant, tobacco, potato, melon, watermelon, pumpkin, cucumber, Fabaceae, or Cruciferous [9] - Associate with parsley, onion, lettuce, radish, sage, carrot, and garden cress [15] - Do not associate with fennel, eggplant, or potato [15]
Turnip	*Brassicaceae* [2, 3, 4, 9]	South Europe [4] Entro-Douro-e-Minho [4] Cool and moist climate [4] Mild climate [3]	Development stop: 3-5 [2, 9] Germination [4] Min: 2 Opt: 20-25 Max: 35 Vegetation Min: 4 Opt: 15-20 Max: 30 Frost tolerance: -5 - -8 [9]	- Low luminosity [9] - Sunny [12, 13]	- Spray irrigation [3] - High water demand during summer [4] - Avoid water excess [3]	- Surface layer should be crushed [4] - Ridges and grooves [4] - Harvest can be mechanical [4]	0.6 [4]	- Biennial crop cultivated as annual [4] - 40 [4] - 100 days cycle [4, 9] - Sowing during July/August-October [9] for harvest in fall/winter [4] - Sowing during March-April [9] for harvest in summer [4]	Direct sowing [4] or transplanting [2]	Sowing on ridges 1.3-1.4 wide and 0.2-0.25 high [2] Planting on ridges 1.4 wide [2]: Rows: 0.2 [2] - 0.5 [9] Plants: 0.1 [2, 3, 4, 9] - 0.2 [4]	- Rotation with species of other families [3] - Plant after Alliaceae, Solanaceae, spinach [27], and Cucurbits [4] - Avoid other Brassicaceae [4] - Associate with peas, carrots, lettuce, mint, tomato, spinach, beans, and strawberry [15] - Do not associate with curly leaf lettuce [15]
Watermelon	*Cucurbitaceae* [1, 3, 9, 20]	Alentejo [18] Algarve [18] Hot climates [1]	Development stop: 11-13 Germination Min: 13 Opt: 25 Max: 45 Blooming Opt: 18-20 Vegetation Opt: 23-28 [9] Frost tolerance: 0 [9] Frost sensitive [20]	- Sunny [1, 9, 12, 20] - Neutral-day plant [9]	- Spray, furrow or drop irrigation [3] - On periods of high demand every 7-9 days [9] - Irrigation starts 1-4 weeks after planting depending on the variety and season [20]	Planting can be mechanical [3]		- Annual cycle [1, 9] - 65-100 days cycle [3] - Planting during March-May [20] - Harvest in 4-5 months [9] - Harvest lasts 1-2 months [9]	Direct sowing or transplanting [20]	3-6 seeds per pit with a 0.3-0.4 m diameter [1] Ridges 2 wide and 0.2-0.3 high [1] Rows: 1.5 [20] - 3 [3, 9] Plants:0.5 [3] - 2 [9]	- Can be associated with Poaceae and Fabaceae [1] - Do not associate with cucumber [1] - Recurrence period of 6 years [1] - Plant after root, bulb, and cereal crops [9] - Should not be planted after melon, cucumber, or pumpkin [9]
Wheat	*Gramineae* [29]	Alentejo [6] Adaptable to the different climates [29]	Germination Min: 4 Opt: 20-22 Max: 32 Vegetation Opt: 16-22	- Long-day plant [29] - Sunny [29]	- Damp soil during germination [29]	- Tillage 25-40 cm deep [29] - Stones must be removed [29]		- Sowing during November (fall/winter) [29] - Affiliation until spring [29] - Tillering for 3 months [29] - Grain filling during 32 days [29] - Maturation during 25 days [29]			- Plant after potato, tomato, and maize [29]

			Max: 30-32 Maturation Opt: 15-20 [29] Frost tolerance: 0 during germination and -25 after emergence [29]								
Zucchini	*Cucurbitaceae* [1, 9, 20]	Portugal [1]	Development stop: 8 Germination Min: 10 Opt: 20-30 Max: 40 Vegetation Min: 10 Opt: 25-30 Max: 35 [9] Frost tolerance: -1 [9] Frost sensitive [20]	- Neutral-day plant [9] - Sunny [9, 13]	- Drop [20] and spray irrigation [1] - High water demand [1] - Irrigation every 2-4 days [9] - Avoid soggy soils [20]	- Plough to an average depth of 25 cm [1] - Ridges and grooves [1]		- Sowing or planting during fall/winter or winter/spring [20] - Harvest in 50-60 days after germination [9] - Harvest lasts 50-70 days [9]	Direct sowing or transplanting [20]	2-3 seeds per pit [20] Ridges separated by 1.5-1.6 [20] Rows: 0.7-1 [9, 20] Plants: 0.6 - 0.9 [9, 20]	- Sow radish around the zucchinis after transplanting [14] - Do not plant before melon, watermelon, or cucumber [9]
HERBS											
Anise	*Apiaceae* [4]	Portugal [30] Mediterranean [4]	Min: 8 Opt: 20 Max: 25 [4]	Sunny [4]			0.4 [30]	- Annual herb [4, 30]	Direct sowing [4]	Rows: 0.6-0.75 Plants: 0.15-0.2 [4]	
Basil	*Lamiaceae* [4, 31]	Middle East until Iran [4] Temperate and temperate-hot climates [4]	Min: 10 Opt: 15-25 [4] Very frost sensitive [4, 31]	Sunny [31]	- Irrigation throughout the cycle [31] - Keep soil moist [32, 33]		0.6 [4]	- Annual herb [4, 31] - Sowing after spring [31] - Sowing in growers during January-March [4] - Transplanting during March-May [4] - Harvest during May-September [32, 33]	Direct sowing [31, 33]	Rows: 0.5-0-7 Plants: 0.2-0.25 [4]	Associate with tomato [15]
Chives	*Liliaceae* [31]	Mediterranean [34] Wild in Europe, in latitudes of 50-60 ºN [4] Mild and cold climate [3]	Opt: 17-25 Max: 44 [4]	Sunny [35]	- Spray, drop or hydroponic [3] - Irrigation during the driest season [31] - Avoid water excess [3]		0.35 [31]	- Perennial herb [4, 31, 35] - 70-100 days cycle [3] - Sowing every 4 weeks from the end of winter until the end of summer [4, 14] - Plantation of splits during spring [4] or fall-winter [3, 4] - Blooming during winter-spring [35]	Direct sowing, splitting or bulb planting [3, 4, 31]	Rows: 0.15 [4] - 0.4 [3] Plants: 0.05 [3] - 0.2 [4]	Associate with carrots [15]
Coriander	*Apiaceae* [4, 19, 31]	Alentejo [30] Mediterranean [4, 34]	Opt: 20 [4] Frost tolerant [31]	- Sunny [31] - Long-day plant [19] - Partial shade tolerant [31]	Irrigation during drought [32, 33]	Seed harvest can be mechanical [4]	1 [4]	- Annual plant [4, 31] - 3-4 months cycle [4] - Sowing from spring until fall [4] - Can be sowed all the year in regions without frost [19] - Blooming begins in May and fruits are mature between June-July [31] - Harvest in 40-60 days [4, 33]	Direct sowing [4, 31, 33]	Low ridges 1-1.2 wide [19] Rows: 0.25 [31] - 0.6 [4] Plants: 0.1 [4, 19] - 0.3 [19]	
Fennel	*Apiaceae* [3, 4, 9, 31]	Alentejo [36, 37] Mediterranean [4] Mild climate [3]	Germination Min: 11 Opt: 18-20 Max: 35	Sunny [12, 31, 35]	- Spray or drop irrigation [3] - Irrigation during drought [32]		2 [35]	- Biennial cycle [9, 35] - Perennial herb [31, 35] - 80-120 days cycle [3] - Can be sowed all year [31]	Direct sowing [9, 32, 33] or staking [3, 4, 9, 35]	Rows: 0.3 [3, 4, 9] - 0.8 [4] Plants: 0.15 [3, 4] - 0.3 [4, 9]	- Rotation with species of other families [3] - Associate with celery and leek [15]

			Vegetation Min: 4 Opt: 20-25 Max: 40 [4] Frost tolerance: -1 [9]					- Plant harvest in 4-12 months [9] - Leaf and stem harvest in May-July [32, 33]			- Do not associate with cabbage, cucumber, spinach, beans, turnip, or tomato [15]
Lavender	*Lamiaceae* [31, 4]	Mediterranean [4, 34] Baixo Alentejo [37] Iberian Peninsula [4]	Tolerates moderate frosts [4]	Sunny [4, 35]	- Drop irrigation [31] - Moderate irrigation to keep the soil moist [32, 33]		1 [35]	- Perennial bush [31, 35] - 8 [31] - 20 years cycle [4] - Germination in growers in early March during 15-20 days [31] - Planting during spring or fall [31] - Leaf harvest before blooming [33] - Flower harvest during the end of spring-summer [32, 33] - Blooming during May-June [35]	Direct sowing or staking [4, 31, 33, 35]	Rows: 0.5 [31] - 1.8 [4] Plants: 0.5 [4, 31] -0.8 [31]	- Do not plant in the same area for 4-6 years [4] - Plant before Gramineae, Fabaceae, and forage crops [4]
Lemon Balm	*Lamiaceae* [31, 4]	Baixo Alentejo [37] Mediterranean [4] Temperate and temperate-hot climates [4]	Frost tolerant [31]	- Sunny [31, 4, 35] - Partial shade tolerant [4, 31, 35]			1 [31]	- Perennial herb [31, 35] - 10 years cycle, but is normally replaced after 3-5 years [4] - Sowing during fall [31] and spring [4, 31] - Propagation by splitting or stakes during fall [31] or spring [4, 31] - Blooming during June-September [4, 31]	Direct sowing, splitting, or staking [4, 31, 35]	Rows: 0.6-0.7 [4] Plants: 0.3-0.35 [4]	
Lemon Verbena	*Verbenaceae* [31]		Min: 4 [31] Not frost tolerant [31]	Sunny [35]	- Local irrigation [31] - Requires damp soil [31]		7 [35]	- Perennial bush [31, 35] - Harvestable all the year [31] - Planting during spring and summer [35]	Staking or sowing [31]		
Mint	*Lamiaceae* [4, 31]	Alentejo [30, 36, 37] Mediterranean [34] Temperate Climate [4]	Frost tolerant [31]	- Sunny [31, 35] - Partial shade tolerant [31, 35]	- High water demand [4] - Irrigation during the entire cycle [32, 33]		1 [31, 35]	- Perennial herb [4, 31, 35] - Propagation by splitting or stakes during spring or fall [4, 31] - Growing during spring [31] - Blooming during May [35] - October [31] - Harvest before blooming [32, 33]	Sowing [35], splitting or staking [4, 31, 33]	Planted in grooves separated by 0.5-0.8 [4] Plants: 0.25-0.3 [4]	- Plant after Gramineae [4] - Can be associated with Fabaceae and Aliaceae [4]
Oregano	*Lamiaceae* [4, 31]	Alentejo [36, 37] Mediterranean [4, 34]	Frost resistant [4]	Sunny [31, 35]	Moderate irrigation [32, 33]		1 [4]	- Perennial herb [31, 35] - 8-10 years lifespan [4] - Sowing during January-February [4] - Transplanting during April-May [4, 35] - Planting on the definitive place during spring or fall [4] - Harvest by start of blooming [32, 33]	Direct sowing [33], splitting or staking [4, 31, 35]	Rows: 0.75-1.2 Plants: 0.35-0.5 [4]	
Parsley	*Apiaceae* [3, 4,9, 19, 31]	Mediterranean [34] European and Asian Mediterranean basin [4] Mild climate [3]	Germination Min: 6 Opt: 18-25 Max: 30-35 Vegetation Min: 7	- Long-day plant [9, 19] - Sunny [12, 31] - Partial shade tolerant [12, 31, 35]	- Spray irrigation [19] or hydroponic [3] - Avoid water excess [3]	- Seedbed preparation [4] - Can be planted mechanically [4]	0.7 [31] 1 during reproduction [4]	- Biennial plant [14] cultivated as annual [4, 35] - 50-60 days cycle [3] - Sowing during spring/February-March and fall/August-September [4, 31]	Direct sowing [19, 35] or transplanting [3]	Low ridges 1-1.2 wide [19] Rows: 0.1 [31] - 0.6 [4] Plants: 0.05 [3] - 0.15 [4]	Rotation with species of other families [3]

			Opt: 18-22 Max: 30 [4] Frost tolerance: 0 [9] Frost tolerant [31]					- Sowing during February-August/September [9, 19] - Blooming during June-September [31] - Harvest in 80-100 days after [4, 9]			
Pennyroyal	*Lamiaceae* [31]	Alentejo [30, 36] Mediterranean [34]	Frost tolerant [31]	- Sunny [31] - Partial shade tolerant [31]	Irrigation throughout the cycle [32, 33]		0.6 [31]	- Perennial herb [31] - Sowing during spring and fall at 15-25 ºC [31] - Germination for 3-10 days [31] - Propagation by splitting or stakes during spring or fall [31] - Growing during March-April [31] - Blooming during May-June [31] - Harvest by begin of blooming [32, 33]	Direct sowing, splitting or staking [31, 33]		
Rosemary	*Lamiaceae* [31]	Alentejo [36, 37] Mediterranean [4, 38] South Europe [38] Temperate climate [38]	Tolerates frost [4]	Sunny [4, 31, 35]	- Low water demand [32, 33] - Avoid water excess [31]		2 [4, 31, 35]	- Perennial herb [35] - 5-15 years lifespan [4] - Sowing during spring [4] - Propagation by stakes during March or October-December [4] - Blooming in October [4] - Harvestable during the year [32, 33]	Direct sowing, splitting or staking [4, 31, 33, 35]	Rows: 0.8 [4, 38] - 1.6 [38] Plants: 0.5-0.8 [4]	
Sage	*Lamiaceae* [4, 31]	Eastern Mediterranean Basin [4] Temperate-hot climate [4]	Tolerates moderate frosts [4]	Sunny [31]			0.8 [31]	- Perennial bush [31] - Sowing during spring [31] - Propagation by stakes during spring-summer [31] - Sowing during January-February [4] - Transplanting in April [4]	Direct sowing, splitting or staking [4, 31]	Rows: 0.6-0.8 [38] Plants: 0.4 [4]	
St. John's Wort	*Hypericaceae* [31]	Baixo Alentejo [37]		- Sunny [31] - Partial shade tolerant [31]			1 [31]	- Perennial herb [31] - Sowing during fall [31] - Splitting during fall or spring [31] - Blooming during April-October [31]	Direct sowing or splitting [31]		
Thyme	*Lamiaceae* [31, 4]	Alentejo [36, 37] Mediterranean [34] Temperate and temperate hot-dry climates [4] Iberian Peninsula [4]	Frost tolerance: - 10 or less [4]	- Sunny [4, 31] - Partial shade tolerant [35]	- Low water demand [32, 33] - Avoid soggy soils [4, 35]		0.6 [31]	- Perennial bush [4, 31, 35] - Sowing during spring [31] - Propagation by stakes during spring-summer [31] - Splitting during November-March [4] - Harvest before and during blooming [32, 33] - Harvestable all the year [31] - Plant should be replaced after 3-4 years [4]	Direct sowing, splitting or staking [4, 31, 33, 35]	Rows: 0.6-0.8 Plants: 0.25-0.3 [4]	

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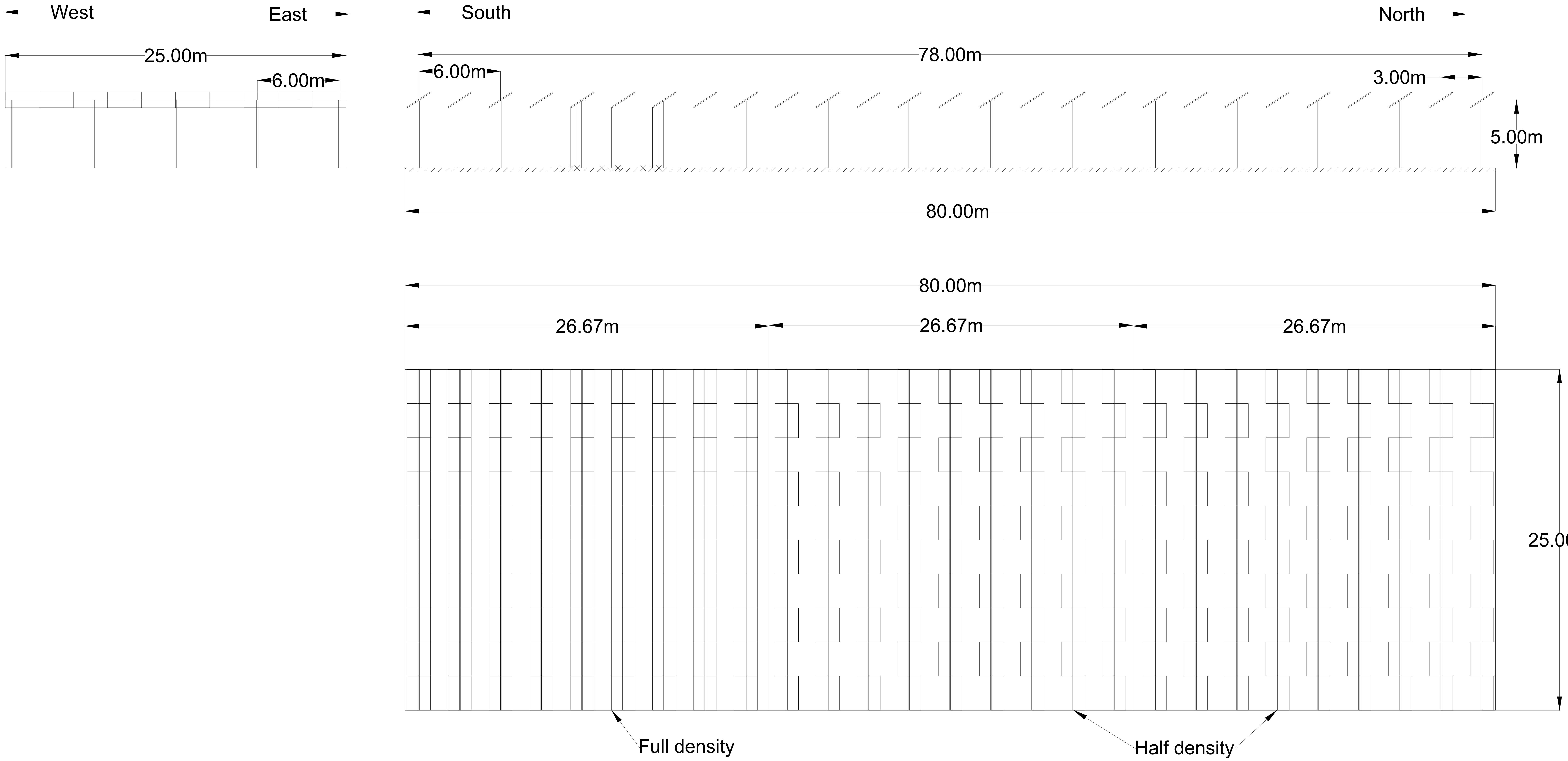
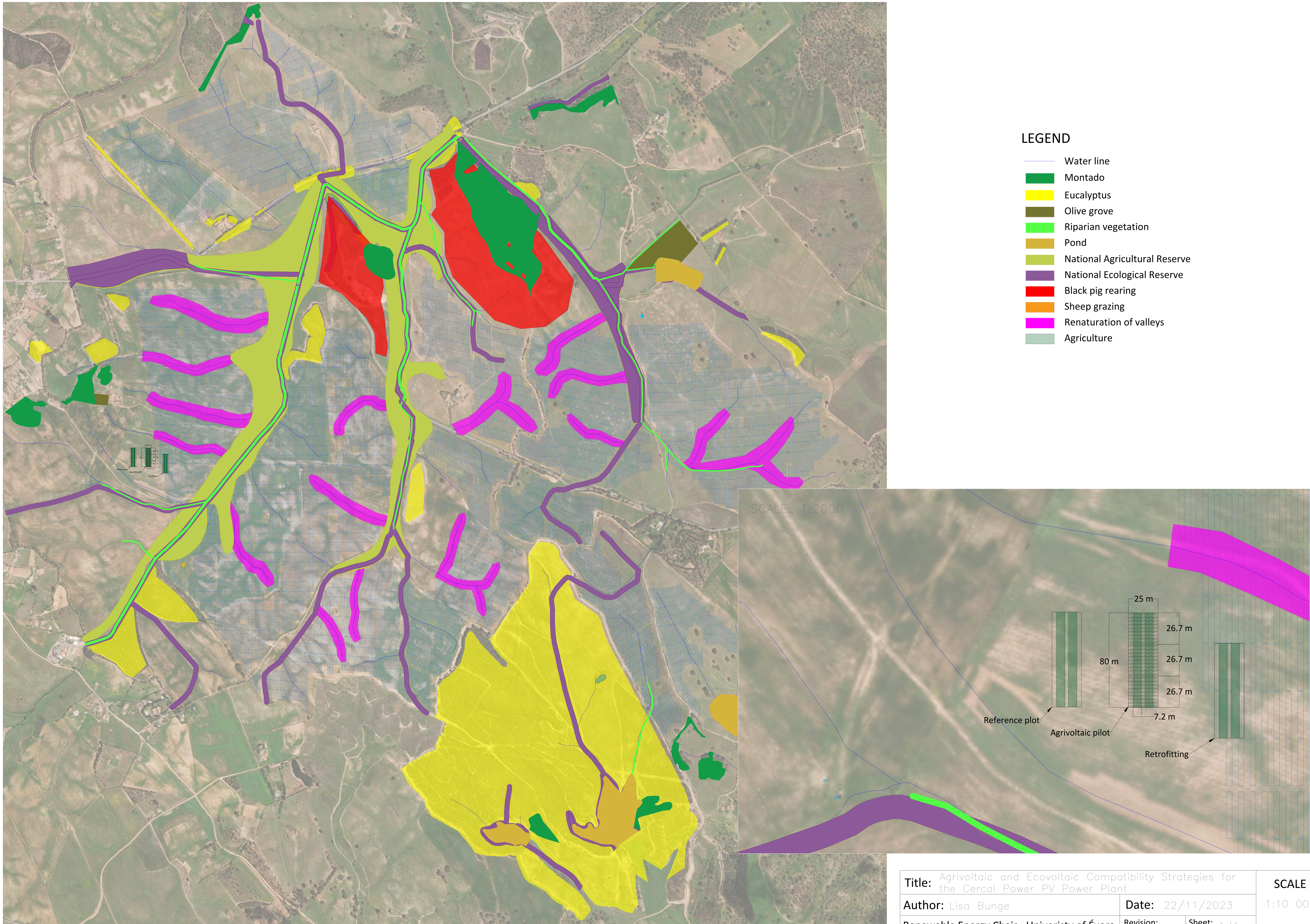
ANNEX 2 – Conceptual Design of the Agrivoltaic Pilot for Cercal Power



Title: Conceptual Design of the Agrivoltaic Pilot for Cercal Power			SCALE
Author: Lisa Bunge	Date: 22/11/2023		1:225
Renewable Energy Chair - Univeristy of Évora	Revision:	Sheet: 1/1	

ANNEX 3 – Agrivoltaic and Ecovoltaic Compatibility Strategies for the Cercal Power PV Power Plant



Title: Agrivoltaic and Ecovoltaic Compatibility Strategies for the Cercal Power PV Power Plant		SCALE
Author: Lisa Bunge	Date: 22/11/2023	1:10 000
Renewable Energy Chair - Univeristy of Évora	Revision:	Sheet: 1/1

ANNEX 4 – Matrix Database of the Agrivoltaic and Ecovoltaic Compatibility Strategies Tool

		Performance	Agriculture		Photovoltaic			Socioeconomic					
		LER	WUE	Agricultural Yield	Soiling	Efficiency	Energy yield	Jobs	LCOE	CAPEX	OPEX	Ecosystem services	Revenue
Agrivoltaic	Livestock grazing	1	1	-1	-1	0	0	1	0	0	1	1	2
	Poultry	1	0	-1	-2	0	0	1	0	0	1	1	2
	Beekeeping	1	1	0	0	0	0	1	0	0	-1	2	2
	Forage	0	1	-1	-1	1	-1	2	-1	-2	-1	1	2
	Permanent crops	0	1	-1	0	1	-1	2	-1	-2	-1	1	2
	Rotational crops	0	1	-1	-1	1	-1	2	-1	-1	-1	1	2
	Vineyard	0	1	-1	0	1	-1	2	-1	-2	-1	1	2
	Orchard	0	1	-1	0	1	-1	2	-1	-2	-1	1	2
	Permaculture	1	1	-1	0	1	-1	2	-1	-1	-1	2	2
	Aquaculture	0	1	0	-2	2	0	2	-1	-1	-1	1	2
	Greenhouse	2	1	0	0	-1	-1	2	0	0	-1	#N/A	2
Ecovoltaic	Nature Conservation	#N/A	#N/A	#N/A	0	1	-1	1	-1	0	-1	2	0
	Reforestation	#N/A	#N/A	#N/A	0	1	-1	1	-1	-1	-1	2	1
	Habitat restoration	#N/A	#N/A	#N/A	0	1	-1	1	-1	0	-1	2	0
	Riparian restoration	#N/A	#N/A	#N/A	0	1	-1	1	-1	0	-1	2	0
	Soil requalification	#N/A	#N/A	#N/A	1	0	0	1	-1	0	-1	2	0

Legend:
-2: Very negative impact
-1: Negative impact
0: Neutral
1: Positive impact
2: Very positive impact

		Environment											
		Landscape Visual Impact	Herbaceous	Shrubs	Trees	Macro vertebrates	Micro vertebrates	Invertebrates	Climate Resilience	Carbon balance	Water retention capacity	Soil quality	Erosion
Agrivoltaic	**Livestock grazing**	0	2	-1	-1	1	-1	1	1	0	0	0	0
	Poultry	0	2	-1	-1	1	-1	-1	1	0	0	0	0
	Beekeeping	1	2	2	2	1	0	1	2	1	0	0	0
	Forage	1	1	-2	-2	1	1	1	1	1	1	0	1
	Permanent crops	1	-1	-2	-2	-1	-1	-1	1	1	1	0	1
	Rotational crops	0	-1	-2	-2	-1	-1	-1	1	1	1	0	1
	Vineyard	1	-1	-2	-2	-1	-1	-1	1	1	1	0	1
	Orchard	1	-1	-2	-1	-1	-1	-1	1	2	2	0	1
	Permaculture	1	0	0	0	1	1	1	2	1	2	1	1
	Aquaculture	0	#N/A	#N/A	#N/A	0	0	0	0	0	1	#N/A	#N/A
	Greenhouse	-2	-2	-2	-2	-2	-2	-2	-1	0	-2	-1	0
Ecovoltaic	**Nature Conservation**	2	1	1	2	2	2	2	2	2	2	2	2
	Reforestation	2	1	1	2	2	2	2	2	2	2	2	2
	Habitat restoration	2	2	2	2	2	2	2	2	2	2	2	2
	Riparian restoration	2	0	1	2	2	2	2	2	2	2	2	2
	Soil requalification	0	0	1	2	1	1	2	2	2	2	2	2