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AGRIPV-Combining Agriculture and Photovoltaic Technology to Mitigate Food and Energy Problems

Miguel Filipe Alves Pereira de Ferreira Monteiro

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Electrical and Computer Engineering

Supervisors: Prof. João Paulo Neto Torres
Prof. Marcelino Bicho dos Santos

Examination Committee

Chairperson: Prof. Célia Maria Santos Cardoso de Jesus
Supervisor: Prof. João Paulo Neto Torres
Member of the Committee: Prof. João Filipe Pereira Fernandes

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Abstract

Agrivoltaic (AgriPV) systems, which integrate agriculture and photovoltaic (PV) technologies, offer a promising solution to the growing global demands for sustainable energy and food production. This dissertation focuses on the implementation of AgriPV systems in greenhouses, combining renewable energy generation with controlled agricultural environments. By examining three case studies in Portugal,Silves, Lagos, and Odemira, the research analyzes site-specific characteristics, solar irradiance trends, and the performance of various PV technologies, including thin-film, organic photovoltaic (OPV), and monocrystalline modules.

The study employs theoretical modeling and simulation techniques to evaluate energy generation and environmental interactions while assessing economic feasibility through financial metrics such as Net Present Value (NPV), Payback Period (PP), and Levelized Cost of Energy (LCOE). The findings highlight the significant potential of AgriPV systems to optimize land use, reduce water stress, and enhance renewable energy production. However, challenges such as high initial investment costs, crop compatibility, and structural adaptations are identified, with recommendations for policy and technological advancements to facilitate broader adoption.

By positioning greenhouse-integrated AgriPV systems as a vital solution to the food-energy nexus, this dissertation aligns with global sustainability goals and provides a roadmap for future research and practical implementation, demonstrating their capacity to address critical environmental and socioeconomic challenges.

Keywords

Agrivoltaic systems, photovoltaic technologies, sustainable agriculture, thin-film PV, organic photovoltaic (OPV), monocrystalline modules

Resumo

Os sistemas Agrivoltaicos (AgriPV), que integram agricultura e tecnologias fotovoltaicas (PV), constituem uma solução promissora face ao crescente desafio global de produzir energia sustentável e alimentos. Esta dissertação centra-se na implementação de sistemas AgriPV em estufas, combinando a geração de energia renovável com ambientes agrícolas controlados. Através da análise de três casos de estudo em Portugal, Silves, Lagos e Odemira, são avaliadas as características específicas dos locais, as tendências de irradiância solar e o desempenho de diferentes tecnologias PV, incluindo módulos de filme fino, fotovoltaicos orgânicos (OPV) e monocristalinos. O estudo recorre a modelação teórica e simulação para avaliar a produção de energia e as interações ambientais, analisando em paralelo a viabilidade económica através de métricas financeiras como o Valor Atual Líquido (VAL/NPV), o Período de Retorno (PP) e o Custo Nivelado de Energia (LCOE). Os resultados evidenciam o potencial significativo dos sistemas AgriPV para otimizar o uso do solo, reduzir a pressão hídrica e aumentar a produção de energia renovável. Identificam-se, contudo, desafios como os elevados custos iniciais de investimento, a compatibilidade com as culturas e as adaptações estruturais necessárias, apresentando-se recomendações de política e de desenvolvimento tecnológico para viabilizar uma adoção mais ampla. Ao posicionar os sistemas AgriPV integrados em estufas como uma solução central para o nexo alimento-energia, esta dissertação está alinhada com os objetivos globais de sustentabilidade e oferece um roteiro para investigação futura e implementação prática, demonstrando a sua capacidade para responder a desafios ambientais e socioeconómicos críticos.

Palavras Chave

Sistemas agrivoltaicos, tecnologias fotovoltaicas, agricultura sustentável, PV de filme fino, fotovoltaico orgânico (OPV), módulos monocristalinos

Contents

1 Introduction **1**

1.1 Motivation . . . 2

1.2 Objectives . . . 2

2 State-of-the-Art **4**

2.1 Introduction . . . 5

2.2 Types of AgriPV . . . 5

2.3 Selected Module Parameters . . . 7

2.4 Economic Impact . . . 8

2.5 Aspects and Technical Challenges . . . 9

2.5.1 The Land Equivalent Ratio: A Key Metric for AgriPV Efficiency . . . 10

2.5.2 Challenges and Considerations in AgriPV System Implementation . . . 10

2.5.3 Modeling Photovoltaic Performance: The 1D3P Approach . . . 11

2.6 Future and Sustainability of AgriPV . . . 12

2.7 Experiments and Examples of AgriPV . . . 13

2.7.1 Europe . . . 13

2.7.2 Asia . . . 15

2.7.3 North America . . . 16

2.7.4 South America . . . 16

2.7.5 Africa . . . 16

2.8 Portuguese Context . . . 17

3 Methodology **18**

3.1 Introduction . . . 19

3.2 Site Analysis and Characteristics . . . 19

3.3 Solar Irradiance and Climatic Trends . . . 21

3.4 Technology Selection: Evaluating Performance in AgriPV Systems . . . 26

3.5 Crop Selection: Agronomic Characteristics and Portuguese Context . . . 27

3.6 Theoretical Power Output and Simulation Analysis . . . 28

3.7 Model assumptions and simplifications . . . 28
3.8 Shading Penalty Values for Avocado Production . . . 29
3.9 Technological and Financial Evaluation . . . 30

4 Results **32**

4.1 Introduction . . . 33
4.2 Energy Performance Results . . . 33
4.2.1 Maximum and Average Power Values . . . 33
4.2.2 Yearly Performance Trends . . . 34
4.2.3 Monthly Comparisons . . . 36
4.2.4 External Validation . . . 38
4.3 Economic Analysis . . . 39
4.3.1 Profit Contribution of PV and Avocado Production . . . 39
4.3.2 Economic Summary Without Degradation . . . 40
4.3.3 Economic Summary With Degradation . . . 41
4.3.4 Sensitivity to Roof Coverage . . . 41
4.3.5 External Validation . . . 45
4.4 Environmental Impact . . . 46
4.5 Comparative Discussion . . . 47

5 Conclusion **50**

5.1 Conclusion . . . 51
5.2 Future Work . . . 53

Acronyms

Acronym	Meaning	Significado
AgriPV	Agrivoltaic	Agrivoltaico (sistema agrivoltaico)
CAPEX	Capital Expenditure	Despesa de Capital
CF	Capacity Factor	Fator de Capacidade
DR	Discount Rate	Taxa de Desconto
LCOE	Levelized Cost of Energy	Custo Nivelado de Energia
LER	Land Equivalent Ratio	Rácio de Equivalência de Terra
NOCT	Nominal Operating Cell Temperature	Temperatura Nominal de Funcionamento da Célula
NPV	Net Present Value	Valor Atual Líquido
O&M	Operations and Maintenance	Operação e Manutenção
PAR	Photosynthetically Active Radiation	Radiação Fotossinteticamente Ativa
PP	Payback Period	Período de Retorno
PV	Photovoltaic	Fotovoltaico
PVGIS	Photovoltaic Geographical Information System	Sistema de Informação Geográfica Fotovoltaico
ROI	Return on Investment	Retorno do Investimento
STC	Standard Test Conditions	Condições de Teste Padrão
TMY	Typical Meteorological Year	Ano Meteorológico Típico
1D3P	Single-Diode Three-Parameter Model	Modelo de Diodo Único de Três Parâmetros

1

Introduction

Contents

1.1 Motivation 2

1.2 Objectives 2

1.1 Motivation

The growing demand for food and energy places significant pressure on land and resources. Agriculture land occupies almost 44% of Earth's habitable land [1] and is increasingly at risk due to urbanization, climate change, and the rising demand for renewable infrastructure. AgriPV has emerged as a transformative solution that combines agriculture and photovoltaic systems(PV), thus enabling the simultaneous use of land for energy harvesting and farming. This dual-use approach addresses the critical challenges of balancing food security, renewable energy production, and combating climate change, all of which are concerns of the World Health Organization United Nations [2, 3].

Greenhouses as a subset of AgriPV systems, present a compelling case for innovation as they provide controlled environments for crop production, allowing for higher yields and reduced water usage. Integrating PV technology into greenhouses will enhance their functionality by generating renewable energy and, reducing reliance on external energy sources. Despite these benefits, the implementation of AgriPV in greenhouses is still in its early stages and requires a deeper understanding of technological, economic, and agricultural considerations.

This thesis is motivated by the pressing need to explore sustainable solutions for global food and energy challenges. By focusing on greenhouse AgriPV, this work aims to contribute to the development of systems that not only support sustainable agriculture but also align with global energy transition goals. Understanding the types of AgriPV systems and their integration into greenhouse agriculture will provide valuable insights into their potential for widespread adoption.

In practical terms, this motivation is made concrete in three greenhouse case studies located in Silves, Lagos, and Odemira, in southern Portugal. These sites were selected because they simultaneously exhibit high solar resource, increasing pressure on water availability, and a strong presence of avocado orchards. By analysing realistic greenhouse-integrated AgriPV layouts in these locations, the thesis aims to translate the global food–energy–water challenges into a specific regional context where AgriPV could provide tangible benefits.

1.2 Objectives

The main goal of this thesis is to explore the possibility of AgriPV with particular attention to greenhouse-integrated AgriPV systems. In order to do this, it is important to identify the main types of AgriPV systems (interspace, overhead, and greenhouse integrated), and to review the design and operating parameters of the various systems with their applications, benefits, and drawbacks.

Then, this thesis will shift its focus to greenhouse AgriPV systems by examining the integration of photovoltaic technology into greenhouses, discussing the effects of various PV technologies on energy production, crop production, and greenhouse environment, and evaluating the effectiveness of the

greenhouse AgriPV systems in increasing the sustainability of agriculture and renewable energy generation.

Building on this, the thesis will analyse three realistic case-study locations in southern Portugal (Silves, Lagos, and Odemira) in order to assess how local climatic conditions influence the technical performance and feasibility of greenhouse-integrated AgriPV. For each site, the study incorporates the modelling of three representative photovoltaic technologies, monocrystalline silicon, thin-film, and organic photovoltaic (OPV), whose performance is simulated using a standard single-diode model driven by PVGIS climatic data. This allows the comparison of energy yield, capacity factor, and temperature behaviour under differing levels of roof coverage and transparency.

In parallel, the thesis evaluates the implications of these PV configurations on crop production through a simplified agricultural modelling approach based on the Land Equivalent Ratio (LER), enabling the assessment of how different shading scenarios might affect avocado production inside the greenhouse. Furthermore, the feasibility of the proposed systems is investigated from an economic perspective by calculating key indicators such as net present value, payback period, and levelized cost of energy for each technology and location.

Finally, the thesis aims to identify the technological, economic, and policy challenges that could hinder the wider implementation of greenhouse AgriPV systems, providing a holistic assessment of their role in supporting more sustainable agricultural and energy systems.

2

State-of-the-Art

Contents

2.1 Introduction 5
2.2 Types of AgriPV 5
2.3 Selected Module Parameters 7
2.4 Economic Impact 8
2.5 Aspects and Technical Challenges 9
2.6 Future and Sustainability of AgriPV 12
2.7 Experiments and Examples of AgriPV 13
2.8 Portuguese Context 17

2.1 Introduction

The present chapter intends to discuss various types, technologies, socioeconomic impacts, and technical challenges in different AgriPV systems and present some examples. AgriPV systems can be interspaced, often used with vertically mounted bifacial PV modules to allow access by machinery, overhead, having raised structures, allowing shade and partial protection to crops, but very expensive by design, or greenhouse systems, integrating PV panels into a controlled environment for a balanced approach in energy generation and plant growth.

Different photovoltaic technologies are used across AgriPV systems, each suited to specific applications. The most common are monocrystalline silicon panels, valued for their high efficiency and durability. Polycrystalline modules offer lower efficiency but remain cost-effective options, though their use is declining. Bifacial panels capture sunlight on both sides, making them ideal for vertical or interspace installations that optimize land use. For greenhouse integration, semi-transparent or glass-glass modules are preferred, as they allow partial light transmission necessary for crop growth while still producing electricity.

Regarding socioeconomic benefits, AGRIPV provides a new way of diversifying farmers income, rural jobs creation, and improved energy autonomy. Yet, several technical barriers persist, such as maintaining crop/light balance, ensuring greenhouse structural stability, and managing costs, storage, and grid integration. If poorly designed, shading and investment costs can outweigh the benefits.

Worldwide adoption of AgriPV is increasing. France, Germany, and Italy lead in Europe, China dominates large-scale development, and South Korea and the United States are expanding pilot programs. Despite Portugal's strong solar resources and agricultural potential, national deployment remains limited, making it an ideal region for AgriPV feasibility research.

2.2 Types of AgriPV

Currently, there are three main types of AgriPV systems, Overhead, Interspace and greenhouses, which can be further categorized into open (Overhead and Interspace) and closed systems (greenhouses), the most common type as illustrated in Figure 2.1.

Overhead systems [Figure 2.2(a)] use elevated structures where photovoltaic (PV) modules are installed above crops, allowing agricultural activities to occur underneath. They offer partial protection and shade but involve higher installation costs due to the supporting structures.

Interspace systems [Figure 2.2(b)] place PV modules between crop rows, usually in fixed or single-axis tracking configurations. This design facilitates machinery access and reduces soil evaporation. The vertical bifacial arrangement, oriented east–west, is a common configuration that increases total light capture and land-use efficiency.

Greenhouse-integrated systems [Figure 2.2(c)] represent closed environments where PV modules are incorporated into the greenhouse structure itself. These systems enable controlled growing conditions and can employ various PV technologies to balance light transmission and energy production, optimizing both crop yield and power output.

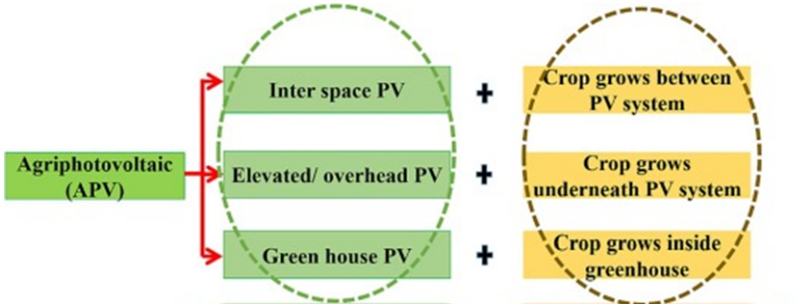


Figure 2.1: Types of AgriPV [4]

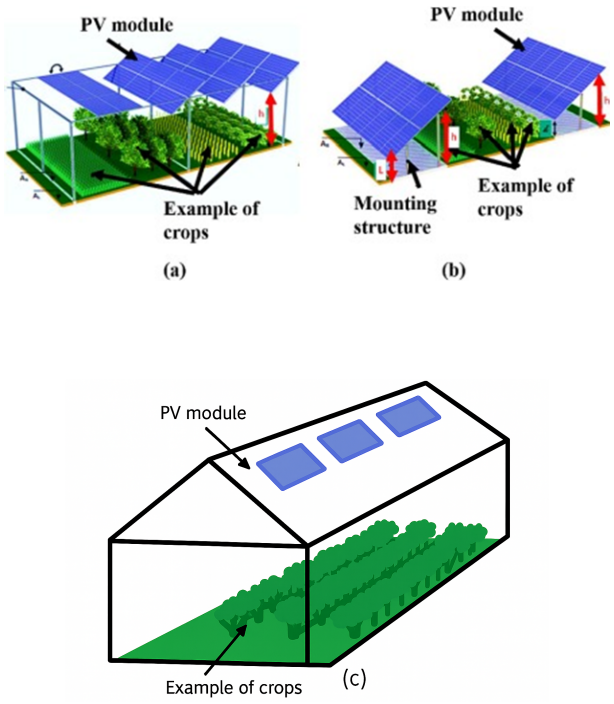


Figure 2.2: (a)Overhead, (b)Interspace, (c) Greenhouse [4]

AgriPV systems employ a wide number of photovoltaic technologies, categorized into three main generations [5, 6].

First-generation technologies include monocrystalline and polycrystalline silicon panels. Monocrystalline modules offer the highest efficiency and longest lifespan, making them common in overhead

systems where maximum energy output is desired. Polycrystalline modules are cheaper but slightly less efficient and are now less frequently used [7, 8].

Second-generation technologies include bifacial crystalline silicon, thin-film, and glass-glass semi-transparent modules. Bifacial panels capture light from both sides and perform well in interspace systems, especially when mounted vertically. Thin-film panels are lightweight and flexible, while glass-glass semitransparent modules combine durability with partial transparency, ideal for greenhouse integration [7].

Third-generation technologies comprise perovskite, dye-sensitized solar cells (DSSC), and organic solar cells (OSC). These are emerging materials offering advantages such as low cost, flexibility, and transparency, though typically with lower efficiency and shorter lifespans compared to silicon-based modules [5, 6].

This wide mix of technologies supports AgriPV's adaptability to various environments and design requirements, allowing optimization between energy generation, light availability, and crop productivity [6, 9].

2.3 Selected Module Parameters

Table 2.1 summarises the main electrical and geometric characteristics of the three photovoltaic technologies analysed in this study: monocrystalline silicon, thin-film, and organic photovoltaic (OPV) modules. These parameters, taken from manufacturer datasheets, include STC electrical variables, temperature coefficients, and physical dimensions, which are later used as inputs to the 1D3P model and to normalise performance per kWp and per square metre of greenhouse roof.

Table 2.1: STC electrical and geometric parameters of the photovoltaic modules used in this study.

Parameter	**Monocrystalline**	**Thin-film (a-Si)**	**OPV**
Module Model	Waaree WFLW-500	Onyx 1245×635 (ref. 00)	HeliaSol 436-2000-CFF-50
Nominal Power (Wp)	500	40	50
Module Efficiency (%)	18.13	50.1 W/m^2 (≈5.0%)	7.2
Dimensions (m × m)	2.270 × 1.190	1.245 × 0.635	2.000 × 0.436
Module Area (m^2)	2.70	0.79	0.87
V_{OC} (V)	49.68	50	56.1
I_{SC} (A)	12.36	1.31	1.60
V_{mpp} (V)	42.48	34	43.1
I_{mpp} (A)	11.78	1.17	1.26
Temp. Coeff. P_{max} (%/°C)	–0.38	–0.19	+0.00
Temp. Coeff. V_{OC} (%/°C)	–0.36	–0.28	–0.25
Temp. Coeff. I_{SC} (%/°C)	+0.07	+0.09	+0.08
Weight (kg)	10.5	16	1.6
Notes	Flexible mono PERC	Glass–glass a-Si	Ultra-light OPV film

2.4 Economic Impact

Before assessing the socioeconomic benefits of this kind of system, one has to consider its financial implications. Therefore, it is important to understand their financial viability through indicators such as the Discount Rate (DR) expressed in 2.1, the Net Present Value (NPV) expressed in 2.2, the Payback Period (PP) expressed in 2.3, Levelized Cost of Energy (LCOE) expressed in 2.4, Rate of Investment(ROI) expressed in 2.5.

The DR (Discount Rate) refers to the opportunity cost of capital, that is the return on investments that could have been earned in other projects but are being invested in the project in question. It is composed of three parcels: inflation rate (T1), risk-free rate of return (T2), and equity risk premium (T3). It is based on the assumption that the inflation is the same for all costs, so it can be ignored during the calculations 2.1 .

$$DR = ((1 - T1)(1 + T2)(1 + T3)) - 1 \tag{2.1}$$

The NPV (Net Present Value) is the difference between the present value of cash inflows and the present value of cash outflows, over a particular period of time. If NPV¿0 profit is expected, if NPV¡0 loss is expected and is NPV=0 there will be neither profit neither loss. NPV is given by the following equation, where n is the project's lifetime, R_t the revenue on time t2.2.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1 + DR)^t} - I_0 \tag{2.2}$$

The PP(Payback Period) is the time required to recover the initial investment and the smaller the payback period, the better as the investment will be recovered sooner and is normally stated for uneven cash flows as the following expression, where A is the last year with a negative cumulative cash flow, B is the absolute value of cumulative cash inflow at the end of year A, and C is the total cash flow during the year after Year A.2.3.

$$PP = A + \frac{B}{C} \tag{2.3}$$

The LCOE (Levelized Cost of Energy) is defined as the cost of generating each unit of power over the entire lifespan of the project and does not take into consideration interest rates as well as does not take into account the discount to the present value. It is calculated by the following equation, where I_0 is the investment at the initial level, $O\&M_t$ is the operation and maintenance costs during a singular period t, n is the number of periods which are equivalent to the lifetime of the project and E_t is the total energy produced during a single period of time of t2.4.

$$LCOE = \frac{I_0 + \sum_{t=0}^{n} O\&M_t}{\sum_{t=0}^{n} E_t} \tag{2.4}$$

The ROI (Return on Investment) is the ratio between the net benefit/profit of a project and the amount invested2.5.

$$ROI = \frac{\text{Net benefit}}{\text{Total Investment}} \tag{2.5}$$

Once the financial viability is established through these indicators, it becomes possible to assess the broader socioeconomic impact of AgriPV systems. These systems can provide multiple social and economic advantages, particularly in rural regions. The introduction of AgriPV contributes to job creation in the installation, maintenance, and operation of systems, while also stimulating local economies through investment in energy infrastructure.

For farmers, AgriPV represents a form of income diversification, reducing their dependence on crop yields alone and increasing resilience against market volatility and climatic uncertainty. At a regional level, it supports energy self-sufficiency and promotes sustainable land management, allowing food and energy to be produced simultaneously on the same area.

Beyond direct financial gains, AgriPV systems foster social development by encouraging technological innovation in agriculture, attracting investment to rural areas, and contributing to national renewable energy and sustainability goals. Thus, the socioeconomic dimension of AgriPV extends beyond profitability, encompassing the long-term enhancement of rural livelihoods, food security, and environmental resilience.

2.5 Aspects and Technical Challenges

All the types and configurations as well as the applications of AgriPV systems can be distinguished by each other, while greenhouse systems have their particular advantages and difficulties. But all the AgriPV systems have the same target as the name suggests, the dual purpose of using the same piece of land for farming and power generation of renewable energy. This dual-purpose approach is particularly useful in conditions where the quality of arable land is limited or where the establishment of energy generation facilities may not be compatible with agricultural activities. Through the integration of the PV modules, AgriPV systems help in the promotion of renewable energy instead of non-renewable energy sources and thus support the worldwide shift toward sustainable energy.

2.5.1 The Land Equivalent Ratio: A Key Metric for AgriPV Efficiency

One important metric used to evaluate the effectiveness of dual-use land systems is the Land Equivalent Ratio (LER), this indicator compares the combined output of agricultural and energy production in AgriPV systems to the output of land dedicated solely to either agriculture or energy, expressed in equation2.6.

$$LER = \frac{Y_a}{Y_s} + \frac{Y_e}{Y_p} \tag{2.6}$$

The agricultural yield under AgriPV systems (Y_a) is combined with the energy yield (Y_e) to measure overall efficiency relative to their respective single-use baselines (Y_s for agriculture and Y_p for energy), if the resulting LER value is greater than 1 this indicates that the dual-use system is more efficient, leveraging land resources to maximize productivity [10].

2.5.2 Challenges and Considerations in AgriPV System Implementation

Among the numerous advantages of the AgriPV systems, it is possible to single out the impact on the microclimate under the PV panels. The shade created by the panels can also assist in managing heat stress in crops and water intake especially if used in the arid regions. But one has to be very careful with the amount of shade that is provided as insufficiency of light can also affect photosynthesis and the yield of the crop. The choice of PV technology,such as bifacial modules, monocrystalline silicon panels, or semi-transparent PV systems depends on the crop, climate, and energy requirement in the specific region. Each of the technologies has its strength and therefore it becomes important to place and orient the equipment in the right manner to ensure high efficiency [11–13].

However, there are some technical problems for AgriPV systems to be developed. Perhaps one of the most serious is the question of how much light is needed for growth and how much energy needs to be generated. It has been established that PV modules block a part of sunlight that would have otherwise reached the crops, while shading is also capable of reducing heat stress but in the wrong way can also affect photosynthesis. Options that exist include semi-transparent PV modules and bifacial panels which help address this challenge to some extent, however, the problem of how to achieve the right configuration is still complex.

There are also several structural and design issues in the case of greenhouse-integrated AgriPV systems. These configurations need strong structures that can carry the extra load of PV panels while at the same time not interfering with the greenhouse's normal operations. Several factors would include weight, ventilation, cooling, and durability of the structure to meet functionality and durability requirements [14].

Energy management is also an important factor that involves the coordination between AgriPV systems and agricultural activities. Efficient energy storage technologies and reliable grid integration are crucial for the effective utilization of these systems especially in regions with erratic sunlight or high

energy consumption [15].

Also, the problem of crop compatibility exists, because not every crop species can fully grow in the conditions of the modified light and microclimate that are provided by AgriPV systems. Choosing the right kind of crops and managing their growth within such systems is very important to enhance the efficiency of agricultural production. In addition, the expensive initial investment required for setting up AgriPV installations, especially the greenhouse integrated systems is a major hindrance to adoption. All these costs plus the costs of maintaining and operating the systems, especially the greenhouse integrated systems, need financial planning and may require subsidies or incentives [16].

2.5.3 Modeling Photovoltaic Performance: The 1D3P Approach

Among the technical challenges faced by AgriPV systems, understanding the effects of temperature and irradiance on photovoltaic performance is crucial. The single-diode three-parameter (1D3P) model is a widely used equivalent circuit representation for photovoltaic cells, this model effectively captures the electrical behaviour of a PV cell by incorporating a current source, a single diode, and one resistor in series. The relationship between current (I) and voltage (V) in the 1D3P model is described by the following equation 2.5.3 [17].

$$I_{\text{max}} = I_{\text{SC}} - I_0 \left(e^{\frac{V_{\text{max}} + R_s I_{\text{max}}}{m_r u_{T,ref}}} - 1 \right)$$

(2.7)

This model will be important in the context of studying the effect of temperature and irradiance, for this to be possible some assumptions must be made. Firstly it is assumed a linear dependence between short-circuit current and irradiance, as described by expression2.8, as well as a logarithmic dependence on the open-circuit voltage, expressed on 2.9. The other two parameters (n and R_s) are not influenced by temperature or irradiance [17].

$$I_{SC}(G) = \frac{G}{G_{ref}} I_{SC,ref} \tag{2.8}$$

$$V_{OC}(G) = n u_{T,ref} \ln \left(\frac{I_{SC}}{I_0} + 1 \right) \tag{2.9}$$

Sometimes, temperature effects on photovoltaic (PV) modules can be analyzed separately from irradiance and the manufacturers often provide temperature related information using a standardized irradiance level equivalent to sunlight under AM1.5 spectrum conditions. For any given temperature and irradiance, a set of temperature coefficients (α) is determined, these coefficients are typically provided

in datasheets, and describe how key PV parameters short-circuit current (I_{SC}) expressed in equation 2.10, open-circuit voltage (V_{OC}) expressed in equation 2.11, and power (P) expressed in equation 2.12 vary with temperature [17].

$$I_{SC}(G,T) = I_{SC}(G,T_{ref})\,(1 + \alpha_I(G,T_{ref})\,(T - T_{ref})) \tag{2.10}$$

$$V_{OC}(G,T) = V_{OC}(G,T_{ref})\,(1 + \alpha_V(G,T_{ref})\,(T - T_{ref})) \tag{2.11}$$

$$P(G,T) = P(G,T_{ref})\,(1 + \alpha_P(G,T_{ref})\,(T - T_{ref})) \tag{2.12}$$

2.6 Future and Sustainability of AgriPV

AgriPV systems are a solution that tackles energy generation, food security, and land optimization, and, as such, have enormous potential to change both the agricultural and energy sectors. AgriPV aligns with the United Nations Sustainable Development Goals of promoting affordable and clean energy, sustainable agriculture, and climate action, furthermore, by integrating energy production with agriculture, they reduce land-use conflicts and contribute significantly to environmental sustainability by reducing greenhouse gas emissions through renewable energy generation and the shading provided by PV modules also minimizes water evaporation and protects crops from extreme weather, but to ensure their widespread implementation, technological breakthroughs and other innovations in material science and energy storage will be required to increase their efficiency, assuring continuous energy supply while fulfilling the different needs of crops [3].

Although promising, AgriPV still has obstacles to overcome, such as the requirement to incorporate effective energy storage systems, guarantee crop compatibility, and optimize structure designs. Advances in agronomic methods and system design will be required to make AgriPV adaptable to varied geographical and climatic environments. Supportive policies, such as subsidies and simplified rules, will be critical in driving adoption.

AgriPV provides a promising future by addressing urgent global concerns in energy and food security, with the potential to pave the path for a sustainable future in which agriculture and renewable energy coexist together. Through continuous study and deliberate implementation, AgriPV has the potential to become a cornerstone of global sustainability initiatives, driving advances in climate action and resource management.

2.7 Experiments and Examples of AgriPV

The growing awareness of the need to find solutions to food and energy security, in light of the vulnerabilities dictated by climate change, has stimulated growth in the development and usage of AgriPV systems all over the world. These systems, which combine agriculture with photovoltaic energy generation, are emerging as an attractive option not only in Europe but also in different parts of the world, including Asia, North America, South America, and Africa. This versatility of AgriPV systems is well demonstrated across different regions with different agricultural practices, climatic conditions and socio-economic needs. The progress and innovation driving the adoption of AgriPV as a pivotal solution to the food-energy nexus are evident through examples from multiple continents as seen in figure 2.3.



Figure 2.3: Examples of AgriPV installations [5]

2.7.1 Europe

Europe plans to be the first carbon-neutral continent by 2050, the 'European Green Deal plan'. As such, plans like reducing greenhouse gas emissions by 55% until 2030 were established. To accomplish this, the use of large-scale AgriPV is beneficial because it creates more economic return and efficient land use, but among all European countries, only Germany, France, and Italy are the places where the growth of AgriPV is more available [18].

France is where the first AgriPV prototype was investigated in Montpellier in 2011, another AgriPV system was built in Seine et Marne in 2019 covering an area of 1440 m^2 and integrating the cultivation of four different types of lettuces, and in recent years significant investment has been made in new AgriPV projects, making France the European country with the most installed AgriPV systems including more than 10 solar greenhouses installations with multiple types of crops, such as avocado, kiwis,

strawberries, zucchini, celery, fennel, and chard [19–21].

Scientific assessments show that these systems can improve land productivity by 60–70 % compared to conventional farming, reaching Land Equivalent Ratios (LER) greater than 1.2 when semi-transparent modules are used. According to Carrausse et al. (2023), France's success is mainly due to public investment and supportive regional programs, but its regulatory framework remains complex and evolving [22].

Italy is also focusing on developing renewable solutions in 2021, about 1 million new photovoltaic systems (from agricultural to residential, and industrial) were installed in different regions, and the area taken up by ground-mounted systems was 152.1 km^2, accounting for just 0.05% of the national total area. AgriPV solutions have also been increasing, as seen in the PoValley system, which reached a price of 90 €/MWh while maintaining viable crop yields [23, 24].

Studies by Agostini et al. (2021) indicate that Italian AgriPV configurations typically achieve LER values between 1.1 and 1.3, depending on module height and transparency. Italy's model benefits from national incentives under its renewable-energy strategy, which encourages farmers to co-generate energy without losing agricultural land designation [25].

Germany differs from most other AgriPV approaches by allowing for a wide range of machine employment. According to Fraunhofer ISE it already has multiple examples of AgriPV , such as Lake Constance in the southwest German 194 kWp system, the Bavaria system introduced by the Weihenstephan-Triesdorf University of Applied Sciences, integrating pointed cabbage and Chinese cabbage, the Merzig-Wellingen system in Saarland , and the Aasen system located in Aasen, Donaueschingen, Baden-Württemberg [21, 26–28].

Field trials have shown that energy production losses due to partial transparency average only 15%, while crops beneath experienced less water stress and higher yields during heat periods. According to Trommsdorff et al. (2021), Germany's AgriPV systems achieved annual energy yields above 1 000 kWh/kWp, confirming their technical reliability and compatibility with mechanised farming [27].

The Netherlands also has commercially available working examples of AgriPV such as the 2.7MW installation near Arnhem in Babberich, Netherlands where crops, such as blueberries, red currants, raspberries, strawberries, and blackberries, are planted [29].

Finally, Portugal remains at an early development stage, with limited commercial AgriPV installations. However, research and pilot projects are underway. Companies such as Akuo and Galp are testing AgriPV models focusing on vineyards and greenhouse/fruit-orchard integration, exploring economic viability under the national solar potential (1 800 kWh/m^2 per year). In particular, Akuo's "FruitPV" pilot in Alcobaça, developed with INIAV and Agriterra, aims to optimise agrivoltaic layouts for Fuji apple trees and assess combined crop–energy performance [30, 31].

Galp + ISA are running a vineyard AgriPV pilot at Tapada da Ajuda (Lisbon), a three-year study of shading effects on grape quality and microclimate. Studies show payback periods below five years for

small-scale agricultural AgriPV systems in southern Portugal, reinforcing favourable conditions for future expansion [10, 32].

2.7.2 Asia

In Asia, there are many examples of countries studying AgriPV that already have working examples of this concept.

China has a lot of investment in this field and for that reason has many different examples of AgriPV applications, from solar greenhouses to ground-mounted fixed-axis PV systems and other examples, but fixed-axis ground-mounted photovoltaic systems are widely used due to their low initial costs and minimal operating and maintenance expenses. Some examples of such installations are a 1 GW solar park in the Binhe New District on the eastern banks of the Yellow River in the Ningxia Province, integrating the cultivation of goji berries, and the Jiangshan 200MW on-grid solar park on degraded land, which reports combined ecological and economic benefits and illustrates China's "PV+agriculture" approach. These cases highlight a trend toward utility-scale AgriPV on marginal lands, prioritizing low CAPEX layouts and crop varieties tolerant to partial shade [33, 34].

Bangladesh is facing a huge problem as in less than 40 years its arable land has reduced by 1242 Mha, if nothing is done 68% of its people will face extreme danger, as such, it is also investing in AgriPV solutions. Recent pilot and modelling studies on rice (Oryza sativa) show that yields under Agripv shading can be maintained near control levels when layout and panel spacing are optimized, while opening a new source of income for farmers, broader feasibility work explores business models to scale pilots on irrigation pump sites. These results support the use of bifacial/raised designs that preserve farm operations and minimize yield penalties [35–38].

In South Korea, East-West Power has completed a 300 kW AgriPV project near the city of Ulsan the solar modules are elevated 4 m above the ground, in order to allow heavy machinery to operate beneath them and ensure that traditional rice farming activities continue unimpeded. This design facilitates the dual use of land for both agriculture and renewable energy generation, exemplifying a sustainable approach to land management [39].

In Saudi Arabia, Mirai Solar, a startup emerging from Saudi Arabia's King Abdullah University of Science and Technology, introduced an innovative solution tailored for AgriPV applications, in particular, for greenhouses in regions with intense solar radiation. This Company already built three pilots greenhouses [40].

2.7.3 North America

In the United States, Agrivoltaics, the simultaneous use of land for both agriculture and photovoltaic energy production, has gained significant traction over recent years. A notable study within the Phoenix Metropolitan Statistical Area (MSA) investigated the implementation of agrivoltaic systems on agricultural lands with a gentle 1° slope, ideal for photovoltaic installations, here it was verified that farmers could grow Alfalfa, Cotton and Barley. Each farmland can generate about 600 MWh/acre per year in the proposed development scenario, illustrating the potential scale of dual-use planning for a rapidly growing metro region [41].

Further research in Arizona explored agrivoltaic systems with south-facing PV panels set at a 32° tilt and 1 m row spacing. These studies involved cultivating two replicate plants of three Solanaceae family species, assessing the viability of integrating specific crops with solar energy production. The field experiments reported that partial shading reduced plant water stress and stabilized microclimate, while PV modules operated at lower temperatures, improving electrical performance consistent with broader findings that agrivoltaic shading can enhance both plant and PV outcomes under dryland conditions [42].

2.7.4 South America

Chile is an important country in AgriPV research and development and already has multiple projects in this area, one of them is from Fraunhofer Chile where three pilot AgriPV plants in El Monte, Curacaví, and Lampa were installed. Each plant has an installed capacity of 13 kWp, collectively generating up to 20.8 MWh annually and preventing 8.8 tons of CO2 emissions per year. The project was executed in collaboration with Fraunhofer ISE in Germany, showcasing a successful international partnership for sustainable energy innovation [43].

2.7.5 Africa

In Africa, the use of AgriPV is not a general concern as significant land is available. Still, even so the use of AgriPV has been studied for West Africa in Niger where the agricultural land availability is low (about 35%), it was verified that it would be beneficial. This study completed an economic case study in Dar Es Salam (Dosso region) modelled a smallholder farm and compared rain-fed, diesel-pumped, solar-pumped, and agrivoltaic (Agripv + solar irrigation) scenarios. The Agripv option achieved positive economic indicators (e.g., benefit–cost ratio higher than 1), while the diesel scenario was negative and emitted 4t CO_2/year for irrigation. The study also reported Land Equivalent Ratio (LER) values of 1.33 (excluding shading-induced yield loss) and 1.13 (including a conservative yield penalty), indicating a net land-use advantage for Agripv under realistic assumptions [44].

2.8 Portuguese Context

Portugal offers a particularly favourable environment for AgriPV systems: its solar irradiation is among the highest in Europe, and a significant portion of agricultural land is protected as “Regime Agrícola Nacional” (RAN). Recent research (Ferreira et al., 2024) finds that for suitable crops and layouts, payback times can fall below five years [10].

On the regulatory side, agrivoltaics in Portugal are currently regulated under Decree-Law 15/2022, which allows agrivoltaic projects only as innovation and development ($I\&D$) initiatives, limiting full commercial roll-out. In practice, projects tend to proceed as innovation pilots or as standard self-consumption plants subject to land-use constraints (notably RAN). Policy planning documents (PNEC 2030) reinforce solar expansion targets but still lack AgriPV-specific incentives. To facilitate experimentation, the Government has designated Zonas Livres Tecnológicas (ZLT)including one in the Mira irrigation perimeter—to host pilot projects and de-risk permitting [45–48].

Overall, Portugal combines excellent solar resources with an evolving policy environment. While clear AgriPV-specific rules and incentives are still missing, the combination of pilot mechanisms, robust self-consumption regulation, and favorable economics in the South suggests near-term scalability especially for crops with partial-shade tolerance and greenhouse-integrated configurations.

3

Methodology

Contents

3.1 Introduction 19
3.2 Site Analysis and Characteristics 19
3.3 Solar Irradiance and Climatic Trends 21
3.4 Technology Selection: Evaluating Performance in AgriPV Systems 26
3.5 Crop Selection: Agronomic Characteristics and Portuguese Context 27
3.6 Theoretical Power Output and Simulation Analysis 28
3.7 Model assumptions and simplifications 28
3.8 Shading Penalty Values for Avocado Production 29
3.9 Technological and Financial Evaluation 30

3.1 Introduction

The methodology chapter outlines the approach to evaluate the performance and feasibility of AgriPV systems, with a focus on selected greenhouses, for this three sites in Portugal were chosen, Silves, Lagos and Odemira, because they are suitable for agriculture, receive sufficient solar radiation and meet the study's objectives of promoting sustainable agriculture practices. It then analyses solar irradiance and climatic trends of the last 15 years in order to better evaluate the viability of the selected sites.

The approach begins with a characterization of each site and its solar irradiance trends based on Photovoltaic Geographical Information System (PVGIS) data. This is followed by the selection of three photovoltaic technologies and the avocado crop. PV performance is modeled theoretically using the single-diode three-parameter (1D3P) method, supported by PVGIS climatic inputs, while Autodesk Revit is used solely for visualization of greenhouse designs. Finally, the chapter outlines the technological and financial evaluation based on metrics such as NPV, LCOE, ROI, and LER, allowing for an integrated assessment of both energy generation and agricultural viability.

3.2 Site Analysis and Characteristics

In this chapter, there will be a projection for three locations: Odemira, Lagos and Silves. These locations were chosen for several factors, such as solar exposure and quality of the soil for agriculture purposes, but the main reasons is to purpose a solution that helps mitigate the effects of lack of water reported in Odemira and make the over-exploration of a water-consuming crop (avocado) in Silves and Lagos more sustainable long-term [49].

The site chosen in Silves has a total area of 6 960 m^2, has good agricultural suitability, is regular and flat, allowing it to be used in its entirety, has a lot of sun exposure, and is surrounded by citrus orchards, demonstrating the good quality of the land, this can also be confirmed by verifying the type of soil the site has, in this case, is *Luvisolos Rodocromicos Calcios* a type of soil known to be known for their fertility, particularly in temperate climates [50].



Figure 3.1: Site in Silves [51]

The site in Odemira has a total area of 88 562 m^2 of agricultural land with already some electric infrastructure available, it is relatively flat, but with a slope downward facing west, has a lot of sun exposure and has suitable soil for agriculture purposes, in this case, *Litosolos Eutricos* a type characterized by a combination of low organic matter content and varying degrees of weathering, resulting in nutrient-rich conditions suitable for agriculture [50].



Figure 3.2: Site in Odemira [52]

The site in Lagos has a total area of 18 496 m^2, close to the electric grid, surrounded by different types of plantations, has good solar exposure, and has a ground of the type *Luvisolos Rodocromicos Calcios* reinforcing the suitability for agriculture projects [50].



Figure 3.3: Site in Lagos [53]

3.3 Solar Irradiance and Climatic Trends

This section will analyze temperature, global irradiance, and direct solar irradiance data from 2005 to 2020 hourly to assess solar radiation and climatic trends. The data were obtained from the PVGIS database using the geographic coordinates of each site, assuming a horizontal plane (0° tilt) and the default ground elevation provided by PVGIS (approximately 12 m above sea level for the selected locations). These parameters define the geometry and height for which the irradiance components (global, diffuse, and beam) are calculated. The focus will be on identifying patterns and seasonal variations that influence agricultural and photovoltaic performance in the selected regions. Graphical representations of temperature, global irradiance, and direct radiation trends over the years will provide visual insight into the feasibility of AgriPV systems under varying climatic conditions.

Firstly, by analyzing the global irradiance during the mentioned 15-year period it is evident that the chosen locations show the highest values during the summer months and that it is possible to verify that the global irradiance values maintain a constant behavior throughout the years; this indicates that the chosen locations are suitable for photovoltaic exploration.

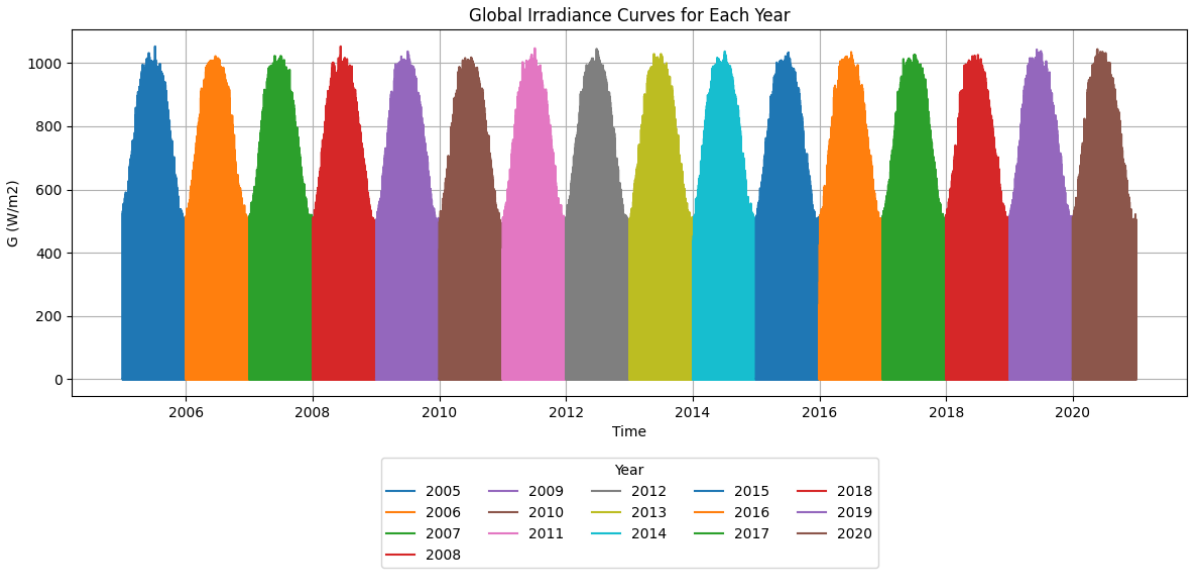


Figure 3.4: Yearly Irradiance in Silves Site

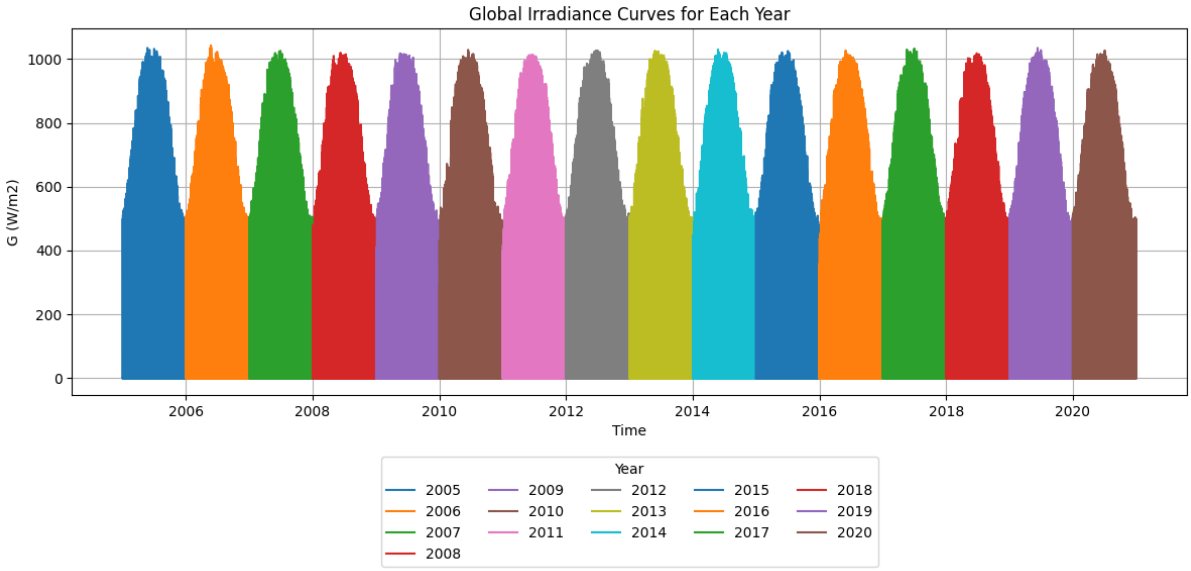


Figure 3.5: Yearly Irradiance in Odemira Site

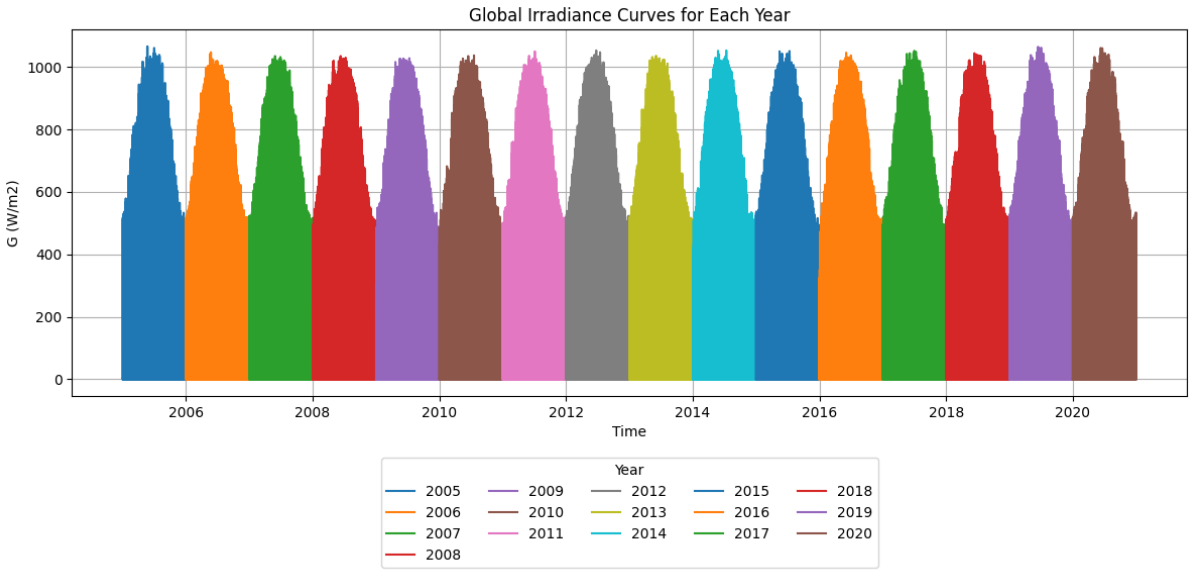


Figure 3.6: Yearly Irradiance in Lagos Site

The temperature trends from the 15-year record show seasonal variations and, as expected, the highest temperatures are concentrated in summer months, which have a direct effect on crop growth and PV efficiency. The long-term data shows that the temperature maintains relatively the same behavior, thus, these regions are quite dependable for AgriPV. Yearly temperature distributions for Silves and Odemira are shown in Figures 3.7, 3.8 and 3.9, respectively.

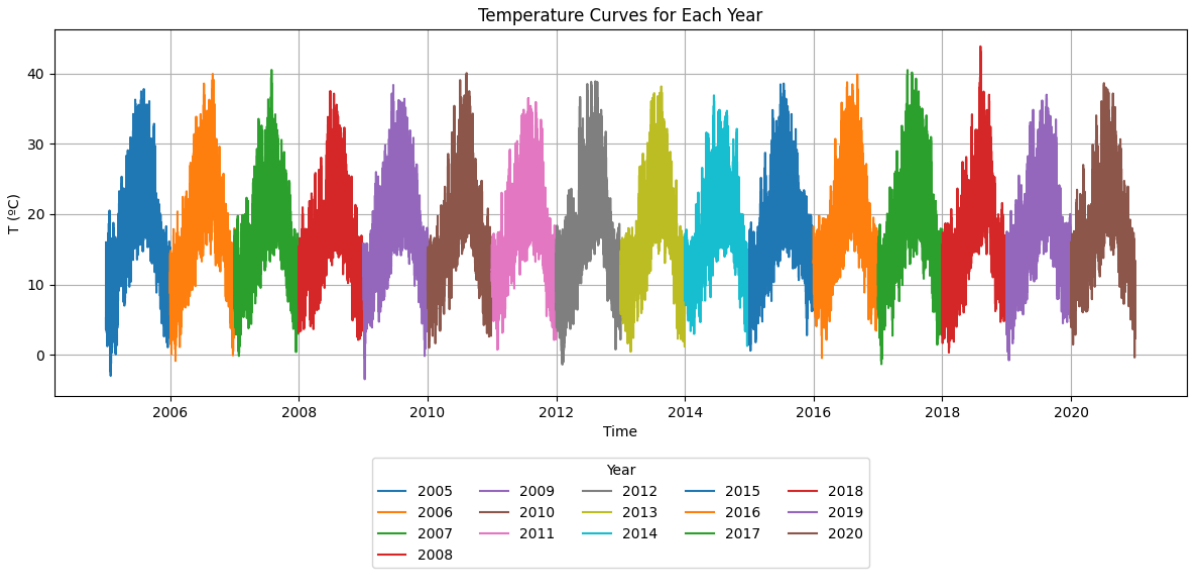


Figure 3.7: Yearly Temperature in Silves Site

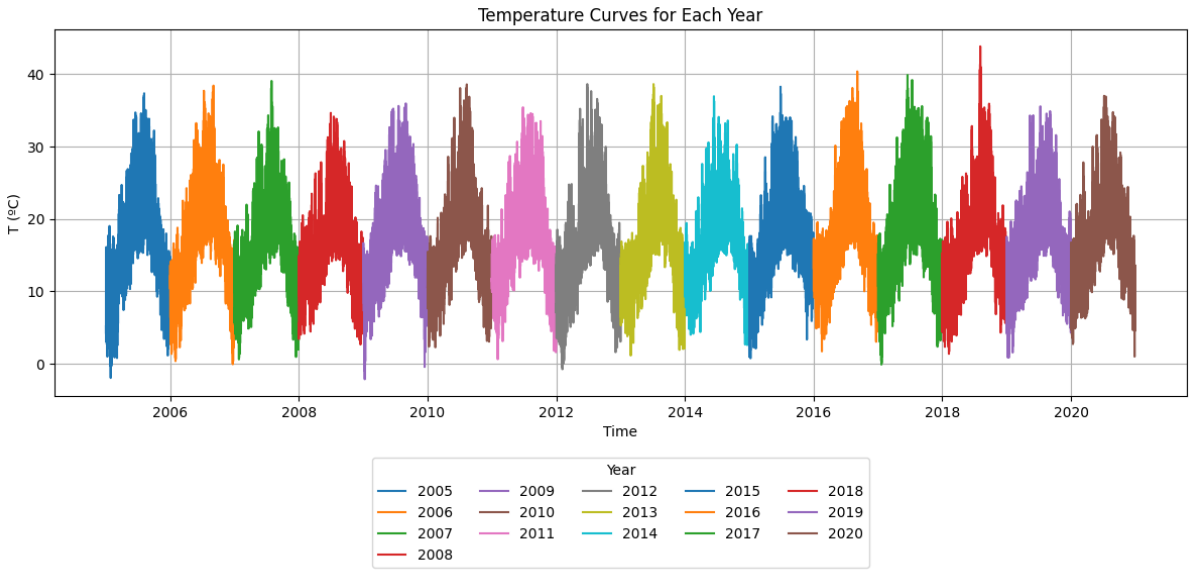


Figure 3.8: Yearly Temperature in Odemira Site

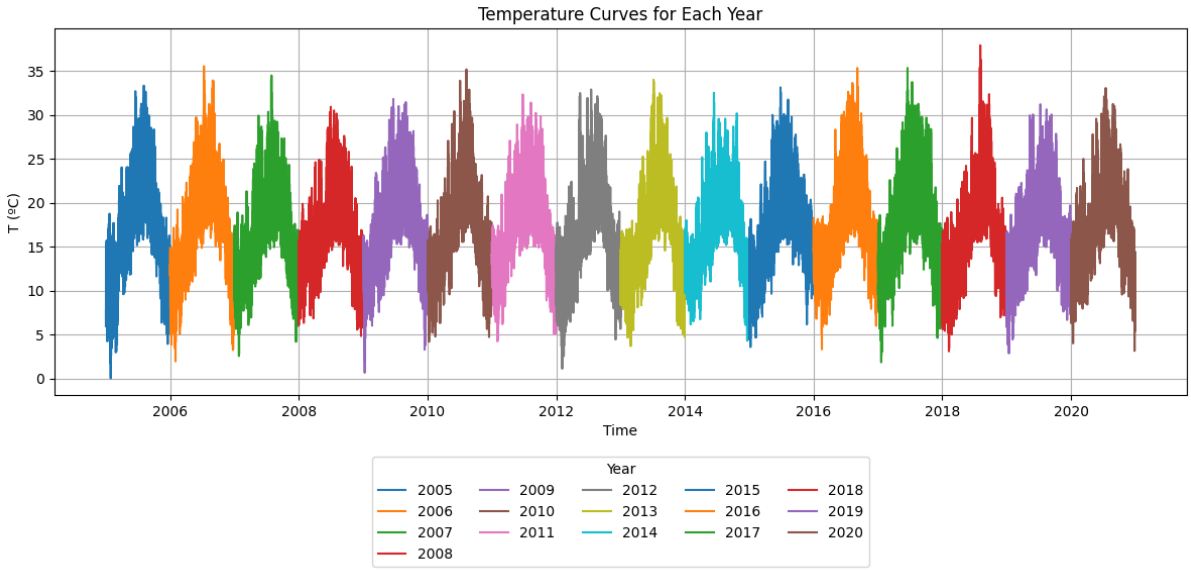


Figure 3.9: Yearly Temperature in Lagos Site

The Typical Meteorological Year (TMY) represents a synthesized dataset compiled to characterize the long-term climatic conditions of a location. In this case, it is possible to visualize what typical values of temperature and solar irradiance are expected for each of the sites chosen in figures 3.10, 3.11 and 3.12, respectively.

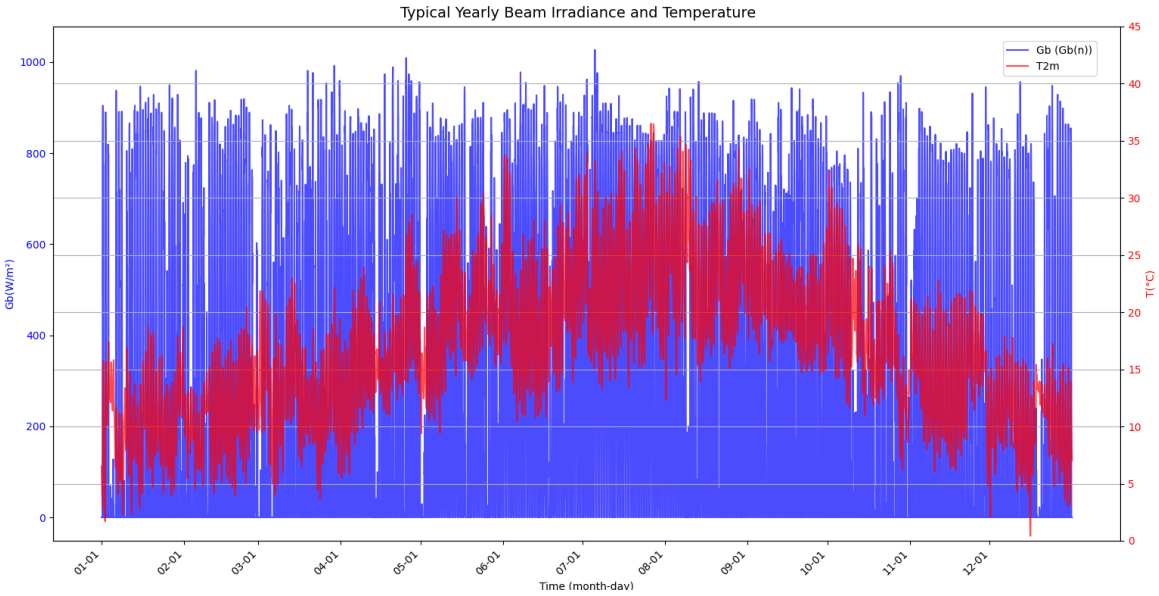


Figure 3.10: Typical Meteorological Year in Silves Site

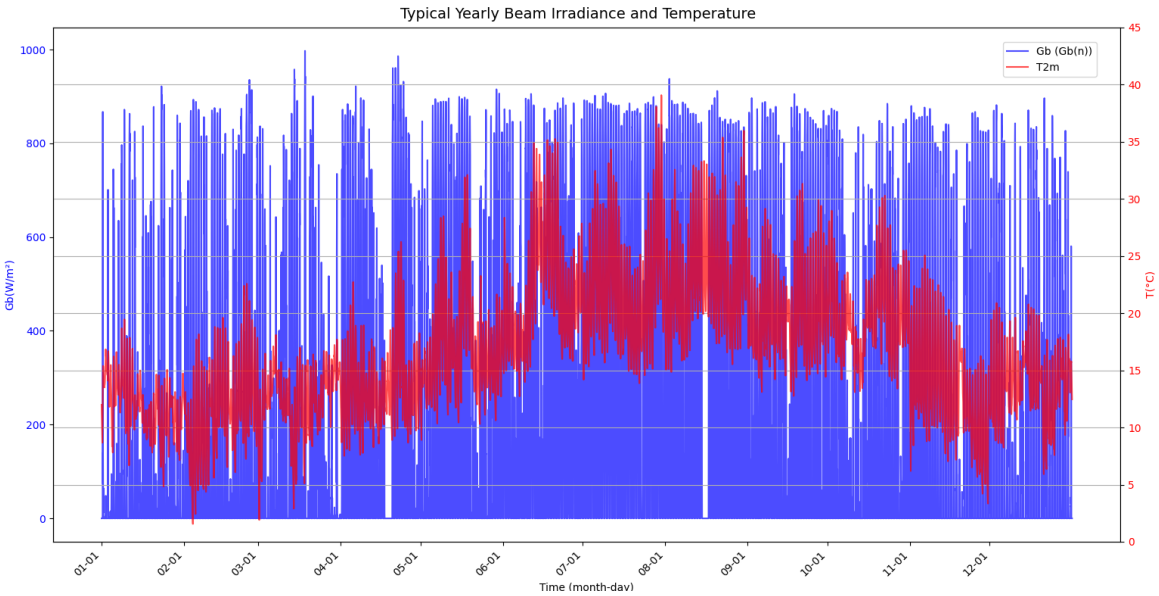


Figure 3.11: Typical Meteorological Year in Odemira Site

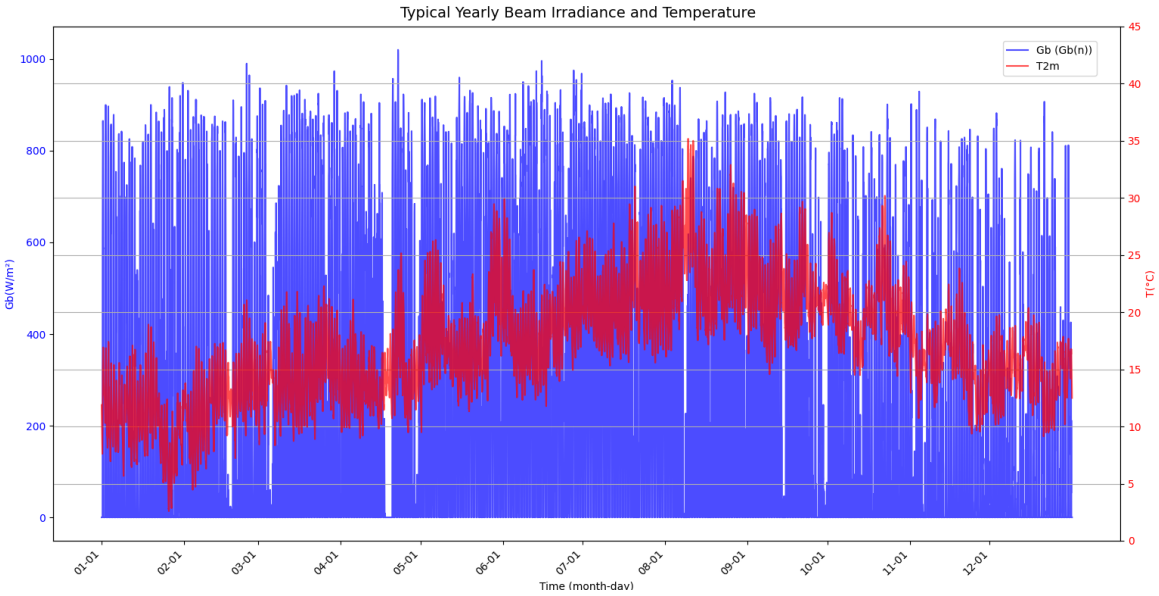


Figure 3.12: Typical Meteorological Year in Lagos Site

PVGIS constructs the Typical Meteorological Year (TMY) by applying a standardised statistical procedure similar to the Sandia/ISO method, in which monthly candidate periods are selected from the multi-year archive (2005–2020 for this study). For each month, PVGIS evaluates the long-term distribution of key variables, global irradiance, diffuse fraction, ambient temperature, and wind speed—and identifies the month whose cumulative distribution function (CDF) most closely matches the multi-year climatology. The twelve selected representative months are then concatenated to form a synthetic year that preserves the long-term statistical behaviour of the site while providing a continuous hourly dataset suitable for energy system modelling. The resulting TMY therefore captures typical meteorological conditions rather than extremes, and is used as input for the PV performance simulations in Section 3.5.

3.4 Technology Selection: Evaluating Performance in AgriPV Systems

The integration of photovoltaic technologies with agriculture in AgriPV systems requires selection of both the PV technology and crop types to optimize performance, hence this chapter aims to highlight how specific PV products and their characteristics influence energy generation and crop growth by evaluating the performance of diverse PV technologies. This study will focus on thin-film solar panels, organic photovoltaic (OPV) panels, and monocrystalline PV modules and for each technology select specifc products: for thin-film, the Onyx Colored Photovoltaic Glass, for OPV, the Heliatek HeliaSol, and for monocrystalline, the WAAREE WFLW-520, these products were chosen due to their diverse capabilities

suitable for various AgriPV scenarios, but in particular for greenhouses.

The Onyx Colored Photovoltaic Glass, is lightweight, flexible, and available in semi-transparent configurations, this product offers customizable colors and transparency levels allowing sufficient light penetration for crop growth while generating electricity, this makes it ideal for greenhouse applications [54]. The Heliatek HeliaSol OPV panels represent a solution which is ultra-lightweight, minimizing structural demands, flexible, and manufactured using organic materials. Furthermore, these panels are semi-transparent and can be easily integrated into greenhouse structures, even if their efficiency is lower than conventional PV technologies [55]. The WAAREE WFLW-520 monocrystalline PV module represents a solution designed for lightweight and flexible applications, due to its unique design it conforms to various roof shapes and sizes making it well-suited for lightweight greenhouse structures, it also eliminates the need for mounting hardware and avoids roof penetration, simplifying installation and reducing associated costs, and delivers a good performance in low light and low sun angle conditions [56].

3.5 Crop Selection: Agronomic Characteristics and Portuguese Context

Avocado was selected due to its regional prevalence in the Algarve and agronomic compatibility with partial shade. Orchard studies under shade netting report moderated canopy temperatures, improved water-use efficiency, and maintained or improved marketable yield of 'Hass' under hot conditions, provided PAR reductions are controlled (typical nettings reduce PAR 10–30% depending on colour and mesh). From a light-response standpoint, young 'Hass' leaves tend to approach photosynthetic saturation around 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD, while mature canopies can operate effectively at higher levels (reports up to 1,100 $\mu mol \cdot m^{-2} \cdot s^{-1}$), which means moderate shade ($\approx$30–60%) can curb heat and water stress without compromising assimilation when overall PAR remains adequate. In semi-arid heat events, shading lowered heat-damage risk and mitigated midday photosynthesis depression, conditions analogous to the diffuse-light environment created by semi-transparent PV in greenhouses. Accordingly, this thesis applies small yield penalties only to higher-opacity roofs and no penalty to low-opacity integrations, as reflected in the LER computation. Another reason for this selection is that avocados are already a proven crop in solar greenhouses in other countries, showcasing their compatibility with this type of AgriPV system [57–63].

The avocado crop was selected for this study due to its growing economic relevance and increasing environmental impact in southern Portugal. Over the last decade, avocado plantations have expanded significantly in regions such as Algarve and Alentejo, driven by high market demand and favourable temperatures. However, avocados are also known for their intensive water requirements throughout the growing season, making them particularly vulnerable to the rising water scarcity affecting the Mediter-

ranean climate. This combination of high economic value and high resource consumption makes avocado production a critical candidate for sustainability-oriented interventions.

Greenhouse-integrated AgriPV systems offer a potential pathway to reduce the environmental footprint of water-intensive crops by enabling controlled microclimates, reducing evapotranspiration, and allowing more efficient irrigation practices. Moreover, the partial shading provided by semi-transparent PV technologies may help mitigate heat stress during summer peaks, which is increasingly relevant under ongoing climate change. Evaluating avocado production under AgriPV conditions is therefore representative of both the agronomic challenges and the sustainability opportunities faced by Mediterranean horticulture. For these reasons, avocado serves as an appropriate and meaningful case study for assessing the feasibility and benefits of greenhouse-integrated AgriPV systems in southern Portugal.

Taken together, these agronomic and regional considerations justify the selection of avocado as the reference crop for this study, ensuring that the results are both scientifically grounded and directly applicable to the sustainability challenges facing southern Portuguese horticulture.

3.6 Theoretical Power Output and Simulation Analysis

This section presents the theoretical evaluation of photovoltaic (PV) performance for the selected AgriPV configurations. The analysis was conducted using the 1D3P model, which enables the estimation of electrical behaviour under varying irradiance and temperature conditions, the model was applied to three photovoltaic technologies to determine their theoretical performance and suitability for integration in greenhouse environments.

Climatic data were obtained from the Photovoltaic Geographical Information System (PVGIS), including hourly values of solar irradiance, ambient temperature, and system losses specific to each study site (Silves, Lagos, and Odemira). These datasets were used as input parameters for the 1D3P model to calculate the main electrical characteristics of each module, the model also incorporated temperature coefficients to evaluate the impact of thermal variations on module efficiency and power output.

To complement the theoretical analysis, Autodesk Revit was used to illustrate and visualize the greenhouse design, this step was not used for quantitative simulation but to generate accurate three-dimensional representations showing roof coverage. These visualizations provide contextual support for understanding how PV integration affects both the structure and light environment available to crops.

3.7 Model assumptions and simplifications

For this feasibility study, PV production is computed exclusively with a standard single-diode, three-parameter (1D3P) electrical model, and no additional greenhouse-specific losses or corrections are

applied. The model takes plane-of-array irradiance and ambient temperature as inputs and derives I–V and power from the module's STC parameters using the usual temperature coefficients; 3D self-shading from rafters or seasonal sun-path geometry, glazing/optical effects (reflection, absorption, angle-of-incidence), spectral shifts in the incident light, soiling, and any other balance-of-system loss terms are not modelled. Accordingly, thermal coupling between the greenhouse microclimate and module temperature is not explicitly simulated beyond standard temperature coefficients. These simplifications are standard for feasibility-level assessments and keep the analysis tractable. All results reported here are based on these stated assumptions and no calculation beyond them has been performed.

3.8 Shading Penalty Values for Avocado Production

To incorporate the agricultural component into the Land Equivalent Ratio (LER), this study employs a simplified shading–yield model in which avocado production is reduced as a function of the photovoltaic (PV) coverage installed on the south-facing roof pitch of the greenhouse. The goal is to represent how increasing shading from different PV technologies affects the availability of photosynthetically active radiation (PAR) reaching the canopy.

Table 3.1: Shading Penalties

		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Penalty for avocado production	Mono	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0
	OPV	0.96	0.864	0.768	0.672	0.576	0.48	0.384	0.288	0.192	0
	Thin-film	0.98	0.882	0.784	0.686	0.588	0.49	0.392	0.294	0.196	0

Table 3.1 summarises the penalty factors applied to the baseline avocado yield for each technology across coverage levels ranging from 10% to 100%.

These penalty factors represent the fraction of baseline yield retained under each shading scenario (e.g. a penalty factor of 0.8 corresponds to a 20% reduction in avocado yield). Their magnitude and evolution with coverage were informed by published studies on avocado and other perennial crops grown under shade nets and greenhouse shading screens, where increased shading is consistently associated with proportional declines in yield once moderate thresholds are exceeded [64–71].

A key simplification in this model is that only the south-facing roof pitch is assumed to be partially or fully covered by PV modules. The north roof pitch and greenhouse side walls are assumed to remain fully transparent and are not modelled explicitly. As a consequence, the penalty factors in Table 3.1

should be interpreted as **conservative, upper-bound estimates** of the shading impact on avocado productivity. In practice, additional daylight entering through the north roof pitch, vertical facades, and diffuse skylight would partially compenyield reductions would likely be lower than those represented here.

The 100% coverage scenario therefore corresponds to an extreme high-shading condition applied to the south roof pitch only, rather than a literal situation where all greenhouse glazing surfaces are fully opaque. This parametrisation is not intended to reproduce the full optical behaviour of a greenhouse but provides a tractable, internally consistent method for comparing technologies and coverage levels within a feasibility-level study.

Despite these simplifications, the relative differences between PV technologies notably the softer penalties associated with more transparent and diffuse OPV and thin-film modules are expected to remain qualitatively robust. Consequently, the resulting LER values reported in Chapter 4 should be interpreted as conservative estimates of the combined agricultural and photovoltaic land-use efficiency achievable with greenhouse-integrated AgriPV systems in the selected regions.

3.9 Technological and Financial Evaluation

This section will assess the financial and technological viability of solar greenhouses using various technologies, such as thin-film, organic photovoltaic (OPV), and monocrystalline PV modules.

From a technological standpoint, thin-film panels like Onyx Coloured Photovoltaic Glass are lightweight, flexible, and semi-transparent, providing changeable transparency for crop development while producing power, making them suitable for greenhouses. OPV panels, such as Heliatek HeliaSol, are ultra-lightweight, flexible, and semi-transparent, but have lesser efficiency than standard PV technologies, whereas monocrystalline PV modules, such as WAAREE WFLW-520, are very efficient and robust, functioning well even in low-light circumstances.

Economic feasibility is assessed using metrics like the Discount Rate (DR), which reflects the cost of capital influenced by factors like inflation and equity risk premiums, the Net Present Value (NPV), which compares inflows and outflows over a project's lifetime to indicate profitability, the Payback Period (PP), which determines how quickly the initial investment is recovered and favors shorter durations, the Levelized Cost of Energy (LCOE), which represents the cost per unit of generated energy, and the Return on Investment (ROI), which compares net benefits to the total investment and highlights financial efficiency, are some of the metrics used to evaluate economic feasibility.

The technological evaluation is expected to verify the possibility of applying thin film, OPV and monocrystalline PV modules in greenhouse integrated AgriPV systems and each technology will be rated based on the scenario. This is because monocrystalline panels are most efficient, thin film and

OPV panels should also be beneficial for flexibility and light weight integration, respectively. The financial analysis is expected to show some economic feasibility with positive Net Present Value (NPV) and Levelized Cost of Energy (LCOE) in some cases, but with the drawback of high initial costs.

4

Results

Contents

4.1 Introduction 33
4.2 Energy Performance Results 33
4.3 Economic Analysis 39
4.4 Environmental Impact 46
4.5 Comparative Discussion 47

4.1 Introduction

This chapter includes results of technical and economical evaluation of greenhouse-integrated AgriPV systems for the three case study sites, Lagos, Odemira, and Silves. For a comparative study of energy production potential and economical viability of three photovoltaic technologies, monocrystalline silicon, organic photovoltaic (OPV), and thin-film module, it was evaluated for each of their technologies. Those results are divided into two main parts, the first one deals with the energy performance, i.e., its maximum and average powers output, and its seasonal and annual behavior for each technology assuming its behaviour under normal meteorological conditions, the other one deals with its economical analysis, evaluating each technology based on economical indicators like Net Present Value (NPV), Payback Period (PP), Return on Investment (ROI), and Levelized Cost of Energy (LCOE), both by considering degradation and neglecting degradation. By bringing together these two viewpoints, the chapter seeks to establish which of these technologies and locations holds the greatest potential for a compromise between energy harvest, cost-effectiveness, and integration into greenhouse missions.

4.2 Energy Performance Results

The energy performance of the selected photovoltaic technologies was evaluated for the sites of Lagos, Odemira, and Silves using typical meteorological year (TMY) data. Both maximum power output and average power values were calculated, and time-series simulations were conducted to illustrate the seasonal and daily variations in PV performance.

4.2.1 Maximum and Average Power Values

Table 4.1 presents the maximum power output recorded for each technology and location, while Table 4.2 shows the corresponding average power values. Because the three photovoltaic modules havedifferent physical areas, all results were normalised per square metre (W/m^2) to allow a fair comparison between technologies. This adjustment ensures that the performance assessment reflects intrinsic conversion efficiency rather than module size.

Monocrystalline modules consistently achieved the highest power densities across all locations, with maximum values ranging from 185 to 194 W/m^2 and average outputs around 36–39 W/m^2. OPV modules exhibited intermediate performance, reaching maximum power densities between 75 and 78 W/m^2 and average values of 14–16 W/m^2. Thin-film modules showed the lowest performance, with maximum outputs of 43–45 W/m^2 and average values close to 8–9 W/m^2.

The differences among the three locations follow expectations based on their solar resource. Lagos and Silves recorded slightly higher maximum and average values compared to Odemira, reflecting their

more favourable irradiance conditions.

Table 4.1: Maximum Power

	Max Power Values (W/m^2)		
	Lagos	Odemira	Silves
Monocristalina	193.70	185.33	189.37
OPV	78.39	75.03	76.68
Thin-film	45.32	43.38	44.33

Table 4.2: Average Power

	Average Power Values (W/m^2)		
	Lagos	Odemira	Silves
Monocristalina	38.68	36.05	38.81
OPV	15.72	14.65	15.77
Thin-film	9.09	8.47	9.12

4.2.2 Yearly Performance Trends

Figures 4.1,4.2, and 4.3 show the typical yearly power density profiles for Lagos, Odemira, and Silves, respectively. The simulations exhibit a clear seasonal pattern characteristic of southern Portugal, with peak production occurring during the summer months (June–August) and minimum output during the winter period (December–January). The curves also reflect the expected daily progression of solar irradiance, with higher midday irradiance leading to pronounced power peaks.

Throughout the year, monocrystalline modules delivered the highest normalised power output, reaching summer peaks of approximately 180–195 W/m^2 depending on the location. OPV modules followed an intermediate profile, with summer peaks between 70 and 80 W/m^2, while thin-film modules consistently remained the lowest, peaking near 40–45 W/m^2. Despite these differences in magnitude, all three technologies exhibit similar seasonal behaviour, with outputs closely tracking annual irradiance trends.

These results confirm that, even after normalising for module area, monocrystalline technology remains the most performant across all three sites, while OPV and thin-film modules produce substantially lower power densities but with comparatively stable behaviour throughout the year.

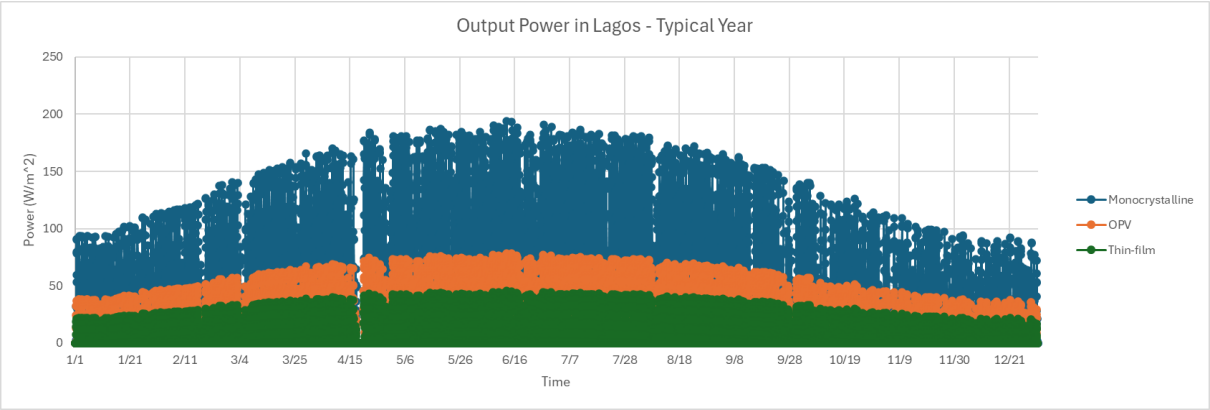


Figure 4.1: Typical Meteorological year in Lagos

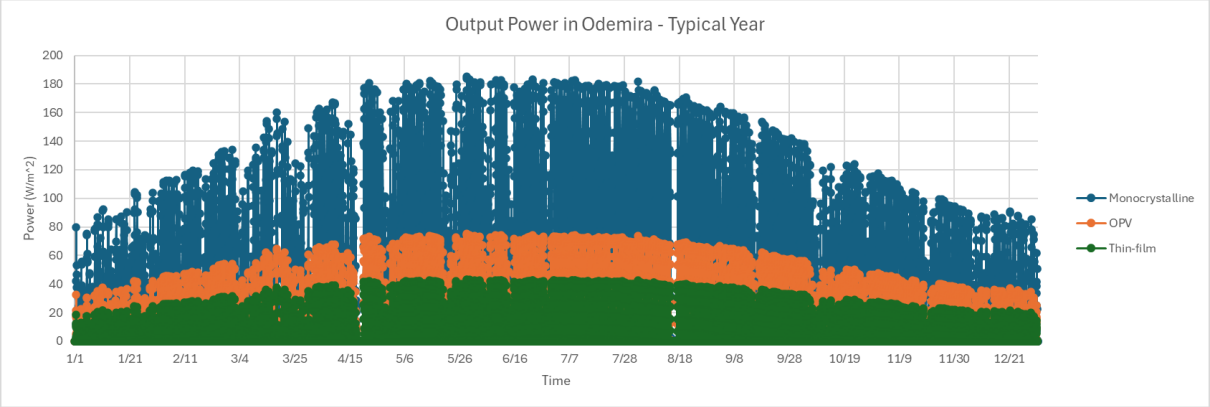


Figure 4.2: Typical Meteorological year in Odemira

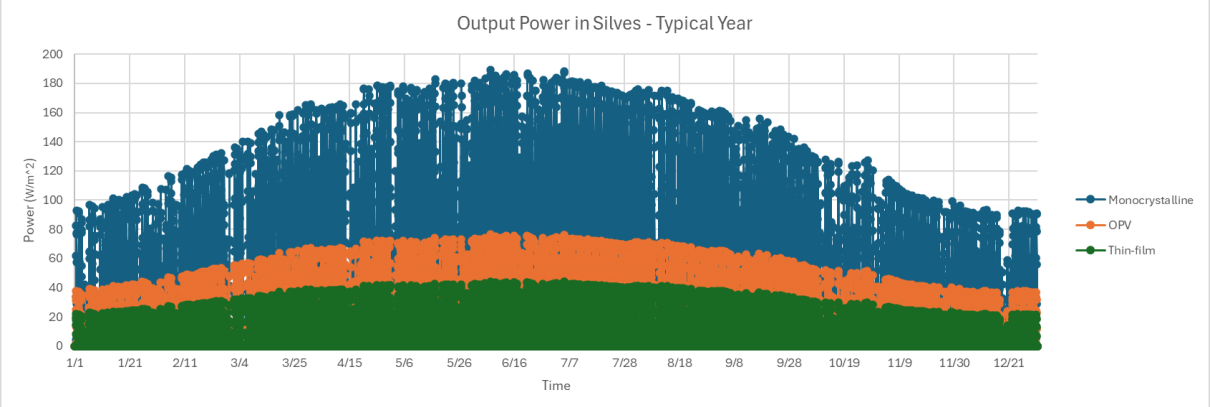


Figure 4.3: Typical Meteorological year in Silves

4.2.3 Monthly Comparisons

To highlight the effect of seasonal variation, Figures 4.4 to 4.9 present detailed daily power outputs for January (representing winter) and July (representing summer) for each site. January consistently showed the lowest power production across all three locations, while July recorded the highest. The normalised January profiles show that peak power densities for monocrystalline modules rarely exceed 90–110 W/m^2, reflecting both reduced winter irradiance and shorter daylight hours. OPV and thin-film modules follow the same pattern but at lower magnitudes, with typical winter peaks of 30–40 W/m^2 for OPV and 15–25 W/m^2 for thin-film.

In contrast, July displays regular and symmetrical daily power curves under clear-sky conditions, with monocrystalline modules reaching peak power densities between 160 and 190 W/m^2. OPV modules typically reach 50–70 W/m^2, while thin-film modules peak around 30–40 W/m^2. These relative differences reflect the inherent efficiency characteristics of each technology, with monocrystalline consistently outperforming the two thin-film-based solutions.

Despite the magnitude differences, the comparative behaviour between technologies remains unchanged: all technologies improve significantly from winter to summer, and the relative ordering of performance (mono $>$ OPV $>$ thin-film) is maintained across all sites [72, 73].

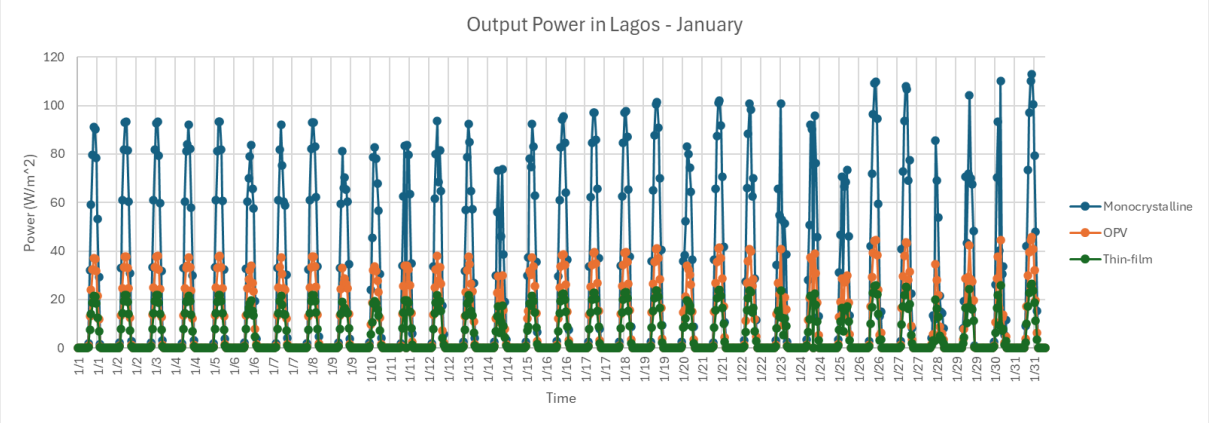


Figure 4.4: Worst month for energy production in Lagos

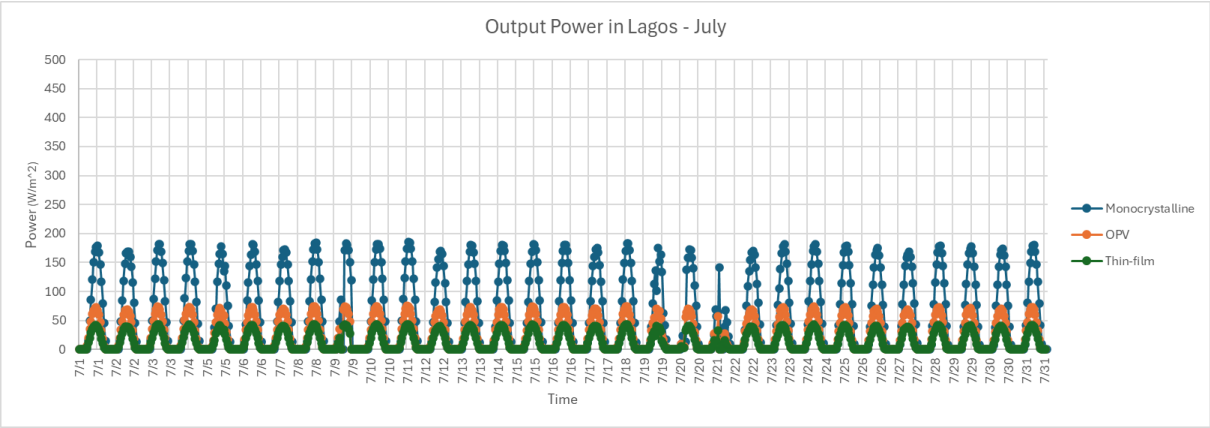


Figure 4.5: Best month for energy production in Lagos

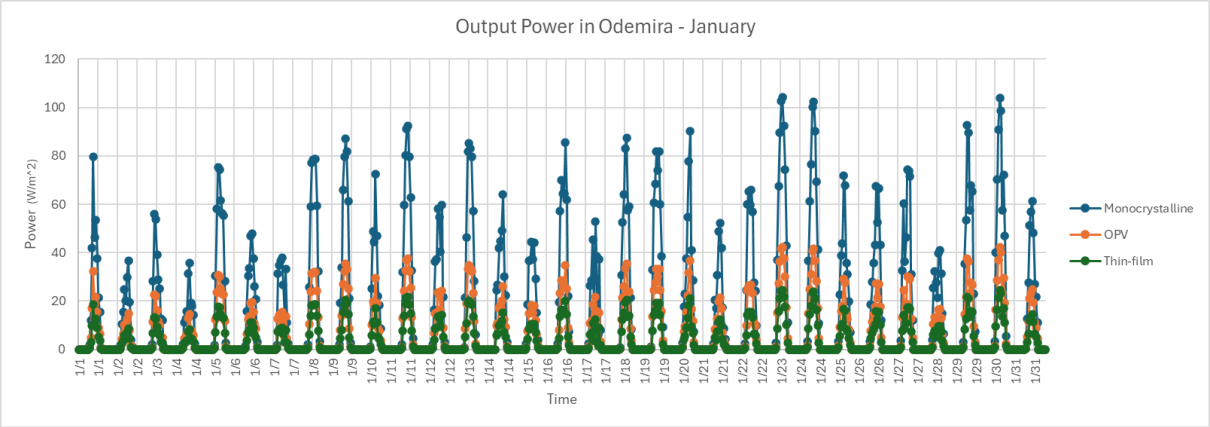


Figure 4.6: Worst month for energy production in Odemira

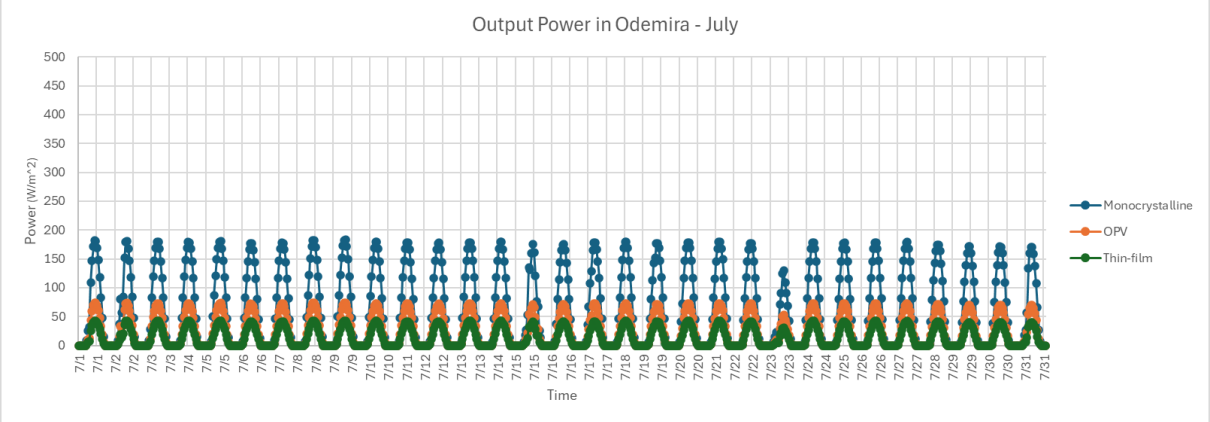


Figure 4.7: Best month for energy production in Odemira

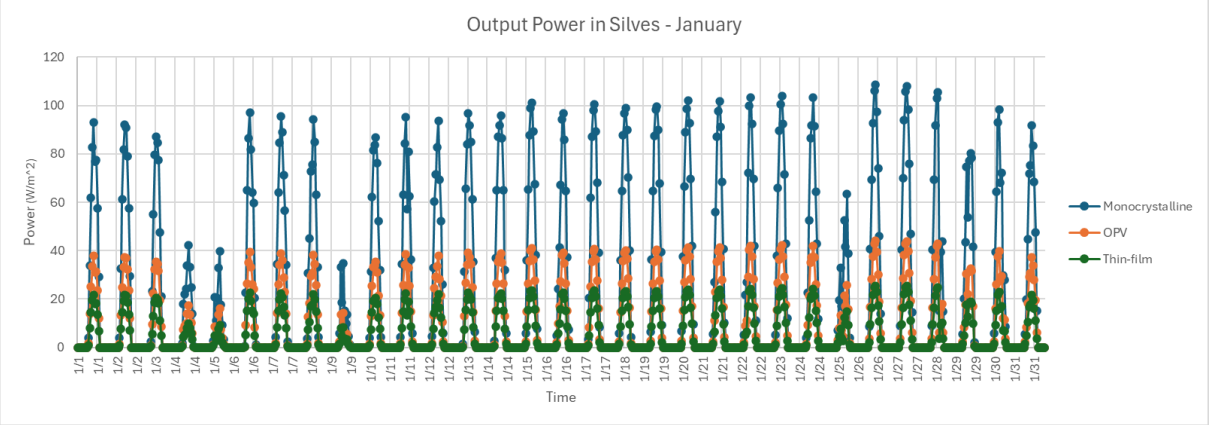


Figure 4.8: Worst month for energy production in Silves

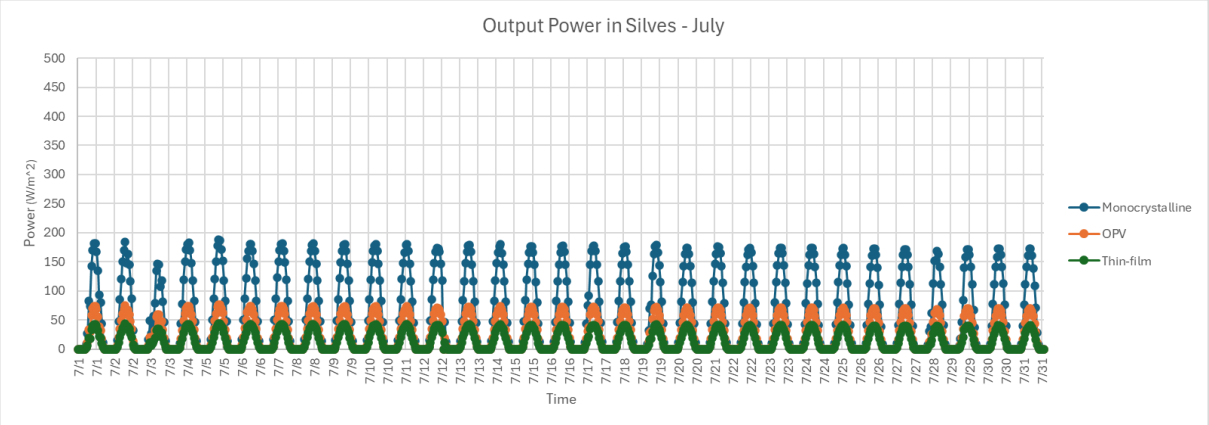


Figure 4.9: Best month for energy production in Silves

4.2.4 External Validation

To validate the simulated energy behaviour at data level, the maxima, averages and seasonal patterns were benchmarked against module nameplate ratings and published performance ranges for comparable locations and agrivoltaic configurations. The monocrystalline traces exhibit instantaneous summer peaks exceeding 500 W per module, given the selected module's STC rating of 520 Wp, peak values of this order under high irradiance and favourable cell temperature are consistent with datasheet expectations. The reported average power of approximately 102 W per monocrystalline module implies a capacity factor of $\approx$ 102/520 = 0.19 (19%), which corresponds to a specific yield of about 0.19 $\times$ 8 760 $\approx$ 1 682 kWh/kWp·yr. This magnitude lies within independent benchmarks for southern Portugal and Mediterranean fixed-tilt crystalline PV (typically $\tilde{1}$ 450–1 800 kWh/kWp·yr) and is compatible with agrivoltaic pilot results at similar latitudes in central Europe ($\approx$ 1 200–1 300 kWh/kWp·yr), noting the higher solar resource in the Algarve/Alentejo. The simulated seasonal envelopes and diurnal bell-

shaped profiles (summer maxima, winter minima) also align with empirical records from agrivoltaic trials and greenhouse-integrated PV studies [28, 74, 75].

For thin-film and OPV, the substantially lower average powers (on the order of 6–7 W and 12–14 W per unit, respectively) are consistent with the lower conversion efficiencies and partial-transparency choices inherent to greenhouse integration. Published greenhouse-PV experiments with semi-transparent glazing or films typically report annual electricity in the range of a few to tens of kWh per square metre (depending on coverage and transmittance), prioritising PAR preservation for crops over absolute electrical yield, this aligns with the lower absolute outputs obtained here for thin-film and OPV relative to monocrystalline. Overall, the quantitative agreement of peak and average power levels, the implied capacity factors/specific yields, and the seasonal/diurnal shapes supports the plausibility of the simulated energy results [76, 77].

4.3 Economic Analysis

The economic feasibility of the three photovoltaic technologies was evaluated for Lagos, Odemira, and Silves using the indicators Net Present Value (NPV), Payback Period (PP), Return on Investment (ROI), Levelized Cost of Energy (LCOE), and Land Equivalent Ratio (LER). The analysis was conducted both without and with degradation, to assess how the long-term decline in module performance affects profitability and land-use efficiency. The Discout Rate (DR) was assumed at 7.62% [78–80].

4.3.1 Profit Contribution of PV and Avocado Production

Before analysing the full economic indicators, it is useful to briefly compare the relative contribution of photovoltaic production and avocado cultivation to the overall yearly profit.

Table 4.3: Avocato vs PV Profit

	Profit from Avocato vs PV (€)					
	Lagos		Odemira		Silves	
	Avocato	PV	Avocato	PV	Avocato	PV
Monocristaline	4400	3780	4400	5264	4400	2633
OPV	4752	3940	4752	5424	4752	2793
Thin-film	4851	3700	4851	5184	4851	2553

Table 4.3 summarises the annual profits associated with each component for the three sites. Across all locations, avocado production provides the largest economic contribution, with annual profits ranging

from approximately €4,400 to €4,851 depending on site conditions. PV revenues, although substantial, remain consistently lower, varying between €2,533 and €5,264 according to the technology and location.

This imbalance reflects the dual nature of greenhouse-integrated AgriPV systems: while PV generation adds an additional revenue stream, agricultural production continues to be the primary economic driver. Consequently, the Land Equivalent Ratio (LER) is strongly influenced by the crop component, meaning that even moderate reductions in avocado yield can outweigh the benefits of higher PV energy production. This interdependence highlights the importance of selecting PV technologies that minimise shading impacts, such as OPV or thin-film—when maximising land-use efficiency is a priority.

4.3.2 Economic Summary Without Degradation

Table 4.4 shows the results for all technologies in the three sites without considering degradation.

Table 4.4: Economic summary without degradation

	Lagos			Odemira			Silves		
	Monocristalina	OPV	Thin-film	Monocristalina	OPV	Thin-film	Monocristalina	OPV	Thin-film
DR	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%
NPV(€)	44,940	-231,576	-257600.31	46,483	-229,960	-255,985	44,060	-232,384	-258,408
PP(years)	9.70	+20	+20	9.71	+20	+20	9.70	+20	+20
LCOE	48.07	279.66	483.71	48.07	279.66	483.71	48.07	279.66	483.71
ROI	1.02	-2.30	-2.55	1.06	-2.28	-2.54	1.00	-2.31	-2.56
LER	1.00	1.06	1.08	1.00	1.06	1.08	1.00	1.06	1.08

The results show that monocrystalline technology yields positive NPVs in all three locations, ranging from €44,060 to €46,483, indicating that the systems can recover their initial investment under the assumed discount rate of 7.62%. The Payback Period (PP) is approximately 9.7 years, which is within an acceptable range for small-scale PV systems integrated into greenhouses.

In contrast, both OPV and thin-film technologies exhibit strongly negative NPVs (–€230,000 to –€258,000) and payback periods exceeding 20 years, confirming their economic infeasibility under current cost assumptions. Furthermore, their ROI values remain negative (–2.3 to –2.55), indicating substantial losses compared with the monocrystalline systems.

Among all locations, Odemira shows the slightly highest NPV and ROI for monocrystalline modules, making it the most promising site under non-degradation conditions. Lagos and Silves follow closely, with only marginally lower profitability.

Regarding land-use performance, the LER values are above 1.0 for all technologies (1.00–1.08), confirming that AgriPV installations make more efficient use of land than conventional separate agriculture and PV systems. Even though the energy contribution of OPV and thin-film modules is modest, their transparency allows partial light transmission to crops, improving overall land productivity.

4.3.3 Economic Summary With Degradation

Table 4.5 shows that the economic viability decreases when degradation is included.

Table 4.5: Economic summary with degradation

	Lagos			Odemira			Silves		
	Monocristalina	OPV	Thin-film	Monocristalina	OPV	Thin-film	Monocristalina	OPV	Thin-film
DR	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%	7.62%
NPV(€)	34,543	-247,722	-261675.25	36,087	-246,107	-260,060	33,663	-248,530	-262,483
PP(years)	10.76	+20	+20	10.77	+20	+20	10.76	+20	+20
LCOE	48.46	282.48	498.77	48.46	282.48	498.77	48.46	282.48	498.77
ROI	0.71	-2.52	-2.60	0.75	-2.51	-2.59	0.69	-2.53	-2.61
LER	1.00	1.06	1.08	1.00	1.06	1.08	1.00	1.06	1.08

The inclusion of degradation leads to an average 20–25% reduction in NPV for monocrystalline modules. Despite this, all three sites maintain positive NPVs, indicating that degradation alone does not compromise system viability. The payback period increases slightly from around 9.7 years to approximately 11 years in Lagos and Silves while Odemira maintains the lowest payback time (9.7 years).

In contrast, OPV and thin-film remain unprofitable in all locations, with their LCOE values remaining more than five times higher than those of monocrystalline modules, NPVs near –€250,000 and negative ROIs below –2.5. Despite this, their LER values remain slightly higher (1.06–1.08) due to their partial light transmission, which supports crop photosynthesis beneath the modules. This means that while they are not financially feasible yet, they still contribute positively to land-use optimization, which could become relevant if future cost reductions occur or if policies start valuing co-benefits of AgriPV.

Overall, when degradation is included, monocrystalline PV continues to be the only economically viable tech nology, offering both financial sustainability and efficient land use (LER = 1.0). [81]

4.3.4 Sensitivity to Roof Coverage

To further evaluate how the system scale influences financial performance, a sensitivity analysis was conducted by varying the percentage of greenhouse roof area covered with PV modules from 10% to 100%. For this part of the analysis, module degradation was not considered, and penalties to avocado production were estimated to provide a more realistic approximation of the overall economic impact of partial shading on crop productivity. Figures 4.10 to 4.18 illustrate the variation of NPV, ROI, and Payback Period (PP) with roof coverage.

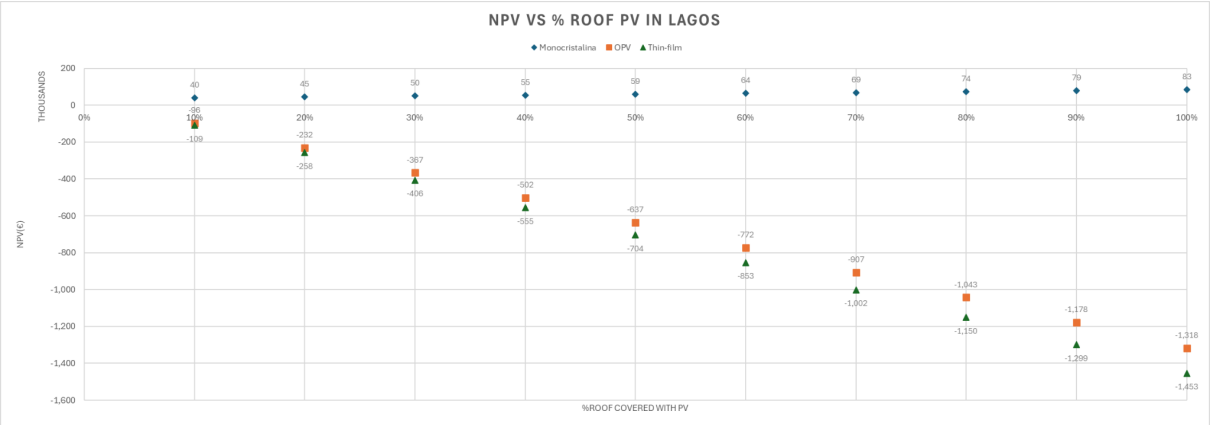


Figure 4.10: Net Present Value (NPV) vs % Roof Coverage in Lagos

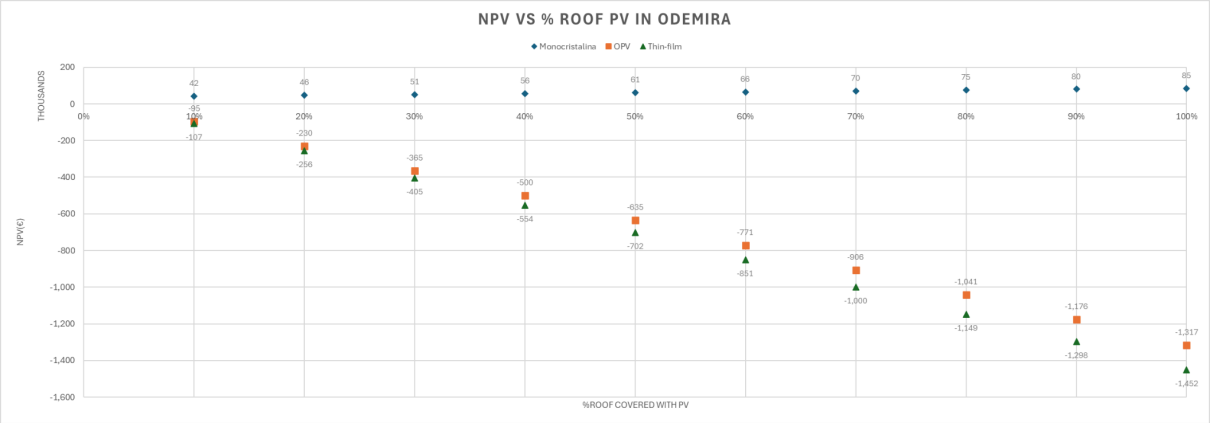


Figure 4.11: Net Present Value (NPV) vs % Roof Coverage in Odemira

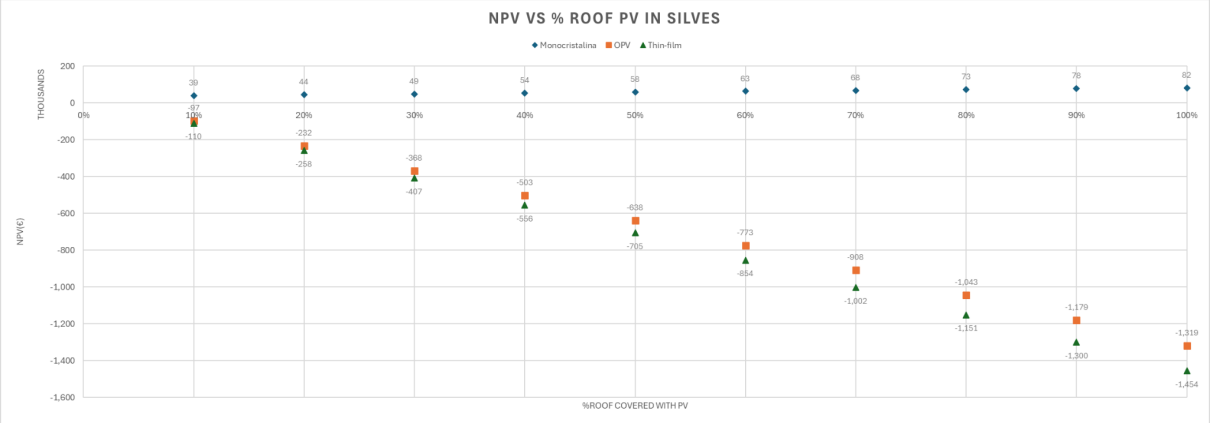


Figure 4.12: Net Present Value (NPV) vs % Roof Coverage in Silves

The NPV trends for Lagos, Odemira, and Silves (Figures 4.10 to 4.12) show that the monocrystalline configuration achieves a positive NPV across all coverage levels, indicating that system expansion pro-

portionally increases project value. In all three sites, NPV rises almost linearly with roof coverage from approximately €40 000 at 10% coverage to €80 000 at 100% confirming scalability without major efficiency losses.

Conversely, both OPV and thin-film exhibit negative NPVs across the full range, decreasing further as roof coverage increases. For example, at 100% coverage, their NPVs drop below –€1.3 million, reflecting high investment cost relative to output.

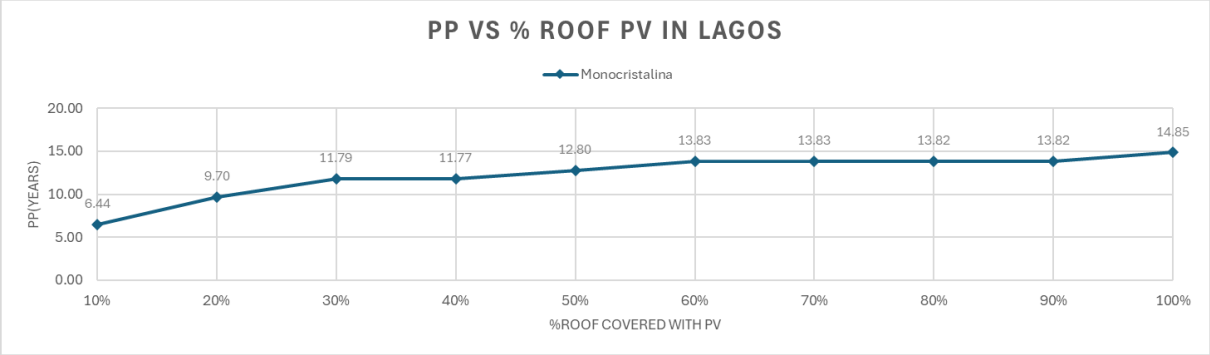


Figure 4.13: Payback Period (PP) vs % Roof Coverage in Lagos

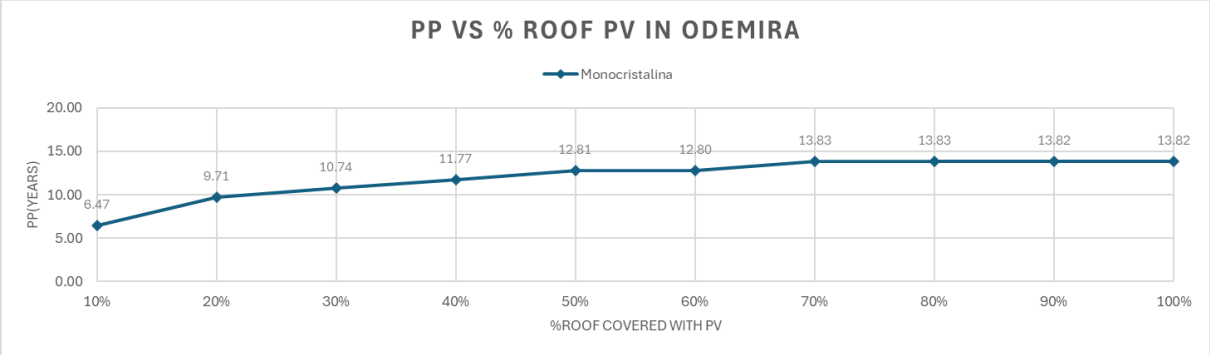


Figure 4.14: Payback Period (PP) vs % Roof Coverage in Odemira

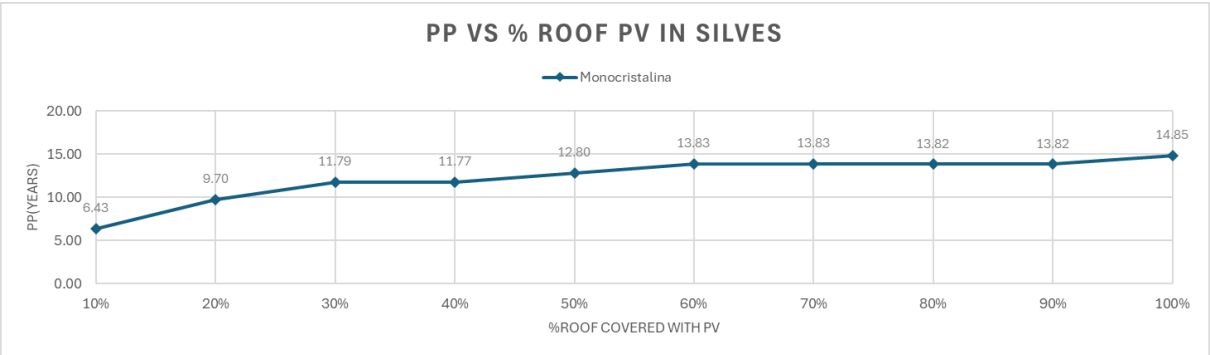


Figure 4.15: Payback Period (PP) vs % Roof Coverage in Silves

Figures 4.13 to 4.15 display the payback period for monocrystalline PV in the three locations. The results show that PP increases slightly with coverage, from around 6.4 years at 10% roof coverage to approximately 14.8 years at 100%, mainly because larger installations require proportionally higher capital costs while revenue growth remains limited by available solar resource and greenhouse consumption. As can be observed, this trend is consistent across all sites, with only minor variations between Lagos, Odemira, and Silves.

The OPV and thin-film technologies are not represented in the graphs, since their payback periods exceed the proposed 20-year project lifetime, rendering them economically unfeasible within the analysis horizon.

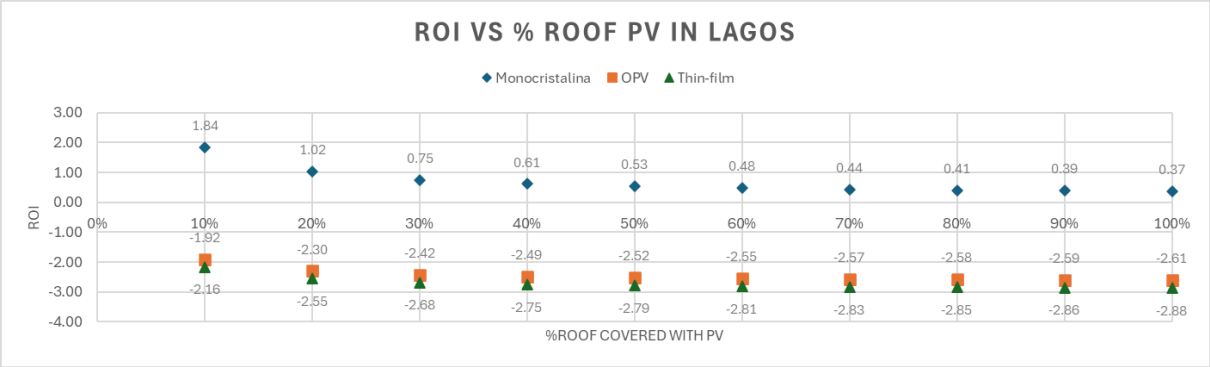


Figure 4.16: Return on Investment (ROI) vs % Roof Coverage in Lagos

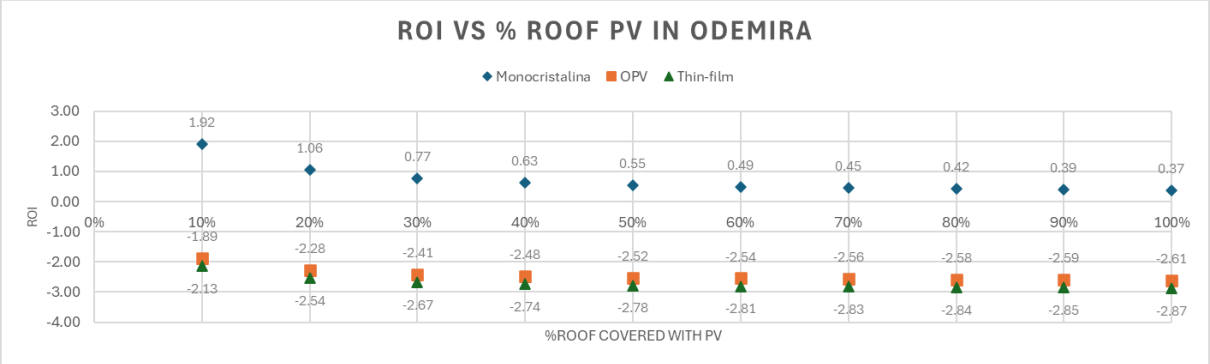


Figure 4.17: Return on Investment (ROI) vs % Roof Coverage in Odemira

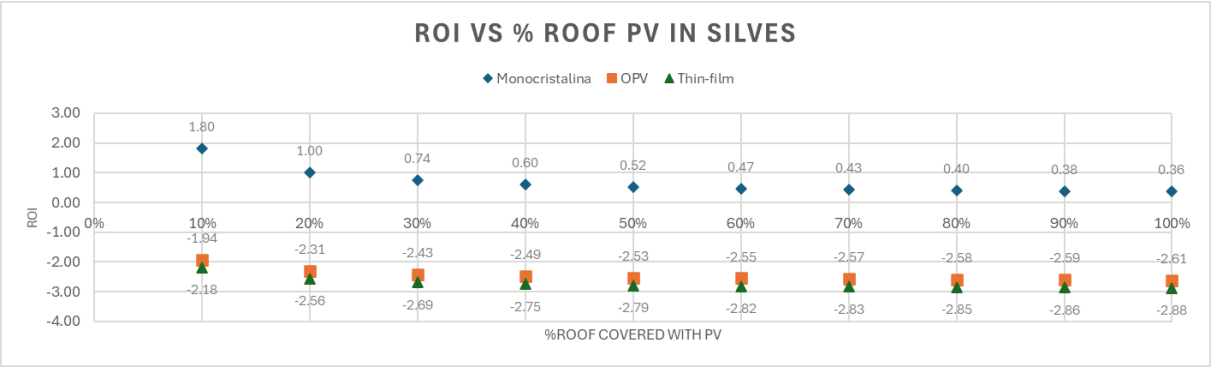


Figure 4.18: Return on Investment (ROI) vs % Roof Coverage in Silves

Figures 4.16 to 4.18 present ROI as a function of roof coverage, for monocrystalline PV, ROI decreases with increasing coverage from approximately 1.9 at 10% to 0.37 at 100% indicating that smaller systems yield proportionally higher returns on invested capital. This suggests that a partial-coverage configuration (10–20%) could represent the optimal balance between cost and return.

In contrast, OPV and thin-film remain negative for all coverage levels (around –2.3 to –2.8), confirming that these technologies are not economically competitive under current market conditions. Their higher material costs and lower conversion efficiencies continue to outweigh any land-use benefits.

4.3.5 External Validation

The economic indicators obtained for the three technologies were benchmarked against peer-reviewed studies and authoritative cost databases for Portugal and Europe. First, payback times reported for agrivoltaics in Portugal provide a direct comparison: recent studies show that Agripv layouts under Portuguese resource and tariff assumptions can achieve paybacks $\leq$ 5 years, with spaced-row designs performing slightly better than elevated structures, this corroborates short-payback findings where specific yield is high and CAPEX is controlled [10].

Real-world deployments support this range,in Germany flagship Agripv pilots at Lake Constance/Heggelbach, field monitoring demonstrated technical viability and positive farm co-benefits. Techno-economic analysis of the elevated layout reported an Agripv LCOE $\approx$ 0.0828 €/kWh (82.8 €/MWh), about 38 % above ground-mount PV, quantifying the structural premium typical of elevated designs [82, 83].

The monocrystalline LCOE of $\approx$ 48.07 €/MWh (0.0481 €/kWh) falls within the lower half of widely reported utility-PV ranges and is close to EU medians for favourable sites, typically $\leq$ 0.05–0.08 €/kWh, this places the greenhouse-integrated crystalline case in clear alignment with external benchmarks. By contrast, thin-film and especially OPV exhibit much higher LCOE due to lower conversion efficiency and higher price of installation, which explains their longer paybacks in the present scenarios [84–86].

Regarding the ROI, a documented 455.9 kWp AgriPV in Kalmar (Sweden) reports ROI $\approx$ 70%,

and a positive NPV at a multi-year horizon, figures that are coherent with moderate spreads between export price and LCOE and illustrate how financial results depend on site, CAPEX, financing, and market design. In markets with stronger incentives, modeled AgriPV cases report higher internal returns, whereas orchard pilots with high structural costs (e.g., Bierbeek, Belgium) show LCOE $\approx$ 200 €/MWh and reduced profitability, underlining the sensitivity of ROI/PP to €/kWp and crop-protection choices. The corrected monocrystalline LCOE $\approx$ 48.07 €/MWh in this thesis is therefore compatible with positive ROI/IRR outcomes under Portuguese tariffs (export $\approx$ 0.08 €/kWh) and explains the short paybacks indicated by the cash-flow analysis [87, 88].

With respect to land performance, foundational experiments in Montpellier (France) and subsequent European pilots report LER values $\approx$ 1.3–1.7 when crop management preserves PAR during critical phenological stages, i.e., combined food-plus-energy output exceeding the monoculture baselines on the same land area. The LER values obtained here therefore fall within the expected band for dual-use layouts that balance PV coverage with crop light requirements [27, 89].

In sum, payback within the $\leq$ 5–10 year window, LCOE compatible with Southern-Europe utility-PV bands (higher for semi-transparent/low-efficiency products), positive ROI/IRR under realistic Portuguese self-consumption conditions, and LER > 1 consistent with European field evidence are all quantitatively coherent with external references. Where differences arise, they are attributable to greenhouse-specific CAPEX, transparency-driven yield trade-offs, financing assumptions, and layout choices noted in the literature.

4.4 Environmental Impact

Annual avoided emissions were estimated as:

$$CO_2\ avoided\ (t/yr) = Annual\ AC\ Energy\ (MWh) \times 0.08\ tCO_2/MWh \tag{4.1}$$

By using the simulated energy and a single conservative Portuguese production-mix factor of 0.08 tCO_2/MWh. These results(Table 4.6)follow the energy ranking observed earlier, monocrystalline maximizes avoided emissions across sites, while thin-film and OPV still contribute some reductions their integration benefits (lightweight, semi-transparency) help preserve crop performance and overall land-equivalent outcomes [90].

Table 4.6: Annual avoided CO_2 emissions

	CO_2 avoided (t/yr)		
Total Number of Modules	Lagos	Odemira	Silves
Monocristalina	15.61	14.55	15.67
OPV	6.33	5.91	6.36
Thin-film	3.66	3.42	3.68

For context, maintaining the same factor over a nominal 20-year operating life (indicative only, ignoring curtailment and degradation) gives totals of roughly 916.6 t CO_2e for monocrystalline, 372.0 t CO_2e for OPV, and 215.2 t CO_2e for thin-film. If a higher (more conservative) factor were chosen (e.g., 0.118 t CO_2e/MWh based on 2023 production-mix, or 0.200 t CO_2e/MWh as a screening value), all figures would scale up proportionally, but the comparative conclusions would remain unchanged. These values reflect use-phase electricity substitution only. A complete appraisal should also consider embedded emissions from manufacturing and transport, O&M/cleaning, and end-of-life pathways (recycling or take-back). While those lifecycle elements are beyond scope here, future work should pair on-site monitoring of PAR/DLI, canopy temperature, and water use with a full LCA to quantify environmental co-benefits alongside avoided CO_2e.

4.5 Comparative Discussion

Table 4.7: Summary table of the main case study (20% of roof covered by PV modules)

Summary Table				
	Parameters	**Lagos**	**Odemira**	**Silves**
Monocrystalline	Paverage(W)	104.49	97.39	104.83
	Eyearly(MWh)	195	182	196
	LCOE(€/kWh)	48.07	48.07	48.07
	NPV(€)	44,940	46,483	44,060
	ROI	1.02	1.06	1.00
	PP(Years)	9.70	9.71	9.70
OPV	Paverage(W)	13.70	12.78	13.75
	Eyearly(MWh)	79	74	79
	LCOE(€/MWh)	279.66	279.66	279.66
	NPV(€)	-231,576	-229,960	-232,384
	ROI	-2.30	-2.28	-2.31
	PP(Years)	+20	+20	+20
Thin-film	Paverage(W)	7.18	6.70	7.21
	Eyearly(MWh)	46	43	46
	LCOE(€/MWh)	483.71	483.71	483.71
	NPV(€)	-257600.31	-255,985	-258,408
	ROI	-2.55	-2.54	-2.56
	PP(Years)	+20	+20	+20

The results obtained clearly distinguish the performance and feasibility of the three studied photovoltaic technologies across Lagos, Odemira, and Silves.

The combined results across the three case-study locations highlight clear and consistent differences in the performance of the evaluated photovoltaic technologies. When comparing sites, Lagos and Silves demonstrated slightly higher annual power densities than Odemira, reflecting their marginally stronger irradiance conditions. The normalised maximum power densities reached approximately 194 W/m^2 in Lagos, 189 W/m^2 in Silves, and 185 W/m^2 in Odemira for monocrystalline modules, while average annual power densities were on the order of 36–39 W/m^2 for these two leading sites and slightly lower for Odemira. OPV and thin-film modules followed the same site ranking, with Lagos and Silves showing modest performance advantages due to more favourable solar resource [72, 73].

From an economic and technological perspective, monocrystalline PV consistently emerged as the highest-performing option in all locations. Its superior efficiency resulted in the largest energy yields per square metre, strongest economic outcomes, and highest avoided CO_2 emissions. In contrast, OPV and thin-film modules delivered significantly lower power densities—typically 14–16 W/m^2 and 8–9 W/m^2 on average, respectively—but provided benefits associated with reduced weight, greater flexibility, and enhanced optical transmittance.

In contrast, OPV and thin-film modules were found to be economically unfeasible, with highly negative NPVs ($\approx$ –€250,000), long payback times exceeding 20 years, and ROIs below –2.5, their elevated LCOE values and limited energy yield make them currently unsuitable for commercial deployment without major cost reductions or technological improvements.

The sensitivity analysis on roof coverage revealed that system scaling has a direct influence on financial performance. Increasing roof coverage enhances total NPV but reduces ROI and lengthens PP, showing diminishing marginal returns. The analysis, which excluded degradation but incorporated avocado yield penalties, confirmed that partial coverage between 10% and 20% represents the optimal trade-off between energy generation, economic return, and agricultural productivity, at this range, shading losses remain acceptable, and the LER and ROI remains well above 1.0, ensuring efficient dual land use, and the PP is lower than 10 years.

From the land-use perspective, the Land Equivalent Ratio (LER) remained > 1 for all cases, demonstrating that AgriPV installations make better use of available land compared to conventional single-use agriculture or stand-alone PV. Here, monocrystalline achieves dual-use efficiency primarily through high electrical yield with modest shading penalties, whereas OPV and thin-film achieve it through higher transmittance (and thus crop preservation) despite lower electricity output. This division of strengths helps explain why monocrystalline dominates on financial metrics, while thin-film/OPV can still be justified in niche greenhouse layouts that prioritise PAR management and lightweight integration.

Finally, the environmental assessment is consistent with the technical–economic ordering. Using a

Portuguese grid-mix factor of 0.08 tCO_2e/MWh, monocrystalline maximizes avoided CO_2e across all sites, OPV and thin-film provide smaller but still meaningful annual reductions where their integration benefits help preserve crop performance and land-equivalent outcomes. Over a nominal 20-year life (indicative only), totals scale accordingly and do not alter the comparative ranking. A full appraisal would add embodied emissions and end-of-life scenarios, but the use-phase substitution alone supports the case for monocrystalline greenhouse AgriPV in the studied conditions.

Overall, the combined results suggest that monocrystalline PV is the only technology that is simultaneously technically strong, economically viable, and land-efficient under current costs and tariffs, Odemira marginally leads among the sites, and partial roof coverage (10–20%) provides the most sustainable and economically balanced greenhouse strategy. OPV and thin-film, while not viable today on pure cost grounds, remain candidates for future iterations if efficiency improves and €/kWp declines, or where transparency-driven agronomic benefits are explicitly valued in project economics. In general, the analysis confirms that greenhouse integrated AgriPV systems are technically feasible and potentially profitable in southern Portugal when using monocrystalline PV modules under optimized coverage configurations.

5

Conclusion

Contents

5.1 Conclusion 51

5.2 Future Work 53

5.1 Conclusion

Agrivoltaic (AgriPV) systems are emerging as new and innovative solutions to the worldwide problems of energy production and food security, these types of systems integrate photovoltaic technologies in agricultural settings to simultaneously produce energy and, therefore, optimize land use.

This dissertation was dedicated to the study of greenhouse-integrated AgriPV systems, analysing how such configurations can better agricultural sustainability while supporting the global energy transition. The research began with an overview of AgriPV concepts, types, and applications worldwide, highlighting three main configurations (interspace, overhead, and greenhouse-integrated) and exploring their socioeconomic implications, advantages, and technical challenges. The state-of-the-art review revealed that while AgriPV has seen rapid expansion in Europe, Asia, and North America, its adoption in Portugal remains limited, revealing an important need for localized studies that consider both climatic and economic contexts to better understand the feasibility of these kinds of systems in the region.

The analysis of the available photovoltaic technologies showed that monocrystalline, thin-film, and organic photovoltaic (OPV) panels differ significantly in terms of efficiency, cost, and suitability for agricultural environments, monocrystalline modules are the most efficient and durable, while thin-film and OPV panels are lighter and more adaptable, allowing flexible integration into greenhouse structures where transparency and reduced weight are required.

To assess the feasibility of AgriPV in Portuguese greenhouse conditions, three case studies were developed in Silves, Lagos, and Odemira, locations representative of southern Portugal's agricultural and solar potential. Using Typical Meteorological Year (TMY) data and the 1D3P photovoltaic model, the study evaluated the performance of three PV technologies under local conditions, calculating power output, temperature effects, and annual energy production. The economic evaluation employed indicators such as Net Present Value (NPV), Payback Period (PP), Return on Investment (ROI), and Levelized Cost of Energy (LCOE), along with the Land Equivalent Ratio (LER) to capture the benefits of dual land use. Methodologically, the approach was intentionally first-order: greenhouse-specific shading, optical and spectral effects were handled through consolidated loss assumptions, the simulated energy results were then benchmarked against external references to provide face validation.

The results demonstrated that monocrystalline PV technology is the only economically viable option for greenhouse integration under current market conditions. It achieved the highest power outputs (average $\approx$ 100 W, peak $>$ 500 W per module) and positive economic indicators in all three sites, even when module degradation was included in the analysis. After correcting the cost model, the greenhouse-integrated monocrystalline case achieved an LCOE $\approx$ 48.07 €/MWh (0.0481 €/kWh), which sits within credible ranges for well-sited PV in Southern Europe and below the export price used (0.08 €/kWh), explaining the positive spreads observed in cash-flows. Among the three case-study locations, Odemira showed the most favourable overall performance, presenting slightly higher NPVs, ROI values, and the

shortest payback period for monocrystalline PV. These advantages stem from its marginally stronger economic returns despite having slightly lower irradiance than Lagos and Silves, demonstrating that local cost structures and site conditions also influence feasibility. Lagos and Silves followed closely, with nearly equivalent energy yields and sustainability outcomes, confirming that all three southern Portuguese regions offer strong potential for greenhouse-integrated AgriPV deployment.

The sensitivity analysis performed by varying roof coverage (10–100%) confirmed that increasing coverage enhances total NPV but reduces ROI and lengthens payback time, showing diminishing marginal returns. Considering avocado shading penalties (but excluding degradation in that test), partial coverage in the 10–20% range provided the best trade-off between economic viability, shading impact, and crop productivity. Furthermore, the Land Equivalent Ratio (LER) remained above 1.0 for all configurations, confirming that greenhouse-integrated AgriPV systems can achieve higher overall land productivity than conventional single-use agriculture or stand-alone PV systems.

Beyond the quantitative results, the socioeconomic assessment confirmed that AgriPV can contribute to diversified income streams for farmers, job creation, and improved energy autonomy in rural communities. However, several challenges were identified: the high initial investment cost, structural complexity of greenhouse integration, the need for suitable energy storage, and the potential mismatch between crop light requirements and shading levels. Moreover, the absence of targeted policy incentives and regulatory frameworks for AgriPV in Portugal represents a major limitation to large-scale implementation, despite the country's exceptional solar potential and agricultural capacity.

The environmental assessment reinforced these findings. Using a location-based Portuguese factor of 0.080 t CO_2e/MWh (80 g CO_2e/kWh), monocrystalline scenarios delivered the largest avoided CO_2e across all sites, with OPV and thin-film providing smaller but non-negligible reductions where their integration benefits (low weight, partial transparency) help preserve crop performance and land-equivalent outcomes. These use-phase results exclude embodied impacts, nevertheless, they indicate that greenhouse-integrated monocrystalline AgriPV can contribute meaningfully to decarbonisation under current conditions.

In conclusion, this study demonstrates that greenhouse-integrated AgriPV systems are technically feasible, economically viable, land-efficient, and environmentally beneficial in southern Portugal when using monocrystalline photovoltaic technology under optimized partial coverage. The comparative analysis across technologies and sites, supported by external benchmarking and transparent methodological assumptions, clarifies where current market conditions favour deployment and where further technological progress (particularly for semi-transparent thin-film and OPV) is required.

5.2 Future Work

Future research should prioritise empirical validation of greenhouse-integrated AgriPV via monitored pilots that jointly measure energy (kWh), PAR/DLI, canopy temperature, soil moisture/ET, and crop yield-/quality, enabling direct calibration of the simplified modelling used here and quantification of agronomic co-benefits. On the modelling side, advancing beyond feasibility-level 1D3P to 3D geometric/ray-tracing of structure and glazing, coupled optical–spectral modelling (PV response and crop PAR), and microclimate–thermal coupling will reduce uncertainty and improve design optimisation for greenhouse roofs.

A key development path is the evaluation of semi-transparent PV materials (e.g., advanced thin-film/OPV/perovskite hybrids) under controlled shading for specific crops. Crop-specific trials should vary coverage/transmittance and spectral coatings to identify safe PAR windows and to quantify yield penalties or gains across phenological stages—particularly for avocado and other Algarve-relevant species. Parallel work on energy storage (battery sizing for self-consumption smoothing and resilience) and automation (adaptive louvers/ventilation, predictive irrigation tied to irradiance forecasts) can stabilise power delivery and improve greenhouse climate control, strengthening whole-system performance.

From an economic and environmental standpoint, future analyses should include a quantitative sensitivity/uncertainty assessment (e.g., OFAT or Monte Carlo) across €/kWp, efficiency, discount rate, tariffs/export prices, O&M, degradation, and greenhouse-specific optical/shading losses, alongside a full life-cycle assessment (LCA) that accounts for embodied carbon, O&M/cleaning, and end-of-life (recycling/take-back). To enhance transparency, avoided-emissions results should be repeated under alternative emission-factor conventions (location-based vs market-based/residual-mix) and, where possible, explored with hourly marginal factors for grid-integration studies.

Finally, policy and delivery dimensions merit dedicated study. This includes pathways for pilot and demonstration programmes, streamlined permitting for greenhouse integrations, incentive design (CAPEX support, tax credits, tariff adders for dual-use), and standards for structural safety and crop-light protection. Business-model work should compare self-consumption, fixed/PPA contracts, and hybrid revenue stacks (energy + agronomic value, e.g., reduced water use or heat-damage losses) to capture the full benefit of partial-coverage designs. Collectively, these steps will accelerate adoption and align AgriPV deployment with Portugal's environmental, agricultural, and socioeconomic goals.

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