

**FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO**

# **Agrivoltaics implementation on a kiwi farm: A case study**

**Diogo Hargreaves Curval**



**MASTERS IN FLUIDS AND ENERGIES**

**Orientadora: Professora Ana Isabel Palmero**

**Co-Orientador: Engenheiro Miguel Marques**

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# Resumo

A energia fotovoltaica é uma das indústrias líderes e de mais rápido crescimento a nível mundial que consiste na produção de electricidade através da conversão de energia solar em células fotovoltaicas. À medida que a procura da energia solar fotovoltaica expande, esta torna-se a mais competitiva opção para a produção de electricidade num número crescente de locais, exigindo grandes parcelas de terra para o seu desenvolvimento.

Atualmente, a maioria das atividades agrícolas são movidas a combustíveis fósseis, aumentando a emissão de gases de efeito estufa (GEE) e consequentemente agravando o aquecimento global. Dito isto, a agricultura é responsável até 8,5 % de todas as emissões de GEE, requerendo uma quantidade crescente de energia, recursos terrestres e água.

Neste contexto, é possível resolver ambos os problemas com a combinação de energia fotovoltaica e produção agrícola, muitas vezes referidos como sistemas agrivoltaicos (agri-pv) ou agrofotovoltaicos (APV), fornecendo uma solução adequada e eficiente para o persistente problema de concorrência para terras aráveis, redução das emissões de GEE e eficiência energética.

A presente tese visa estudar a viabilidade técnico-económica da implementação de um sistema agri-pv dentro de uma quinta produtora de kiwis situada a 20 km Este de Aveiro. O objectivo do estudo não é apenas abordar a compatibilidade da produção de energia com a produção de kiwis, mas também avaliar a possibilidade de tornar a quinta auto-suficiente e de fazer uso do excesso de energia através da respectiva comercialização a agentes de mercado. Dito isto, foram selecionados três locais pertencentes à mesma produção que, por sua vez, foram subdivididos em parcelas que constituíam diferentes tipos de aplicações fotovoltaicas. Posto isto, o estudo assenta em três pilares. O estudo da projeção de sombras por parte dos colectores solares sobre a produção existente, e de que modo esta é afetada na quantidade de luz solar incidente. O dimensionamento e análise dos sistemas fotovoltaicos simulados com o software PVsyst. E por último, uma análise económica sobre todas as áreas analisadas.

Considerando todas as simulações efetuadas nas três parcelas avaliadas, estas possuem uma capacidade de produção de 113 MW. As aplicações que envolveram sistemas agri-pv elevados demonstraram uma compatibilidade promissora no que toca a combinar a produção simultânea de energia e alimentos, com uma capacidade de produção avaliada em 42 MW. No entanto, provaram ser menos economicamente viáveis do que os sistemas fotovoltaicos convencionais, com valores de CAPEX cerca de 157 % superiores. Porém, todos os sistemas considerados provaram ser rentáveis dentro de um período de análise de 20 anos.

**Keywords:** Energia fotovoltaica, Agricultura, Agrivoltaics, Produção de energia, Auto-suficiente



# Abstract

Photovoltaic energy is one of the leading and most fast-growing industries worldwide which consists in the generation of electricity through the conversion of solar energy in photovoltaic cells. As demand for solar PV is spreading and expanding, it becomes the most competitive option for electricity generation in a growing number of locations, requiring large chunks of land for its development.

Currently, most of the agricultural activities are powered by fossil fuels, increasing greenhouse gas (GHG) emissions and climate change as a consequence. With that said, agriculture is responsible for up to 8,5 % of all GHG emissions requiring an increasing amount of energy, land resources and water.

In this context, it is possible to tackle both problems with the combination of photovoltaics and plant production, often referred as agrivoltaics (agri-pv) or agrophotovoltaic (APV) systems, providing an adequate, resource-efficient solution to the persistent problem of competition for arable lands, reduced GHG emission and energy efficiency.

The present thesis aims to study the techno-economic viability of implementing an agri-pv system within a kiwifruit farm located 20 km East of Aveiro. The purpose of the study is not only to address the compatibility of energy production with food growth but also to make the farm energetically self-sufficient and to make use of the excess energy through the respective commercialization with market agents. With that said, three sites belonging to the same production were selected and then divided into plots that constituted different types of photovoltaic applications. All things considered, the study was based on 3 fundamental pillars. The study of the shadow projection by the PV panels onto the existing plantations and how this affected the amount of incident sunlight. The sizing and analysis of the photovoltaic systems simulated with PVsyst on the selected areas. And finally, an economic overview on all designed systems.

Results have shown that combining photovoltaics with agriculture can be highly beneficial from an energetic point of view. With all considered simulated variants in the three areas of study, the totality of possible energy production is around 113 MW. Applications involving overhead agri-pv systems have demonstrated a promising compatibility when it comes to combining energy production and food growth, with an estimated production capacity around 42 MW. However, they have proven to be less economically viable, with CAPEX values about 157 % higher than conventional ground-mounted PV systems. Nevertheless, all considered systems have proven to be profitable within the 20 year analysis period.

**Keywords:** Photovoltaics, Agriculture, Agrivoltaics, Energy Production, Self-sufficient



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Diogo Curval



*Experience is simply the name we give our mistakes*

Oscar Wilde



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# Symbols and Abbreviations

## Symbols

| Symbol         | Description                                                    | Unit       |
|----------------|----------------------------------------------------------------|------------|
| A              | Height between peak of the peak and beggining of the collector | [m]        |
| a              | solar azimuth                                                  | [°]        |
| $a_{sup}$      | surface azimuth                                                | [°]        |
| ah             | Hour angle                                                     | [h]        |
| B              | crop length                                                    | [m]        |
| d              | Shadow projected distance from the collector                   | [m]        |
| D              | Distance between collector rows                                | [m]        |
| $E_{sp}$       | Amount of surplus energy                                       | [kWh]      |
| H              | Collector height                                               | [m]        |
| $h_{sun}$      | solar height                                                   | [°]        |
| $h_{max}$      | Maximum solar height                                           | [°]        |
| k              | Crop height                                                    | [m]        |
| k'             | Quota withdrawn by the commercializing agent                   |            |
| l              | Collector width                                                | [m]        |
| LCOE           | Levelized cost of electricity                                  | [€/kWh]    |
| $LCOE_{APV}$   | Levelized cost of electricity for agrophotovoltaics            | [€/kWh]    |
| $LCOE_{PVGGM}$ | Levelized cost of electricity for ground-mounted PV            | [€/kWh]    |
| $M_{APV}$      | Annual electrical yield per ha for APV                         | [kWh/ha/a] |
| $M_{PVGGM}$    | Annual electrical yield per ha for PV-GM                       | [kWh/ha/a] |
| $N_t$          | Net balance for year t                                         | [€]        |
| p              | price                                                          | [€/ha/a]   |
| pa             | payback period                                                 | [years]    |
| pb             | performance benefit                                            | [€/ha/a]   |
| ppr            | price-performance ratio                                        |            |
| PR             | Performance Ratio                                              |            |
| $R_t$          | Redemption part of the loan for year t                         | [€]        |
| ROI            | Return on Investment                                           |            |
| $S_t$          | Self consumption saving for year t                             | [€]        |
| ST             | Solar Time                                                     | [h]        |
| $W_{fv}$       | OMIE wholesale market fixed value for each hour of the day     | [€/MWh]    |
| x              | Incident shadow distance on following crop rows                | [m]        |
| x'             | Incident shadow distance on first crop row                     | [m]        |
| z              | Collector height with respect to the ground                    | [m]        |
| $\phi$         | latitude                                                       | [°]        |
| $\delta$       | Sun declination                                                | [°]        |
| $\beta$        | Tilt angle                                                     | [°]        |

**Abbreviations**

|         |                                                            |
|---------|------------------------------------------------------------|
| Agri-pv | Agrivoltaics                                               |
| APV     | Agrophotovoltaics                                          |
| CAP     | Common Agricultural Practices                              |
| CAPEX   | Capital Expenditure Costs                                  |
| GHG     | Greenhouse Gas Emissions                                   |
| CVG     | Conventional Greenhouses                                   |
| CGIAR   | Consultative Group on International Agricultural Research  |
| EU      | Europe                                                     |
| NUTS    | Nomenclature of Territorial Units for Statistical Purposes |
| OPEX    | Operational Expenditure Costs                              |
| OPV     | Overhead photovoltaics                                     |
| PV-GM   | Ground-mounted photovoltaics                               |
| PAR     | Photosynthetically Active Radiation                        |
| PV      | Photovoltaics                                              |
| PVG     | Photovoltaic Greenhouse                                    |
| PUSC    | Production Unit for Self-Consumption                       |
| R&D     | Research and Development                                   |
| STC     | Standard Test Conditions                                   |



# Chapter 1

## Introduction

### 1.1 Context

Photovoltaic energy is one of the leading and most fast-growing industries worldwide which consists in the generation of electricity through the conversion of solar energy in photovoltaic cells. In 2021, solar PV had another record-breaking year, with new installations capacity reaching values of 139 GW, which brought the global total to an estimated 760 GW installed capacity, including both on grid and off-grid capacity [1]. Looking at figure 1.1, it is possible to see the evolution of the total installed PV capacity in the world throughout the years [1].

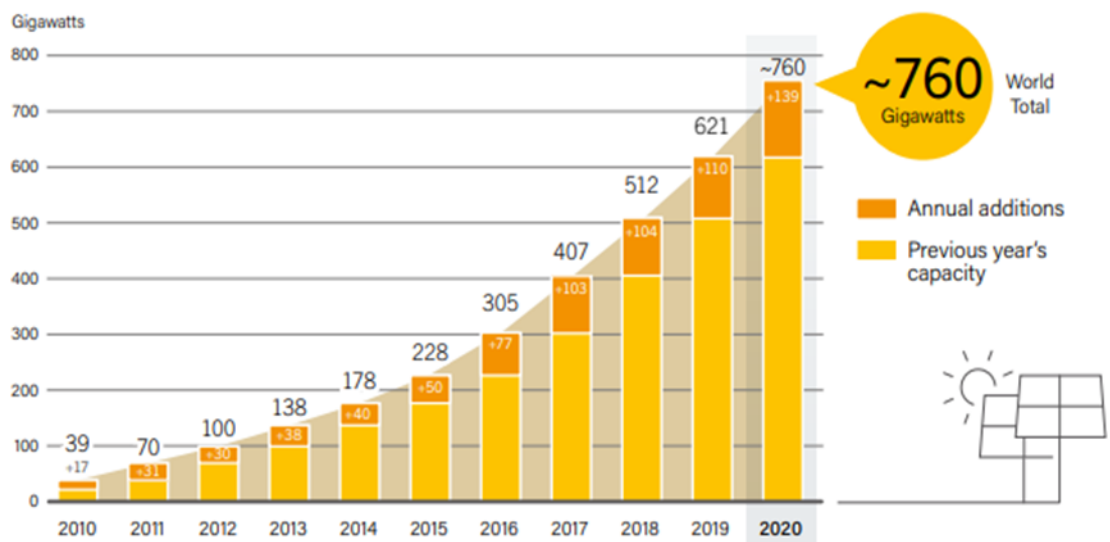


Figure 1.1: Solar PV global capacity and its annual additions.

As demand for solar PV is spreading and expanding, it becomes the most competitive option for electricity generation in a growing number of locations. A constant rhythm of growth promotes a systematic development of new concepts as a mean to improve photovoltaic cells efficiency as well as better energy consumption technologies in the fabrication of these components [2].

One of the main advantages of photovoltaic systems consists in the acceleration process of decentralization, specially by promoting a paradigm shift in the way we obtain electricity. It boosts the economy and creates numerous job opportunities, furthermore photovoltaic development helps in the transition to a sustainable future and it is implemented without significant environmental impacts, specially by not emitting carbon dioxide [3].

Currently, most of the agricultural activities are powered by fossil fuels, increasing greenhouse gas (GHG) emissions and climate change as a consequence. The global food system, from fertilizer manufacture to food storage and packaging is responsible to almost 30 % of all human caused GHG emissions, according to the 'Consultative Group on International Agricultural Research' (CGIAR), where cultivation activities solely contribute to about 8,5 % of the annual total carbon dioxide emissions [4][5].

In this context, energy and food are the two main requirements for human civilization, however demands for these two resources are increasing with a fast rate [6]. On one side, the expansion of renewable energies aims at meeting the global energy demand while replacing fossil fuels, however this transition requires large chunks of land. On the other hand, agricultural activities are mainly dependent on three constituents: energy, water and land resources. Within this frame, it is conceivable to tackle both problems with the combination of photovoltaics and plant production, often referred as agrivoltaics (agri-pv) or agrophotovoltaic (APV) systems, providing an adequate, resource-efficient solution to the persistent problem of competition for arable lands, reduced GHG emission and energy efficiency. All things considered, agrivoltaics can be briefly described as the combined use of the same land area for agricultural production as the primary use and for electricity PV as the secondary use.

## 1.2 Objectives and Motivation

As agriculture is responsible for up to 8,5 % of all greenhouse gas emissions with a further 14,5 % coming from land use change (mainly deforestation in the developing world to clear land for food production) [7], optimizing land use by sharing food production with photovoltaic energy would reduce greenhouse gas emission from agricultural activities and aid with the transition from the use of fossil fuels to renewables.

This coexistence has the potential to boost benefits in food production and sustainability by making farmland self-sustainable. Agrivoltaics can reduce the use of natural resources such as land and water, when designed carefully they can improve productivity per ha, while simultaneously reducing soil degradation and water usage. Furthermore, it enables development in rural areas through higher yields and new business opportunities, all this whilst promoting sustainable agricultural practices.

With the addition of the rapid growth of photovoltaics in terms of solar cells efficiency and increasingly lower module prices, the opportunity of deploying this technology with agriculture comes at a great timing. As it is a recent concept, there is no evidence of its implementation in Portugal, and by analyzing the plans for 2022 from the general direction of agriculture and rural development in Portugal [8], there was no mention of the possibility of implementing agrivoltaics.

With that said, the present study is carried out with the objective of introducing and evaluating the potential of implementing this concept in Portuguese territory. With data made available from a 10 hectare farm present 20 km East of Aveiro that produces kiwifruit, an assessment on the possibility of implementing agrivoltaic systems in order to maximize land-use efficiency whilst maintaining crop production is made. In order to do so, three agricultural plots were selected and then divided into sub-areas that represented the possibility of implementing different types of photovoltaic projects. This assessment is divided into three major phases. First, the projection of incident shade by the solar collectors placed above the crops is analyzed in order to evaluate the compatibility of this technology with crop production regarding solar limitation. Secondly, based on the available areas in each sub-project and their respective limitations, photovoltaic systems were designed and reviewed using the PVsyst software. Lastly, an economic overview of each conducted sub-project is conducted intending to evaluate the economic viability of the photovoltaic systems.

## 1.3 Document structure

This document is divided into five chapters. Chapter 1 focuses on a contextualization of the work to be developed throughout the project, from the background, motivation, objective and structure of the dissertation, allowing the reader a preliminary contact with the reality on how the project will be developed as well as the most important information about the connection of objectives and motivations with the different project stages.

Chapter 2 reviews the current state of photovoltaics, from the present and emerging technologies in this sector to the current state and potential for development in Portugal. Furthermore, introduces the reader to the concept of agrivoltaics, providing a definition of the technology and a broad and detailed overview of its applications.

Chapter 3 aims to introduce the case study in which the development of this dissertation is inserted, giving an overview of the methodology followed to collect the data and achieve the results of this work. First, the objectives of the case study are enumerated, then the climate zone where the project is located is defined and the various areas subject to the case in question are presented. Additionally, A brief introduction in solar geometry is presented in order to frame the reader with the equations to be used in the study of shadow projection. Finally, an overview of how the PV systems will be sized in PVsyst is presented.

Chapter 4 refers to the results and discussions. A detailed analysis on the shadow projection study is performed, followed by the presentation and examination of the simulation results conducted on the PVsyst software. Lastly, a brief economic analysis is conducted.

Finally, chapter 5 presents the conclusions regarding all the work developed during the project, as well as future work, to put it simply, what steps should be executed with the purpose to ensure the continuation of the project.

## Chapter 2

# Literature Review

In order to better understand the concept in hand, how it is currently developed in our society and how we can cope with it, it is essential to conduct a detailed research on the subjects that are being explored throughout this thesis.

Being aware on how the problem is currently situated in our society is crucial to adopt the strategies that better match it, this awareness is essential to prevent mistakes that may arise in the future.

In addition, it provides us the knowledge to approach the problem in hand with the better and most suitable solution, whilst giving us the opportunity to combine different strengths and approaches.

### 2.1 Different types of PV cells

Nowadays, there is a wide variety of photovoltaic cells in the marketplace which use different types of materials. They can be categorized into three generations, according to their level of commercial maturity and material used [2]:

- First generation: Photovoltaic systems that are fully commercial and use crystalline silicon (c-Si) technology both in its simple crystalline form (sc-Si) and multicrystalline form (mc-Si). These represent for about 90 % of the photovoltaic cell market.
- Second generation: Photovoltaic systems that are based on thin film technologies and generally include three main families:
  1. amorphous silicon (sc-Si) and micro amorphous silicon (a-Si /  $\mu$ c-Si);
  2. cadmium telluride (CdTe);
  3. copper indium selenide (CIS) and copper, indium gallium diselenide (CIGS);

They represent a great potential in the PV cell market as thin-film solar cells require up to 99 % less material than crystalline solar cells in order to absorb the same amount of sunlight.

However, efficiency rates (5-13 %) compared to the crystalline silicon cells (11-20 %) are still relatively low.

- Third generation: Photovoltaic systems that include organic photovoltaic technologies that are still in demonstration or have not been widely marketed. Altogether, organic photovoltaic cells offers characteristic that makes them very attractive such as the potential to be flexible and semi-transparent, to be manufactured in a continuous printing process resulting in low manufacturing costs, low weight per unit area  $0,5 \text{ Kg/m}^2$  (Si- based PV's  $22\text{Kg/m}^2$ ), amongst others. Efficiency rates in this technology are still relatively low compared to their peers, however these cells have shown great improvement in terms of efficiency throughout the years. This type of PV cells are of great interest in the agri-pv market as we will later discuss in section 2.3.3.

Figure 2.1 shows the evolution of different solar cells efficiency tested in laboratory (optimal conditions) throughout the years. Note that when they are assembled in photovoltaic modules they lose efficiency [9].

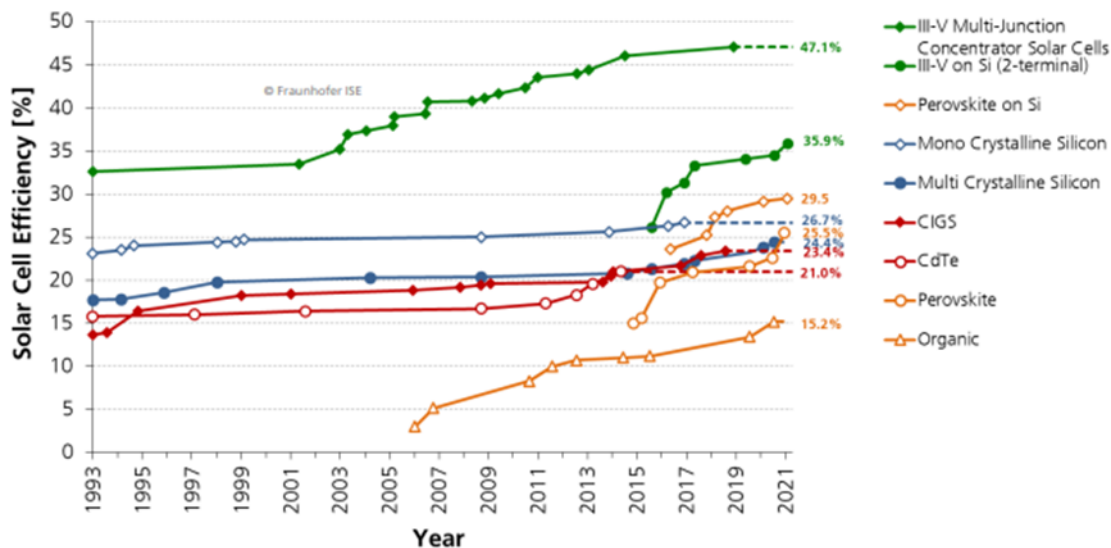


Figure 2.1: Evolution of different solar cells efficiency tested in laboratory throughout the years.

As stated before, organic photovoltaics have shown great evolution in terms of efficiency in the past years making it a very promising technology for the PV market in the future.

Fundamentally, all types of solar modules can be used in agrivoltaic systems, however some types are briefly mentioned due to their particular interesting characteristics for agrivoltaics implementation.

**Transparent covering modules** (glass, foil), as seen in figure 2.2, the spaces between the cells allows the light to pass through and reach the plants. The spaces can be enlarged and the module frames replaced by clamp mountings to increase light transmission. Modules that present a higher ratio of transparency to total area are able to protect plants against environmental influences without diminishing the availability of sunlight to some extent [10].



Figure 2.2: Transparent covering modules.

**Bifacial modules**, as seen in figure 2.3, can use the ambient light incident on the reverse side for power generation, increasing the electricity yield. This comes particularly interesting in agrivoltaics since the row-to-row distance tends to be larger and the supports taller, thus making the light available on the reverse side of the modules higher [11].



Figure 2.3: Ground-mounted bifacial solar panel array.

## 2.2 PV potential in Portugal

Solar photovoltaic technologies are seen worldwide as an essential part of any power sector technology portfolio aiming for climate change mitigation and energy security. The Iberian Peninsula has a high number of daylight hours (2200-3000) and a high daily irradiation ( $5000 \text{ W/m}^2/\text{day}$ ) [12]. As shown in figure 2.4, the Southern Iberian Peninsula has the highest level of global horizontal radiation in Europe [13] [14].

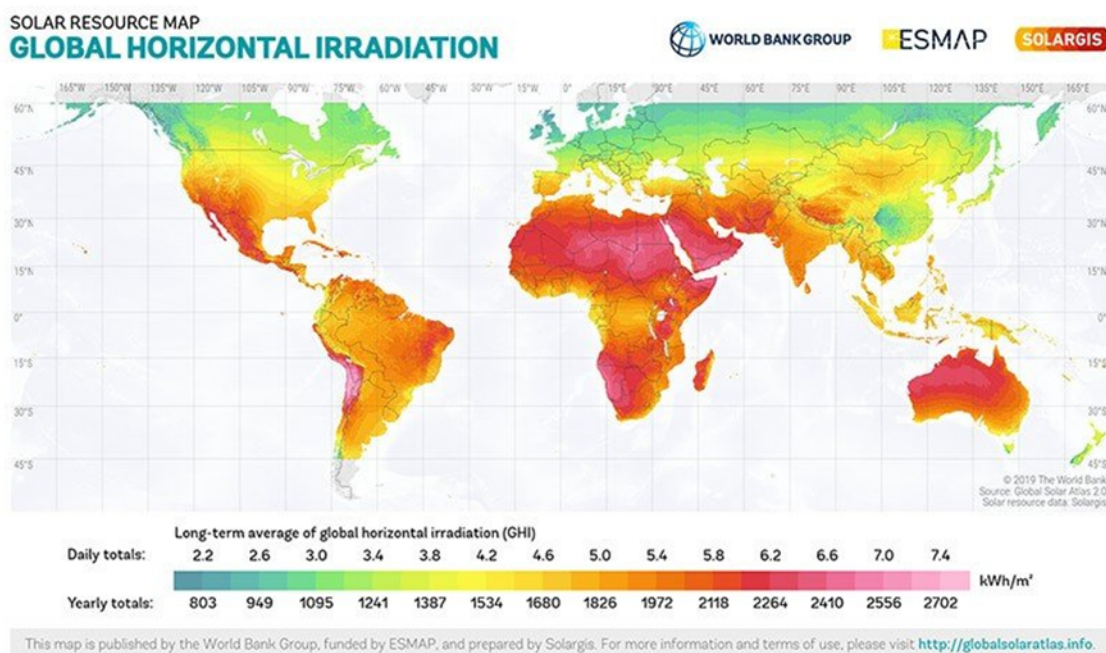


Figure 2.4: Long term average of daily/yearly sum of global horizontal radiation [kwh/m2].

Portugal has a total photovoltaic installed capacity of 1777 MW [15] and an index solar irradiation of  $1,8 \text{ MWh/m}^2$  (almost as double as Germany  $1 \text{ MWh/m}^2$ ). With all things considered, the potential of PV technology in Portugal is huge and efforts to continue to increase its development are constantly being made. Therefore, the combined use of agriculture with photovoltaic energy will tackle land use efficiency as well as food and energy production.

Figure 2.5 displays the PV potential present in Portugal, this image relates the annual production of energy in kWh with the total installed capacity in kWp<sup>1</sup> [14].

<sup>1</sup>Maximum quantity of electrical energy that a PV panel can produce, in a determined instant, through the capture and transformation of solar energy, considering ideal conditions.



Figure 2.5: PV potential in Portugal.

As stated before, Portugal is located in a very favorable geographical position in order to implement photovoltaic plants.

### 2.2.1 Portuguese Legislation

With regards to the Portuguese legislation concerning the self-consumption of renewable energy, according to the Decree Law nº162/2019, it is said[16]:

’This Directive provides a legal framework that allows self-consumers of renewable energy to consume, store, share and sell electricity without being faced with disproportionate burdens.’

Until now, only self-consumption was allowed. However, since the start of January of 2020 self-consumers are allowed to group together and the same unit of energy production may have several self-consumers (collective self-consumption). In addition, it is also allowed that self-consumers and other participants in renewable energy projects constitute legal entities (the Energy Communities) for the production, consumption, sharing, storage and sale of renewable energy. Meaning

that this decree-law is intended for Portugal to achieve the goals defined by the National Energy-Climate Plan for 2021-2030. This plan aims to achieve a 47 % share of energy from renewable sources, implying that in the power sector at least 80 % of the electricity produced is contributed from renewable sources. So as to attain this objective, the total solar installed capacity should be at least 1 GW by 2030.

Some key points can be highlighted in order to better comprehend the directives that users are subject to. Regarding the working conditions we have:

1. A production unit for self consumption (PUSC) with an installed capacity inferior or equal to 350 W is not subject to prior check.
2. A PUSC with an installed capacity superior to 350 W and equal or inferior to 30 kW is subject to a mere prior communication.
3. A PUSC with an installed capacity superior to 30 kW and equal or inferior to 1 MW is subject to a prior registration and an operating certificate for its installation.
4. A PUSC with an installed capacity greater than 1 MW is subject to attribution of a production and exploration license

In respect of remuneration, the surplus produced energy can be traded:

- (a) In an organized or bilateral market, including through a purchase contract for renewable energy;
- (b) Through the market participant against payment of a price agreed between the parties;
- (c) Through the market facilitator.

More information on the current legislation can be consulted at [16].

## 2.3 Agrivoltaics

The concept of agrivoltaics was initially proposed in the year 1982 by Gochtberger and Zastrow [13] and the main principle was that the energy collectors and agriculture could share the same land area and that this coexistence would in fact boost the benefits. As seen in figure 2.6, agrivoltaics systems are broadly classified according to various measures. These include the type of the system (being closed or open), type of the structure (interspace PV, overhead PV, PV integrated greenhouses), the tilt of modules (fixed, one axis tracking, two-axis tracking), and type of the application (grassland farming, arable farming, horticulture, and aquaculture)[4].

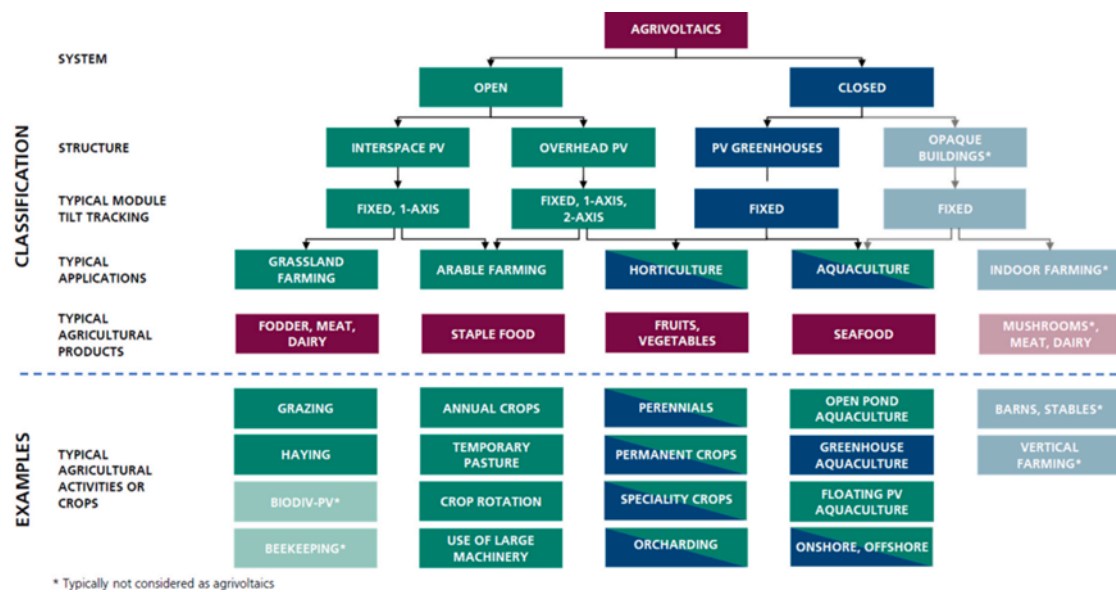


Figure 2.6: Broad classification of agrivoltaic systems.

There is major potential in agrivoltaics as it can accelerate the transition to a sustainable agricultural system which contributes to the European Green Deal objectives. Agrivoltaics have the potential to [17]:

- Contribute to a responsible use of natural resources such as land and water: when designed carefully they can improve productivity per ha, while simultaneously reducing soil degradation and water usage. In addition, agrivoltaics systems can lower the water needs of agriculture by shielding crops from heat thus reducing evapotranspiration.
- Promote sustainable agricultural practices: these installations can deploy physical pest control measures, such as netting, and thereby reducing chemical pest control product use, contributing to food safety and biodiversity protection.
- Increase the EU's agriculture resilience to climate change and other shocks and stresses: Agrisolar solutions can protect and shade agricultural activities from unexpected and extreme weather events such as hail, excessive solar radiation and from pests and diseases
- Enable development in rural areas through higher yields and new business opportunities: figure 2.7 shows an experimental agri-pv system in Germany, led to a 103 % yield when compared to a control, while the PV systems generated 83 % of the electricity that would have been generated on the similar plot of land, leading to an 86 % increase in land use efficiency [17].

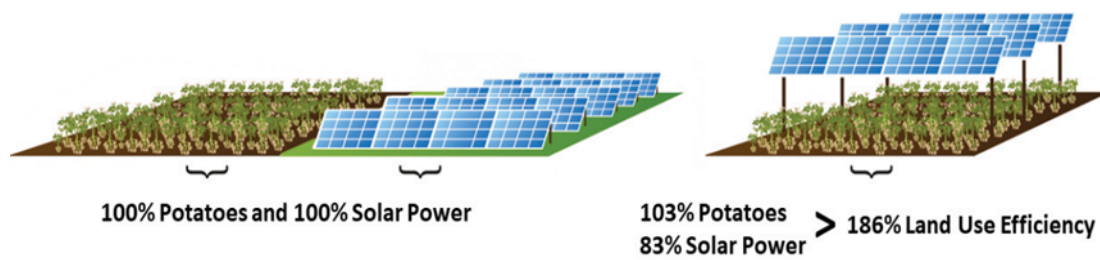


Figure 2.7: Increased land use efficiency from deployment of agri-pv systems.

Solar panels can too benefit from this coexistence:

- Solar panels over vegetation were found to be significantly cooler (on average, 8,9 °C cooler) during daylight hours compared to panels above bare land. This indicates that the presence of vegetation beneath panels can have a positive impact for solar PV panels in hot climates due to the fact that solar PV efficiency is diminished when ambient temperature increases [18].
- Vegetation also acts as an effective dust suppressant, typically a significant inhibitor to solar module efficiency [19].
- Animal grazing delivers benefits for solar farms as the vegetation is maintained in a cost-effective and safe manner by reducing the need for mowing or spraying in addition to reducing risks of fire hazard and protecting the solar assets [20].

An example of an agrivoltaic system is depicted in figure 2.8, demonstrating the possibility of combining both food and energy production. The energy surplus could eventually be sold to the grid or to other households in the area [21].

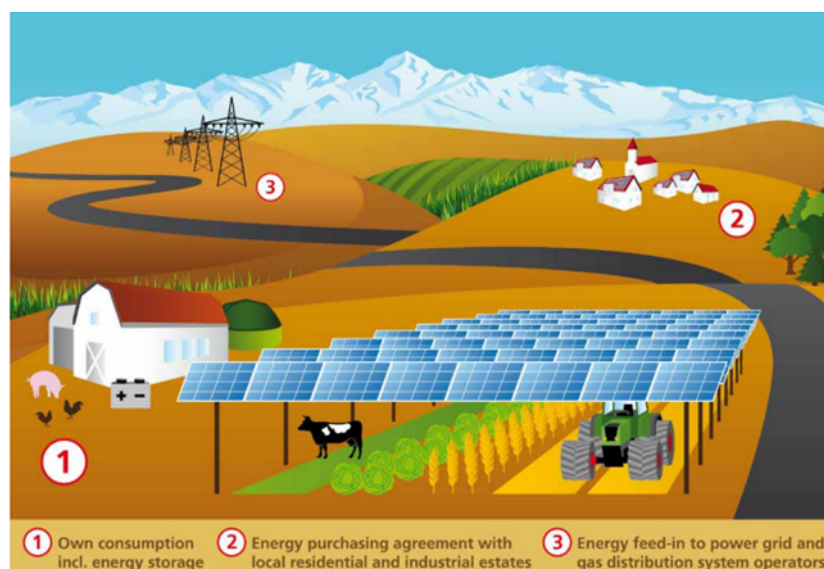


Figure 2.8: Illustration of an agrivoltaics system.

Still, there are some existing challenges for agri-pv projects around EU as lack or absence of regulatory framework makes it difficult to support the development of agrisolar projects. Countries with significant potential to develop agrivoltaic projects such as Portugal and Spain lack the framework to do so. With that said, there are exceptions such as France and Germany who have made progresses on this matter, the German DIN SPEC provides a definition for agrivoltaics [22]:

“Agrivoltaics is the combined use of the same land area for agricultural production as the primary use and for electricity PV as the secondary use” German DIN SPEC 91434.

In addition, the French Environment and Energy Management Agency has defined a new definition for agrivoltaics [23]:

“An agrivoltaic installation is a PV system whose modules are located on the same surface of an agricultural production, to which they bring the following services, without causing a significant qualitative and quantitative degradation of the agricultural yield, as well as a reduction of the revenue generated from the agricultural activity. Service of adaptation to climate changes, service of protection to extreme weather events, service of improving animal welfare, agronomic service for specific cultures.”

However, promising investments opportunities presented by the Portuguese Ministry of Agriculture may help with the boost start that Portugal needs, offering a €10 million call to support innovative agrivoltaic projects that could cover up to 70 % of a project’s upfront costs [24].

### 2.3.1 Shade tolerant crops for agrivoltaic systems

An assessment on shade tolerance levels in different types of crops is made based on several studies performed on agrivoltaic systems throughout the world, as seen in table 2.1 [25].

Table 2.1: Shade-tolerant crops for potential use in agrivoltaic systems.

| Major commercial<br>shade-intolerant<br>crops                                  | Shade Tolerant Crops                                                                                                                                                                                                             |                                                                            |           |
|--------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|-----------|
|                                                                                | Full shade                                                                                                                                                                                                                       | Moderate light                                                             | Low light |
| Cabbage, corn,<br>cucumber, pumpkin,<br>rice, tomato, turnip<br>and watermelon | Alfalfa, arugula, Asian<br>greens, broccoli,<br>cassava, chard,<br>collard greens, hog<br>peanuts, kale,<br>kohlrabi, lettuce,<br>mustard greens,<br>parsley, scallions,<br>sorrel, spinach, sweet<br>potatoes, taro, and<br>yam | Beans, carrots,<br>cauliflower,<br>coriander, green<br>peppers, and onions | Mushroom  |

Still, there is no consistent definition on what percentage of reduced irradiation can define what a moderate light and low light shade tolerant crop is. Nonetheless, based on accessible literature, when available irradiation under agrivoltaic systems is reduced by 15 % to 40 % it is considered moderate shading. Lettuce is considered to be a suitable crop for agrivoltaic systems since it can tolerate up to 30 % of shade. Low shading rates represents percentages equal or under 15 % [25].

### 2.3.2 Overhead PV

According to figure 2.6, when an elevated photovoltaic structure is mentioned, it will be referred throughout this paper as overhead PV (OPV). Continuing, solar panels can be deployed on elevated structures to provide shelter for horticulture, perennial crops, and special crops in addition to generating electricity. These structures can be particularly suitable for the cultivation of berries such as raspberries, currants, blueberries, strawberries and blackberries. Fruit orchards and vines are also appropriate for the cultivation under these structures [17].

The design of a typical overhead PV (OPV) structure is displayed in 2.9. When planning an agrivoltaic system of this kind, practical requirements must be taken into account in order to minimize the impact on crop cultivation. The system must be oriented in the same direction as that of the field work, and the distances between the supports of the mounting structure must be compatible with the heights and widths of conventional farm machinery. In addition, cultivation under these systems require increased attention from the driver to prevent collisions with the supports. There is always a small percentage of land loss ( approximately 8 %) due to the supporting structure and impracticability of cultivation near these supports when working with machinery [21] [26].

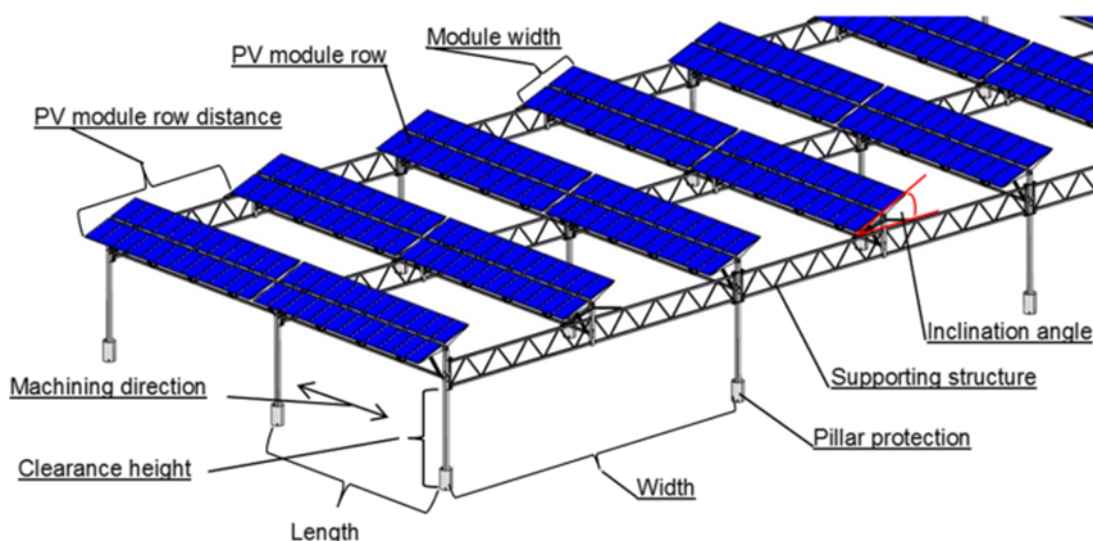


Figure 2.9: Design and fundamental parameters of an overhead PV structure.

The shading structures can bring several positive benefits on the crops as they are simultaneously protected from extreme weather, pests and excessive sunlight [17].

Figure 2.10 displays a wine farm in France with implemented OPV structures with solar tracking systems [21].



Figure 2.10: OPV wine farm with solar tracking system in France.

Moreover, designs that include a rainwater harvest system, as seen in 2.11, can contribute to water management. Collecting and storing rainwater can help to conserve groundwater resources, especially in arid regions, or make agriculture possible in the first place [21].



Figure 2.11: Concept of a rainwater harvest system with underground storage tank.

A study in Korea replaced its rain-hit-protection facility with a solar power generation system in a grape farm in order to observe the differences in crop growth and its characteristics, plus

adding an increase in the farmer's revenue from the photovoltaic generation. The main contribution of the research was to examine the impact of crop growth above 30 % shading. The structure of the photovoltaic system was designed to be similar to the existing rain-shield facility in order to replicate as best as possible the cultivation environment present before. Figure 2.12 displays the rain-hit-protection solar facility present in the farm [27].



Figure 2.12: Rain-hit-protection solar facility in a grape farm.

The solar panels were fitted onto the roof using a checkerboard pattern, as shown in figure 2.13 [27].

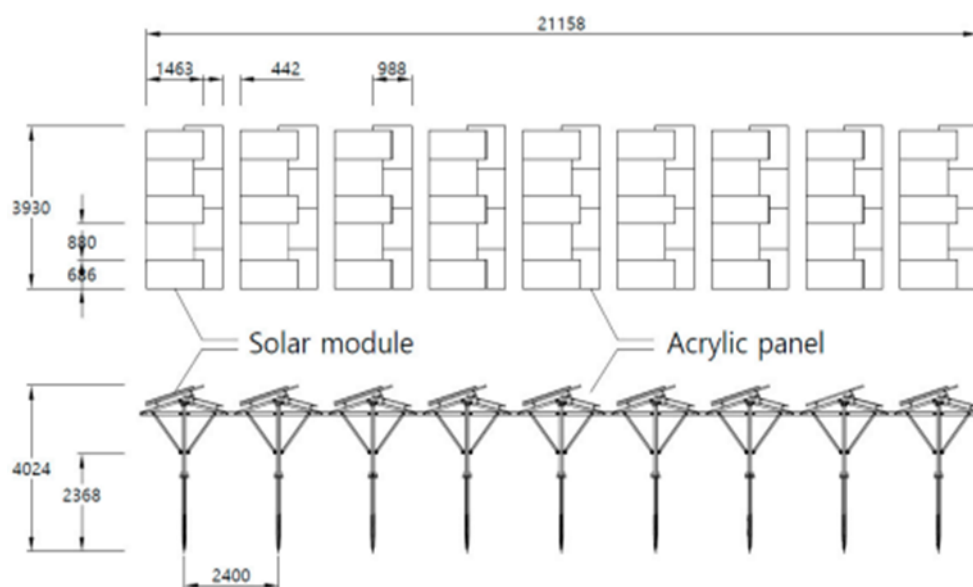


Figure 2.13: Structure of the photovoltaic system.

The total installed capacity of the test bed was 99 kW. Three types of modules were installed using bifacial, transparent and normal photovoltaic panels, but no real differences could be drawn in the power output of the models due to the fact that these presented different orientations. In table 2.2 the power output of the farm in the course of 5 months is presented [27].

Table 2.2: Agricultural solar plant proceeds.

| Contents             | Unit    | April | May    | June   | July   | August | Total  |
|----------------------|---------|-------|--------|--------|--------|--------|--------|
| Days                 | Days    | 30    | 31     | 30     | 31     | 31     | 153    |
| PV energy            | kWh     | 8978  | 11,454 | 12,393 | 10,426 | 12,631 | 55,882 |
| Electric price (SMP) | USD/kWh | 0.117 | 0.094  | 0.093  | 0.094  | 0.1    | 0.1    |
| Sales income         | USD     | 1057  | 1081   | 1153   | 985    | 1270   | 5551   |
| PV exchange time     | hours   | 3.02  | 3.73   | 4.17   | 3.40   | 4.12   | 3.69   |

The study came to show that no real differences on grape crop growth was shown. The distinctive factor was that grapes grown under solar panels showed slower growth compared to those grown on the control site. Further observations implied that grapes under solar panels could be harvested with the same quality (sugar-concentration levels, colour, granule weight) as grapes cultivated under control conditions by controlling the harvesting period [27]. In conclusion, this study confirmed that the coexistence of agriculture and renewable energy is possible, no significant negative impacts were visible in the crops cultivated, plus there was a 5551 USD profit (2.2) related to the power transaction translating into an additional source of revenue to the farmers.

#### Overhead PV economic viability

Implementing an agrivoltaics project in a farm represents in additional costs to the land owners. Additional investing, operational and maintenance costs are needed in order to deploy this projects. The cost of agrivoltaics can vary considerably from case to case, depending on factors such as the installed capacity, agricultural management, field location, chosen PV module technology, among others [28]. A case study in Heggelbach compared the capital expenditure costs (CAPEX) and operational expenditure costs (OPEX) regarding an OPV implementation with those of a conventional ground-mounted PV (PV-GM). Figure 2.14 and 2.15 presents the different cost factors [28].

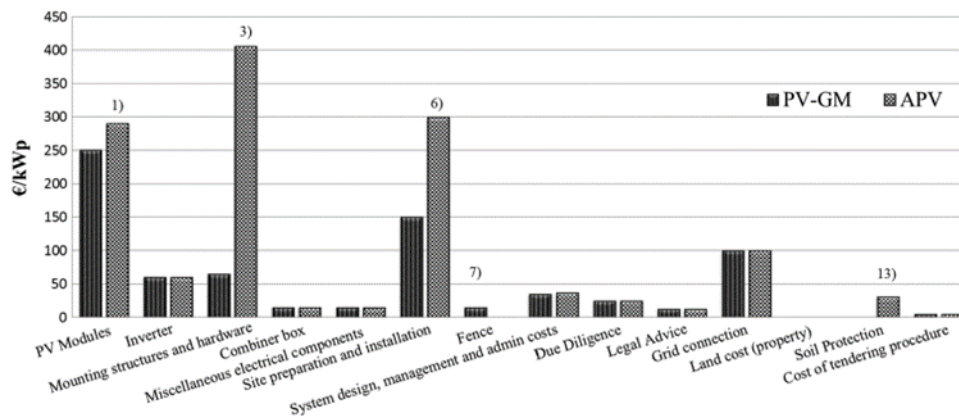


Figure 2.14: Comparison of CAPEX costs associated with OPV and PV-GM in  $\text{€kWp}^{-1}$ .

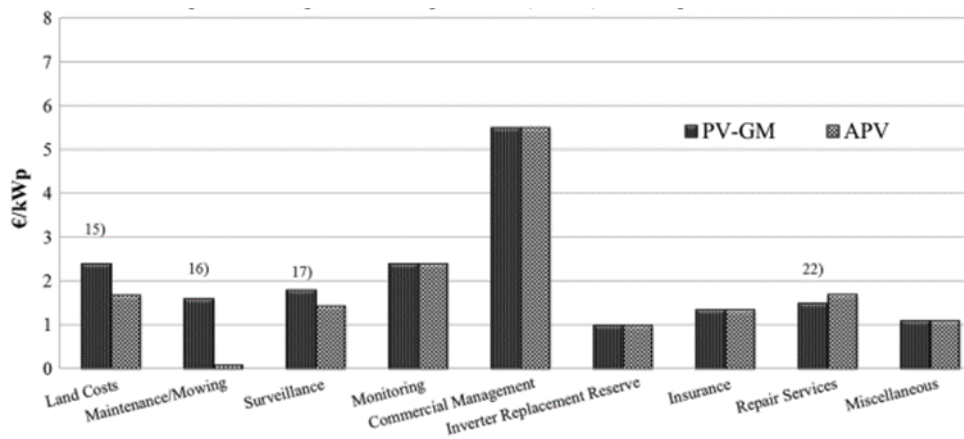


Figure 2.15: Comparison of OPEX costs associated with OPV and PV-GM in  $\text{€kWp}^{-1}$ .

Noting that in figure 2.14 the higher costs were due to mounting structure, as expected, as well as of the PV modules due to the fact that they were bifacial photovoltaic panels. Site preparation along with soil protection were a considerable factor in the cost difference as well. Regarding figure 2.15, it can be seen that the land cost per year is lower for OPV than for PV-GM. Additionally, costs of maintenance and mowing are significantly lower as well as surveillance costs. Repair services costs have a cost-increasing effect for OPV. However, OPEX costs only represent 1,1 % of the CAPEX for OPV and 2,2 % of the CAPEX for PV-GM [21].

### 2.3.3 Photovoltaic Greenhouses

Greenhouse cultivation contributes to increased crop yields because of crop protection (from exogenous factors), disease prevention, controlled interior conditions and reduced losses. In addition, the operation of modern greenhouses infrastructures requires a large amount of energy to cover needs for heating, cooling, ventilation, irrigation, automation and product preservation [29]. The PV Greenhouse (PVG) is an agrosystem potentially able to combine food and energy production on the same land unit by integrating the PV systems on the greenhouse roof. Therefore,

farmers can both benefit from crop and energy production, the generated electricity from the PV panels can be used to power the greenhouse systems above mentioned. However, the shading of the PV panels on the greenhouse area affects yield, growth and development of the plants. The cumulated radiation inside PVG's decreases as a function of the increasing PV cover ratio (PVr), that is the ratio of the projected area of PV panels to the ground and the total greenhouse area[30].

A study realized in Sardinia implemented PV panels on top of four PVG with different PVr's ranging from 25 % to 100 %, as seen in table 2.3.

Table 2.3: Difrent types of PVGs according to their roof-type and PVr.

| PV Greenhouse Type | Roof Shape   | PVr [%] | Area [m <sup>2</sup> ] | Total PV Power |
|--------------------|--------------|---------|------------------------|----------------|
| 1                  | Gable Roof   | 25      | 480                    | 1 MWp          |
| 2                  | Gable Roof   | 50      | 480                    | 1 MWp          |
| 3                  | Venlo-Type   | 60      | 840                    | 2 MWp          |
| 4                  | Mono-Pitched | 100     | 837                    | 3 MWp          |

Figure 2.16 displays the 4 types of PVGs that were used in the study in discussion [30].



Figure 2.16: Representation of the 4 commercial PVG's. At the top is PVG type 1 (left) and 2 (right), at the bottom is PVG type 3 and 4 (left and right, respectively).

### Daily Light Requirements for different crops

Before assessing the production of the different types of crops that were analysed in the study, it is important to bear in mind that each crop can be classified according to their light requirements inside the greenhouse. Horticultural and floricultural crops light requirements are usually expressed as Daily Light Integral (DLI), that is the average light sum of the Photosynthetically Active Radiation (PAR) received during a day, expressed in  $\text{mol.m}^{-2}.\text{d}^{-1}$  [30]. Moreover, the light saturation point is an important criterion for determining the crop suitability for agrivoltaics (see figure 2.17). From this point on, the plants are not able to convert additional light into photosynthesis output and may even be damaged. The lower this light saturation point is for a plant, the better suited it is for growing under an agrivoltaic system [21].

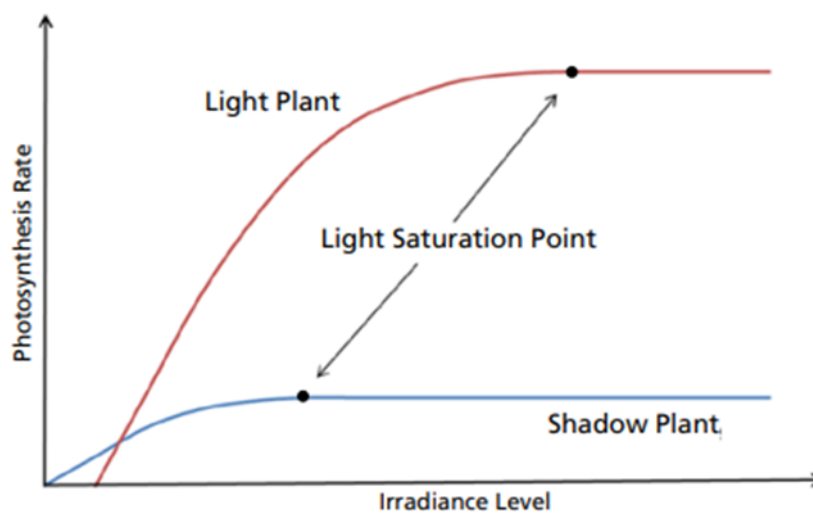


Figure 2.17: Photosynthesis rate depending on the light intensity for sun and shade plants.

Table 2.4 shows the Daily Light Requirements for 14 common greenhouse horticultural and floricultural crops, as well as its variation range in fresh yield according to the 1 % rule, that meaning with 1 % additional production for each 1 % additional light inside the greenhouse [31] [30].

Table 2.4: DLI for 14 common horticultural species.

| Species                                                                         | DLI crop requirements $\text{mol m}^{-2} \text{d}^{-1}$ |                 |                         | Variation range in fresh yield with 1 % additional light (%) | Mean Variation $V_c$ (%) |
|---------------------------------------------------------------------------------|---------------------------------------------------------|-----------------|-------------------------|--------------------------------------------------------------|--------------------------|
|                                                                                 | Insufficient ( $DLI_{min}$ )                            | Sufficient/good | Optimal ( $DLI_{opt}$ ) |                                                              |                          |
| High light demanding:<br>$DLI_{opt} > 30 \text{ mol m}^{-2} \text{d}^{-1}$      |                                                         |                 |                         |                                                              |                          |
| Cucumber                                                                        | < 12                                                    | 12.0 - 30.0     | > 30.0                  | 0.6 - 1.2                                                    | 0.90                     |
| Sweet Pepper                                                                    | < 12                                                    | 12.0 - 30.0     | > 30.0                  | 0.8 - 1.3                                                    | 1.05                     |
| Tomato                                                                          | < 15                                                    | 15.0 - 30.0     | > 30.0                  | 0.6 - 1.1                                                    | 0.85                     |
| Medium light demanding:<br>$DLI_{opt} 10 - 20 \text{ mol m}^{-2} \text{d}^{-1}$ |                                                         |                 |                         |                                                              |                          |
| Asparagus                                                                       | < 6.5                                                   | 6.5 - 16.7      | > 16.7                  | 0.8 - 1.0                                                    | 0.90                     |
| Basil                                                                           | < 5.3                                                   | 5.3 - 17.3      | > 17.3                  | 0.8 - 1.0                                                    | 0.80                     |
| Lettuce                                                                         | < 12.0                                                  | 12.0 – 20.0     | > 20.0                  | 0.8                                                          | 0.80                     |
| Strawberry                                                                      | < 12.0                                                  | 12.0 – 19.0     | > 19.0                  | 0.6 – 1.0                                                    | 0.80                     |
| Spinach                                                                         | < 8.0                                                   | 8.0 – 17.0      | > 17.0                  | 0.9                                                          | 0.90                     |
| Chrysanthemum                                                                   | < 10.0                                                  | 10.0 – 20.0     | > 20.0                  | 0.3 – 1.0                                                    | 0.65                     |
| Rose                                                                            | < 10.0                                                  | 10.0 – 20.0     | > 20.0                  | 0.8 – 1.0                                                    | 0.90                     |
| Ficus                                                                           | < 8.0                                                   | 8.0 – 16.0      | > 16.0                  | 0.65                                                         | 0.65                     |
| Low light demanding:<br>$DLI_{opt} 5 - 10 \text{ mol m}^{-2} \text{d}^{-1}$     |                                                         |                 |                         |                                                              |                          |
| Dracaena                                                                        | < 4.0                                                   | 4.0 – 8.0       | > 8.0                   | 0.65                                                         | 0.65                     |
| Kalanchoe                                                                       | < 4.0                                                   | 4.0 – 8.0       | > 8.0                   | 0.8 – 1.0                                                    | 0.90                     |
| Poinsettia                                                                      | < 6.0                                                   | 6.0 – 10.0      | > 10.0                  | 0.5 – 0.7                                                    | 0.60                     |

Due to shading of the panels, the solar radiation distribution is heterogeneous on the greenhouse area. The heterogeneity of solar distribution inside the greenhouse increases with the increment of the PVr, therefore the light distribution inside PVGs (difference between global radiation under the photovoltaic roof and standard roof) should be carefully considered for the crop management, in terms of fertigation, crop protection and transplantation period among the plant rows.

An analysis of the average montly  $S_{PG}$  (PVG average daily photosynthetically active radiation) for each PVG type on the considered study is made in order to compare each DLI crop requirements, as shown in figure 2.18 [30].

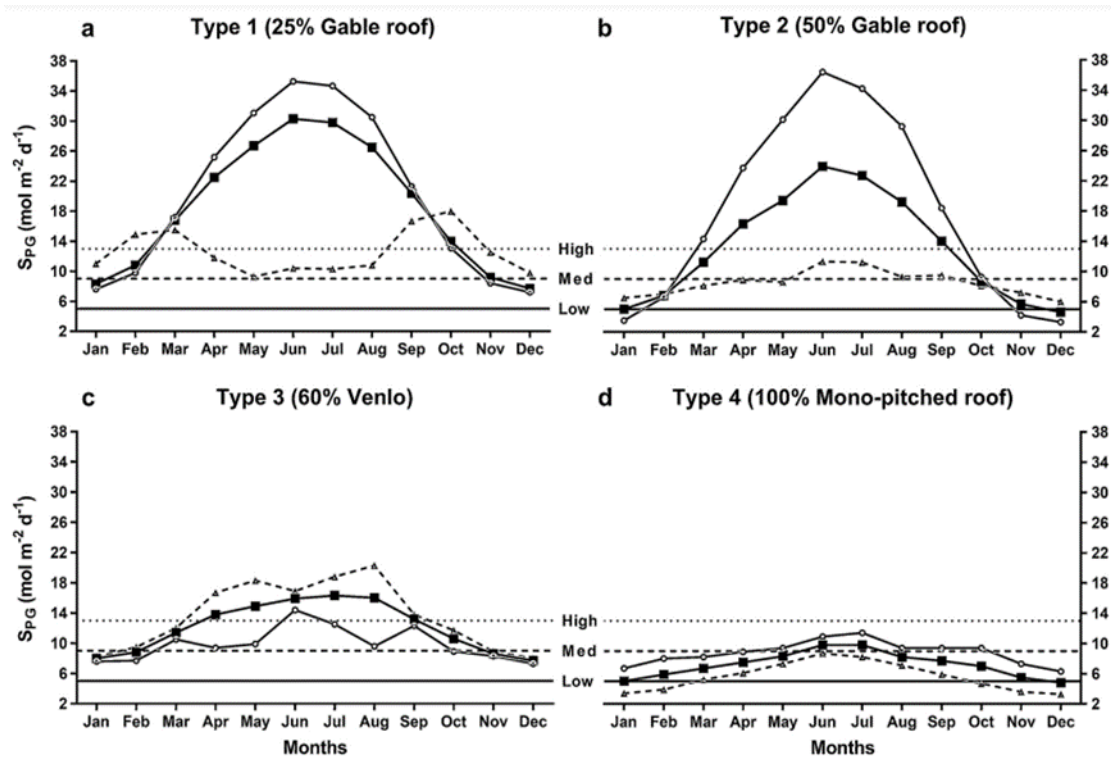


Figure 2.18: Average monthly  $S_{PG}$  inside the four PVG types, compared to the average DLImin of the species considered in the study: high, medium and low light demanding crops. The average  $S_{PG}$  of the whole PVG area is reported (black lines and squares), together with the  $S_{PG}$  under the standard (ST) roof (grey lines and circles) and the photovoltaic (PV) roof (grey dotted lines and triangles). For PVG type 4 (PVR 100 %), the PV and the ST roof correspond to the N-half and the S-half greenhouse area, respectively.

This consists in a very important study in order to show which roof type is more suitable for each crop. As expected, high light demanding crops are most suitable for roofs 1 and 2 due to their low PVr, medium light species are not suitable for roof type 4, whereas low light demanding species can be cultivated in all roof types. It is essential to take note that there are months where the min DLI is not met in certain crops, take for example the high light demanding species, where in roof 2 from January to March and October to December that value is not met. This suggests the implementation of crop management strategies that can identify the proper periods to start the crop cycle, allowing the plants to find the best light conditions during their growth and development in order to mitigate these months when the minimum DLI can't be attained.

#### Yield estimation inside the Photovoltaic Greenhouses

When comparing to a conventional greenhouse (CVG), it is considered that a maximum yield reduction of 25 % is allowed for assessing the agricultural sustainability of PVGs for crop production, corresponding to yearly minimum Yf (Yield factor) of 75 %.

All things considered, a general assessment according to the light requirements of each species is made based on the results on the case study performed [30]:

- High light demanding species: These crops can be cultivated inside PVGs with 25 % PVr showing limited yield reduction (below 25 %), however restrictions on growth and yield occurred when the PVr raised from 50 % to 100 %.
- Medium light demanding species: When the optimum DLI is lower than  $17 \text{ mol.m}^{-2}.\text{d}^{-1}$  (such as asparagus) they can be grown inside PVGs with a PVr up to 60 %.
- Low light demanding species: When the DLI is equal or lower than  $10 \text{ mol.m}^{-2}.\text{d}^{-1}$  these crops can be cultivated in all considered PVGs types, such as poinsettia, kalanchoe and dracaena.

Innovative cropping systems should be considered to overcome the penalizing light scenarios of the PVGs with high PVr, also implementing LED supplementary lighting. For more detailed information on the yield factor for each specie according to their light requirements and roof type in which they were cultivated can be consulted figure A.1.

#### Organic Photovoltaics inside a Photovoltaic Greenhouse

A study realized in a Mediterranean greenhouse covering 22 % of its roof area ( $24\text{m}^2$ ) was conducted in order to investigate its effect on the growth and behavior of pepper plants (*Capsicum annuum*) using organic photovoltaics.

There were 3 groups of pepper plants cultivated, the plants grown inside the greenhouse were divided into two groups: the “Shaded Plants” and the “Control Plants”. At the exterior of the greenhouse there was placed another group of plants, referred as the “Outdoor Plants” [29]. The Mediterranean greenhouse with implemented organic photovoltaic panels is shown in figure 2.19 [29].

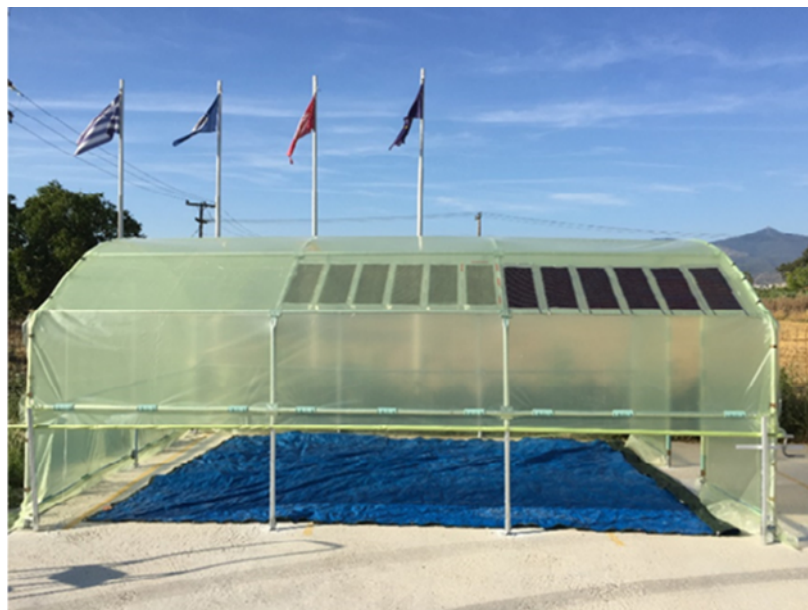


Figure 2.19: Mediterranean Greenhouse integrated with semi-transparent fully printed organic photovoltaic modules.

The range of solar radiation ranges from 290 to 3000 nm. Approximately 40 % of the total energy is emitted into the Photosynthetically Active Radiation (PAR) area (400 to 700 nm) and approximately 50 % is emitted to the near infrared radiation (700-2500 nm) of the plants [29]. The optical transmittance of the manufactured organic photovoltaic panels is shown in figure 2.20 [29].

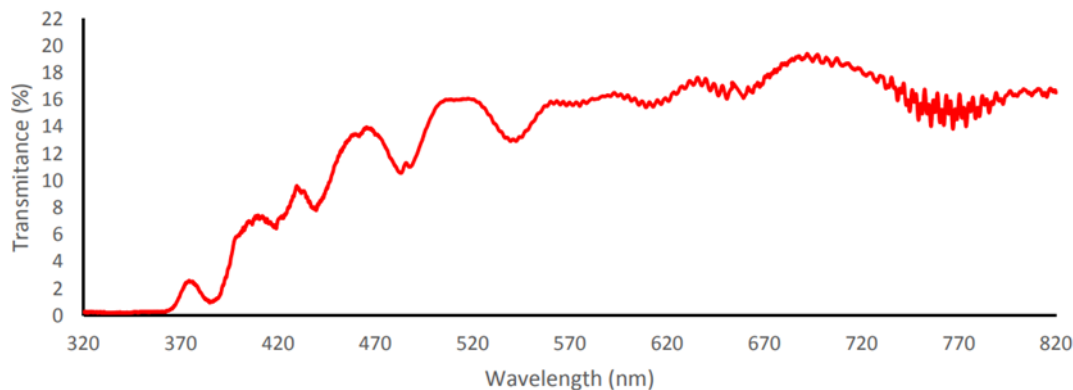


Figure 2.20: Optical transmittance of the manufactured organic photovoltaic panels.

The optical transmittance results confirm the transparency of the organic panels in PAR region at levels between 8-19.4 %, with the last value corresponding to the peak of maximum transmittance at  $\lambda=691$  nm.

According to these results, determination of the growth response of plants cultivated under irregular light conditions through the integrated semitransparent organic photovoltaic modules was performed. The period of examination lasted 154 days and the data regarding plant frutification was collected and analysed, as depicted in figure 2.21 [29].

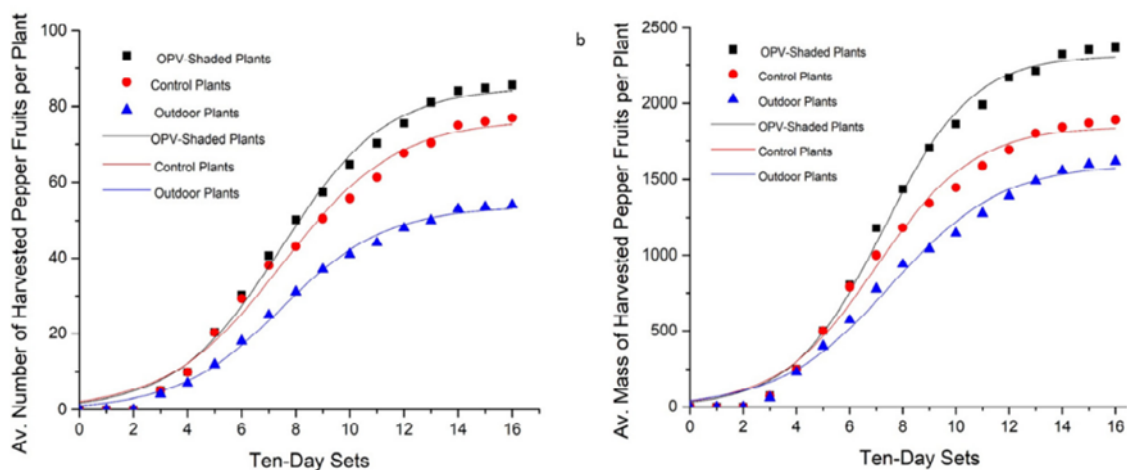


Figure 2.21: Experimental results and S-fitting curves respecting the average number of produced pepper fruits (a) and the average fruit mass produced (b) throughout the experimental period.

Analysing figure 2.21 the “Shaded Plants” produced 9,9 % more pepper fruits and 20,2 % more pepper fruit mass than the “Control Plants”. In addition, they produced 36,8 % more pepper

fruits and 31,6 % more pepper fruit mass than the "Outdoor Plants". Therefore, the shading effect from organic photovoltaic modules on plant growth can be considered beneficial for pepper plants cultivation, these favorable results could be due to their protection from UV light that is absorbed by materials integrating the modules device. Interaction with ultraviolet radiation with the epidermis or inner plant tissues has been found to cause temperature increase, leading to thermal stress and often tissue burns and damage [29]. Furthermore, by looking at table 2.4, sweet pepper plants are considered to be a high light demanding plant, suggesting a promising possibility of growing other high light demanding plants such as tomatoes and cucumber under the shading of organic photovoltaic panels.

### 2.3.4 Interspace PV

Open field ground-mounted agri-pv systems can be referred as interspace PV, according to figure 2.6. These systems, which include agricultural activity in parallel to renewable energy generation have already been in operation for many years. The possibility of herding sheep, cows, or poultry is already established. In addition, it is possible to combine beekeeping with solar farms and to cultivate crops between the rows of solar panels [17]. However, very little investigation on large scale facilities (>1.0 MW) including livestock grazing has been directed. Most of the case studies conducted in large scale facilities are located in Australia. This consists in an important gap in our knowledge as regions around the world where grazing is prominent are the ones with the greatest PV potential [25].

A case study in Queensland, Australia in a 10 hectares solar farm with an installed capacity of 3.2 MW and approximately 100 sheep's was conducted. Results showed that sheep well-being increased with the panels providing protection from the elements (sun, wind, rain etc.) whilst supporting improved vegetation growth thus increasing feed for the animals. Moreover, security provided from the solar farm perimeter fences prevented many injuries and deaths from natural predators, increasing livestock density. Lastly, an estimated \$100,000 was saved from mowing costs [20].

In figure 2.22, it is possible to see an interspace PV project in France which combines the use of photovoltaics with sheep grazing. This project currently herds 35 sheep, who graze under solar panels installed at a 0.9 m height. The agri-pv project included the planting of pasture, which will be re-seeded every 5 years [21].



Figure 2.22: Sheep grazing at a solar farm in Affite-Vigordane, Haute-Garrone, France.

The presence of agrivoltaic systems do not seem to affect livestock density as well as presenting the opportunity to use land with low efficiency or with soil and climatic conditions more adapted for grassland. Nevertheless, considerations about the choice of livestock must be given, grazing of larger animals such as cattle and horses will require the mounting system to be higher to accommodate their size. Solar developers found sheep and poultry grazing more suitable as solar modules are elevated only to a height of 1 m, removing the need to adapt the solar panels extensively in terms of spacing and inclination [25][21].

## 2.4 Techno-economic Analysis

As mentioned before, implementing an agrophotovoltaic (APV) project in an agricultural land with no existing structure represents an additional cost to the land owners. A method of price-performance ratio calculation can be an indicator to measure the techno-economic quality of an intended APV project within an APV permitting process. Therefore the price performance ratio can be calculated as following [28]:

$$ppr = \frac{p}{pb} \quad (2.1)$$

where:

- ppr = price-performance ratio
- p = price [€/ha/a]
- pb = performance benefit [€/ha/a]

The general assumption of the price-performance ratio (ppr) is that a ratio larger than 1 is not reasonable to support APV dissemination of the analyzed systems since the techno-economic synergies are not great enough. On the other hand, ratio of 1 assumes that APV implementation is economically reasonable since the resilience of the farmer in question has been improved by

income diversification, adaptation to global warming, contribution to the energy transition, and achievements in land use efficiency. Finally, a ratio less than 1 means that the price of maintaining the cropland is lower than the performance of the same cropland, meaning that the benefits are higher than the affiliated costs.

The **price of APV implementation (p)** is defined as the extra annual costs resulting from the adaption of the ground mounted PV (PV-GM) structure in order to maintain the cropland [28].

$$p = LCOE_{APV} * M_{APV} - LCOE_{PVGM} * M_{PVGM} \quad (2.2)$$

where:

- $p$  = price [€/ha/a]
- $LCOE_{APV}$  = levelized cost of electricity for agrophotovoltaics [€/kWh]
- $LCOE_{PVGM}$  = levelized cost of electricity for ground-mounted PV [€/kWh]
- $M_{APV}$  = annual electrical yield per ha for APV [kWh/ha/a]
- $M_{PVGM}$  = annual electrical yield per ha for PV-GM [kWh/ha/a]

The **performance benefits (pb)** from APV implementation are the preservation of cropland and the annual revenue from harvest under APV in  $\text{€} \cdot \text{ha}^{-1}$ .

The LCOE calculation method is used to calculate and compare the specific costs per unit of electricity produced, this method is the current cost comparison criterion of different electric power plant systems. The calculations are based on the following equation [28]:

$$LCOE = \frac{I_0 + \sum_{t=1}^n A_t * (1+i)^{-t} - R_n}{\sum_{t=1}^n M_{t,el} * (1+i)^{-t}} \quad (2.3)$$

The calculation methodology is to contrast the capital expenditures  $I_0$  (CAPEX) and all operating expenses  $A_t$  (OPEX) minus the residual value  $R_n$  available at the end of the useful life  $n$  of the total generated electrical energy. Both the cost and the annual average amount of electrical energy produced are reduced to a common reference date using the calculation interest rate  $i$ .

The electrical energy produced in a year  $M_{t,el}$  is calculated according to the equation [28]:

$$M_{t,el} = \sum_{t=1}^n S * \eta * (1-d)^t \quad (2.4)$$

It represents the sum of the annual solar irradiation  $S$  multiplied by the system efficiency  $\eta$  and the annual efficiency losses  $d$ .

The range of the LCOE for agrivoltaics compared to ground mounted photovoltaic systems and small rooftop systems is presented in figure 2.23 [21].

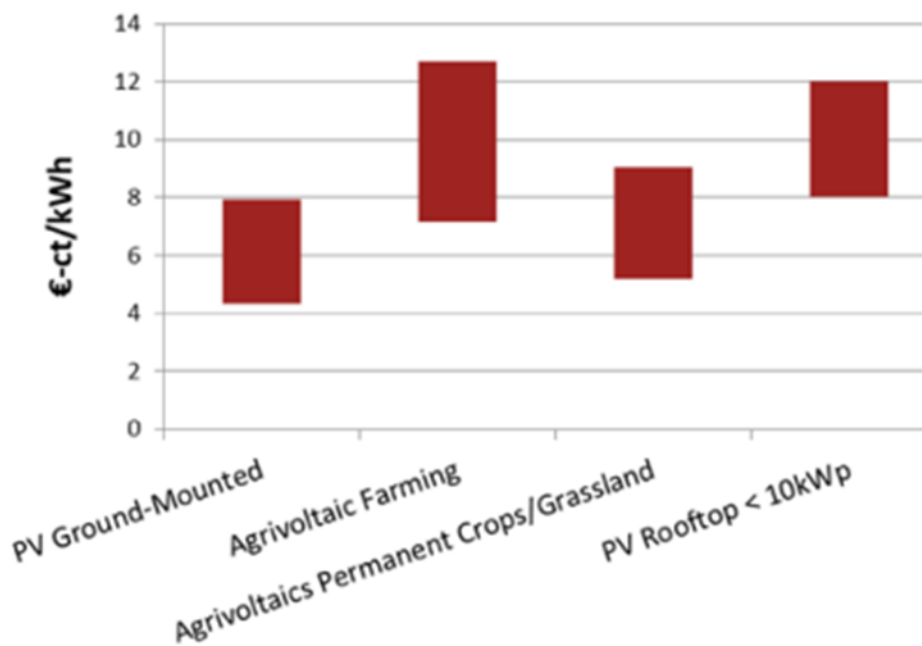


Figure 2.23: Estimated average of the levelized cost of electricity for different systems.

For permanent crops with a low clearance height, the LCOE is only about one third higher compared to ground mounted photovoltaic systems.

## 2.5 Agrivoltaics challenges

The potential of agrivoltaics to aid the transition to sustainable agriculture and decarbonise the energy system must be supported by regulatory and political authorities (at EU, national, regional, and local level) in order to overcome identified barriers. These obstacles decelerates the growth of agrivoltaics across the EU and can be identified as [21]:

- Regulatory and administrative barriers, one of the main challenges for agrivoltaics to develop across Europe is the low quality or absence of regulatory frameworks to support the development of agri-pv projects. Another important aspect is the potential loss of Common Agricultural Practices (CAP) subsidies by farmers who deploy solar on their land
- An important technical barrier is the availability of solar panels, modules and structures that are appropriate for agri-pv projects. Accessibility can also be a challenge for an agrivoltaics project. Grid connections and capacity are also a concerning issue as existing grid capacity in rural areas is lower and may increase connection costs and impair the business case of the project.
- Financial barriers are also presented, the innovative nature of an agrivoltaics project results in higher costs of capital when compared to a conventional ground mounted solar project.

Furthermore, regulatory and political authorities (also at EU, national, regional, and local level) should provide targeted support to overcome the barriers identified above, some of them can be highlighted due to their important nature [32]:

1. Farmers who deploy agri-pv projects should continue to receive income support through CAP.
2. Tax reductions or additional revenue streams should be provided for agrivoltaic projects that provide important biodiversity and carbon capture services.
3. Governments should create enabling frameworks that facilitates the development of agri-pv projects. A crucial example is removing unnecessary administrative barriers and providing technical support for farmers and rural communities who are looking to develop agrivoltaic projects.
4. Governments should develop “agrivoltaic indexes” that capture the agro-economic, environmental, and social externalities of agri-pv systems, making them available for the community.
5. Agri-pv frameworks should channel public and private R&D funding research programmes focused on the identification of suitable crops for cultivation in combination with PV, the impacts of agri-pv systems on yields, profitability and on the demonstration of different PV concepts.



## Chapter 3

# Case Study

This chapter aims to introduce the case study in which the development of this dissertation is inserted, giving an overview of the methodology followed to collect the data and achieve the result of this work. A case study regarding the possibility of implementation based on an agrivoltaic system on a kiwi farm was carried out as well as the main requirements and ideas for an effective implementation.

### 3.1 Objectives

The present 10 hectare kiwi farm is divided into 12 pieces of land all located about 20 km East of Aveiro. The main objective of this case study is to analyse the best locations in each plot of land and design the most suitable photovoltaic system in order to maximize land-use efficiency whilst maintaining crop production. Therefore, this project aims to perform an extensive analysis on each piece of land in order to:

- Study the shading projections of overhead PV panels on consecutive cultivated kiwi rows with the aim of analysing its viability in terms of energy production, ground coverage ratio as well as sun light exposure on the kiwi production.
- Identify unproductive cultivated areas that could be better suitable for the implementation of photovoltaic panels.
- Locate empty parcels of land as well as possible constructions (irrigation booths, wells...) that could be used for PV installations.

All things considered, one of the main objectives of the current project is to develop a self sufficient farm by analysing its current energy needs and therefore design an agrivoltaic system that is capable to meet those energy demands. However, there was no restraints involved in the projection of photovoltaic panels as the possibility of generating energy surplus was taken into account by selling it to market agents.

The study and design of the photovoltaic systems was conducted with the aid of the PVsyst software.

### 3.2 Climatic area

The climate zoning of the country is based on the Nomenclature of Territorial Units for Statistical Purposes (NUTS) level III, whose composition by municipalities is based on the Decree Law No. 68/2008 of April 14. All tables and figures from this section are taken or adapted from [33].

The current area of study is located in the Baixo Vouga municipality as identified in image 3.1.

| NUTS III            | Municípios                                                                                                                                                                                                                                                                         |
|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Minho-Lima          | Arcos de Valdevez, Caminha, Melgaço, Monção, Paredes de Coura, Ponte da Barca, Ponte de Lima, Valença, Viana do Castelo, Vila Nova de Cerveira                                                                                                                                     |
| Alto Trás-os-Montes | Alfândega da Fé, Boticas, Bragança, Chaves, Macedo de Cavaleiros, Miranda do Douro, Mirandela, Mogadouro, Montalegre, Ribeira de Pena, Valpaços, Vila Flor, Vila Pouca de Aguiar, Vimioso, Vinhais                                                                                 |
| Cávado              | Amares, Barcelos, Braga, Esposende, Terras de Bouro, Vila Verde                                                                                                                                                                                                                    |
| Ave                 | Cabeceiras de Basto, Fafe, Guimarães, Mondim de Basto, Póvoa de Lanhoso, Vieira do Minho, Vila Nova de Famalicão, Vizela                                                                                                                                                           |
| Grande Porto        | Espinho, Gondomar, Maia, Matosinhos, Porto, Póvoa de Varzim, Santo Tirso, Trofa, Valongo, Vila do Conde, Vila Nova de Gaia                                                                                                                                                         |
| Tâmega              | Amarante, Baião, Castelo de Paiva, Celorico de Basto, Cinfães, Felgueiras, Lousada, Marco de Canaveses, Paços de Ferreira, Paredes, Penafiel, Resende                                                                                                                              |
| Douro               | Alijó, Armamar, Carraceda de Ansiães, Freixo de Espada à Cinta, Lamego, Mesão Frio, Moimenta da Beira, Murça, Penedono, Peso da Régua, Sabrosa, Santa Marta de Penaguião, São João da Pesqueira, Sernancelhe, Tabuaço, Tarouca, Torre de Moncorvo, Vila Nova de Foz Coa, Vila Real |
| Entre Douro e Vouga | Arouca, Oliveira de Azeméis, Santa Maria da Feira, São João da Madeira, Vale de Cambra                                                                                                                                                                                             |
| Baixo Vouga         | Águeda, Albergaria-a-Velha, Anadia, Aveiro, Estarreja, Ílhavo, Murtosa, Oliveira do Bairro, Ovar, Sever do Vouga, Vagos                                                                                                                                                            |

Figure 3.1: Nomenclature of Territorial Units for Statistical Purposes (NUTS)

There are 3 climatic zones defined in the winter (I1, I2, I3) plus another 3 in the summer (V1, V2, V3) for the application of thermal quality requirements of its surroundings. For the winter climate zones, these are defined based on the number of degree days (GD) on the basis of 18 °C, corresponding to the heating season, as shown in table 3.1.

Table 3.1: Criteria for determining the winter climate zone

| Criteria | $GD \geq 1300$ | $1300 < GD \leq 1800$ | $GD \geq 1800$ |
|----------|----------------|-----------------------|----------------|
| Zone     | I1             | I2                    | I3             |

In table 3.2 it is possible to see the relevant climatic parameters for the heating season (winter) with respect to the Baixo Vouga area.

Table 3.2: Relevant climatic parameters for the heating season

|             | GD        |                | $\theta_{ext,i}$ |                | $G_{sul}$<br>kWh/m <sup>2</sup><br>/month |
|-------------|-----------|----------------|------------------|----------------|-------------------------------------------|
|             | REF<br>°C | $a$<br>°C / km | REF<br>°C        | $a$<br>°C / km |                                           |
| Baixo Vouga | 1337      | 1100           | 9,5              | -5             | 140                                       |

where

- Number of degree days, on a 18 °C basis, corresponding to the conventional heating season.
- Average outside temperature of coldest month in heating season.
- Monthly average solar energy during the season, received on a vertical south-oriented vertical surface, [kWh/m<sup>2</sup>.month]

Consequently, based on the criteria displayed on table 3.1 it is possible to assess that Baixo Vouga is classified as a I2 winter zone.

Moreover, the summer climate zones are defined from the average outside temperature corresponding to the conventional cooling season ( $\theta_{ext,v}$ ), as shown in table 3.3.

Table 3.3: Criteria for determining the summer climate zone

| Criteria | $\theta_{ext,v} \leq 20$ °C | $20$ °C < $\theta_{ext,v} \leq 22$ °C | $\theta_{ext,v} \geq 22$ °C |
|----------|-----------------------------|---------------------------------------|-----------------------------|
| Zone     | V1                          | V2                                    | V3                          |

In table 3.4 it is possible to see the relevant climatic parameters for the cooling season (summer) with respect to the Baixo Vouga area 3.4.

Table 3.4: Relevant climatic parameters for the cooling season

|             | $\theta_{ext,i}$ |                | $I_{sol}$<br>kWh/m <sup>2</sup> cumulated from June till September |          |           |          |           |          |           |          |           |  |
|-------------|------------------|----------------|--------------------------------------------------------------------|----------|-----------|----------|-----------|----------|-----------|----------|-----------|--|
|             | REF<br>°C        | $a$<br>°C / km | 0°                                                                 | 90°<br>N | 90°<br>NE | 90°<br>E | 90°<br>SE | 90°<br>S | 90°<br>SW | 90°<br>W | 90°<br>NW |  |
| Baixo Vouga | 20,6             | -2             | 810                                                                | 220      | 355       | 490      | 490       | 420      | 490       | 490      | 355       |  |

where:

- $\theta_{ext,v}$  outside average temperature

- $I_{sol}$  is the accumulated solar energy during the season, received horizontally ( $0^\circ$  tilt) and on vertical surfaces ( $90^\circ$  tilt) for the four cardinal and four collateral points, [ $\text{kWh/m}^2$ ]

Therefore, based on table 3.4 Baixo Vouga is characterized as a V2 summer zone.

Finally, by looking at figure 3.2, it is possible to see the distribution of the climatic areas throughout Portugal as well as a general picture of where the current area of study is located.

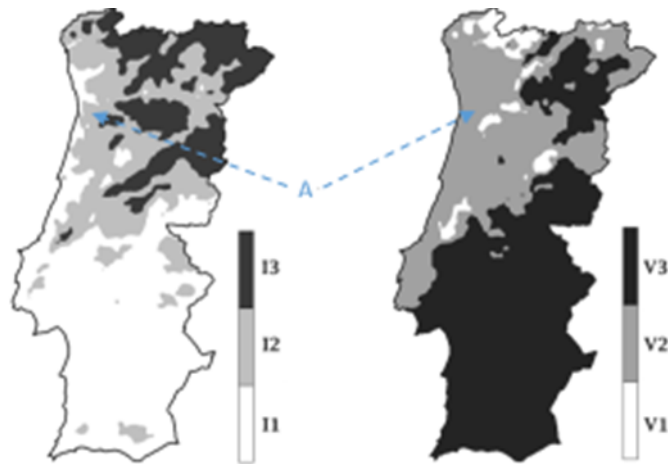


Figure 3.2: Portugal winter (left) and summer (right) climatic areas, the letter A represents the location of the current areas of study.

### 3.3 Areas of Study

This section presents the cultivation areas that will be subject to the case study. All areas discussed are in close proximity to each other, therefore all solar geometry calculations were performed for the same latitude.

#### Moliçal

One of the selected agricultural areas for this study limited by the red area and with the geographic coordinates of 40,35°N 8,32°W, is situated  $\approx 20$  km East of Aveiro and can be seen in figure 3.3.



Figure 3.3: Area of study for the agrivoltaic project, Moliçal plot.

In table 3.5 it is possible to observe the corresponding captions and descriptions relative to figure 3.3.

Table 3.5: Moliçal areas used for agrivoltaic implementation.

| Caption    | Area [m <sup>2</sup> ] | Description                                             |
|------------|------------------------|---------------------------------------------------------|
| Red Border | 30 500                 | Total Moliçal cultivated area                           |
| A          | 70 m                   | Overhead pv implementation along working track          |
| B          | 800                    | Example of possible area for overhead pv implementation |
| C          | 800                    | Possible area for ground mounted pv implementation      |

Figure 3.4 and 3.5 represent pictures that were taken in the Moliçal plot correspondent to the areas A and B that are being analyzed for the case study.



Figure 3.4: Working track that would be subjected to an overhead pv implementation (Case A).



Figure 3.5: Possible area for an overhead pv application above crop production (Case B).

## Barreiro

Next to Molıçal, another cultivation area (located in 40,36°N 8,32°W) that has a parcel with the potential to be used more optimally is shown in figure 3.6.



Figure 3.6: Area of study for the agrivoltaic project, Barreiro plot.

Delimited by the red area, this plot was chosen purely to optimize the space occupied by the well of approximately 7 m in diameter (represented by the letter A) with the implementation of photovoltaic panels

The cultivated and possible photovoltaic area is given by table 3.6.

Table 3.6: Barreiro area used for agrivoltaic implementation.

| Caption    | Area [m <sup>2</sup> ] | Description                     |
|------------|------------------------|---------------------------------|
| Red Border | 12 000                 | Total Barreiro cultivated area  |
| A          | 154                    | Gound-mounted pv implementation |

## Quintal

Figure 3.7 represents one more plot of land that is bounded by the red area and located in 40,35°N 8,31°W. Again, this plot has the potential to optimize its land use by implementing ground-mounted photovoltaics in an unused area represented by the letter A.



Figure 3.7: Area of study for the agrivoltaic project, Quintal plot.

Moreover, the cultivated and possible photovoltaic area is given by the table 3.7.

Table 3.7: Quintal area used for agrivoltaic implementation

| Caption    | Area [m <sup>2</sup> ] | Description                      |
|------------|------------------------|----------------------------------|
| Red Border | 4 500                  | Total Quintal cultivated area    |
| A          | 280                    | Ground-mounted pv implementation |

## 3.4 Modelling

### 3.4.1 Solar Geometry

For the purpose of the study at hand, it is essential to have some notions on solar geometry in order to better comprehend some issues that will be addressed in subsequent chapters. A study on the shadow projections of elevated pv panels on cultivated crops is performed and therefore the concepts of solar geometry are of great importance to better frame the subject in hand.

The solar height,  $h_{sun}$ , is the angle between the sun's rays and a horizontal plane and it can be calculated through the following formula:

$$\sin(h_{sun}) = \sin\delta * \sin\phi + \cos\delta * \cos\phi * \cos ah \quad (3.1)$$

where:

- $\phi$  represents the latitude
- $\delta$  corresponds to the sun's declination
- $ah$  is the hour angle

The sun's declination,  $\phi$ , is the angle between the equatorial plane and the ecliptic plane, varying from  $-23,45^\circ$  (21 Dec) to  $+23,45^\circ$  (21 Jun) and can be obtained as follow:

$$\delta = 23,45 * \sin(0,986 * d - 80), \text{ with } d \text{ day from 1 Jan} \quad (3.2)$$

Moreover the hour angle,  $ah$ , is the coordinate between the place's meridian plane and the hour circle (solar meridian plane), when it is noon. It can be calculated as shown below:

$$ah = 15 * (ST - 12), \text{ with } ST - \text{true / solar time (h)} \quad (3.3)$$

The solar azimuth,  $a$ , is the angle of the sun's rays measured in the horizontal plane from due south for the Northern Hemisphere or due north for the Southern Hemisphere; westward is designated as positive. The mathematical expression for the solar azimuth is given by the following equation:

$$\sin(a) = \frac{\cos\delta * \sin ah}{\cos h_{sun}} \quad (3.4)$$

Figure 3.8 depicts the sun's relative position to a general surface in order to better understand its geometry parameters

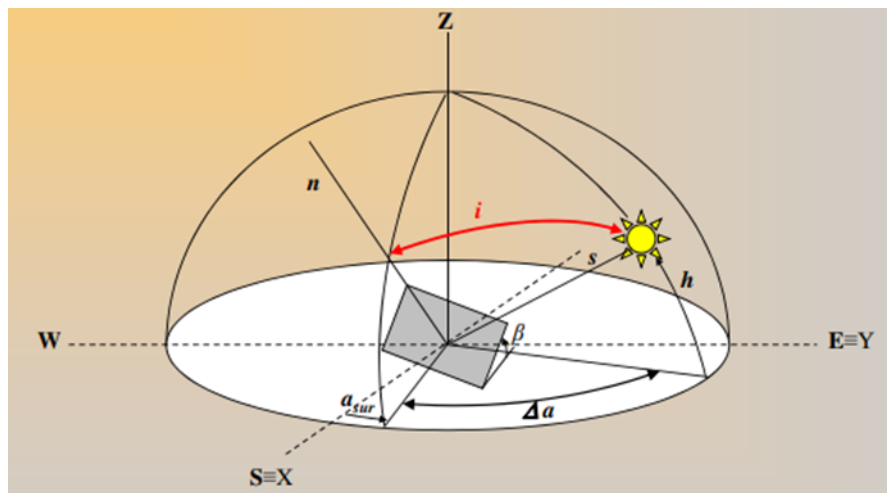


Figure 3.8: Relative position of the sun general to any surface

Where  $\Delta a = | \text{surface azimuth} - \text{solar azimuth} |$

Finally the sunrise and sunset can be calculated as:

$$\cos(ah_0) = -\tan\phi * \tan\delta, \text{rise} < 0; \text{set} > 0 \quad (3.5)$$

### 3.4.2 Shadow Projection Study

For the development of the case study it is essential to perform a study on how the casted shadings from the solar panels will behave throughout the year and how these will impact the cultivated kiwi crops. Figure 3.9 is a generic representation on the solar azimuth ( $a$ ), the collectors azimuth ( $a_{sup}$ ) and the difference between these two angles ( $\Delta a$ ).

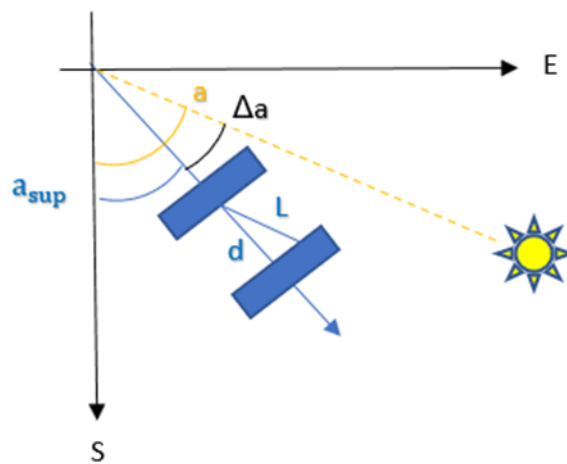


Figure 3.9: Generic representation of the different azimuth's present with a given orientation

Moreover, it is possible to relate the distance between the casted shadow from the first collector  $d$ , and the hypotenuse of the angle,  $L$ .

$$\cos\Delta a = \frac{d}{L} \quad (3.6)$$

Figure 3.10 serves the purpose to better understand the shadow that is projected by the collectors, it is essential to keep in mind that the solar height varies throughout the day and year making the  $d$  distance also a variable number. The distance between collectors is represented by the letter  $D$ .

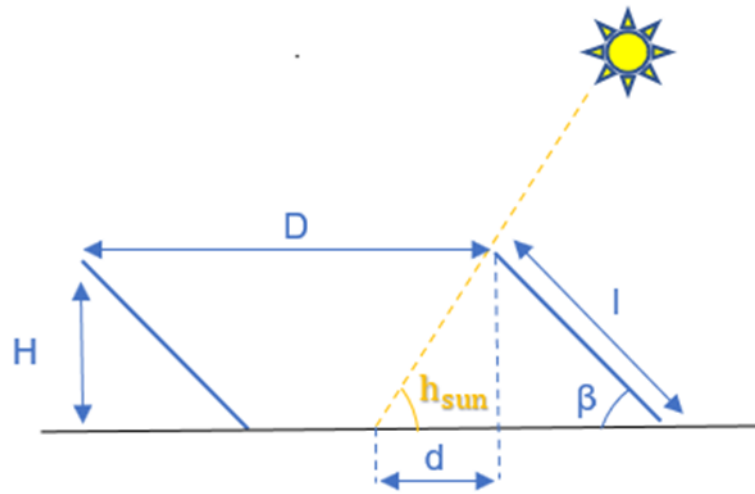


Figure 3.10: Generic representation of the solar height, collectors tilt and relevant dimensions as well as the distance of the projected shadow.

An important relation between the collectors angle and dimensions can be drawn out:

$$\sin\beta = \frac{H}{l} \quad (3.7)$$

where:

- $\beta$  represents the tilt angle of the solar panels
- $H$  is the height of the collector, depending on the tilt angle
- $l$  represents the module width

Figure 3.11 is a representation of an elevated solar panel and its shadow projection on a crop at a certain distance. This portrayal is of a very important nature as it correlates deeply with the case study A and B represented in figure 3.3, as we will later discuss.

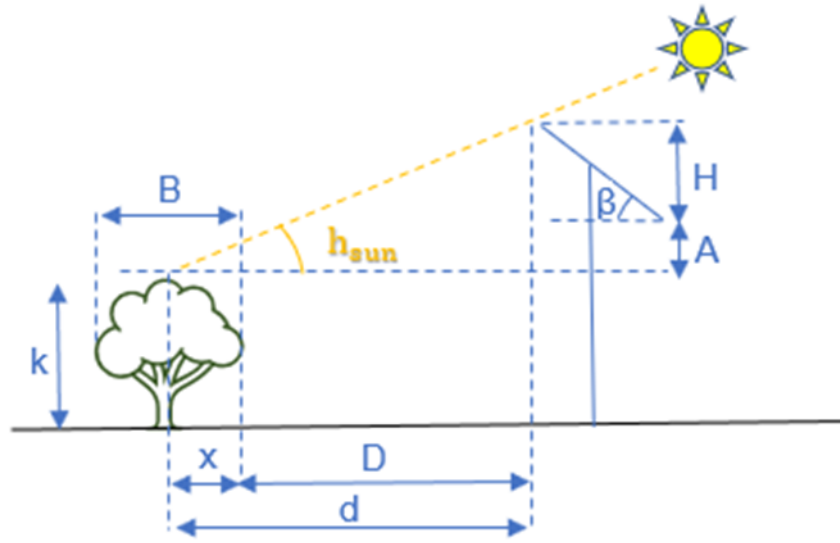


Figure 3.11: Representation of an elevated solar panel with crop production

In order to better comprehend the picture in hand the presented variables can be defined as:

- **k** represents the crop height.
- **A** is the height between the peak of the crop and the beginning of the solar panel.
- **d** is the distance of the shadow projected by the collector, if  $d < D$  then no shadow is casted on the crops if  $d > D$  as shown in the picture, there is shadow present on the crop.
- **x** is a variable distance that represents the shadow that is projected along the crop length,  $B$ , therefore  $0 \leq x \leq B$ .
- **D** is a fixed distance between the end of the first collector and the start of the crop \beginning of the next collector.

As a consequence, another important relation can be drawn from figures 3.9 and 3.11 as seen in the following equation:

$$\tan(h_{sun}) = \frac{H + A}{L} \quad (3.8)$$

The percentage of incident shade on the crops projected by the collectors at a certain distance,  $D$ , is given as:

$$\text{Shadow}[\%] = \frac{x}{B} * 100 \quad (3.9)$$

Lastly, figure 3.12 represents the maximum solar height where the crops that are underneath the collectors are still absent from the shadow cast by them.

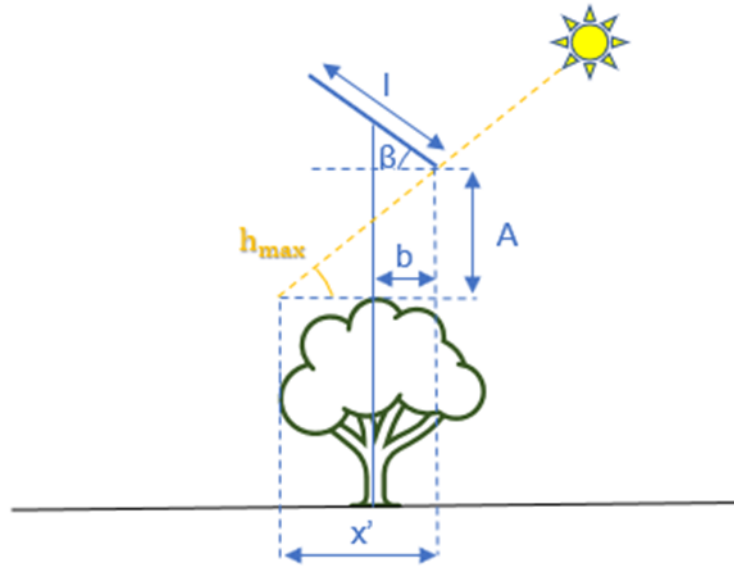


Figure 3.12: Representation of a solar panel elevated above a crop

Where the new variables can be defined as follow:

- **b** is a fixed distance that is calculated by the following equation:

$$b = \frac{l * \cos(\beta)}{2} \quad (3.10)$$

this equation is obtained assuming that the collectors are placed in the middle of the crop length;

- **x'** is a variable distance that represents the shadow that is projected along the crop length,  
 $0 \leq x \leq B/2 + b$ ;
- **h<sub>max</sub>** is the maximum solar height where the crops underneath the collectors are still not receiving any shading from them. This is a calculated value that is obtained through the equation below:

$$\tan(h_{max}) = \frac{A * \cos(\Delta a)}{B/2 + b} \quad (3.11)$$

This value was calculated for the hours subject to the shadow calculations, given by table 3.8, and then compared to the actual solar height correspondent to the same hours, if  $h_{max} < h_{sun}$  then there is shadow.

The shadow projected by the collectors immediately above the crops is given by:

$$\text{Shadow}'[\%] = \frac{x'}{B} * 100 \quad (3.12)$$

It is essential to take into account the shadow cast by the panels above the crops plus the shadow projected by the panels in the row before it. Thus, the percentage of incident shadow on all the rows of kiwis following the first one is calculated as a sum of the shadow percentage of figure 3.11 and 3.12:

$$\text{Total Shadow}[\%] = \text{Shadow}'[\%] + \text{Shadow}[\%] \quad (3.13)$$

As a mean to obtain the value  $d$ , distance of the shadow projected by the collector, from the previous equations it is necessary to calculate the solar azimuth and height. For that reason, it was calculated for an average day of each month (day 15th of each month, except for February where the calculations were performed for the 14th day) the correspondent sun's azimuth and height for each hour of the day. An average solar height of  $\approx 10^\circ$  was considered to mark the significant hours where the global incident irradiation on collectors is meaningful. With that said, table 3.8 represents the starting and finishing hours of the day, in Solar Time (ST), that were taken into account in each month for the shading calculations.

Table 3.8: Starting and finishing hours for the shading calculations in each month.

| Month     | Shading calculation time |         |                                      |
|-----------|--------------------------|---------|--------------------------------------|
|           | Start (h)                | End (h) | Number of significant sunlight hours |
| January   | 8                        | 16      | 8                                    |
| February  | 8                        | 16      | 8                                    |
| March     | 7                        | 17      | 10                                   |
| April     | 7                        | 17      | 10                                   |
| May       | 6                        | 18      | 12                                   |
| June      | 6                        | 18      | 12                                   |
| July      | 6                        | 18      | 12                                   |
| August    | 6                        | 18      | 12                                   |
| September | 7                        | 17      | 10                                   |
| October   | 8                        | 16      | 8                                    |
| November  | 8                        | 16      | 8                                    |
| December  | 8                        | 16      | 8                                    |

In addition, figure 3.13 depicts a solar chart for  $40^\circ\text{N}$  latitude where it is possible to see for an approximate solar height of  $10^\circ$  the respective solar time for each month [34].

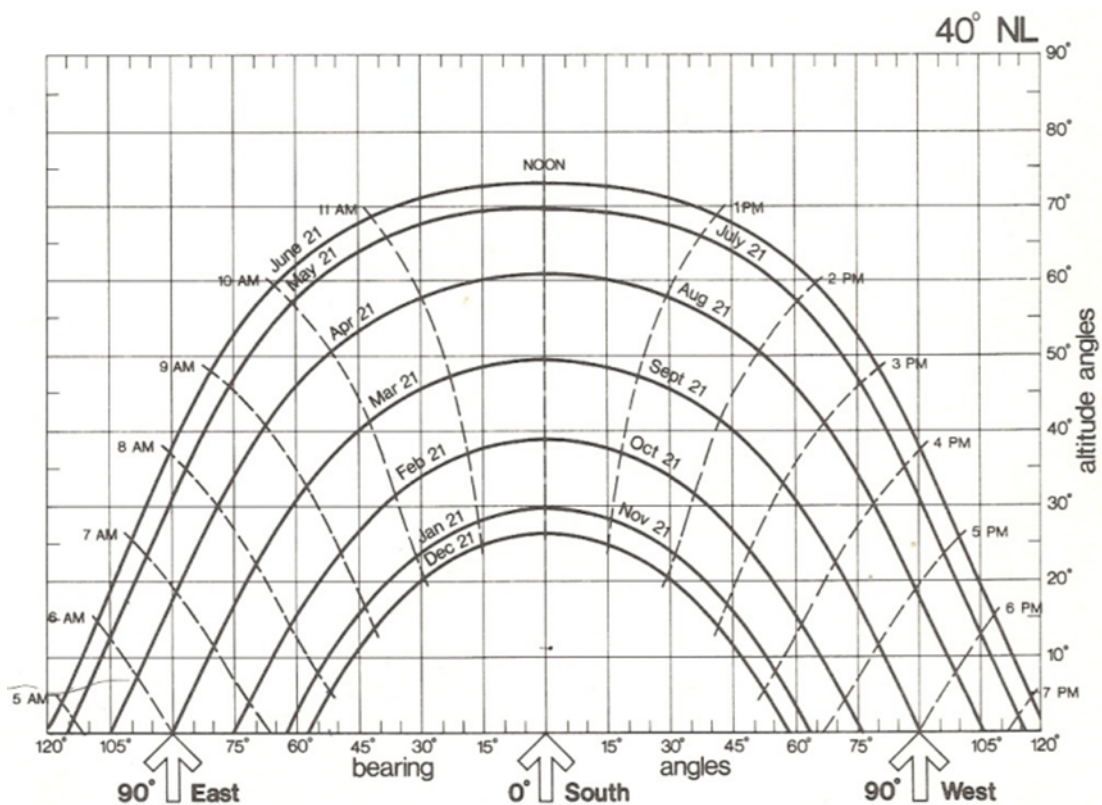


Figure 3.13: Solar chart for a latitude of 40°N.

### 3.4.3 PVsyst

PVsyst 7.2 is a PC software developed for the study, sizing, and data analysis of complete PV systems. It deals with grid-connected, stand-alone, pumping and DC-grid (public transportation) PV systems, in addition it includes extensive meteorological and PV systems components databases, as well as general solar energy tools [35]. This section gives an overview of the steps taken to execute the PVsyst simulation

## General Parameters

A few general parameters which remain constant for all sub-projects in the particular region are required to be defined. These assure that the simulations are inherently accurate and coherent amongst each other. Some of these general parameters include albedo, reference temperatures and detailed losses.

### Reference Temperatures

The design conditions, namely reference temperatures, were defined as follow:

- Lower temperature for absolute voltage limit: -10 °C. This value represents the minimum temperature that the systems may experience.
- Winter operating temperature: 10 °C. This represents the mean winter ambient temperature

- Usual operating temperature under 1000 W/m<sup>2</sup>: 15 °C. This represents the mean ambient temperature throughout the year.
- Summer operating temperature: 45 °C. This represents the maximum temperature that the systems may experience.

These values were carefully considered after an analysis of the local meteorological data in Aveiro (40,5°N 8,32°W) through the Meteonorm file from the year 1996 till 2015.

### Detailed losses

With respect to the detailed losses, these were defined as follow:

- Limit overload loss for design: 3 %. This represents the loss that may occur during the year due to potential oversized PV array with respect to the inverter.
- Loss fraction at STC (Standard Test Conditions): 1.5 %. This represents the array ohmic wiring losses between the power available from the modules and the power at the terminals of the sub-array.

Some additional defined losses are shown in figure 3.14.

The figure shows four panels from the PVsyst software interface for configuring detailed losses:

- Module quality:** Module efficiency loss is set to 1.5 % (checked). Description: Deviation of the average effective module efficiency with respect to manufacturer specifications.
- Module mismatch losses:** Power Loss at MPP is set to 2.0 % (checked). Loss when running at fixed voltage is set to 2.5 % (checked). Description: Not relevant when MPPT operation. A 'Detailed computation' button is present.
- LID - Light Induced Degradation:** LID loss factor is set to 0.0 % (unchecked). Description: Degradation of crystalline silicon modules in the first operating hours with respect to the manufacturing flash test STC values.
- Strings voltage mismatch:** Power Loss at MPP is set to 0.1 % (checked). Description: A 'Detailed study' button is present.

Figure 3.14: Module quality, LID, and mismatch losses (PVsyst)

### Site-specific parameters

Site-specific parameters are unique for each sub-project and are highly contingent on location. These include: Meteorological data, orientation, shading, module choice, and inverter choice.

#### Meteorological data

The selected sites in the case study are very close to each other, therefore all the meteorological data was gathered relative to the Moliçal area (40,5°N 8,32°W). The collected meteorological was obtained from Meteonorm 8.0 and it includes monthly temperature values, sun paths as well as monthly radiation.

#### Orientation

The orientation parameters, tilt and azimuth, are very site dependent. The surface azimuth is an intrinsic characteristic of the collectors orientation with respect to south, as seen in figure 3.8, and it may vary accordingly to different project areas. Sub-projects regarding one area can have more than one surface azimuth.

With respect to the tilt angle this can be calculated and defined for optimal performance (the more perpendicular a module is to the sun's rays, the better). Generally speaking, literature address that the tilt angle shouldn't vary more than  $10^\circ$  from the respective local latitude value. Consequently, a PV module installed in latitude of  $41^\circ\text{N}$  should have a tilt angle between  $31^\circ$  for the summer and  $51^\circ$  for the winter.

PVsyst presents features that help in the orientation design as it shows graphically the optimum tilt angle. Moreover, by using the optimization tool it is possible to find the best correlation between parameters such as tilt, azimuth, pitch and other relevant parameters on a given project.

Figure 3.15 shows the PVsyst layout for orientation analysis on the Molıçal area, more specifically in plot C, as seen in image 3.3.

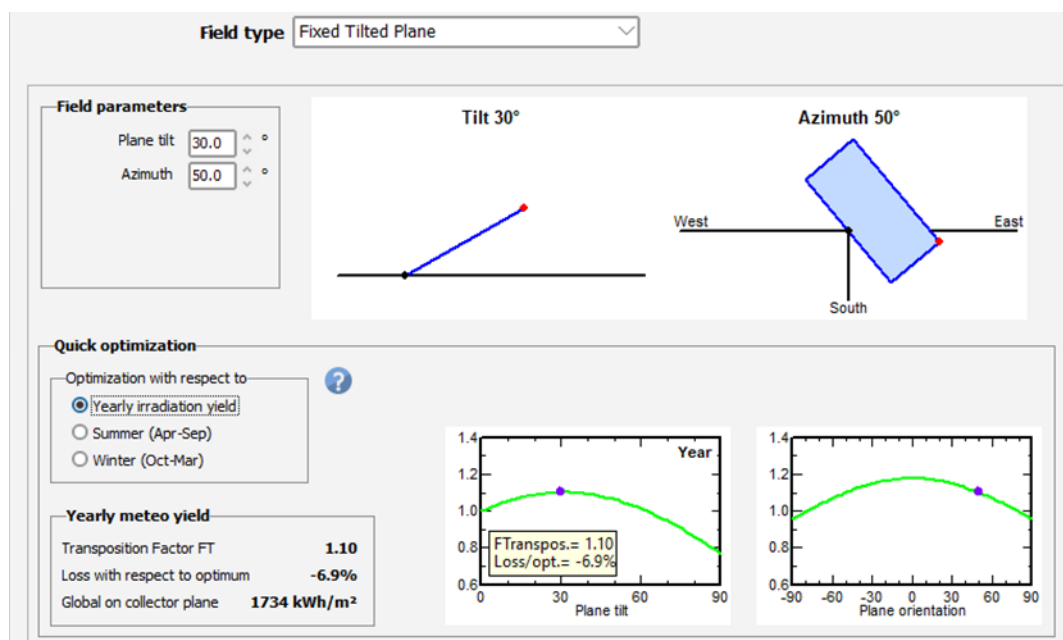


Figure 3.15: Orientation analysis on Molıçal area, plot B (PVsyst).

Furthermore, figure 3.16 depicts the results from the optimization scan performed on the same area with respect to the collectors optimal tilt. No scan regarding the collectors azimuth was performed due to the fact that it consists on an agri-pv application, therefore its orientation is the same as the crops orientation towards south.

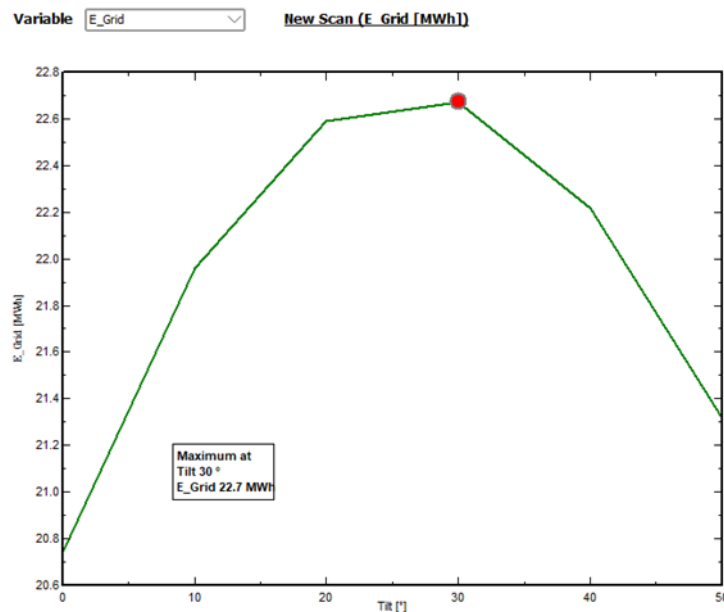


Figure 3.16: Optimization tool analysis regarding optimal tilt angle on Molıçal area, plot B (PVsyst).

### Shading

A shading analysis was performed for each sub-project in order to minimize the total shading losses when it comes to row spacing, tilt angle and pitch between collectors. For case B and D of the Molıçal area (see figure 3.3) it was possible to take all these variables into account, however when it comes to case C some restrictions appear as the azimuth and spacing between collector rows is the same as the cultivated crops.

To better understand shading influence, 3D models were built for every site and corresponding sub-projects. For each sub-project, solstice simulations for 12 o'clock of 21/12/2021 were computed in order to visualize the sun's beams at this time of the year, since it is when the north hemisphere experiences less daily sunlight (because the sun height is the lowest) and thus more shading impact. Image 3.17 represents the computed 3D scene for case C in the Molıçal area.

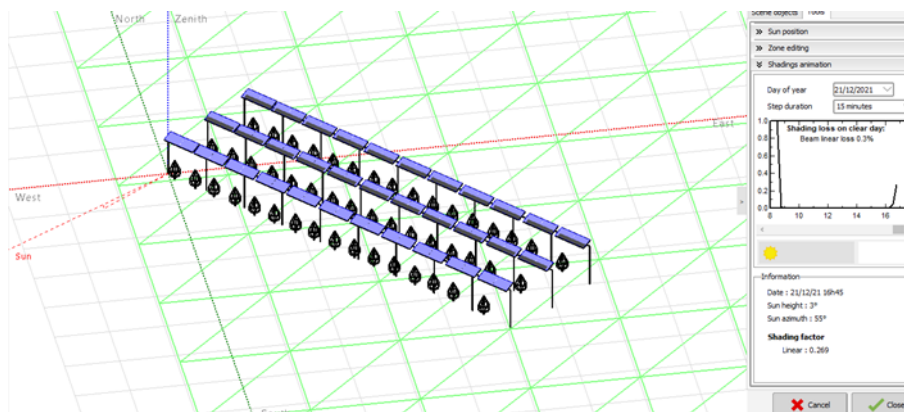


Figure 3.17: Shading model on Molıçal area, plot B (PVsyst).

## Chapter 4

# Results and Discussions

The results obtained from the reported study are exposed and discussed in this chapter. A detailed analysis on the shadow projection study will be performed, followed by the presentation of the simulation results on PVsyst software. Finally, a brief economic analysis is conducted.

### 4.1 Results of Shadow Projection

The shadow projection study results were conducted in excel. An extensive analysis on the Moliçal area is conducted due to the possibility of overhead pv implementation. For the ground mounted application in this area (case D) and in the Quintal plot, no shadow projection study was executed as there is no incident shadow on the present crops from the collectors, the same occurs for the Barreiro plot. Additionally, it is important to keep in mind that the percentage of incident shadow is calculated taking into account the number of relevant daily sun hours for that specific month (as presented in table 3.8), so for different months there may be a different accounting of daily sun hours.

#### 4.1.1 Moliçal area

Table 4.1 represents the essential parameters that were taken into account when calculating the shadow projection distance as well as incident shadow percentage on crops, some of these parameters can be visualised in figure 3.11.

Table 4.1: Main parameters taken into account for the shadow projection calculations in the Molıçal area

| Parameters                                                         | Case A  | Case B  |
|--------------------------------------------------------------------|---------|---------|
| Collector width                                                    | 0,992 m | 0,992 m |
| Collector length                                                   | 1,974 m | 1,640 m |
| Collector height with respect to the ground (Z)                    | 4 m     | 4 m     |
| Tilt                                                               | 25°     | 25°     |
| Surface azimuth ( $a_{sup}$ )                                      | -50°    | 50°     |
| Crop length (B)                                                    | 3 m     | 3 m     |
| Crop height (k)                                                    | 2 m     | 2 m     |
| Collectors distance to crops (D)                                   | 2,5 m   | 4 m     |
| Height between peak of the crop and beginning of the collector (A) | 2 m     | 2 m     |

## Case A

Looking at figure 3.4, case A refers to the implementation of solar collectors along a dirt road that serves as a passage for machinery, vehicles, workforce... For the current case it was considered a height of implementation correspondent to 4 m for the collectors so as the workers driving the tractor wouldn't be disturbed by them.

Figure 4.1 shows the simulated shading scene of the plot where the collectors would be installed.

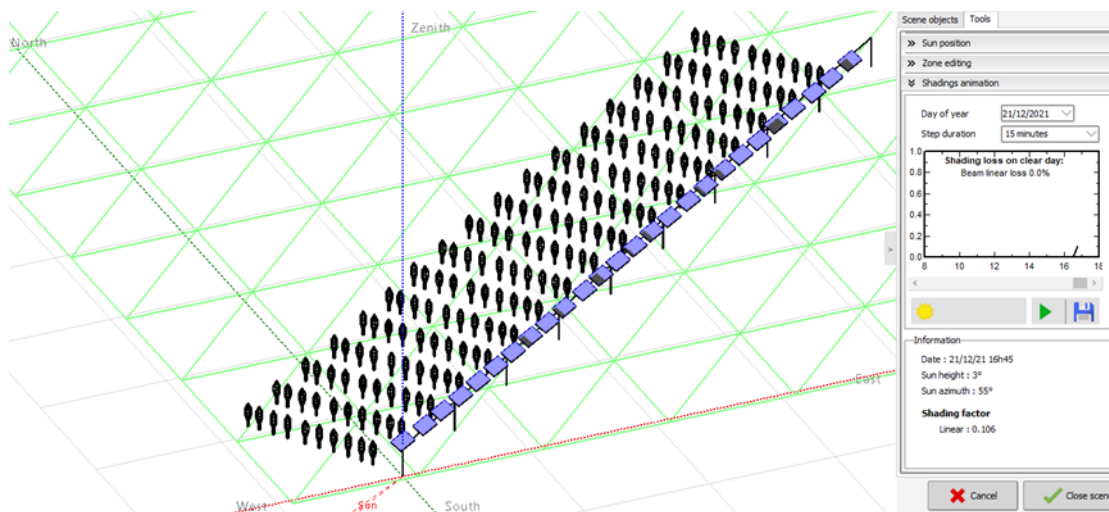


Figure 4.1: Shading model on Molıçal area, plot A (PVsyst).

The hourly shadow projection distance towards the crops was calculated for an average day of each month (the 15th expect for February where it was used the 14th) in order to better comprehend how the crops would be affected by it. Figure 4.2 shows the distance of the projected shadow where

the straight line  $D = 2,5$  m represents the distance of the collectors with respect to the beginning of the crops, meaning that all values that are below this line correspond to hours when no shadow is cast on the plantation.

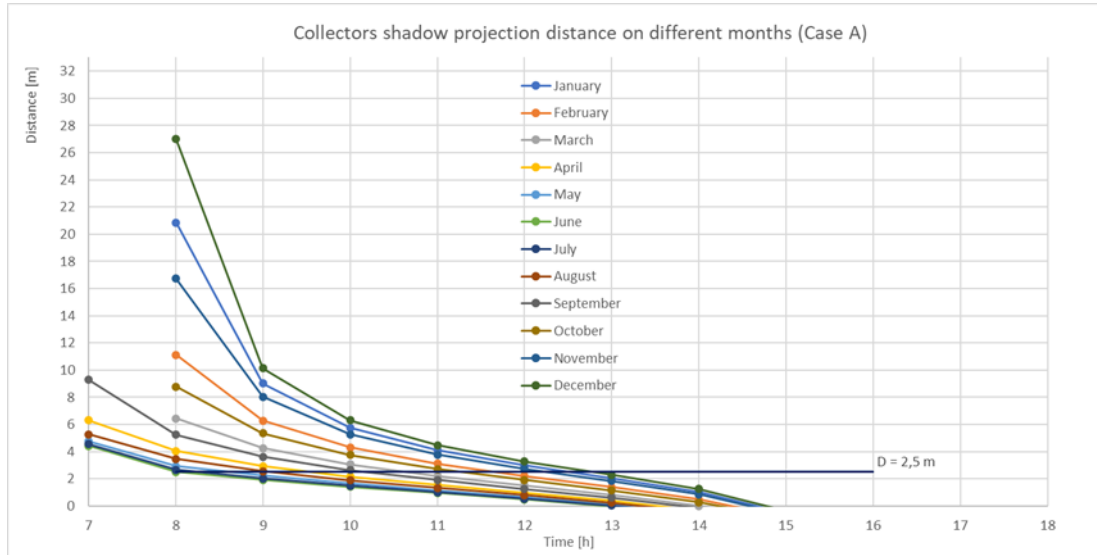


Figure 4.2: Hourly shadow projection distance for an average day of each month (Case A).

Initially, it is possible to observe that for all months, after 1 pm, none of the shadow cast by the collectors reaches the kiwifruit production throughout the year. In addition, the months where shadow projection is the highest are from October (brown line) till March (grey line). Kiwifruit production may have some solar limitation from December till February which is the time when the harvesting takes place, meaning that on this period where shadow projection is more relevant matches the range where possible solar limitation is the highest. From April till September there is no solar limitation on crop production starting from 10 am.

On a more general analysis, the percentage of incident shade on crops in each month was calculated for different distances in order to better comprehend at which reach the shadow cast by the panels becomes insignificant to the production, as shown in figure 4.3.

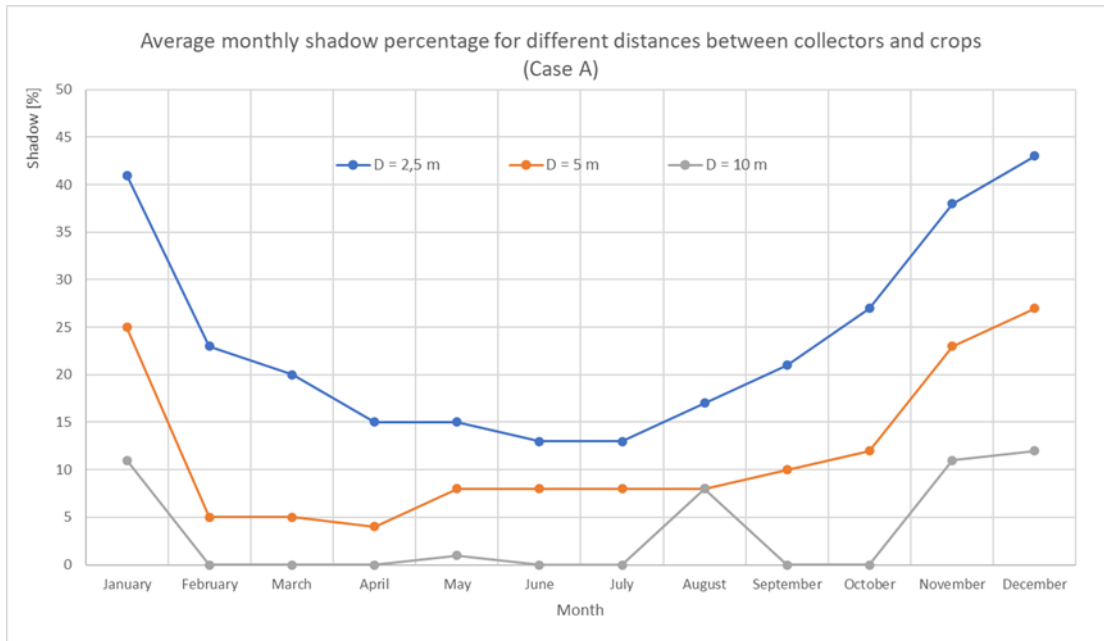


Figure 4.3: Monthly shadow percentage incident on crops for different distances (Case A).

Following the previous graphic reasoning, with regards to the first row of kiwis (at a 2,5 m distance in the direction of the collectors) this will be the most affected by incident shade with values of shaded area around 40 % of the total kiwis area in the months of December and January. However, with increasing distance, these values gradually become less significant and it can be considered that from the 10 m line onwards the shaded area values can be considered negligible. Furthermore, the casted shade correspondent to the blue line (2,5 m) can be somewhat considered as beneficial as it produces shade for the workers along the dirt road.

## Case B

The following presented graphics are relative to the agri-pv simulation, more specifically plot B (see image 3.5). The shading scene presented in image 3.17 gives us an overview of the possible implementation design on this parcel. It is important to take into account that transparent solar modules with 10 % transparency were used in the shading calculations for this case.

A first look on how the collectors implemented above each crop row affects incident sunlight throughout the months was computed in order to better understand the feasibility of implementing an overhead pv project in the cultivated area. The results are displayed in figure 4.4

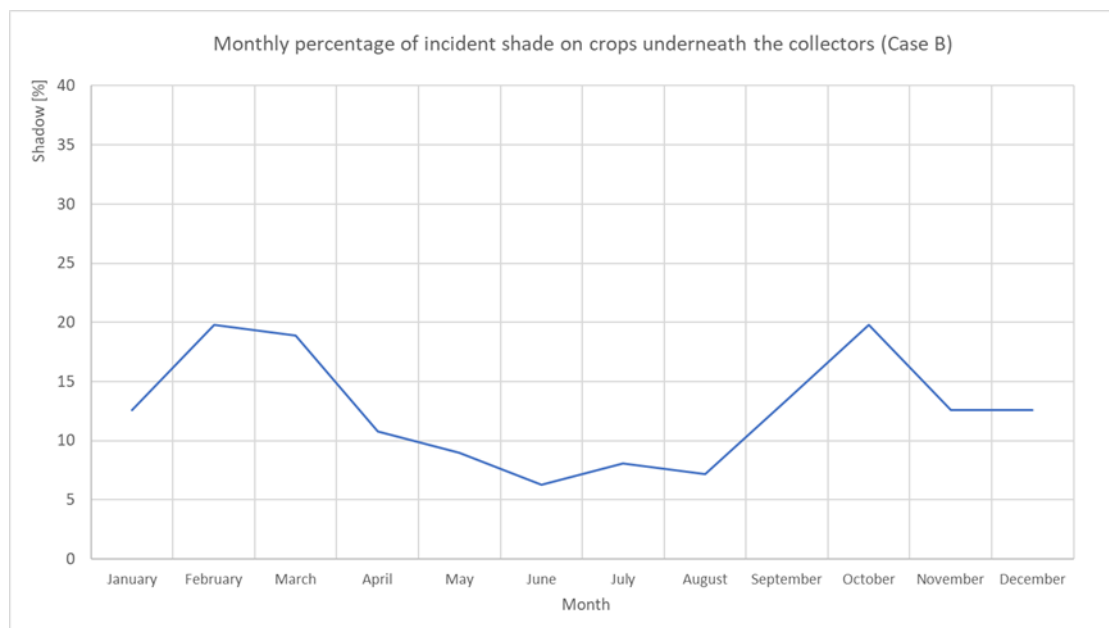


Figure 4.4: Monthly shade percentage incident on crops underneath the collectors (Case B).

As seen in the figure above, shade percentages will never surpass the 19 % mark, as this maximum value is only met on the months of February, March and October. However, only the first row of crop production will present this values of shade due to the fact that the following ones will be affected by the shade projection from the collectors present in the rows before them. With that said, figure 4.5 depicts this variation.

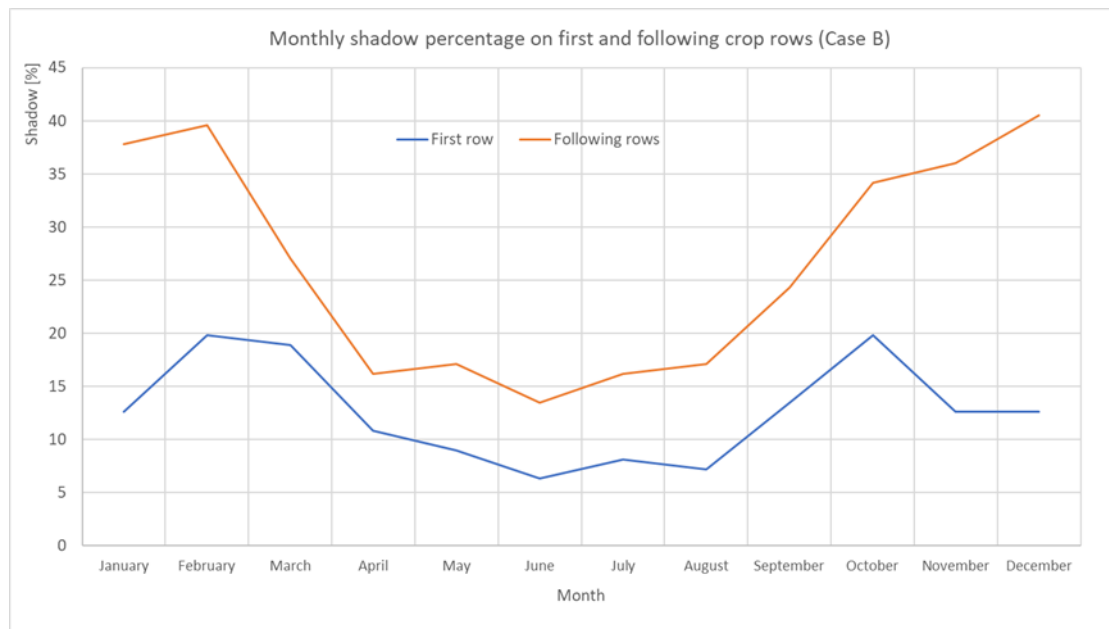


Figure 4.5: Monthly shade percentage incident on crops for the first and following rows

As expected, it is possible to see a higher shade percentage on the following rows (orange line).

Values ranging from 35 % to 40 % of projected shade are present from the months of November till February. However, a big drop in these values is registered in the months of April to August (with percentages between 13 % and 17 %). Moreover, months where incident shading on crops is higher (December and January) are correspondent to the months where kiwi harvest is taken, thus incident solar radiation may have some limitation on the crops. Nevertheless, shadings above 20 % may be considered as ineffective towards yield production on kiwifruit [36].

With that said, all the shading calculations were used with a photovoltaic cover ratio ( $PV_r$ ) above crops of 100 %. In agrivoltaic implementations and studies, various  $PV_r$ 's are used in order to find the optimal balance between crop production (a 20 % decrease on yield growth is often seen as acceptable in agri-pv applications) and generated electricity. On that basis, figure 4.6 shows the shading variation for different  $PV_r$ .

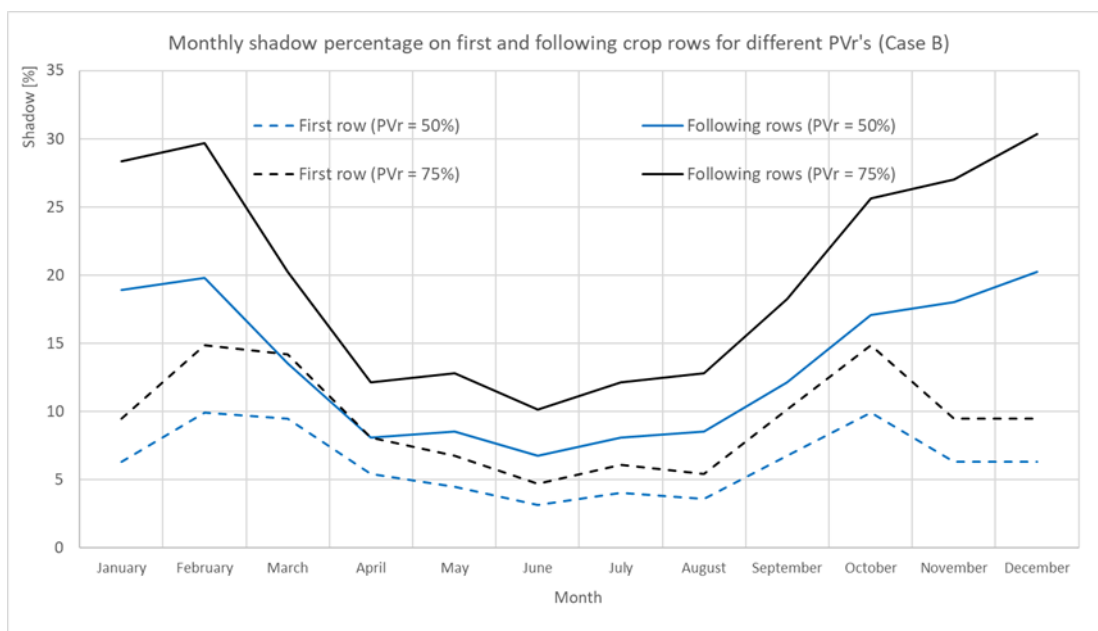


Figure 4.6: Monthly shade percentage incident on crops for the first and following rows with different  $PV_r$ 's.

When diminishing the photovoltaic cover ratio by 25 % ( $PV_r = 75$  %), with respect to the following rows, only the months from October till February will surpass the 20 % threshold, all the other months (8 out of 12) presents shading levels mostly below 15 %. For a  $PV_r$  of 50 %, regarding the following rows, only the month of December surpasses the 20 % mark, having a value of 20,7 %. This can be seen as an optimal value of cover ratio regarding a possible decrease in kiwifruit production due to shading effects.

Lastly, shade incidence on crops varies with different tilt angles, therefore a variation study on this parameter is presented in figure 4.7 in order to analyse the possibility of adjusting the tilt angle on months where solar incidence on the production is limited due to the shading of the panels.

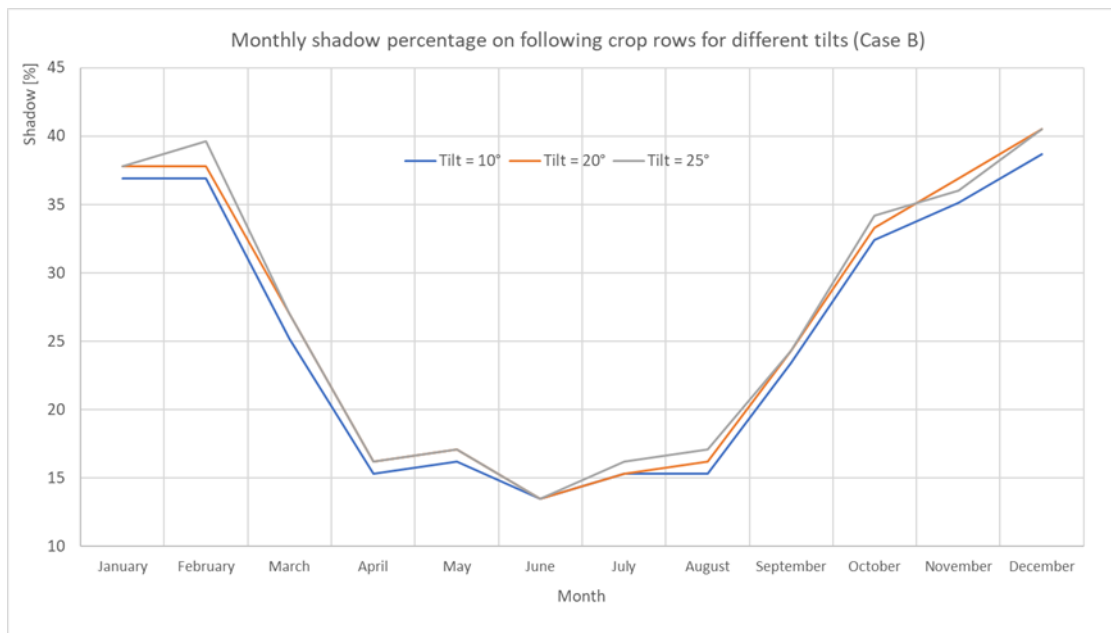


Figure 4.7: Monthly shade percentage incident on crops for the following rows with different tilt angles.

It is observable that tilt variation in order to minimize shade incidence is not a decisive factor. When comparing to the tilt angle implemented in the simulation (25°), the highest drop in shade incidence was of 10 % with regards to a tilt angle of 10° in the month of August, through the rest of the year drops in shade level percentage were all below the 10 % value, for that reason the consideration of using a seasonal tilt adjustment was ruled out.

## 4.2 PVsyst simulation

In this section, simulation results are presented and discussed. The following parameters are of higher importance and therefore a brief definition of each one is presented:

- **Module area**, as expected is the sum of the area of the collectors to be used in each project;
- **Produced Energy** is directly related to module area, higher module area results in more energy being produced;
- **Specific production** follows a similar pattern to energy production, since it is the ratio between this parameter and the solar installed capacity. After discussing the energy production outcome, it is easy to understand the specific production's results by simply analysing its' denominator, i.e., the solar installed capacity;
- **System losses**, these are related to a number of factors, being inverter efficiency the most influential one;

- **PV conversion efficiency at STC** is the percentage of electrical power that can be produced from the solar irradiance received under standard test conditions (STC), hence this parameter depends on the utilized solar modules;
- **Performance ratio (PR)** compares the actual produced energy with the energy which would be produced in an ideal scenario, meaning if a system was continuously working at its nominal STC. In short, the PR depends only on the effectively produced energy and on the overall system losses.

#### 4.2.1 Molıçal Area

The main PV array characteristics and orientations for the simulated projects in this area can be seen in table 4.2.

Table 4.2: PV array characteristics and orientation

| <b>PV module</b>              | <b>Case A</b>       | <b>Case B</b>       | <b>Case C</b>      |
|-------------------------------|---------------------|---------------------|--------------------|
| Manufacturer                  | Amerisolar          | Amerisolar          | Amerisolar         |
| Model                         | AS6M-BN-400         | AS-6M30 Transparent | AS6M-BN-400        |
| Unit nominal power            | 400 Wp              | 275 Wp              | 400 Wp             |
| Number of PV modules          | 26 units            | 66 units            | 64 units           |
| Total PV power (Nominal)      | 10 kWp (STC)        | 18 kWp (STC)        | 26 (STC) kWp       |
| Module area                   | 50,9 m <sup>2</sup> | 107 m <sup>2</sup>  | 125 m <sup>2</sup> |
| <b>Inverter</b>               | <b>Case A</b>       | <b>Case B</b>       | <b>Case C</b>      |
| Unit nominal power            | 10,0 kWac           | 18,0 kWac           | 24,0 kWac          |
| Number of inverters           | 1 unit              | 1 units             | 1 unit             |
| <b>Orientation</b>            | <b>Case A</b>       | <b>Case B</b>       | <b>Case C</b>      |
| Surface azimuth ( $a_{sup}$ ) | -50°                | 50°                 | 60°                |
| Tilt                          | 25°                 | 25°                 | 20°                |
| Pitch between sheds           | -                   | 5 m                 | 2,5 m              |

#### Case A

The plot area for this sub-project can be seen in figure 3.4, in addition the shading scene is presented in figure 4.1. The selected working trail where the collectors would be placed has a length of 70 m, therefore the simulation was designed for the placing of the maximum number of solar panels possible in order to understand what is the highest possible amount of energy that can be produced. The chosen tilt angle, 25°, for the simulation was obtained through the optimization tool in PVsyst.

Table 4.3 shows the balances and mains results on a monthly basis for the current case.

Table 4.3: Monthly balances and main results for case A (PVsyst)

|           | <b>GlobHor</b><br>kWh/m <sup>2</sup> | <b>DiffHor</b><br>kWh/m <sup>2</sup> | <b>T_Amb</b><br>°C | <b>GlobInc</b><br>kWh/m <sup>2</sup> | <b>GlobEff</b><br>kWh/m <sup>2</sup> | <b>EArray</b><br>MWh | <b>E_User</b><br>MWh | <b>E_Solar</b><br>MWh | <b>E_Grid</b><br>MWh | <b>EFrGrid</b><br>MWh |
|-----------|--------------------------------------|--------------------------------------|--------------------|--------------------------------------|--------------------------------------|----------------------|----------------------|-----------------------|----------------------|-----------------------|
| January   | 58.7                                 | 24.49                                | 9.69               | 86.9                                 | 84.6                                 | 0.817                | 0.539                | 0.173                 | 0.631                | 0.366                 |
| February  | 79.2                                 | 34.48                                | 10.24              | 106.9                                | 104.8                                | 1.006                | 0.487                | 0.179                 | 0.812                | 0.309                 |
| March     | 122.0                                | 54.35                                | 12.43              | 142.7                                | 139.8                                | 1.326                | 0.539                | 0.226                 | 1.081                | 0.314                 |
| April     | 154.6                                | 65.91                                | 13.87              | 164.6                                | 161.3                                | 1.513                | 0.522                | 0.245                 | 1.245                | 0.277                 |
| May       | 197.1                                | 79.27                                | 16.44              | 195.2                                | 190.8                                | 1.771                | 0.539                | 0.278                 | 1.466                | 0.262                 |
| June      | 199.4                                | 69.79                                | 18.58              | 192.0                                | 187.7                                | 1.724                | 0.522                | 0.274                 | 1.423                | 0.248                 |
| July      | 212.0                                | 77.01                                | 20.05              | 207.9                                | 203.3                                | 1.860                | 0.539                | 0.287                 | 1.545                | 0.252                 |
| August    | 191.1                                | 71.05                                | 20.57              | 197.4                                | 193.2                                | 1.765                | 0.539                | 0.273                 | 1.466                | 0.267                 |
| September | 145.0                                | 54.99                                | 19.16              | 164.3                                | 161.2                                | 1.479                | 0.522                | 0.230                 | 1.226                | 0.292                 |
| October   | 99.6                                 | 46.12                                | 17.04              | 126.2                                | 123.3                                | 1.157                | 0.539                | 0.215                 | 0.924                | 0.324                 |
| November  | 64.0                                 | 29.54                                | 12.42              | 89.6                                 | 87.0                                 | 0.835                | 0.522                | 0.176                 | 0.646                | 0.346                 |
| December  | 52.1                                 | 23.17                                | 10.57              | 81.2                                 | 78.9                                 | 0.761                | 0.539                | 0.164                 | 0.585                | 0.375                 |
| Year      | 1574.8                               | 630.16                               | 15.12              | 1754.9                               | 1716.0                               | 16.015               | 6.351                | 2.721                 | 13.049               | 3.630                 |

where:

- **GlobHor** is the global horizontal diffuse irradiation.
- **DiffHor** is the horizontal diffuse irradiation.
- **T\_amb** is the ambient temperature.
- **Globinc** is the global incident irradiation on the collectors plane.
- **GlobEff** is the effective global irradiation with IAM and shading corrections.
- **EArray** is the effective energy at the output of the array.
- **E\_user** is the energy supplied to the user.
- **E\_solar** is the energy from the sun.
- **E\_grid** is the energy injected into grid.
- **EFrGrid** is the energy from the grid

The main results of the simulation are displayed on table 4.4.

Table 4.4: Main results obtained from the PVsyst simulation (Case A).

| <b>Produced Energy</b><br>(MWh/year) | <b>Specific Production</b><br>(kWh/kWp/year) | <b>System Losses</b><br>(kWh/kWp) | <b>PV Conversion Efficiency at STC</b> | <b>PR</b> |
|--------------------------------------|----------------------------------------------|-----------------------------------|----------------------------------------|-----------|
| 15,77                                | 1516                                         | 21,9                              | 20,29 %                                | 0,864     |

## Case B

As presented before, the plot area for this project can be seen in figure 3.3, additionally the shading scene is displayed in figure 3.17. Due to the fact that the study area has a low surface albedo, the use of bifacial solar panels was not considered. As for the orientation parameters, the possibility of a seasonal tilt adjustment was considered for the possibility of decreasing shade incidence on the crops with respect to the months where its values were higher (winter months). However, as shown by figure 4.7, adjusting the tilt revealed no major differences and consequently a fixed tilted plane orientation with an optimal tilt of 25° (see figure 3.16) was considered for the simulation. Again, the the tilt value was selected through the use of the PVsyst optimization tool.

Table 4.5 shows the balances and mains results on a monthly basis for the current case.

Table 4.5: Monthly balances and main results for case B (PVsyst).

|           | GlobHor<br>kWh/m² | DiffHor<br>kWh/m² | T_Amb<br>°C | GlobInc<br>kWh/m² | GlobEff<br>kWh/m² | EArray<br>MWh | E_User<br>MWh | E_Solar<br>MWh | E_Grid<br>MWh | EFrGrid<br>MWh |
|-----------|-------------------|-------------------|-------------|-------------------|-------------------|---------------|---------------|----------------|---------------|----------------|
| January   | 58.7              | 24.49             | 9.69        | 80.0              | 77.1              | 1.275         | 0.539         | 0.178          | 1.064         | 0.362          |
| February  | 79.2              | 34.48             | 10.24       | 96.2              | 93.0              | 1.528         | 0.487         | 0.184          | 1.307         | 0.304          |
| March     | 122.0             | 54.35             | 12.43       | 136.8             | 132.9             | 2.143         | 0.539         | 0.233          | 1.860         | 0.307          |
| April     | 154.6             | 65.91             | 13.87       | 162.2             | 157.9             | 2.509         | 0.522         | 0.255          | 2.195         | 0.267          |
| May       | 197.1             | 79.27             | 16.44       | 195.9             | 190.8             | 2.988         | 0.539         | 0.286          | 2.634         | 0.254          |
| June      | 199.4             | 69.79             | 18.58       | 191.4             | 186.1             | 2.873         | 0.522         | 0.287          | 2.517         | 0.235          |
| July      | 212.0             | 77.01             | 20.05       | 205.5             | 200.1             | 3.074         | 0.539         | 0.294          | 2.710         | 0.246          |
| August    | 191.1             | 71.05             | 20.57       | 199.3             | 194.6             | 2.984         | 0.539         | 0.279          | 2.639         | 0.260          |
| September | 145.0             | 54.99             | 19.16       | 160.1             | 155.9             | 2.412         | 0.522         | 0.238          | 2.120         | 0.284          |
| October   | 99.6              | 46.12             | 17.04       | 118.6             | 115.0             | 1.831         | 0.539         | 0.216          | 1.570         | 0.323          |
| November  | 64.0              | 29.54             | 12.42       | 85.8              | 82.2              | 1.347         | 0.522         | 0.187          | 1.125         | 0.335          |
| December  | 52.1              | 23.17             | 10.57       | 73.4              | 70.0              | 1.155         | 0.539         | 0.172          | 0.951         | 0.368          |
| Year      | 1574.8            | 630.16            | 15.12       | 1705.2            | 1655.7            | 26.118        | 6.351         | 2.807          | 22.691        | 3.544          |

The main results of the simulation are displayed on table 4.6.

Table 4.6: Main results obtained from the PVsyst simulation (Case B).

| Produced Energy<br>(MWh/year) | Specific<br>Production<br>(kWh/kWp/year) | System Losses<br>(kWh/kWp) | PV Conversion<br>Efficiency at STC | PR    |
|-------------------------------|------------------------------------------|----------------------------|------------------------------------|-------|
| 25,67                         | 1405                                     | 32,85                      | 14,74 %                            | 0,824 |

The 66 units of solar collectors were placed along 3 crop rows of 40 m each, assuming a photovoltaic cover ratio of 100 %. Thus, a ratio comparison between the used area for photovoltaic implementation and cultivated area is important:

$$\frac{A_{PV}}{A_{Cultivated}} * 100 = \frac{107}{780} * 100 = 13,72\% \quad (4.1)$$

## Case C

This particular case represents two crop rows that have an approximate distance of 50 m, however these 2 columns have shown lack of productivity over the years. With that said, the possibility of eliminating these two rows and replace them with photovoltaic panels was studied and assessed. There was no need to perform a shadow projection study on this particular area due to the fact the implemented collectors are ground-mounted, consequently no incident shade from them will affect crop production. The same surface azimuth as the present crops, 60°, was chosen in order to fit the maximum number of collectors possible. Furthermore, a fixed tilted plane orientation with a tilt of 20° was picked with the aid of the optimization tool from PVsyst. Lastly, the pitch between sheds is correspondent to the maximum possible, 2,5 m, with respect to the available area width in order to minimize shading losses between collector rows.

The respective shading scene is presented in figure 4.8.

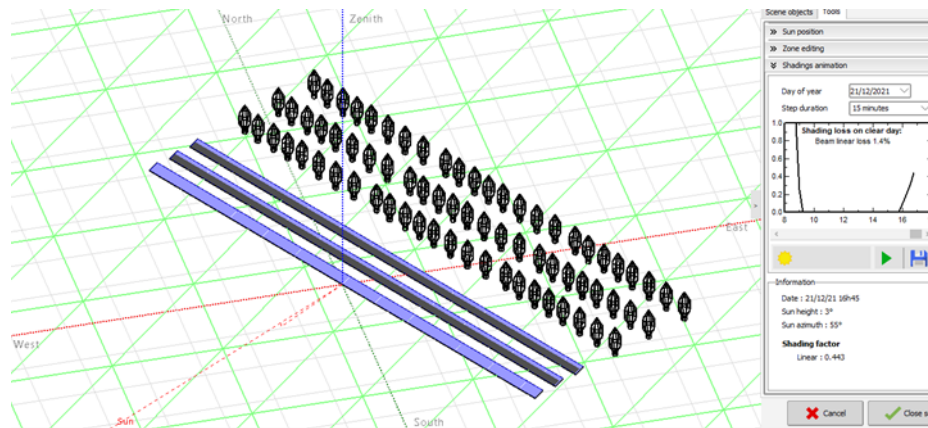


Figure 4.8: Shading model on Moliçal area, plot C (PVsyst).

The monthly balances and main results obtained from the simulation are displayed in table 4.7.

Table 4.7: Monthly balances and main results for case C (PVsyst).

|           | GlobHor<br>kWh/m <sup>2</sup> | DiffHor<br>kWh/m <sup>2</sup> | T_Amb<br>°C | GlobInc<br>kWh/m <sup>2</sup> | GlobEff<br>kWh/m <sup>2</sup> | EArray<br>MWh | E_Grid<br>MWh | PR<br>ratio | E_Grid<br>MWh | EFrGrid<br>MWh |
|-----------|-------------------------------|-------------------------------|-------------|-------------------------------|-------------------------------|---------------|---------------|-------------|---------------|----------------|
| January   | 58.7                          | 24.49                         | 9.69        | 72.7                          | 68.8                          | 1.646         | 1.430         | 0.867       | 1.430         | 0.355          |
| February  | 79.2                          | 34.48                         | 10.24       | 89.9                          | 85.9                          | 2.044         | 1.817         | 0.873       | 1.817         | 0.297          |
| March     | 122.0                         | 54.35                         | 12.43       | 131.6                         | 126.9                         | 2.977         | 2.687         | 0.868       | 2.687         | 0.302          |
| April     | 154.6                         | 65.91                         | 13.87       | 159.8                         | 154.9                         | 3.586         | 3.262         | 0.862       | 3.262         | 0.260          |
| May       | 197.1                         | 79.27                         | 16.44       | 196.6                         | 191.0                         | 4.365         | 4.000         | 0.853       | 4.000         | 0.248          |
| June      | 199.4                         | 69.79                         | 18.58       | 194.0                         | 188.1                         | 4.247         | 3.877         | 0.840       | 3.877         | 0.227          |
| July      | 212.0                         | 77.01                         | 20.05       | 207.5                         | 201.4                         | 4.529         | 4.151         | 0.838       | 4.151         | 0.238          |
| August    | 191.1                         | 71.05                         | 20.57       | 197.3                         | 192.1                         | 4.320         | 3.963         | 0.841       | 3.963         | 0.254          |
| September | 145.0                         | 54.99                         | 19.16       | 155.0                         | 150.2                         | 3.405         | 3.105         | 0.844       | 3.105         | 0.279          |
| October   | 99.6                          | 46.12                         | 17.04       | 112.1                         | 107.5                         | 2.495         | 2.228         | 0.854       | 2.228         | 0.316          |
| November  | 64.0                          | 29.54                         | 12.42       | 78.6                          | 74.1                          | 1.759         | 1.534         | 0.858       | 1.534         | 0.330          |
| December  | 52.1                          | 23.17                         | 10.57       | 66.1                          | 61.6                          | 1.470         | 1.260         | 0.851       | 1.260         | 0.360          |
| Year      | 1574.8                        | 630.16                        | 15.12       | 1661.2                        | 1602.4                        | 36.842        | 33.314        | 0.851       | 33.314        | 3.466          |

Table 4.8 shows the main results of the simulation

Table 4.8: Main results obtained from the PVsyst simulation (Case C).

| Produced Energy<br>(MWh/year) | Specific<br>Production<br>(kWh/kWp/year) | System Losses<br>(kWh/kWp) | PV Conversion<br>Efficiency at STC | PR    |
|-------------------------------|------------------------------------------|----------------------------|------------------------------------|-------|
| 36,20                         | 1414                                     | 25,55                      | 20,29 %                            | 0,851 |

## 4.2.2 Barreiro

As stated before, this particular plot was chosen in order to optimize land use, in this case, the irrigation well that is present around the middle of the cultivated area (as seen in figure 3.6. This is a beneficial situation because in addition to optimizing the available area, the photovoltaic structure on the well will serve as protection from external agents (namely dust and dirt).

The shading scene of the case in hand is presented in figure 4.9.

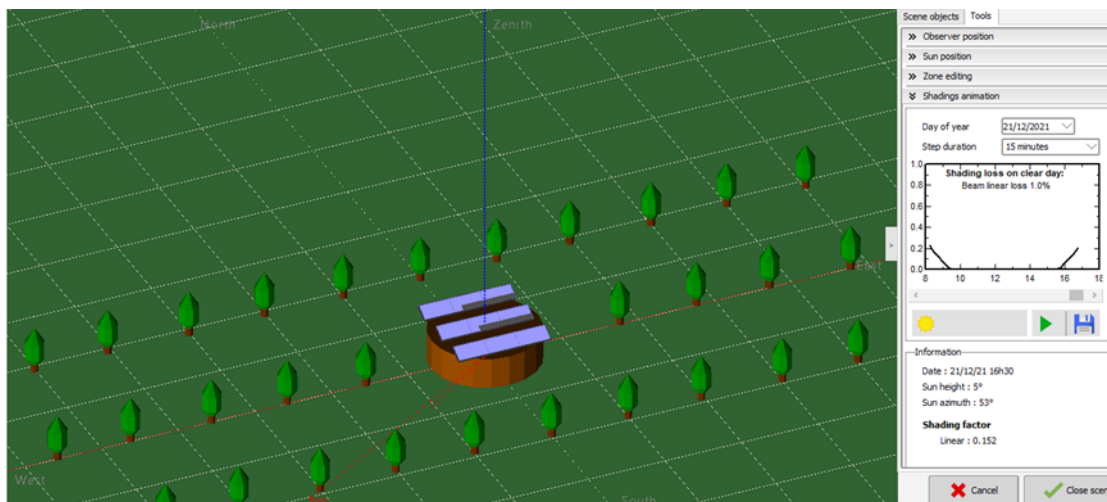


Figure 4.9: Shading model on Barreiro area (PVsyst)

The main PV array characteristics and orientation for the simulated case can be seen in table 4.9

Table 4.9: PV array characteristics and orientation for Barreiro plot

| <b>PV module</b>              | <b>Case A</b>       |
|-------------------------------|---------------------|
| Manufacturer                  | Amerisolar          |
| Model                         | AS6M-BN-400         |
| Unit nominal power            | 400 Wp              |
| Number of PV modules          | 9 units             |
| Total PV power (Nominal)      | 4 kWp (STC)         |
| Module area                   | 17,6 m <sup>2</sup> |
| <b>Inverter</b>               | <b>Case A</b>       |
| Unit nominal power            | 3,60 kWac           |
| Number of inverters           | 1 unit              |
| <b>Orientation</b>            | <b>Case A</b>       |
| Surface azimuth ( $a_{sup}$ ) | 0°                  |
| Tilt                          | 30°                 |
| Pitch                         | 2,50 m              |

The chosen pitch between the sheds was the maximum possible considering the well diameter, in addition the selected tilt angle was considered with the aid of the PVsyst optimization tool whilst taking into account minimizing shading losses between collector rows.

The monthly balances and main results obtained from the simulation are displayed in table 4.10.

Table 4.10: Monthly balances and main results for Barreiro (PVsyst)

|                  | <b>GlobHor</b><br>kWh/m <sup>2</sup> | <b>DiffHor</b><br>kWh/m <sup>2</sup> | <b>T_Amb</b><br>°C | <b>GlobInc</b><br>kWh/m <sup>2</sup> | <b>GlobEff</b><br>kWh/m <sup>2</sup> | <b>EArray</b><br>MWh | <b>E_Grid</b><br>MWh | <b>PR</b><br>ratio |
|------------------|--------------------------------------|--------------------------------------|--------------------|--------------------------------------|--------------------------------------|----------------------|----------------------|--------------------|
| <b>January</b>   | 58.7                                 | 24.49                                | 9.69               | 96.1                                 | 93.0                                 | 0.310                | 0.302                | 0.873              |
| <b>February</b>  | 79.2                                 | 34.48                                | 10.24              | 113.5                                | 110.5                                | 0.366                | 0.358                | 0.875              |
| <b>March</b>     | 122.0                                | 54.35                                | 12.43              | 150.1                                | 145.6                                | 0.477                | 0.466                | 0.862              |
| <b>April</b>     | 154.6                                | 65.91                                | 13.87              | 168.8                                | 163.3                                | 0.530                | 0.517                | 0.851              |
| <b>May</b>       | 197.1                                | 79.27                                | 16.44              | 195.6                                | 188.5                                | 0.605                | 0.591                | 0.839              |
| <b>June</b>      | 199.4                                | 69.79                                | 18.58              | 189.2                                | 182.1                                | 0.579                | 0.565                | 0.829              |
| <b>July</b>      | 212.0                                | 77.01                                | 20.05              | 205.5                                | 198.1                                | 0.627                | 0.613                | 0.828              |
| <b>August</b>    | 191.1                                | 71.05                                | 20.57              | 201.9                                | 195.4                                | 0.617                | 0.602                | 0.829              |
| <b>September</b> | 145.0                                | 54.99                                | 19.16              | 172.2                                | 167.1                                | 0.530                | 0.517                | 0.835              |
| <b>October</b>   | 99.6                                 | 46.12                                | 17.04              | 134.4                                | 130.5                                | 0.422                | 0.412                | 0.853              |
| <b>November</b>  | 64.0                                 | 29.54                                | 12.42              | 99.9                                 | 96.4                                 | 0.319                | 0.311                | 0.865              |
| <b>December</b>  | 52.1                                 | 23.17                                | 10.57              | 90.0                                 | 86.2                                 | 0.287                | 0.279                | 0.863              |
| <b>Year</b>      | 1574.8                               | 630.16                               | 15.12              | 1817.1                               | 1756.6                               | 5.667                | 5.534                | 0.846              |

The main results of the simulation can be displayed on table 4.11.

Table 4.11: Main results obtained from the PVsyst simulation for Barreiro.

| Produced Energy<br>(MWh/year) | Specific<br>Production<br>(kWh/kWp/year) | System Losses<br>(kWh/kWp) | PV Conversion<br>Efficiency at STC | PR    |
|-------------------------------|------------------------------------------|----------------------------|------------------------------------|-------|
| 5,54                          | 1537                                     | 36,50                      | 20,29 %                            | 0,846 |

### 4.2.3 Quintal

Again, this parcel was selected as a reason to optimize and unused area of land within the cultivated area, more specifically bounded by the polygon B, as seen in figure 3.7.

The respective shading scene is represented in figure 4.10

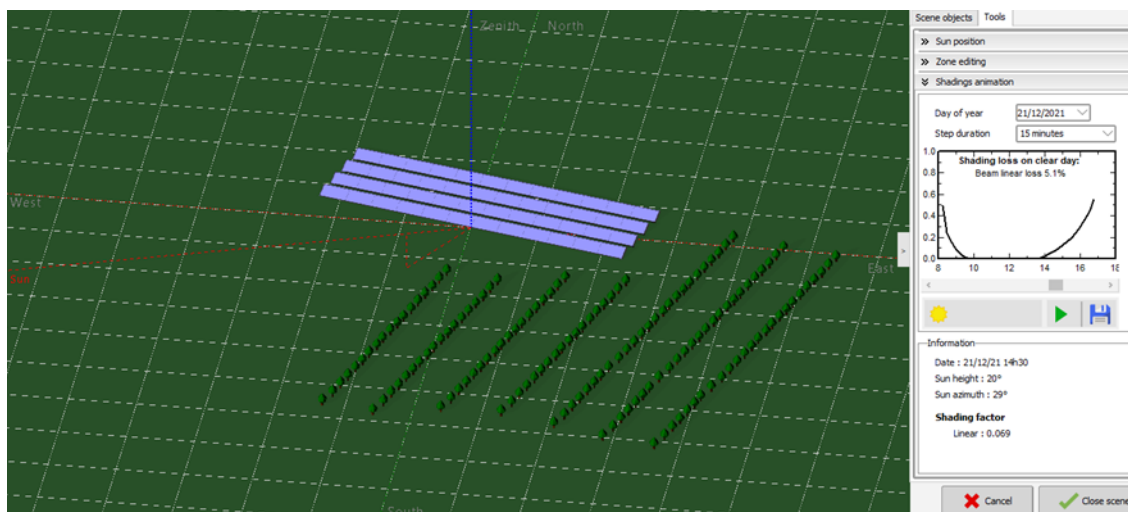


Figure 4.10: Shading model on Quintal area (PVsyst)

The main PV array characteristics and orientation for the simulated case can be seen in table 4.12.

Table 4.12: PV array characteristics and orientation for Quintal plot

| <b>PV module</b>              | <b>Case A</b>     |
|-------------------------------|-------------------|
| Manufacturer                  | Amerisolar        |
| Model                         | AS6M-BN-400       |
| Unit nominal power            | 400 Wp            |
| Number of PV modules          | 48 units          |
| Total PV power (Nominal)      | 19,2 kWp (STC)    |
| Module area                   | 94 m <sup>2</sup> |
| <b>Inverter</b>               | <b>Case A</b>     |
| Unit nominal power            | 18 kWac           |
| Number of inverters           | 1 unit            |
| <b>Orientation</b>            | <b>Case A</b>     |
| Surface azimuth ( $a_{sup}$ ) | 15°               |
| Tilt                          | 30°               |
| Pitch                         | 2,0 m             |

A surface azimuth of 15° and a pitch between collector rows of 2 m was selected as a mean to fit the maximum number of collectors in the area as well as minimizing shading losses between the rows. Lastly, an optimal tilt of 30° was chosen with the aid of the optimization tool provided by PVsyst.

The monthly balances and main results obtained from the simulation are displayed in table 4.13.

Table 4.13: Monthly balances and main results for Quintal (PVsyst)

|                  | <b>GlobHor</b><br>kWh/m <sup>2</sup> | <b>DiffHor</b><br>kWh/m <sup>2</sup> | <b>T_Amb</b><br>°C | <b>GlobInc</b><br>kWh/m <sup>2</sup> | <b>GlobEff</b><br>kWh/m <sup>2</sup> | <b>EArray</b><br>MWh | <b>E_User</b><br>MWh | <b>E_Solar</b><br>MWh | <b>E_Grid</b><br>MWh | <b>EFrGrid</b><br>MWh |
|------------------|--------------------------------------|--------------------------------------|--------------------|--------------------------------------|--------------------------------------|----------------------|----------------------|-----------------------|----------------------|-----------------------|
| <b>January</b>   | 58.7                                 | 24.49                                | 9.69               | 95.2                                 | 88.5                                 | 1.573                | 0.130                | 0.047                 | 1.487                | 0.084                 |
| <b>February</b>  | 79.2                                 | 34.48                                | 10.24              | 111.8                                | 106.8                                | 1.888                | 0.118                | 0.047                 | 1.798                | 0.071                 |
| <b>March</b>     | 122.0                                | 54.35                                | 12.43              | 148.9                                | 143.1                                | 2.499                | 0.130                | 0.059                 | 2.383                | 0.071                 |
| <b>April</b>     | 154.6                                | 65.91                                | 13.87              | 168.4                                | 161.5                                | 2.794                | 0.126                | 0.065                 | 2.664                | 0.061                 |
| <b>May</b>       | 197.1                                | 79.27                                | 16.44              | 195.7                                | 187.3                                | 3.209                | 0.130                | 0.071                 | 3.064                | 0.059                 |
| <b>June</b>      | 199.4                                | 69.79                                | 18.58              | 188.5                                | 180.3                                | 3.057                | 0.126                | 0.074                 | 2.910                | 0.052                 |
| <b>July</b>      | 212.0                                | 77.01                                | 20.05              | 204.8                                | 196.0                                | 3.310                | 0.130                | 0.074                 | 3.159                | 0.056                 |
| <b>August</b>    | 191.1                                | 71.05                                | 20.57              | 202.7                                | 194.8                                | 3.277                | 0.130                | 0.070                 | 3.134                | 0.060                 |
| <b>September</b> | 145.0                                | 54.99                                | 19.16              | 171.3                                | 165.0                                | 2.787                | 0.126                | 0.060                 | 2.665                | 0.066                 |
| <b>October</b>   | 99.6                                 | 46.12                                | 17.04              | 133.1                                | 127.4                                | 2.198                | 0.130                | 0.055                 | 2.092                | 0.075                 |
| <b>November</b>  | 64.0                                 | 29.54                                | 12.42              | 99.7                                 | 92.5                                 | 1.631                | 0.126                | 0.047                 | 1.545                | 0.079                 |
| <b>December</b>  | 52.1                                 | 23.17                                | 10.57              | 89.1                                 | 80.5                                 | 1.429                | 0.130                | 0.045                 | 1.347                | 0.085                 |
| <b>Year</b>      | 1574.8                               | 630.16                               | 15.12              | 1809.2                               | 1723.7                               | 29.652               | 1.533                | 0.714                 | 28.247               | 0.819                 |

The main results of the simulation can be seen in table 4.14.

Table 4.14: Main results obtained from the PVsyst simulation for Quintal.

| Produced Energy<br>(MWh/year) | Specific<br>Production<br>(kWh/kWp/year) | System Losses<br>(kWh/kWp) | PV Conversion<br>Efficiency at STC | PR    |
|-------------------------------|------------------------------------------|----------------------------|------------------------------------|-------|
| 28,96                         | 1508                                     | 36,5                       | 20,29 %                            | 0,834 |

#### 4.2.4 Summary

In conclusion, a summary on the presented results is displayed on table 4.15, where some additional parameters considered as relevant were added. It is important to take into account that the considered energy needs were provided by the farm owner and only concern energy consumption by the irrigation system. Therefore, the energy surplus is obtained by subtracting the produced energy with the energy needs.

Table 4.15: Main results obtained for all simulated cases

| Parameters                                                | Moliçal |         |         | Barreiro | Quintal |
|-----------------------------------------------------------|---------|---------|---------|----------|---------|
|                                                           | Case A  | Case B  | Case C  |          |         |
| Module area<br>(m <sup>2</sup> )                          | 50,9    | 107     | 125     | 17,6     | 94      |
| Produced Energy<br>(MWh/year)                             | 15,77   | 25,67   | 36,20   | 5,54     | 28,96   |
| Produced Energy<br>per used area<br>(MWh/m <sup>2</sup> ) | 0,225   | 0,033   | 0,121   | 0,143    | 0,172   |
| Energy Needs<br>(MWh/year)                                | 6,35    | 6,35    | 6,35    | -        | 1,53    |
| Energy Surplus<br>(MWh/year)                              | 9,42    | 19,32   | 29,85   | 5,54     | 27,43   |
| System Losses<br>(kWh/kWp)                                | 21,9    | 32,85   | 25,55   | 36,50    | 36,5    |
| PV Conversion<br>Efficiency at STC                        | 20,29 % | 14,74 % | 20,29 % | 20,29 %  | 20,29 % |
| PR                                                        | 0,864   | 0,824   | 0,851   | 0,846    | 0,834   |

Case A demonstrated higher efficiency in energy production per square meter of area used (0,225 Mwh/m<sup>2</sup>). This can be explained due to the fact that the considered used area for the calculation was the length of the ground path (70 m) by the cosine of the width of the panels. These were the distances considered because the panels are elevated on structures (overhead PV) and are not filling the ground path where they are installed nor implemented above crop production. However, despite the fact that there is a higher energy production per square meter, the implementation

costs of this variant are significantly higher, as we will see in the following section. On the other hand, case B revealed to be the less efficient project regarding the produced energy per used area (0,033 MWh/m<sup>2</sup>). As the collectors in this variant are implemented above crop production, the considered area for the calculation was the cultivated area ( $\approx 780 \text{ m}^2$ ), the highest of all simulations. In addition, the solar panels efficiency is the lowest due to the fact that transparent collectors were used in the simulation.

For the ground-mounted pv simulations (Case C, Barreiro and Quintal) it is possible to see a correlation between the module area and produced area. Case C has a module area 7 times bigger than Barreiro and 1,33 times bigger than Quintal, thus its produced energy will follow the same pattern as it is 7 and 1,3 times larger than the Barreiro and Quintal project, respectively. However, Case C shows the least efficiency in terms of produced energy per used area, one of the reasons for this is the fact can that the considered surface azimuth for this project was ( $60^\circ$ ), the furthest from optimal orientation ( $0^\circ$  in relation to the south) relative to the Barreiro and Quintal projects. Another relevant explanation is the pitch between collector rows, higher pitch between rows the more area is being used, therefore less efficiency in produced energy per used area. When comparing projects, the lowest used pitch in the ground-mounted pv applications was for Quintal (2,0 m), thus translating into a higher value in this parameter. Nevertheless, it is important to arrange the best combination possible between pitch and shading losses amongst collector rows.

### 4.3 Economic Evaluation

In this section, a brief economic analysis on the simulated cases is performed in order to analyse differences between CAPEX (Capital Expenditure Costs) and OPEX (Operational Expenditure Costs) costs, levelized costs of electricity (LCOE), payback period and return on investment (ROI).

Table 4.16 and 4.17 represents the module and inverter prices used in the simulations.

Table 4.16: PV module prices used in the simulations.

| PV module           | €/unit |
|---------------------|--------|
| AS6M-BN-400         | 300    |
| AS-6M30 Transparent | 150    |

Table 4.17: Inverter prices used in the simulations.

| Inverter                            | €/unit |
|-------------------------------------|--------|
| Sunways (3,6 kWac)                  | 500    |
| Platinum GmBH (10 kWac)             | 1200   |
| Shenzen Clou Electronics (18 kWac)  | 1400   |
| Next City Labs Technology (24 kWac) | 1800   |

In addition, other relevant CAPEX costs considered for the economical analysis are displayed in table 4.18 and divided into two categories, overhead pv (OPV) CAPEX costs and ground-mounted pv (GM-PV) CAPEX costs. Case A and B are associated with the OPV costs, the remaining projects are associated with GM-PV costs. The values used in this table were obtained based on [28].

Table 4.18: Capital Expenditure Costs (CAPEX) of each specific investment in €/ kWp for OPV and GM-PV.

| Type of cost                        | OPV (€/ kWp) | GM-PV (€/ kWp) |
|-------------------------------------|--------------|----------------|
| Mounting Structures and hardware    | 405,1        | 65             |
| Miscellaneous electrical components | 15           | 15             |
| Site preparation and installation   | 299          | 150            |
| Grid connection                     | 100          | 100            |
| Soil protection                     | 30,9         | 0              |
| $\Sigma$                            | 850          | 330            |

From analysing table 4.18, CAPEX costs associated with OPV are 157 % higher than those associated with GM-PV. This value can be explained due to the use of elevated structures for OPV, the most weighting factor in the CAPEX costs of this type of implementation. In addition, the soil preparation and protection for the implementation of these structures also presents an increased value when compared to GM-PV.

Moreover, table 4.19 represents the OPEX costs that were used for each case. The used values were taken and adapted from [37].

Table 4.19: Operational Expenditure Costs (OPEX) analysis for different scenarios in €/ kWp/ year

| OPEX                                  | Low scenario | Medium scenario | High scenario |
|---------------------------------------|--------------|-----------------|---------------|
| Ground-mounted utility ( $\geq 1$ MW) | 13 €         | 15 €            | 20 €          |

For the OPV applications (Case A and B) a low scenario cost was used as for this type of pv implementation the maintenance costs are lower [28]. For the remaining variants, a medium scenario was adapted.

In order to obtain the summary of financial results of each case, a fixed feed-in tariff was defined for the sale of the produced surplus energy associated with a production unit for self consumption (PUSC). The value of this tariff was calculated based on the equation [38]:

$$\text{Purchase price} = E_{sp} * (W_{fv} * (1 - k')) \quad (4.2)$$

where:

- $E_{sp}$  is the amount of surplus energy.

- $W_{fv}$  is the OMIE wholesale market fixed value for each hour of the day, available at [38], at the present time being 132 €/ MWh.
- $k'$  is the quota withdrawn by the commercializing agent (20 %)

For the self-consumption savings, a fixed value for the consumption tariff was adopted based on the current average daily energy value on the Iberian market, available at [39], at the present time being 132 €/ MWh.

Moreover, the payback period is the duration in years required to recover the cost of the net investment, in this case defined as the CAPEX costs. With that said, the amount recovered for each year is calculated as:

$$\text{Recovered amount for year}_t = N_t + S_t + R_t \quad (4.3)$$

where:

- $N_t$  is the net balance of the year t, corresponding to the after-tax profit minus possible dividend payments. For the considered projects, the after tax profit corresponds to the energy sales income minus the OPEX costs, as no income tax rates were defined.
- $S_t$  is the self-consumption saving of the year t. It is obtained through the energy consumed from own production during the respective year multiplied by the consumption tariff.
- $R_t$  is the redemption part of the loan for year t, corresponding to the capital repayment of the borrowed amount. This portion will be null since for the financing of the projects no loans were considered.

Finally the summary of the financial results computed through the economic evaluation tool on PVsyst can be seen in table 4.20, a project lifetime of 20 years was considered.

Table 4.20: Financial summary for all simulated cases (PVsyst).

| Financial summary                  | Moliçàl   |           |           | Barreiro | Quintal   |
|------------------------------------|-----------|-----------|-----------|----------|-----------|
|                                    | Case A    | Case B    | Case C    |          |           |
| Installation costs (CAPEX) (€)     | 17 839,36 | 26 868,82 | 29 053,28 | 4 375,00 | 22 040,00 |
| Total yearly costs (OPEX) (€/year) | 135,20    | 236,60    | 384,00    | 54,00    | 288,00    |
| LCOE (€/kWh)                       | 0,065     | 0,062     | 0,051     | 0,049    | 0,048     |
| Payback Period (years)             | 11,1      | 10,6      | 8,3       | 8,2      | 7,9       |
| Return on Investment (ROI)         | 79,7 %    | 88,5 %    | 142,2 %   | 142,7 %  | 153,4 %   |

Considering the price of electricity in the Iberian market at the present date, 0,132€/kWh, it is evident that the LCOE for all the considered variants is significantly lower than the current price of electricity purchased from the grid.

Moving towards a more detailed analysis on each variant, the levelized cost of electricity for the OPV cases (Case A and B) present a higher value due to the significantly higher CAPEX costs in relation to the total module area used, as seen in table 4.15. Although these variants seem less economically fitting, in areas where no possible ground mounted pv applications are possible, it comes as an extra source of income. In addition, it can provide benefits to the available crops by shielding them from heat, reducing evapotranspiration thus lowering water needs. Moreover, these solutions can protect the production from extreme solar radiation, strong winds and pests and diseases. These solutions would be more economically desirable if the structures were elevated at a lower height and presented a smaller space between rows, this can happen in perennial cropping, where the cultivated crops don't require heavy machinery in its maintenance, such as tractors, thus making the implementation costs lower.

The GM-PV applications (Case C, Barreiro and Quintal) showed the most promising results due to the lower CAPEX costs in relation the used module area (see table 4.15). The Quintal plot has revealed to be the most economically fitting with a payback period of 7,9 years with a ROI of 153,4 %.

## Chapter 5

# Conclusions and Future Works

### 5.1 Conclusions

The conducted study reached its primary objective of assessing the technical and economical viability of implementing photovoltaic energy simultaneously with agriculture and if that coexistence would in fact boost the benefits.

Different subject fields were interconnected throughout this work, from the fundamentals of solar technologies and PV systems to the non-conventional applications of those systems in agriculture. From the study of incident shadow projection on crops to the 3D model creation and PV simulation with PVsyst software, as well as an economic overview. The collectiveness of knowledge covered in this study allowed a wide and wholesome perspective on the latest PV technologies and their integration on agricultural environment, demonstrating a strong potential for development in the upcoming years.

The case study was divided into three major phases. First, the study of the shadow projection for the cases where the PV implementation was performed on elevated structures and how these affected the solar incidence on the crops, namely for case A and B. Secondly, an analysis of the results obtained in PVsyst regarding the simulated PV deployments was performed. Finally, an analysis of the economic viability of each project was performed, also with the aid of PVsyst.

By developing equations in order to know the projected shade distance for the two present cases, it was possible to arrive at generalized expressions that can be applied to several cases, allowing to obtain the percentage of shaded area present in the crops. Moreover, for Case A, the possibility of implementing an OPV project showed promising results, as shade percentages for distances above 5 meters in the direction of the collectors revealed values below the 20 % mark for the months of February till October. Furthermore, for Case B a photovoltaic cover ratio of 100 % proved to be incompatible from the point of view of incident amount of sunlight required for good development of the kiwifruit crops. However, for a photovoltaic cover ratio of 75 % the paradigm changed, there was indeed some undesirable solar limitation (above 20 % from November till

February) that could translate into an acceptable crop yield reduction when compared to the energy produced. Finally, PVr's of 50 % presented the most desirable values of incident shade, below 20 % all year round.

The PVsyst simulations revealed that the present farm, considering the three areas, has an enormous potential of implementing photovoltaic energy. With all considered simulated variants, the totality of energy production is around 113 MW. All this taking into account that only a small cultivation area (780 m<sup>2</sup>) is being used for the implementation of overhead pv projects above crop production. All three considered parcels have an active cultivated area around 44 000 m<sup>2</sup>, this is the available area that can be used for the implementation of overhead pv projects. Furthermore, GM-PV projects have proven to be very effective in the use of inefficient or unused crop areas, with the ability to produce up to 0.172 MWh/m<sup>2</sup>.

Finally, the economical analysis revealed that the GM-PV projects are more economically attractive when compared to the OPV projects mainly due to their lower CAPEX costs, being the most preponderant factor in its difference the implementation of the elevated structures. However, when no available area for the implementation of ground mounted projects is available, the possibility of applying overhead pv projects is also a viable option, providing the farm owner the prospect of owning a self-sustainable farm. It is also important to take into account that the considered energy needs used in this case study only concerned the energy consumption provided by the irrigation system, a scenario where other energy needs would be considered such as refrigeration systems (to store food), electric machinery (vehicles, tractors...) or even household energy needs would be more beneficial. This is due to the fact that the surplus energy sold to the market is affected by the quota withdrawn by purchasing agents as well as the current constant volatility of electricity prices, which can be beneficial or harmful.

## 5.2 Future Works

Since this is a case study, it would be highly interesting to transport and adapt certain aspects of what has been studied into practice.

Regarding case B, it would be interesting to use a smaller area to actually gauge whether energy and kiwi production sharing the same area would be compatible. In order to do this the following procedure could be performed:

1. Divide a cultivated area into five equal parcels.
2. The five plots of cultivated area would then be divided into two categories: agri-pv area and control area.
3. The agri-pv area would hold four out of the five cultivated plots, with each plot being used to implement OPV structures with different PVr's ranging between ( 25 %, 50% , 75% and

100 %). The control area as the name implies would serve as a reference point relative to a parcel of equal area that is not affected by incident shadow from the collectors

4. At the end of a year, assess for the different PVr's their effect on kiwifruit production in terms of crop yield and fruit quality ( granule weight, sugar content...), relative to the control area.
5. Find the most suitable case between crop and energy production.

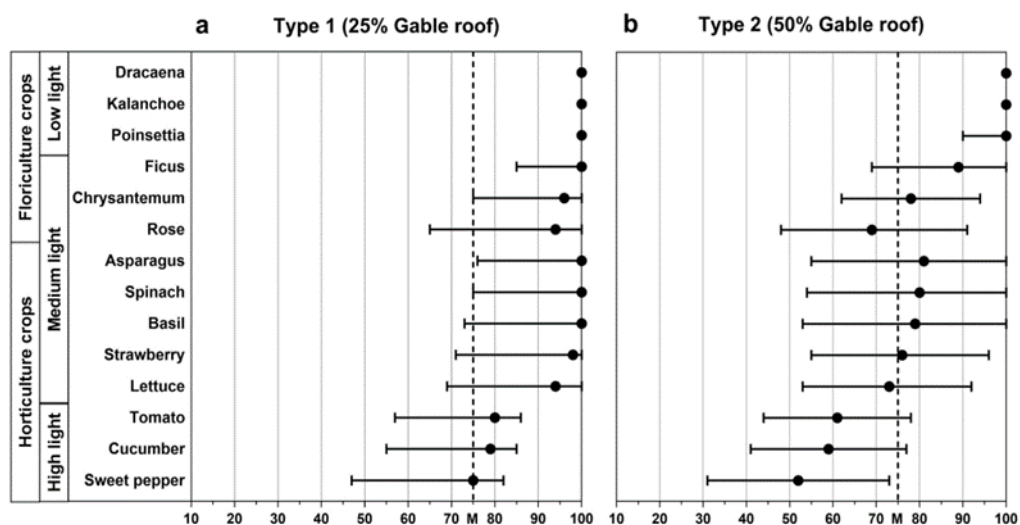
The economic analysis would benefit from using more realistic figures. The values of equipment were obtained through online catalogs and it is likely that, through mass implementation, there would be a cost reduction due to quantity discount or direct purchase from supplier. Furthermore, knowing the price of elevating photovoltaic structures per meter of height would be beneficial in order to better define the CAPEX costs associated with OPV implementation.



## Appendix A

# Yield factor for each specie according to their light requirements and roof type

Figure A.1 represents the yield factor for each specie according to their light requirements and roof type in which they were cultivated based on the case study performed in Sardinia [30].



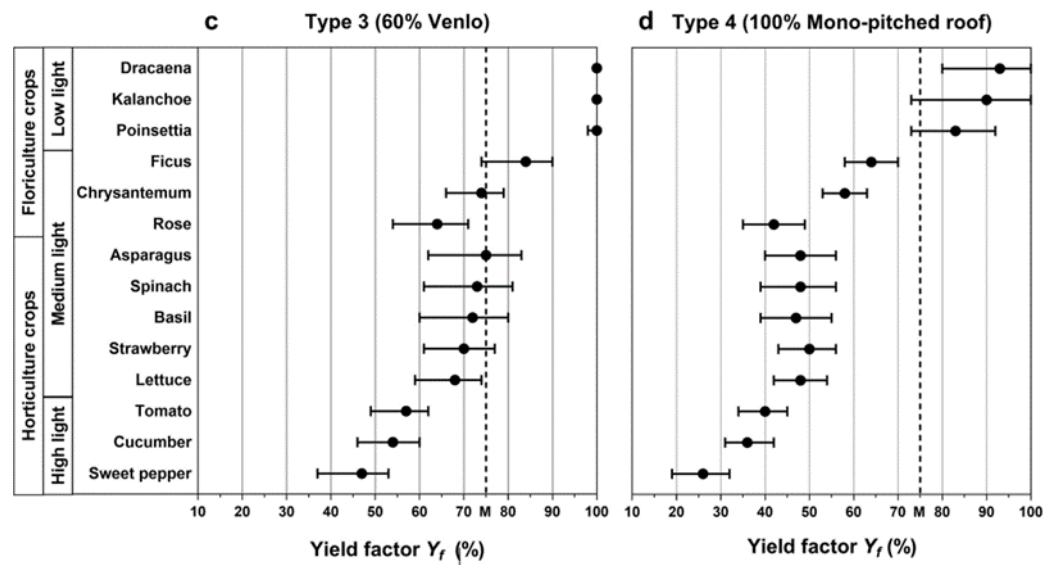


Figure A.1: Agriculture compability of the four PVGs types towards the considered crops, classified according to their DLI. The M value on the x axis is the minimum  $Y_f$  acceptable on yearly basis (75 %).

## Appendix B

### Loss diagrams from PVsyst

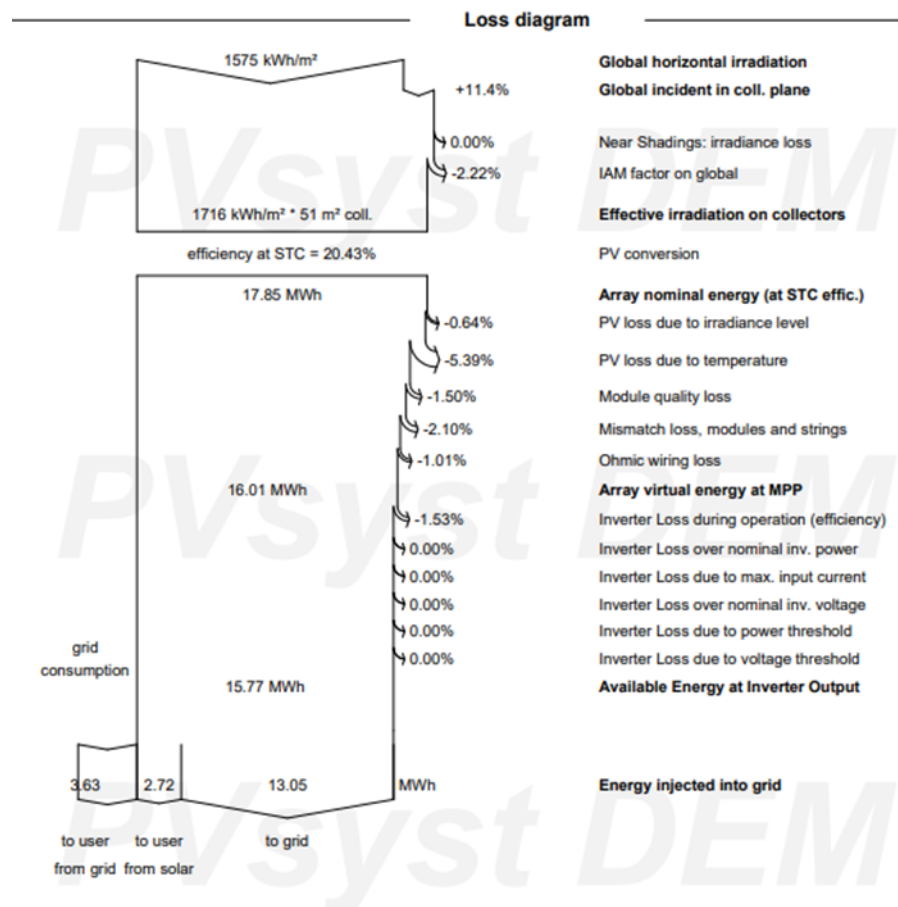


Figure B.1: Losses diagram for case A (Moliçal).

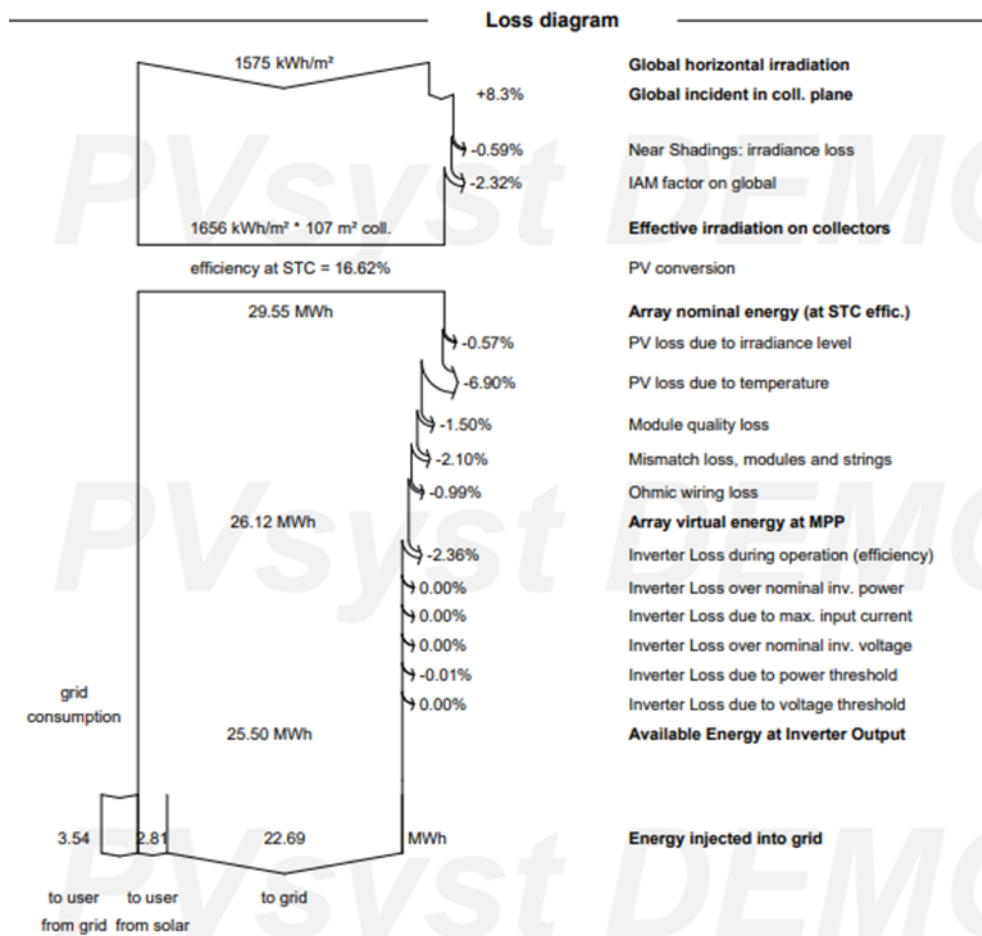


Figure B.2: Losses diagram for case B (Moliçal).

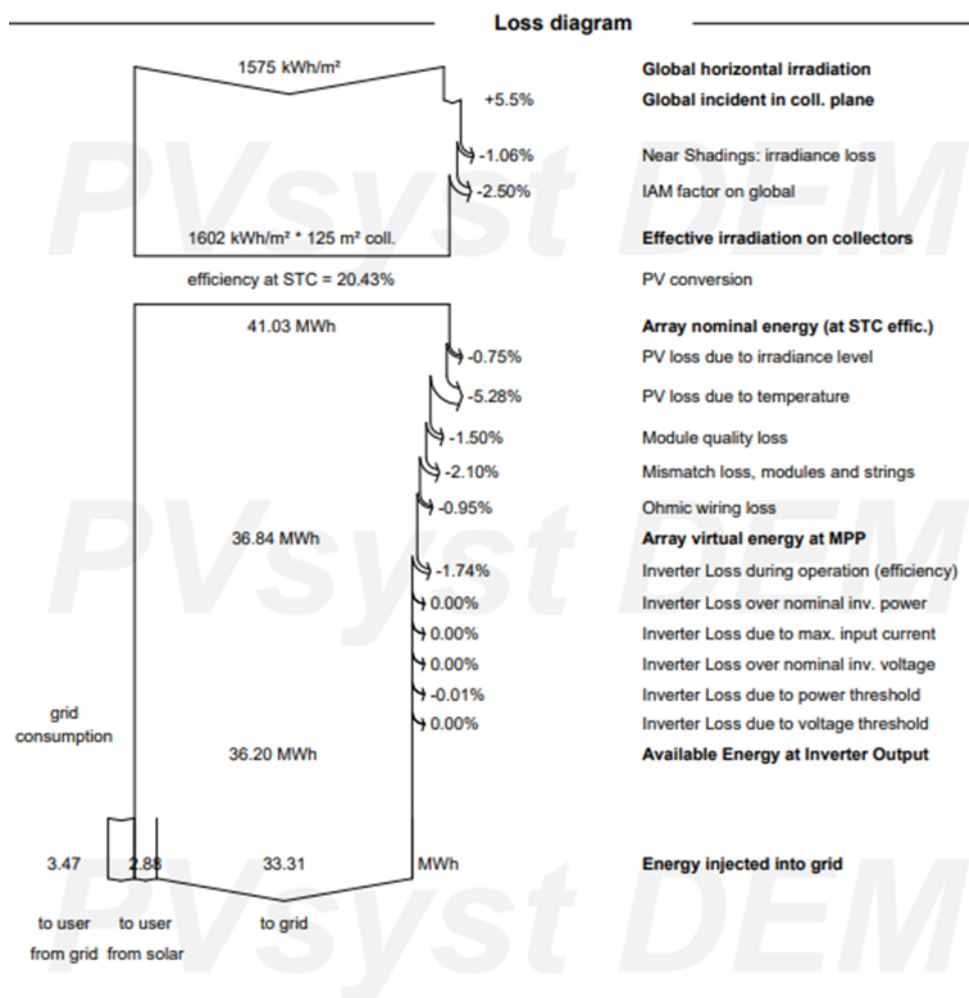


Figure B.3: Losses diagram for case C (Moliçal).

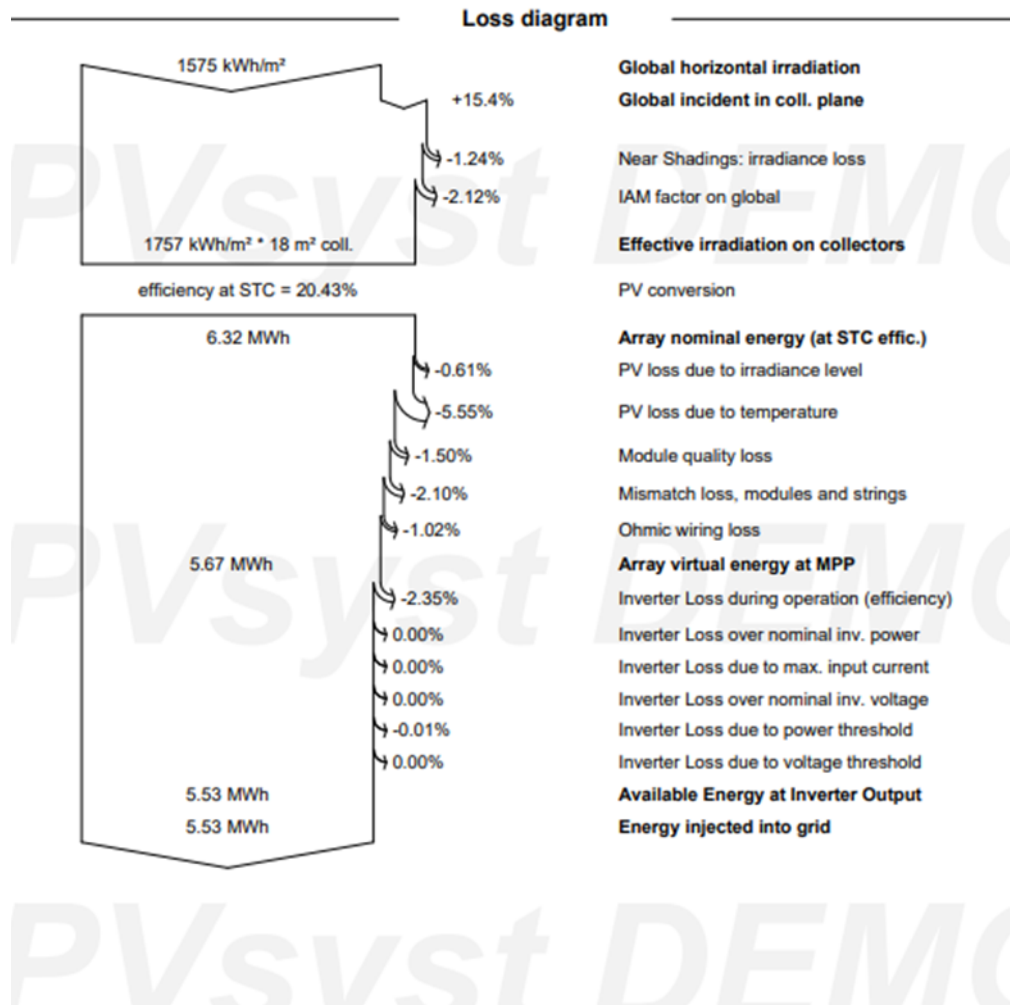


Figure B.4: Losses diagram for Barreiro plot.

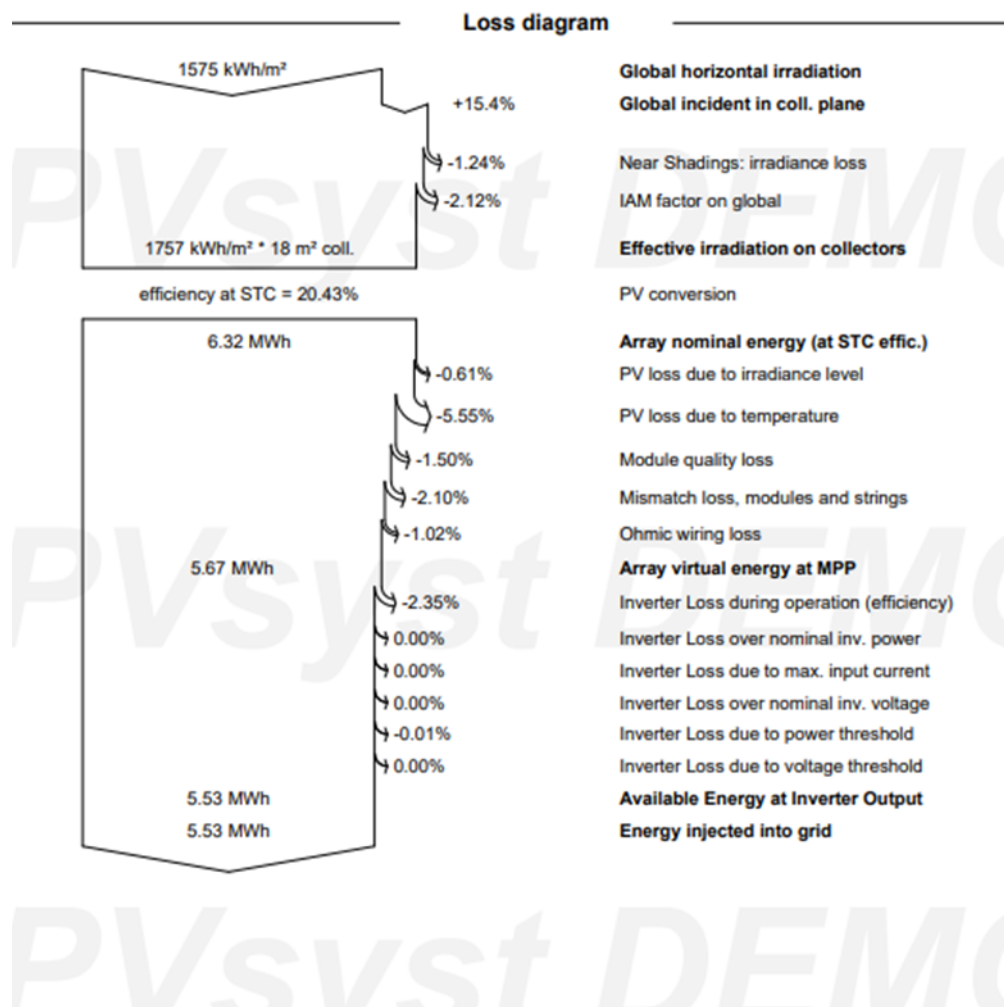


Figure B.5: Losses diagram for Quintal plot.



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