

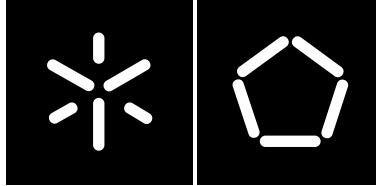


Semi-transparent Cu(In,Ga)Se₂
Solar Cells for agricultural-
integrated photovoltaics
applications

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Master's Dissertation in Physical
Engineering
Microsystems Devices and
Nanotechnology

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Acknowledgements

This thesis presents the work conducted at INL throughout the 23/24 and 24/25 academic years, detailing the challenges faced, solutions explored, and progress achieved. Unfortunately big part of the data was lost and therefore the use of some less detailed pictures, as they were taken by my phone. Before delving into the technical aspects, I want to share what truly motivated me: my passion for future technology and my beginnings.

I come from a small village where community and friendship were at the heart of our daily lives. Many times, my family and neighbors would bring food to share, a simple act that always filled me with joy. I have always wanted to give back and contribute in the same way, by helping to improve food production. The best way I envisioned doing so was by finding innovative solutions to make cultivation easier and more efficient, even at home. This aspiration became a reality when I discovered I could merge agriculture with my field of study, leading me to explore the exciting field of Agri-Photovoltaics, which became the foundation of this thesis.

I would like to express my deepest gratitude to my mother and father, who provided me with unwavering support and the best conditions to pursue my studies, allowing me to focus without worry. To my friends, who have been by my side throughout these university years, offering both encouragement and the occasional much-needed escape from work, I am grateful to have you now and for the rest of our lives.

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A special thanks to everyone at INL, for making my time there both enriching and enjoyable. Every person contributed in some way, and it was truly a pleasure to work and learn alongside such an inspiring group.

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

University of Minho, Braga, June 2025

Ricardo da Silva Magalhães

Resumo

As células solares fotovoltaicas (PV SC) são uma tecnologia fundamental para alcançar um futuro mais sustentável, aproveitando a energia renovável que é o sol. Desde a primeira observação do efeito fotovoltaico (PV) em 1839, a energia solar passou a ser amplamente utilizada, principalmente por meio de painéis à base de silício instalados em residências, quintas solares e aplicações em larga escala. No entanto, ainda existe uma lacuna significativa na integração da tecnologia PV em aplicações agrícolas, onde os efeitos da sombra e os altos custos iniciais representam grandes desafios.

As células solares semi-transparentes de Cu(In,Ga)Se_2 (CIGS) oferecem uma solução promissora para sistemas agrivoltaicos (APV), pois permitem que uma fração da luz solar atinja as plantas, enquanto convertem o resto em eletricidade. Como uma tecnologia de filme fino, o CIGS requer 99% menos material do que os PVs convencionais de silício, tornando-se uma alternativa atraente para o duplo uso do solo.

Esta tese tem como objetivo desenvolver células solares de filme fino com microestruturas à base de CIGS, demonstrando seu potencial para mitigar os problemas da sombra associados aos painéis de silício tradicionais. Além disso, compara tecnologias fotovoltaicas existentes e emergentes para avaliar as suas vantagens e limitações na integração na agricultura.

O método proposto envolve a fabricação de células solares segmentadas espacialmente por meio de fotolitografia, alcançando a semi-transparência através da implementação de linhas finas de CIGS. O processo começa com a deposição de molibdênio num substrato de vidro de soda-lime, seguido pela deposição da camada absorvedora utilizando um processo de duas etapas: pulverização catódica (sputtering) de Cu-In-Ga e selenização via deposição química de vapor (CVD). Utilizando fotolitografia com lift-off, obtém-se o micro padrão desejado, seguido pela deposição de uma camada de buffer (via deposição química em banho) e de uma camada final (window) (via pulverização catódica por magnetron).

Embora a fabricação de um dispositivo totalmente funcional não tenha sido alcançada, o estudo analisa detalhadamente os desafios enfrentados, identificando possíveis causas de falha e melhorias para futuras tentativas. Os resultados fornecem informações valiosas sobre a viabilidade das células solares semi-transparentes de CIGS para aplicações agrivoltaicas e o seu potencial impacto na sustentabilidade agrícola e na geração de energia.

Resultados preliminares indicam que os micro designs de STPV conseguem equilibrar com sucesso a conversão de energia solar e a transmissão de luz, permitindo que uma quantidade suficiente de radiação fotossintética ativa (PAR) atinja as plantas, mantendo ao mesmo tempo uma geração de energia eficiente. Estrefoam o potencial das células solares semi-transparentes de

CIGS como uma solução viável para sistemas sustentáveis de produção de alimentos e energia.

Abstract

Photovoltaic solar cells (PV SC) are a critical technology for achieving a more sustainable future by harnessing renewable energy from the sun. Since the first observation of the photovoltaic (PV) effect in 1839, solar energy has become widely used, primarily through silicon-based panels deployed in homes, solar farms, and large-scale applications. However, there remains a significant gap in integrating PV technology into agricultural applications, where shading effects and high upfront costs pose major challenges.

Semi-transparent $\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGS) solar cells offer a promising solution for agrivoltaics (APV), as they allow a fraction of sunlight to reach crops while converting the remaining portion into electricity. As a thin-film technology, CIGS requires 99% less material than conventional silicon PVs, making it an attractive alternative for dual land use.

This thesis aims to develop micro-structured thin-film solar cells based on CIGS, demonstrating their potential to mitigate shading issues associated with traditional silicon panels. Additionally, it compares existing and emerging PV technologies to assess their advantages and limitations in agricultural integration.

The proposed method involves fabricating spatially segmented solar cells through photolithography, achieving semi-transparency by structuring narrow CIGS lines. The process begins with the deposition of molybdenum on a soda-lime glass substrate, followed by the absorber layer formation using a two-step process: Cu-In-Ga sputtering and selenization via chemical vapor deposition (CVD). Using lift-off photolithography, the desired micro-pattern is obtained, followed by the deposition of a buffer layer (via chemical bath deposition) and a window layer (via magnetron sputtering).

Although the fabrication of a fully functional device was not achieved, the study thoroughly analyzes the challenges encountered, identifying potential causes of failure and improvements for future iterations. The findings provide valuable insights into the feasibility of semi-transparent CIGS solar cells for agrivoltaics and their potential impact on agricultural sustainability and energy production.

Preliminary results indicate that structured STPV designs successfully balance solar energy conversion and light transmission, allowing sufficient photosynthetically active radiation (PAR) to reach crops while maintaining efficient power generation. These findings reinforce the potential of semi-transparent CIGS solar cells as a viable solution for sustainable food-energy systems.

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Abbreviations

AC	– Alternate Current	LSC	– Luminescent Solar Concentrator
AEV	– Agricultural Electric Vehicle	PAR	– Photosynthetically Active Radiation
APV	– Agri-Photovoltaics	PCE	– Power Conversion Efficiency
AVT	– Average Visible Transmission	PPFD	– Photosynthetic Photon Flux Density
BSE	– Backscattered Electrons	PR	– Photoresist
CBD	– Chemical Bath Deposition	PV	– Photovoltaics
CdS	– Cadmium Sulfide	PVSC	– Photovoltaic Solar Cell
CIG	– Copper Indium Gallium	RF	– Radio Frequency
CIGS	– Copper Indium Gallium Selenide	SCGI	– Selenium-to-(Copper+Indium+Gallium) Ratio
CIS	– Copper Indium Selenide	SEM	– Scanning Electron Microscopy
CPV	– Concentrated Photovoltaics	SQ Limit	– Shockley-Queisser Efficiency Limit
DC	– Direct Current	SSE	– Spectrally Selective Electrode
DLI	– Daily Light Integral	STAR	– Sputtering for Advanced Research
DNI	– Direct Normal Irradiance	STPV	– Semi-Transparent Photovoltaics
DSSC	– Dye-Sensitized Solar Cell	TCO	– Transparent Conductive Oxide
EDX	– Energy Dispersive X-ray Spectroscopy	THEIA	– Translucency and High Efficient
EMR	– Electromagnetic Radiation	Voc	– Open Circuit Voltage
FF	– Fill Factor	XRD	– X-Ray Diffraction
GGI	– Gallium-to-(Gallium+Indium) Ratio		
i-ZnO	– Intrinsic Zinc Oxide		
LED	– Light-Emitting Diode		
LOR	– Lift-Off Resist		

Introduction

The world energy and food demand are increasing the expected 25% population growth in the next 20 years. Although, directly or indirectly, most of the world's energy comes from burning fossil fuels, which are increasing greenhouse gases released into the atmosphere, causing climate change [1]. Therefore, it is necessary to accelerate the transition to cleaner and more sustainable energy sources, to end our dependence on fossil fuels. These renewable energy sources include the sun, wind, water, and heat (thermal). Among all renewable energy technologies, photovoltaics play a significant role in this transition and have experienced substantial growth over the past decade, increasing from approximately 136 GW in 2013 to over 1406GW in 2023, as shown in Figure 1. This represents a remarkable 931% increase in total installed capacity.

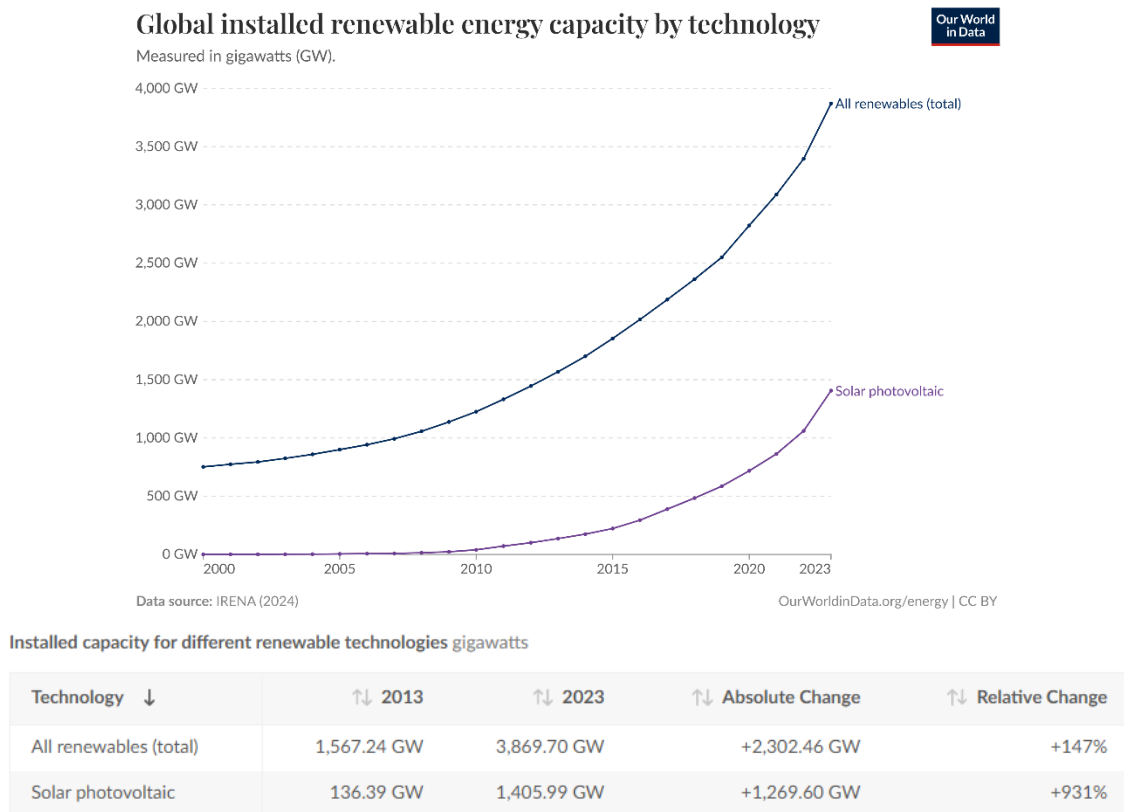


Figure 1 - Adapted from BP statistical Review of Global energy
OurWorldInData.org/renewable-energy

Photovoltaic (PV) energy is primarily harnessed through PV modules, commonly known as solar panels. These panels can be installed in almost any location with sufficient sunlight, with the most frequent applications being on rooftops of buildings and houses, as well as in large-scale solar farms. The transition from fossil fuels to PV energy could be fully realized if extensive land areas were available for deployment [2].

However, since land is a limited resource essential for both human and non-human life, alternative solutions must be explored where space constraints are not a limiting factor.

The photovoltaic effect occurs when a semiconductor material generates a voltage upon exposure to electromagnetic energy. At absolute zero temperature, semiconductors have a fully occupied valence band and an empty conduction band. When photons with sufficient energy strike the material, they excite electrons, enabling their transition from the valence band to the conduction band. This excitation creates an electron-hole pair, which is then influenced by the electric field of a p-n junction. The field separates the pair, allowing the electron to move toward the collection region.

To extract electrical energy, metallic contacts are placed on either side of the semiconductor, enabling the flow of electrons as an electrical current. However, some electrons recombine with holes before reaching the contacts, dissipating energy and reducing efficiency.

The overall electrical output of a solar cell, its efficiency, is determined by how effectively these excited electrons are collected. Several factors influence this efficiency, such as:

- Material properties
- Band Gap
- Reflection and transmission
- Carrier Recombination
- Contact Resistance
- Temperature
- Incident Light Intensity

For an ideal single-junction solar cell, the maximum theoretical efficiency is given by the Shockley-Queisser (SQ) limit at 33% , for an optimum semiconductor with a band gap of 1.34 eV illuminated by a AM1.5 solar spectrum (Figure 2) [2].

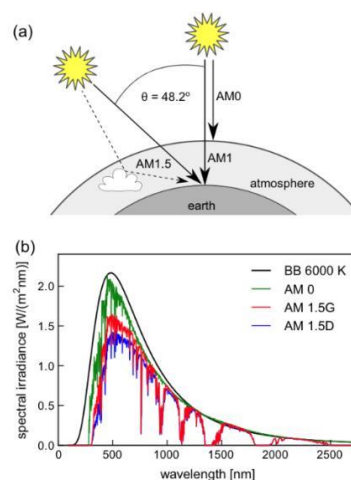


Figure 2 - AM1.5 solar spectrum (Ruhle, 2016)

Currently, silicon (Si) based, or 1st generation PV systems, dominate the market. Crystalline silicon (c-Si) and multi-crystalline (mc-Si) devices represent almost 90% of the installed PV capacity [3]. Si dominates because the band gap is within the optimal range for efficient PV conversion and its abundance on earth's crust. Monocrystalline Si cells hold a record efficiency of 26.7%[4] .

The 2nd generation PV system, which is based on thin-film technology, is primarily represented in 3 groups: amorphous silicon (a-Si), cadmium telluride (CdTe), and Copper-Indium-Gallium-diSelenide (CIGSe). These have thicknesses between 1µm – 4µm, therefore, they use up to 99% less material than c-Si solar cells. Single-crystalline GaAs cells show 28.8%, polycrystalline CdTe thin-film cells with 21.5%, perovskites with 21%, and CIGSe with 23.6% [From EENews and NREL websites].

Lastly, the 3rd generation PV systems are represented by concentrated photovoltaics (CPV) and organic photovoltaics (OPV) Novel PV systems also make part of this 3rd generation, like Dye-Sensitized Solar Cells(DSSCs) and quantum dot PVs, all with much lower efficiencies of around 10-12% or less. Figure 4 shows several solar cell materials, ranging from 1st, 2nd and 3rd generation, with their efficiencies and bandgap

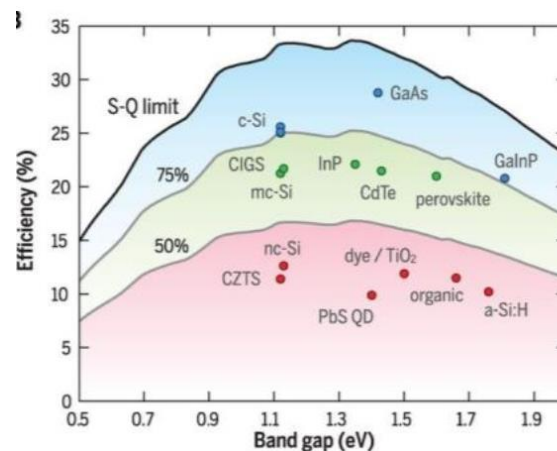


Figure 3 - Theoretical Shockley-Queisser detailed-balance efficiency limit as a function of band gap (black line) and 75% and 50% of the limit (gray lines). The record efficiencies for different materials are plotted for the corresponding band gaps. [6]

All the materials we talked above can be used to produce opaque solar cells or semi-transparent solar cells. Their use as energy sources is widely recognized by people as we start seeing them everywhere, including in Agriculture. The graph below taken from NREL (Figure 4) shows the record efficiencies of every photovoltaic technology and their respective record efficiency:

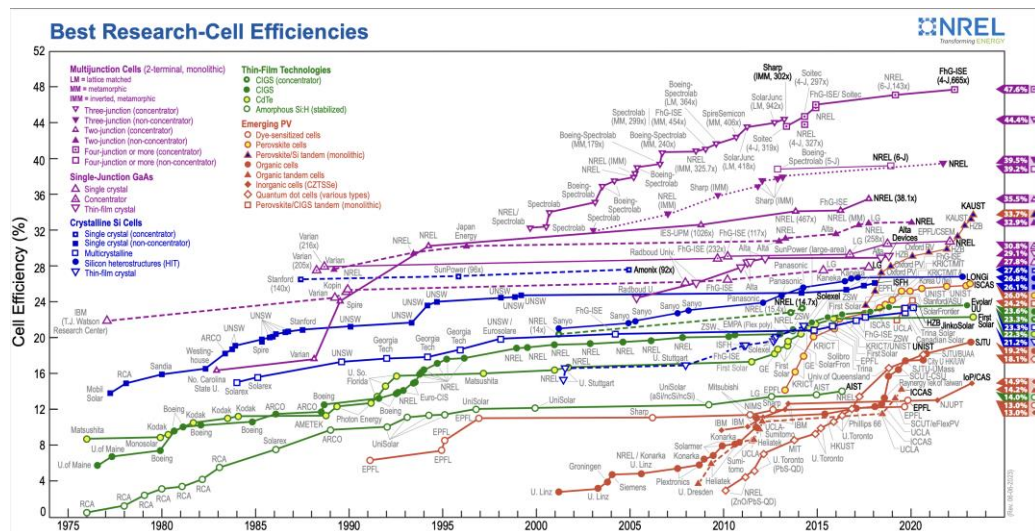


Figure 4 - NREL Record efficiencies of numerous Photovoltaic technologies

Semi-transparent PV can be a solution to the area problem and material usage, since this technology can be integrated into building windows as building integrated PV (BIPV), which represent massive areas where standard opaque PV is not the best option to be deployed, mostly due to aesthetics and functional reasons. The same goes for Agricultural PV, where we can use the versatility of the Semi-Transparent Photovoltaics (STPV) to have a dual use of the land for food and electricity production.

Weather conditions such as temperature, humidity, and sunlight vary with latitude and are often suboptimal for crop growth. To mitigate these challenges, protective structures like greenhouses are commonly used. Because the conditions are often suboptimal, climate control remains essential throughout the year, during winter and fall to prevent insufficient heat retention at night, and in spring and summer to regulate high temperatures and intense solar radiation.[5]

While light is a crucial factor for photosynthesis, increased solar exposure does not always equate to higher productivity. Many plants have a photosynthetic saturation point, beyond which additional light provides no further benefit and may even cause stress, reducing overall efficiency



Figure 5 - Different solar farming configurations adapted from [7]

Agrivoltaics (APV) is the integration of agriculture and photovoltaics, enabling simultaneous crop cultivation and energy production. Early implementations of this concept primarily followed two approaches: placing solar panels directly above the crops (Figure 5a and 5b) or positioning them side by side with the greenhouses (Figure 5c). However, these methods introduced two significant challenges, excessive land use in the case c) and unwanted shading effects in a) and b).

To address these issues, semi-transparent photovoltaic (STPV) technology offers a promising solution by balancing light transmission and energy generation, mitigating shading concerns while optimizing land utilization

STPV technology can help mitigate the challenges of agrivoltaics by balancing energy production and crop growth. By absorbing part of the sunlight to generate electricity while allowing sufficient light to reach the plants, STPV ensures that crops receive the necessary light for photosynthesis.

For this to be a truly symbiotic system, it is important to consider the Daily Light Integral (DLI), the total amount of photosynthetically active radiation (PAR) a plant requires daily to grow without harm. If too much light is harvested by the solar panels, crop development may be compromised. Therefore, optimizing STPV design requires careful selection of light transmission levels, ensuring that the amount of harvested sunlight does not exceed what plants can tolerate.

The DLI for a specific plant species can be calculated using Equation (1), allowing for an optimal balance between electricity generation and agricultural productivity.

$$DLI = \frac{PPFD * 3600 * Photoperiod}{1 * 10^6} \quad (1)$$

Equation (1) shows that to determine the DLI of a plant, we need to know its photoperiod, the number of hours it requires exposure to light. This information

is available from florists, plantation workers, or online resources. The concept of DLI has been applied, knowingly or unknowingly, for centuries as people have instinctively adjusted plant placement based on their light requirements. Without any calculations, plants have been positioned in brighter or shadier areas purely through trial and error, ensuring they receive an appropriate amount of sunlight.

Since different plant species have varying photoperiods and DLIs, it is essential to recognize that a plant with a lower DLI cannot be exposed to the same light intensity as one with a higher DLI. Excessive exposure can result in wasted light, while extreme cases may lead to leaf scorching or even plant death. However, the common practice of placing plants in different areas of a home is not related to photoperiod. The key factor here is Photosynthetic Photon Flux Density (PPFD), which determines how many photosynthetically active photons reach a given area over time. Unlike photoperiod, PPFD measures only photons within the Photosynthetically Active Radiation (PAR) range (Figure 6), making it a critical parameter for optimizing light exposure in both natural and controlled environments.

Since PPFD represents the number of photosynthetically active photons reaching a given area, its value varies depending on the time of day and the intensity of sunlight. For example, if a flower is placed in a location where it receives sunlight only in the morning, the PPFD will be lower compared to a spot where it receives midday sun, as solar intensity is significantly higher at noon, resulting in a greater number of photons. Consequently, even with the same photoperiod, the DLI can differ depending on the plant's placement, as it is directly influenced by the total number of photons accumulated over time.

Understanding this concept is critical for optimizing light exposure in controlled environments, as it means that DLI is not solely determined by photoperiod but also by light intensity throughout the day. With our spatial segmentation approach, we can fine-tune light exposure by adjusting the number and spacing of structured lines in a given area. By modifying this pattern, we

effectively regulate the number of photons passing through, thereby directly influencing both DLI and PPFD.

The key distinction between these two parameters lies in the type of photons considered:

- DLI accounts for the entire light spectrum, representing the total light energy available for the plant.
- PPFD considers only the photons within the Photosynthetically Active Radiation (PAR) range, as illustrated in Figure 6.

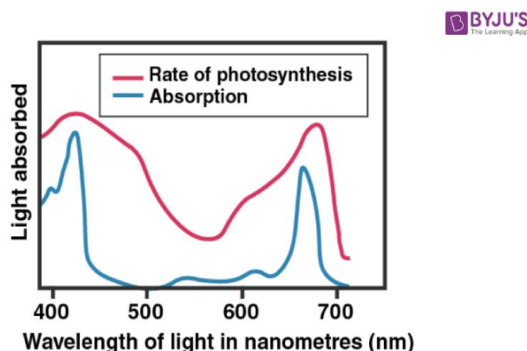


Figure 6 - Rate of photosynthesis and absorption on plants, Adapted from <https://byjus.com/global/>

The photons within the PAR range are the only ones (known so far) that plants can absorb to produce energy and grow. The $\frac{3600}{1 \times 10^6}$ is a constant to give the DLI in (mol/m²/day) instead (μmol/ m²/s).

With this in mind, the spatial segmentation parameters, such as the distance between structured lines, can be optimized to regulate PPFD (the amount of light reaching the plants), ensuring optimal light transmission through the STPV device. By carefully tuning the amount of light allowed to pass, we can control the DLI, which is determined by the total light exposure over time.

This control is essential for selecting suitable plant species, maximizing the symbiotic relationship between energy generation and crop growth. Additionally, our technology contributes to temperature regulation within the greenhouse, as excess light—often responsible for unwanted heat buildup, is filtered out by the STPV layers. This effect has been highlighted in multiple studies on STPV technologies, demonstrating its potential to create a more stable microclimate for plant cultivation.

It is now evident why STPV plays a crucial role in APV, not only by enabling land to be used for both food and energy production but also by contributing to the reduction of fossil fuel dependence while addressing the growing demand for energy and food. When effectively implemented, STPV can optimize land use while significantly lowering material consumption—using 99% less material than traditional PV—potentially reducing installation costs.

Moreover, the versatility of STPV allows for the seamless integration of PV technology and agriculture, making it a valuable solution for areas where land competition is a concern. PV systems, with their adaptability, offer unique opportunities for the energy sector to develop tailored energy service packages for remote rural regions. Additionally, STPV mitigates shading issues commonly associated with conventional opaque PV panels, improving light distribution for crops.

A practical approach to further developing this technology is continued testing of STPV devices in greenhouses, as these structures cover large areas that could support low-density PV module integration, enhancing their feasibility for agrivoltaic applications. [1]

Semi-transparent PhotoVoltaics

STPV (or Semi-transparent Photovoltaics) is a beneficial technology that can be deployed where other opaque PV technologies fail to be the most fit. It's a technology that combines the advantages of being transparent to visible light (or some part of the spectrum we choose) while converting sunlight into electricity or by allowing some light through and convert the rest. Semi-transparency can be achieved by three main approaches: (i) by absorbing some specific wavelength of the light spectrum (wavelength selective) and letting the other wavelengths through; (ii) by using a sufficiently thin or low-concentration photoactive material (thickness around 200nm - 350nm), or (iii) spatial segmentation. ii) and iii) are part of the non-wavelength selective family [6]. In this work, we will use approach iii) by fabricating thin lines of opaque solar cell material separated from each other by a fixed distance. In this way, the solar cells absorb part of the sunlight, and the other passes through the clear space between the lines like in example 2 from the left in (Figure 7).

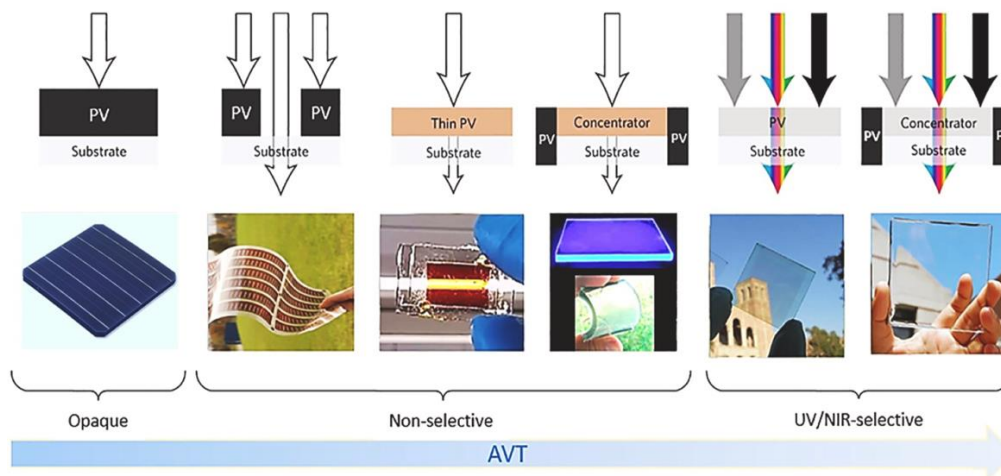


Figure 7 - PV systems with increasing AVT. From left to right: Opaque Solar Cell. Spatially segmented SC. Non-wavelength-selective thin-film SC. Non-wavelength-selective solar concentrator. Wavelength-selective thin film SC. Wavelength-selective luminescent solar concentrators (LSC). Image adapted from [7]

Some of the biggest opportunities for STPV lie in their integration into windows and skylights in energy-efficient buildings, but also in wearable electronics PV vehicles and APV [8]. Currently, the building-integrated photovoltaics (BIPV) market is dominated by c-Si devices. Nevertheless, the opacity of silicon creates opportunities for introducing new photovoltaic candidates, the STPVs. STPV-based devices include solar cell materials based on amorphous silicon, kesterite, chalcopyrite, CdTe, dye-sensitized, organic, and perovskite-based solar cells [9]. Due to its low-temperature and mature manufacturing process, amorphous silicon has been the most used material for STPV applications. However, a-Si STPV are usually colored, making them unappealing for BIPV applications.

Figure 7 shows the two main approaches (a) and (b) currently used in BIPV, and another method, approach (c), developed at LaNaSC. Approach (a) uses spatially segmented c-Si in a chess-like pattern, however, it doesn't allow a continuous view which is a major downside comparing to approach (c). Approach

(b) uses very thin a-Si, resulting in an unimpeded view, but its natural color make it very unaesthetic. Also as we see in the graph (e) it cuts most of the UV and visible wavelengths (only wavelengths above 750nm pass through). Approach (c) uses spatially segmented CIGS solar cells but with a geometry that results in a clear view and no coloration, we can clearly see what's beyond but with a lower intensity (meaning a lower PPFD if we talk about plants)

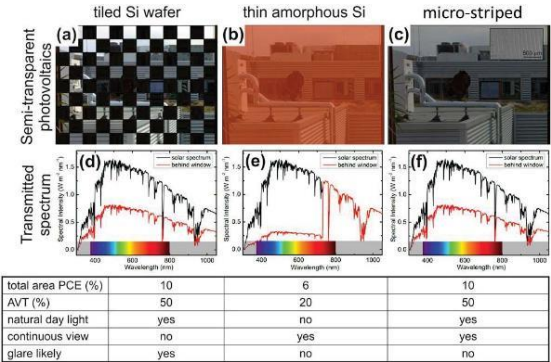


Figure 8 - Three types of STPV approaches and materials used. Image provided by LaNaSC (unpublished).

Agricultural PhotoVoltaics

Agricultural photovoltaics (APV) is the integration of two essential systems, solar energy generation and agricultural production, within the same land area. This approach maximizes land use efficiency by enabling both crop cultivation and energy production simultaneously. The goal of APV is to create a mutually beneficial system that addresses the growing demand for food and renewable energy while contributing to a more sustainable and efficient agricultural model.

Beyond food production, APV systems offer additional applications, such as powering farm machinery, irrigation and water pumping systems, desalination units, drying systems, and security installations, all with significantly lower energy costs.[10]

For many years, and still today, the APV market has been dominated by opaque solar panels, which are installed using various placement strategies, as shown in Figure 9.

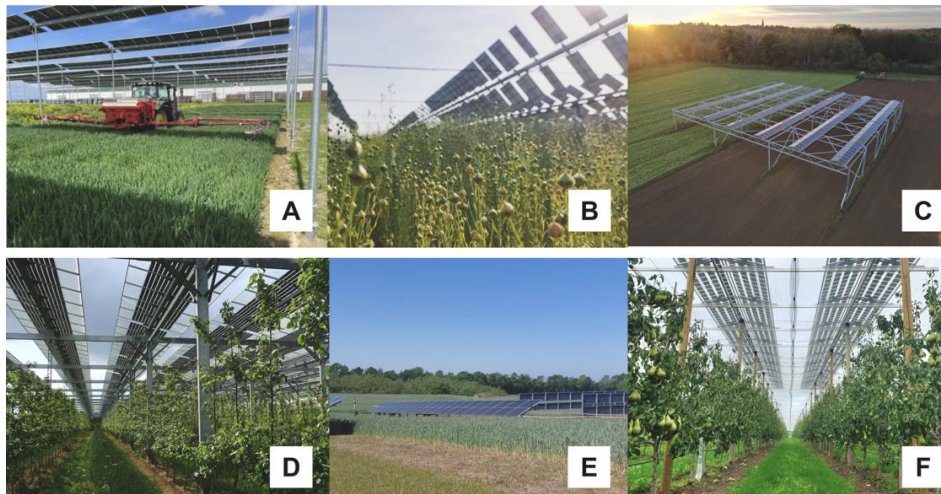


Figure 9 - Different possible implementations to use in APV, adapted from [11]

Studies have demonstrated that APV systems can significantly improve land productivity, with research suggesting that global land efficiency can increase by 35–73% when PV panels are installed at sufficient heights, allowing approximately two-thirds of solar radiation to reach the crops [1]. After three decades of research and technological advancements, APV has transitioned from a concept to a commercial reality, with numerous projects and pilot plants successfully operating worldwide. However, despite the benefits, the shading effect caused by opaque solar panels remains a significant challenge, particularly in greenhouse applications, where the lower panel height further intensifies this issue. One of the most effective solutions to this problem is the use of semi-transparent photovoltaic (STPV) modules, as discussed in later sections.

There are two primary reasons driving the adoption of APV:

1. Energy independence – APV allows farmers to generate renewable energy on-site, reducing reliance on external electricity sources.

2. Maximizing land use for both food and energy production – This dual-function approach increases economic returns by avoiding high energy costs while maintaining agricultural productivity.

Additionally, APV systems can serve as a reliable power source for rural areas with limited or unstable electricity access. Beyond localized benefits, implementing APV at scale contributes to improving the regional electrical grid, enhancing food security, and increasing the stability of heat and water supplies [12].

One of the main drawbacks of APV systems is the higher initial investment cost compared to conventional farms or greenhouses. However, this expense can be offset by long-term energy savings through the electricity generated by the system, which ultimately reduces operational costs. The financial feasibility of APV is often assessed through the Estimated Time of Return (ETR) or Payback Period (PBP), indicating the time required for the system to pay for itself through energy savings and agricultural revenue.

Greenhouses in APV applications can be categorized into passive and active systems, each with distinct energy management strategies:

1. Passive Greenhouses

- Utilize thermal energy storage systems, such as thermal panels, phase change materials (PCMs), and soil, to collect and store heat during the day.
- At night, these storage units release the accumulated heat gradually, stabilizing temperature fluctuations and reducing heating demand.

2. Active Greenhouses

- Incorporate solar photovoltaic (PV) systems to generate electricity, which is then used for greenhouse operations or fed directly into the grid.
- Semi-transparent PVs (STPVs) or conventional PVs enable greater control over internal energy usage, optimizing power supply for heating, cooling, ventilation, and automated systems.

In greenhouse environments, the major energy costs are associated with temperature, humidity, and CO₂ regulation, which require cooling, heating, and air ventilation systems. These factors must be precisely controlled to ensure optimal plant growth conditions. According to [10], these energy-intensive systems account for 65–85% of the total energy demand and approximately 50% of total production costs.

By integrating STPV technology, greenhouse APV systems can reduce dependence on external energy sources, optimize light distribution for crops, and increase economic sustainability, making them a key solution for the future of controlled-environment agriculture.

Concentrated PV

Concentrated Photovoltaics (CPV) is an emerging technology that utilizes optical components, such as mirrors or lenses, to focus sunlight onto a smaller, highly efficient solar cell, thereby increasing its power output. By concentrating light, CPV systems aim to achieve higher energy conversion efficiencies compared to conventional flat-panel photovoltaics. Concentrated PV consist mainly of 3 components: a solar cell (or solar collector in some cases), an optical system for light concentration and a sun tracking mechanism to adjust the normal of the incident light.

CPV technology that uses mirrors/lenses is divided in 2 major concentration paths: Reflection and Refraction. Additionally they can also be divided by what is their main output: Electricity (Photovoltaic) or Heat (Concentrated Solar Power). We then have many different choices and approaches we can do with optical instruments and solar cells geometry as shown in Figure 10.

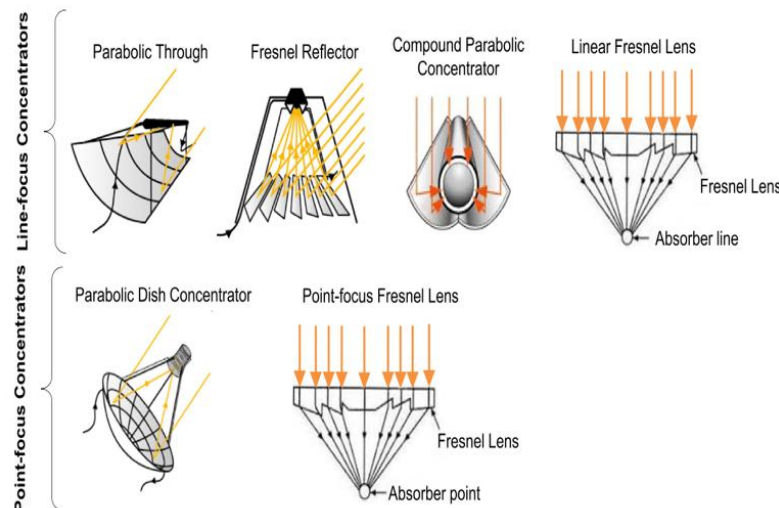


Figure 10 - taken from [13], shows several ways to concentrate EMR.

The key advantages of CPV include improved solar cell efficiency and lower material costs by replacing expensive semiconductor materials with cheaper optical elements such as mirrors or lenses. However, CPV technology still faces significant challenges, including:

- High initial costs, requiring improvements in module design, performance, and production scalability.
- Heat management issues, as concentrated sunlight causes thermal stress on solar cells, leading to long-term degradation.
- Cooling limitations, as no universally effective cooling solution has been developed to prevent heat-related efficiency losses [13]

While excess heat presents a major issue for PV-based CPV systems, it can be beneficial in thermal collectors, where higher heat generation directly increases energy output. However, this limits the application scope, as thermal concentrators are primarily useful for solar heating rather than electricity

generation. The chosen material for the lens in a CPV system also affects the optical performance, for reflective concentrators it seems that silvered PMMA (polymethylmethacrylate) is the best choice with its 97% reflectance and 93% over the years (with regular cleaning). As for refractive concentrators, like Fresnel lenses, are traditionally made from PMMA with other materials being only now tested for CPV applications (Note that this information is from 2016 and might no longer be up to date). [14].

Even if not implemented in the presented work, concentrated PV could be the next step for improving the efficiency of solar cells in AgriPV applications.

Motivation and Objectives

The transition towards sustainable energy solutions has become one of the most pressing challenges of modern times. With global energy demand continuously increasing and climate change accelerating, renewable energy technologies have emerged as the primary alternative to fossil fuels. Among these, solar photovoltaic (PV) technology stands out due to its scalability, efficiency improvements, and cost reductions over the last decade. However, large-scale solar energy deployment often conflicts with land use priorities, particularly in agricultural regions where available space must be carefully allocated between food production and energy generation.

Agrivoltaic (APV) systems offer a potential solution by integrating solar panels with agricultural activities, allowing for simultaneous food and energy production on the same land. The challenge, however, lies in balancing solar energy generation with the photosynthetic requirements of crops. The use of opaque PV panels in greenhouses or open fields has been shown to significantly reduce light availability, potentially compromising crop yield. In contrast, semi-transparent PV (STPV) technologies provide an opportunity to optimize light transmission, ensuring that plants receive sufficient radiation for photosynthesis while still enabling energy generation.

This study is motivated by the need to develop an optimized APV system that leverages CIGS (Copper Indium Gallium Selenide) solar cells as a promising solution for future agrivoltaic applications. CIGS technology stands out due to its high absorption coefficient, tunable bandgap, and potential for semi-transparent applications, making it well-suited for integrating solar energy generation into greenhouse environments without severely impacting plant growth. Unlike traditional opaque PV technologies, structured CIGS-based STPV designs allow for fine-tuned light management, reducing shading effects while maintaining energy output.

The goal of this research is to investigate how CIGS-based STPV devices with microstructured light-permeable designs can improve the overall efficiency of agrivoltaic systems and serve as a viable future solution for sustainable, high-yield agricultural models. By focusing on CIGS as the key photovoltaic material, this study aims to explore its potential advantages, challenges, and optimal configurations to enhance agrivoltaic performance. For that objective to be fulfilled, it is important to develop the following processes in order to fabricate and characterize the CIGSe cells:

1. Use microfabrication techniques, such as photolithography, to pattern the desired geometry of the STPV devices on glass substrates.
2. Use the thin-film deposition system at LaNaSC to deposit the solar cell molybdenum back contact, the CIGSe absorber, the buffer layer and the window layers, onto the substrates prepared during the lithography

3. Perform material characterization of every deposited layer by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD).
4. Validate the performance of semi-transparent CIGSe solar cells by accessing the J-V curve characteristics and external quantum efficiency (EQE).

Besides that, testing different AVTs (75%, 50% and 25%) would be interesting to show how it would impact the plants growing below. These AVTs can be achieved by spatial segmentation of the lines on the solar cell. The idea here is to show how the DLI of a plant would affect it's growth, directly correlating to the need of STPVs.

State of the art

Different types of Solar Cells

To categorize the different types of solar cells, we will first classify them into distinct groups, analyze their characteristics, and then discuss their respective advantages and disadvantages. The two primary categories are opaque and transparent/semi-transparent solar cells. Opaque solar cells, commonly referred to as solar panels, are predominantly composed of monocrystalline silicon, achieving record efficiencies of 26.7% [4].

Beyond this basic classification, solar cells are also divided into three generations: 1st, 2nd, 3rd generation technologies, as illustrated in Figure 11. Third-generation solar cells stand out due to their innovative properties, offering promising advancements in electricity generation [4]. While these emerging materials can potentially reduce costs, their current efficiencies remain relatively low. However, with continued research and technological advancements, they hold the potential to shape the future of photovoltaics.

The technologies mentioned above will be explored in greater detail in the following chapter. Additionally, Figure 11 provides a visual representation of the classification, facilitating a clearer distinction between the various solar cell types.

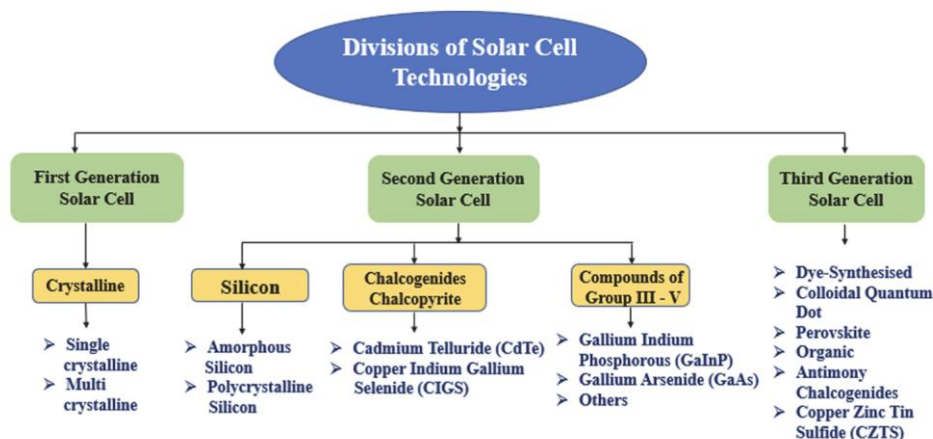


Figure 11 - Classification of Solar Cell Technologies from [4]

In the next chapter, we will analyze the advantages and disadvantages of each solar cell technology, providing real-life examples of their integration with agriculture. This comparison will allow us to evaluate how these technologies perform in agrivoltaic applications and, ultimately, contrast them with our own approach. By doing so, we can identify areas for improvement and determine the most suitable applications for our technology.

Opaque PVs in Greenhouses

The opaque PV system analyzed in this study is based on polysilicon modules, though no specific efficiency values were disclosed. It was estimated to increase total land productivity by 60-70%, based on crop modeling and PV radiation simulations. This productivity gain is attributed to the ability of solar panels to generate electricity without significantly harming crop yields or, in cases where shading does impact plant growth [14], the electricity production is expected to compensate for any agricultural losses.

The power generation system had a 200 kWh capacity, covering 0.47 ha², with an estimated annual electricity production of 0.28 million kWh in China—though this value varies depending on the greenhouse's geographic location [15]. The study did not specifically analyze the effects of shading on plant growth, but as previously discussed, the overall outcome remains advantageous. While crops may experience reduced size and total yield, the substantial electricity generation offsets these potential downsides.

The study also estimated an average payback period of approximately 10 years.

Furthermore, according to the same study, a 75 kW PV system installed on the roof of a 1,000 m² greenhouse would yield around \$13,500 per year in power generation revenue, alongside an agricultural net income of \$12,000 per year. This setup required an initial investment of \$120,000, resulting in a payback period shorter than the 10-year average.



Figure 12 - Two possible ways to place opaque solar panels on greenhouses, taken from [15]

Figure 13, taken from [16], presents the estimated costs of connecting a greenhouse to the grid in Italy. The data highlights the financial advantage of integrating on-site electricity generation, as relying solely on grid power can be particularly costly, especially for farms located in remote rural areas. By generating their own electricity, greenhouse operators can significantly reduce operational costs associated with energy consumption.

Additionally, the use of Agricultural Electric Vehicles (AEVs) offers dual benefits: reducing atmospheric pollution and minimizing overall electricity demand. A study conducted in the Mediterranean region estimates that implementing a 10 kWp PV array can lead to annual diesel fuel savings of 4,200–5,200 liters for a 10-hectare vineyard, further emphasizing the economic and environmental advantages of renewable energy integration in agriculture.

Distance (m)	Cost (€)
$D \leq 200$	186
$200 < D \leq 700$	279
$700 < D \leq 1200$	836
$D > 1200$	1950

Figure 13 - Costs of connecting to the grid according to the distance

Semi-Transparent PVs in Greenhouses

STPVs in greenhouses are being tested with all the technology available nowadays. We have modules based on c-Si, thin-film (a-Si, CIGS, and CdTe), Dye-Sensitized Solar Cells (DSSCs), (Organic PV) OPV, and perovskite, as well as novel technologies of concentrating PVs (CPVs) and luminescent solar concentrators (LSCs) [1]. We have seen above how we can achieve semi-transparency and now we will see how these technologies are being tested in greenhouses.

The study [17] provides a global assessment of photovoltaic (PV) applications in greenhouse farming. The research highlights the potential of semi-transparent solar modules in greenhouses, showing that APV systems could reach transparency factors of approximately 68% while maintaining optimal crop growth. The results indicate that APV could produce up to 200 kWh/m² annually without negatively affecting plant photosynthesis. The study focuses on four key agricultural regions, Spain, Italy, Turkey, and Mexico. Analyzing different crop types (e.g., tomatoes, cucumbers, cereals).

c-Si (Crystalline Silicon)

The study [18] presents an approach of two PV spherical modules (Figure 14) made of c-Si, where semi-transparency was obtained through spatial segmentation. The 2 approaches were implemented with efficiencies of 4.5% and 1.6% (These efficiency values are referring to the overall area efficiency). For PV1, 39% of the area was covered with the spherical cells and for PV2 only 13% of the area was covered. When irradiated with 1213 Wm⁻² of sunlight and ground reflection, the PV1 module had a peak output of 540mW and PV2 only had 202mW. For PV1 we have a density of 15.4 cells cm⁻² vs 5.1 cells cm⁻² for PV2 with an occupied area of 97.2 cm². Of course this study was made in much less area than we usually see in silicon solar cells, but it was used as a proof of concept for spatial segmentation.

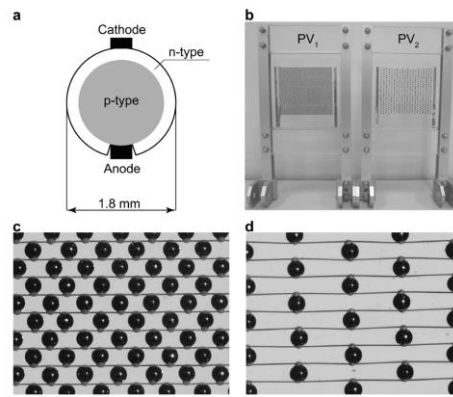


Figure 14 - a) Structural illustration of the spherical SC, c) PV1 with 39% area coverage, d) PV2 with 13% area coverage

This study also provided an estimated yearly production of the electrical energy (East and West roof coverage) of 1.1 million kWh per year for PV1 and 0.074 million for PV2.

Table 1 – Estimation of annual electrical energy production by PV ₁ and PV ₂ modules mounted on greenhouse roofs.			
Greenhouse orientation	PV module	PV roof coverage	Annual electrical energy production per unit greenhouse area ^a (kWh m ⁻² yr ⁻¹)
East–west	PV ₁	South roof only	64
		North roof only	39
		South and north roofs	102
	PV ₂	South roof only	23
		North roof only	14
		South and north roofs	36
North–south	PV ₁	East or west roof only	55
		East and west roofs	110
	PV ₂	East or west roof only	20
		East and west roofs	39

^a $p = 0.65$; albedo = 0.20; cloudless sky; $\beta = 26.5^\circ$; present study location (35°29'N, 133°04'E).

Figure 15 - PV electrical production regarding the orientation of the PV module

In another study [19], c-Si double glazed PV were mounted on 20% of the top of a greenhouse. Each module had a peak power of 170 Wp and efficiency of 8.25%. The results revealed that the annual generated electric yearly energy was 110 kWh/m². Furthermore there were no significant differences in the growth of the tomatoes between the shaded and the control greenhouses.

a-Si (Amorphous Silicon)

In this next study [20], the greenhouse is formed by a simple rectangular structure 12 m long and 2.5 m wide, with a monopitch roof, oriented to the southwest, and with a 35° inclination. The greenhouse is divided into two contiguous equal sections, each with an area of 15 m², and physically separated by an interior partition transparent wall as shown in Figure (16). With a transparency of 30% and a rated output power of 22W per module (1320W in total), it was used lettuce and broad beans in the study and the complete vegetative cycle of the broad beans had not ended by the time the study concluded but they had enough recorded growth measurements to have some results.

The mass of lettuces in both sections after harvesting were similar. This is not a result because in the autumn-winter cycle dates there is not much sunlight available and the reduced radiation result in a lower photosynthetic capacity,

therefore, less production of plant tissues. The beans did also not have a great impact on their growth.

The semitransparent amorphous silicon PV panels occupied 20% of the roof surface and reduced radiation by 35–40%. Therefore, it is interesting to note that the crops, both lettuce and broad beans, have been able to develop similarly despite the fact part of the incident PAR radiation was reduced, with part of the light being used for electricity generation.

During the study period (18 October 2019–29 November 2019), the installed PV system produced 90.15 kWh. In that period, the energy demanded had a positive net balance, which means that PV panels are able to provide 100% of the energy demanded in this case. It shows, therefore, that the greenhouse is completely self-sufficient for the studied site. Taking this numbers of 90.15 kWh in 41 days, we get an average of 802 kWh per year.



Figure 16 - Greenhouse setup used for the study [21]

In another study [21], used an a-Si STPV module that strongly absorbed the UV rays and let the rest go to plants. In this study it was also demonstrated that even though they got a yield loss of biomass, the calculations for financial overall gain (electricity and yield) were positive, 2.5% for basil and 35% for spinach. In the following figure we can better see the differences between both growth conditions as well the values for several aspects measured by the team. In summary the Figure 17 (A) and (B) are images of the spinach of the growth with clear glass on top (GU-C) and the spinach growth with the STPV on (GU-PV), (H) and (I) being some leaves from the GU-C and GU-PV, respectively. C, D, E, F and G are the aspects measured where we can see that in total biomass, root biomass and leaf+stem biomass with the clear glass (white bar) on top was beneficial but in photosynthetic use of solar radiation and Tissue energy distribution we had better values when we had the STPV on top (orange bar).

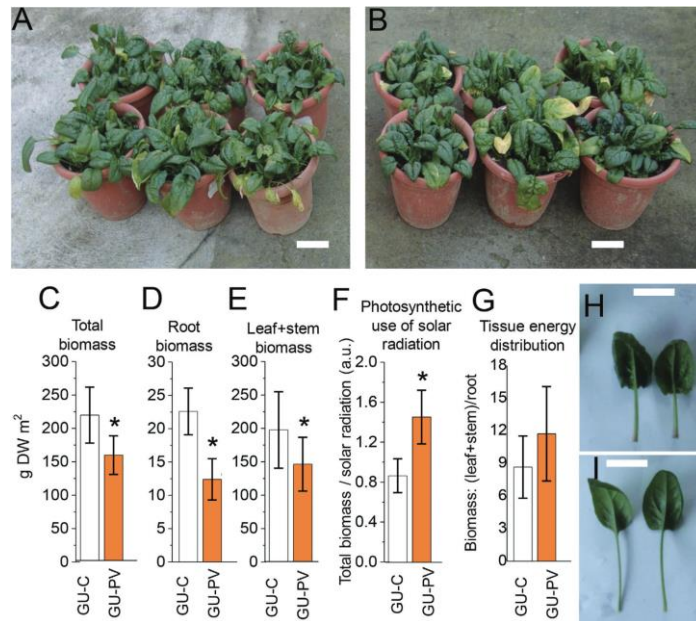


Figure 17 - (A) is the spinach with clear glass on top (GU-C); (B) is the spinach growth with the STPV (GU-PV); (H) and (I) leaves from the GU-C and GU-PV, respectively; (C), (D), (E), (F) and (G) measurements: biomass, root biomass and leaf+stem biomass with Clear Glass (white bar) and with STPV (orange bar).

Organic PVs

Many of the photovoltaic solutions previously discussed share a common challenge: reducing the total amount of available light for plant growth. However, organic photovoltaics (OPVs) offer an alternative approach, utilizing abundant, non-toxic materials, low-temperature processing, and cost-effective, fast manufacturing techniques. Additionally, OPVs can be wavelength-selective[7], potentially shifting APV from a solar-sharing concept to a selective solar spectrum utilization strategy [22].

Theoretically, OPVs could produce more energy per unit area due to their greater design flexibility, but the narrower absorption spectrum limits their maximum theoretical efficiency. Unlike broad-spectrum absorbers, OPVs cannot surpass the efficiency of solar cells that capture the entire solar spectrum. However, their ease of integration into flexible substrates and plastic materials broadens their application potential. Despite these advantages, OPV efficiency and stability are significantly affected by oxygen exposure, heat, moisture, irradiation, and morphological changes over time [7]. The semitransparency of an OPV module depends on the thickness of the absorber and transport layers, reducing thickness enhances transparency but at the cost of lower efficiency, and vice versa.



Figure 18 - Different ways of installing Organic STPV modules in a greenhouse facing different directions. Adapted from ([8])

A computational study [22] analyzed the effect of semi-transparent organic solar cells on tomato crop growth under different transmittance levels. The study used organic STPV modules with 9.4% power conversion efficiency (PCE) and 24.6% average visible transmittance (AVT), integrated into a greenhouse design. The simulations estimated that with an installed capacity of 18.48 kW, these OPV modules produced 9,147 kWh over a 90-day cycle. Using a global average of 5.5 full-sun hours per day, the annual energy yield was calculated at 36,588 kWh/year. Additionally, the study conducted a detailed analysis of Photosynthetic Photon Flux Density (PPFD) to assess plant response under these conditions.

A study in [23] applied spatial segmentation, similar to our approach, to analyze how different AVTs impact PAR transmission and plant growth. Although they utilized OPV modules instead of CIGS-based STPV, the objective remained

the same: quantifying the effects of different AVTs on photosynthesis and energy production. The results showed that only configurations with 47% total roof coverage (using OPV and polyethylene film) maintained the minimum PAR transmission threshold of 4 MJ/m² per day, which corresponds to 60% transmittance of PAR. The study simulated three AVT values, 30%, 45%, and 60%, applied to two rows of tomato plants, leading to the following photosynthesis rate reductions: 33%, 21% and 12%, respectively. They also simulated the yearly power production which was 323, 242 and 158kWh/m² /year, respectively. These results confirm that higher AVT values lead to lower energy production but also minimize the impact on plant photosynthesis, demonstrating the trade-off between energy harvesting and agricultural productivity

Another study related to the application of organic photovoltaic (OPV) modules in greenhouses is presented [24]. It considers the impact of nonhomogeneous shading by semitransparent OPV modules, placed on the cover of a greenhouse tunnel housing a tomato crop. Experiments were conducted in two similar tunnels covered by a diffuse polyethylene sheet. Flexible semitransparent strips of OPV modules were placed on 37% of the roof area of one tunnel, creating an approximately 23% nonhomogeneous shading, while the other tunnel, homogeneously shaded by a 25% black shading net, served as a control greenhouse. The results show that on cloudy days (high diffuse radiation), spatial variability of radiation in the OPV tunnel was smaller than on sunny days (low diffuse radiation).

The presented study focused more of its efforts in Vapour Pressure Deficit (VPD) and other forms of energy like heat, not giving information about the OPVs energy production. But once again proves that nonhomeogeneous shading problems can be mitigated and that, even if the available irradiance drops, plants can still grow and we can still produce energy meanwhile.

DSSCs

The main difference between organic solar cells (OSCs) and dye-sensitized solar cells (DSSCs) lies in their composition and working principles. OSCs are made of organic materials, such as polymers or organic molecules. On the other hand, DSSCs use a dye that is sensitive to light to generate electricity and are known for their effectiveness in low-light conditions, such as at dawn or dusk.

One advantage they share with OPVs is that they don't need to be spaced out to achieve semi-transparency. Instead, they only let part of the light go through. That can be a major benefit if the wavelength collected is not helpful for plants (only Photosynthetically Active Radiation (PAR) matters for plants from 400 – 700nm).

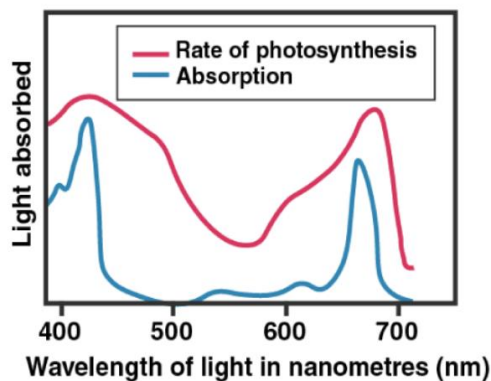


fig 6 - Adapted from <https://byjus.com/global/>

Semi-transparency can also be achieved by reducing the thickness of the absorbing layer. One of the major advantages of these technologies is that they can substitute the glass used on the top of greenhouses, making it a synergetic relationship toward price reduction. Greenhouses also provide large enough installation surface areas, which is a major advantage for low-energy module deployment.

In summary, the main conclusions about these technologies are that STPV modules can mitigate the effect of shadow on crops because the light is more continuous and sorted on STPV than on opaque PV modules. Thin-film STPV modules are promising technology for the roof of greenhouses due to their synergetic relation with substituting the glass on top of it, bringing the overall price of the greenhouse down. DSSCs are flexible, lightweight, and work under diffuse light, which is a major advantage, but they need to improve efficiency if they want to compete with thin-film modules, for example. Wavelength-selective PVs can be promising if we let PAR go through and only use the rest of the spectrum to power our solar cells, and in Concentrated PV, we can save much space, and plants would still get the diffuse light they need to grow. The main advantages are mitigating the shadow effect and the possibility of cost reduction once all the efficiency problems are dealt with. The use of 99% less absorbing material than normal PV also means we have less impact on earth mining.

We know at this point that CIGS technology can help control the temperature inside the greenhouses due to the fact that it can reduce the amount of solar energy reaching inside. Because of this fact we might be solving another problem of the greenhouses in extreme conditions of huge amount of solar radiation, like around the equator line. In this area the temperatures can rise above some plants limit. In this case, having a solar technology capable of permitting ideal light to plants while absorbing the rest to produce energy and lower temperatures inside the greenhouses poses an enormous synergy between agriculture and photovoltaics.

CPV in Greenhouses

This paper [25] examines the potential of transparent CPV modules with tracking integration for dual-use agricultural applications. The study introduces a direct-diffuse light-splitting CPV system, which efficiently separates direct sunlight for energy conversion while allowing diffuse light to pass through to crops. The system was tested in greenhouses and compared to conventional silicon solar arrays, showing that CPV could generate similar power while maintaining better light distribution for plants. Worth noting that CPV tracking systems significantly increase solar energy capture without excessive shading and that the system effectively splits light, allowing PAR wavelengths to reach crops while capturing other wavelengths for energy conversion, showing that CPV integration in greenhouses is feasible, maintaining crop growth while ensuring stable electricity generation.

The next study [26] presents a new CPV approach using diffractive and interference technology to selectively split sunlight into wavelengths necessary for plant growth and those suitable for solar energy generation. The technology was successfully tested in field trials, showing promising results for simultaneous crop growth and power generation. The study suggests that only 10% of sunlight is needed for optimal plant growth, meaning the remaining 90% could be utilized for solar power generation. This does not necessarily mean that only 10% of the light goes through but instead, that the 10% refer to the wavelengths of the sunlight that are used for the plants, the other 90% of the total wavelength goes to electricity production.

Diffractive CPV technology enhances both energy production and agricultural yield. By blocking Near IR and Far IR light, CPV also reduces water evaporation, an advantage in arid regions and the system allows for customizable sunlight filtering, optimizing light conditions for different crops.

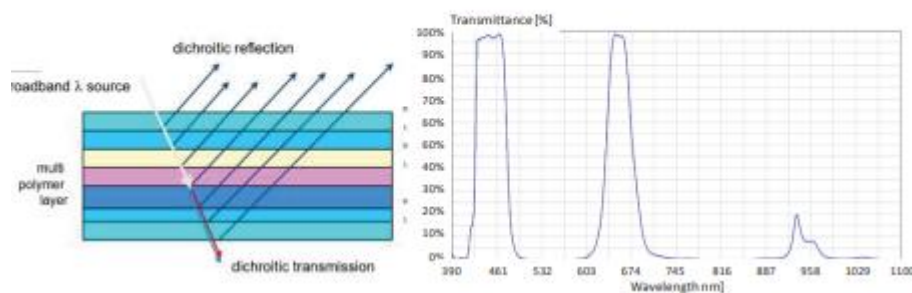


Figure 19 - Demonstration of how the selective split of lighting works, from [26]

This research [27] evaluates a CPV greenhouse system using static linear Fresnel lenses to concentrate direct sunlight while allowing diffuse radiation to pass through to crops. The tracking-integrated Fresnel lens system demonstrated a high thermal efficiency, significantly reducing cooling demand in summer. The system achieved an electrical efficiency of 11% and a thermal efficiency of 56%, resulting in an overall efficiency of 67%. Regarding this study we can take that

Fresnel lenses effectively separate direct and diffuse light, optimizing greenhouse conditions. CPV integration reduces cooling needs, making it ideal for hot climates and Hybrid CPV-Thermal systems could store excess thermal energy for winter heating.



Figure 20 - Linear Fresnel lenses focusing light on a strip of a PV module taken from [27]

In Figure 20 we can see an example of how our technology could be implemented in APV.

Shadow problems on greenhouses

In [28], a grape farm was used as the test site, with three control farms and three different solar panel configurations under evaluation. The results showed that no major differences were observed in grape production across the three types of panels, suggesting that under certain conditions, solar panels may not significantly impact plant growth. However, this finding does not universally apply to all crop types, as subsequent studies indicate stronger dependencies on light availability and panel configuration.



Section B

Section D

Section F

Figure 21 - Section A,C and E where the control sections. Section B – normal PV module. Section D – Bifacial module. Section F – transparent type [28].

All test sections maintained a 30% panel coverage of the total roof area, with each configuration having an equal system capacity of 33 kW. Despite the different solar panel types, no significant impact on grape yield was detected, suggesting that under the given conditions, the shadow effect was similar in all sections and configurations. The total electrical output from the panels reached 55 MWh over a five-month period.

The impact of shading depends significantly on the type of solar panels used. In [29], opaque panels arranged in a linear pattern blocked up to 40% of sunlight, significantly reducing plant growth. Even when reconfigured into a checkerboard pattern, crop yield remained negatively impacted, although to a lesser extent. Unlike opaque panels, semi-transparent PVs (STPVs) enhanced photosynthesis and plant development. The study showed that STPVs actually increased photosynthetic activity, proving that controlled light transmission can optimize plant growth rather than hinder it. These findings reinforce that the amount of available light is a major determining factor in plant development and that STPV can serve as an effective compromise between energy production and maintaining agricultural productivity.

The percentage of greenhouse coverage by solar panels directly affects crop yield. In [29] and [30], opaque solar panels covering 30-40% of the greenhouse area negatively impacted crop yield due to excessive shading. In contrast [31], found that reducing panel coverage to 20% allowed for a better balance, still enabling an annual energy production of 637 kWh. Studies suggest that adaptive placement strategies, such as adjusting panel angles or spacing them more effectively, could allow for better light distribution. Dynamic panel orientation, as explored in the single-axis agrivoltaic study, shows potential to optimize crop growth while maximizing energy generation. The CIGS STPV approach, which uses fine structured PV lines, can achieve better results by

minimizing shading impact while still generating energy. Future research should investigate the best placement strategies for different types of crops and seasonal variations.

Another study [31], was selected due to its use of spherical solar cells measuring only 1.8 mm, which produced minimal shading on the plants. This shading effect is similar to that of CIGS microstructured PV lines, which in this research are being tested. The smaller the shading structures, the less disruptive they are to plant growth, allowing better light diffusion. This confirms that structured segmentation, as in the STPV design, could help minimize shading intensity compared to standard opaque PVs. This study further supports the hypothesis that fine-tuned PV microstructures could allow for better plant development while still contributing to energy generation, making it a promising direction for further research.



Figure 22 - From left to right. STPV shaded greenhouse. Lettuce growing inside Greenhouse. Control Greenhouse

The impact of shading varies depending on the photosynthetic requirements of each crop. The study in [29] showed that high-light crops such as tomatoes and peppers were significantly impacted by shading, whereas low-PPFD crops such as lettuce, spinach, and cabbage adapted more easily. In contrast, the grape farm study in [28] showed no significant reduction in yield, suggesting that certain crops are more resilient to reduced sunlight levels. This reinforces the importance of choosing the right crops for agrivoltaic applications. Low-PPFD crops like lettuce, spinach, carrots, and broccoli could be the best candidates for STPV integration. Future experiments should include multi-crop analysis to determine which plants can thrive under specific solar panel configurations.

Unlike conventional opaque solar panels, the CIGS-based STPV system allows for a higher level of irradiance control, directly depending on the Average Visible Transmittance (AVT) selected. Unlike opaque panels that create strong shadow contrasts, microstructured CIGS lines allow gradual light diffusion, preventing the formation of dark microclimates. Since transparency (AVT) can be adjusted based on plant requirements, the system can be tailored to different crops and seasonal conditions. The results in [29] and [31] suggest that opaque PV's impact on crops can outweigh the benefits of energy production. The STPV system reduces this trade-off by allowing more light through while still generating electricity. Unlike fixed opaque panels, the structured STPV design could potentially be adjusted dynamically, further optimizing performance throughout the year.

The studies confirm that opaque PV panels can severely impact crop growth, but strategic design choices such as semi-transparency, spatial segmentation, and dynamic adjustments can significantly mitigate these effects

Cu(In,Ga) Semi-transparent solar cells

Semi-transparent Solar Cell Design

Spatial segmentation of opaque solar cells is a viable approach to achieving semi-transparency in photovoltaic applications. However, there is an inherent trade-off between Average Visible Transmittance (AVT) and Power Conversion Efficiency (PCE). Reducing the spacing between solar cells increases PCE by maximizing the active area available for energy generation, but simultaneously decreases AVT, limiting the amount of light that can reach the underlying environment. Conversely, increasing the spacing improves light transmission at the cost of lower energy output, as illustrated in Figure 23.

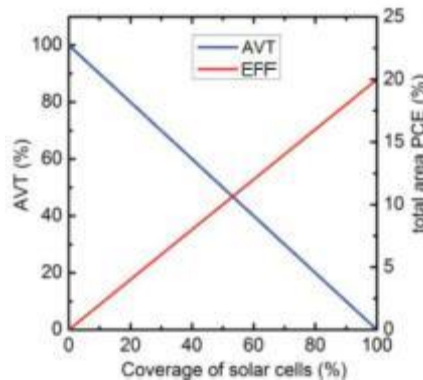


Figure 23 - Image adapted from J. M. Salgado Fonseca PhD thesis
AVT and efficiency (EFF) or PCE as a function of the coverage of solar cell

One of the key objectives of this thesis is to develop and optimize the fabrication processes of CIGS-based semi-transparent solar cells to demonstrate their potential for integration into agrivoltaic (APV) applications. The study focuses on enhancing the deposition, patterning, and structuring techniques required to create efficient, semi-transparent CIGS thin-film solar cells, ensuring that they meet both energy generation and light transmission requirements for agricultural environments.

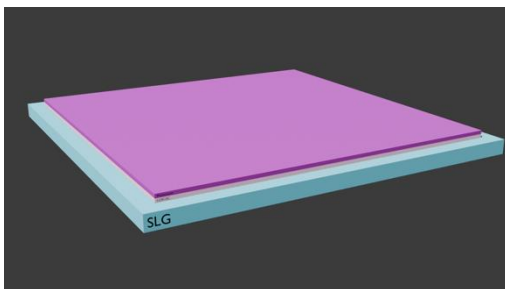
A critical aspect of this research is the optimization of spatial segmentation strategies, where different line spacing configurations will be explored to achieve varying Average Visible Transmittance (AVT) levels. Since AVT is directly correlated with Photosynthetic Photon Flux Density (PPFD) and solar intensity, this approach allows for fine-tuning the balance between photon absorption for energy conversion and light availability for crop growth. To validate the feasibility of CIGS-STPV in agrivoltaics, advanced characterization techniques will be employed to analyze the optical, electrical, and structural properties of the fabricated solar cells.

STPV Fabrication Process

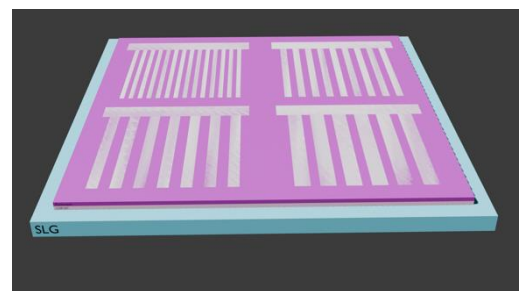
Micro-structured CIGSe STPV can be fabricated following two different approaches: top-down and bottom-up. In the top-down we start from full solar cell stack and remove selected parts of that, i.e., the window layer (ZnO:Al and iZnO), a buffer layer (CdS), CIGS, and back contact, stopping at the soda-lime glass substrate. Techniques such as reactive ion etching (RIE) or wet etching are used to create the desired pattern for the overall device. These tend to function in an anisotropic or isotropic manner. Although each has its uses, anisotropic etching is often preferred as it offers extra control over the process. On the other hand, the bottom-up approach, which we will follow in this work, consists of building upon the base layer, the substrate. After cleaning procedures are performed to remove particles from the soda-lime glass (SLG) substrate, the fabrication process begins with the sequential spin-coating of a lift-off resist (LOR) layer followed by a photoresist (PR) layer (1). These layers are then patterned via photolithography to define the geometry of the solar cell's active lines (2). The pattern is then developed, removing the exposed material and etching the design into the surface (3). Next, the back contact layer of molybdenum (Mo) is deposited using DC sputtering (4), followed by the deposition of the Cu-In-Ga (CIG) metallic precursor via the same method (5). In practice, both steps (4) and (5) leave the same amount of material on top of the photoresist (PR), but for illustrative purposes, this was not shown. A lift-off process is then carried out, in which the underlying PR and LOR are dissolved in an ultrasonic bath, leaving behind well-defined CIG patterns atop the Mo/SLG structure. (6)

The CIG is then converted into CIGSe (Cu(In,Ga)Se_2) through a selenization step performed in a tube furnace under selenium vapor (7). The process concludes with the deposition of the buffer layer (CdS) by chemical bath deposition (CBD) (8), followed by the window layers, intrinsic ZnO (i-ZnO) and aluminum-doped ZnO (ZnO:Al), deposited by RF sputtering (9).

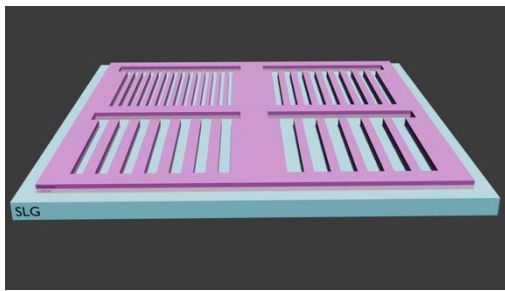
A visual summary of the fabrication steps is presented in Figures below, illustrating stages (1) through (9).



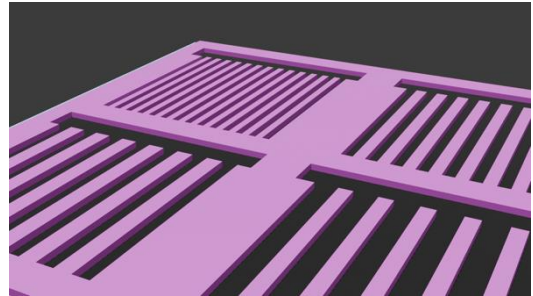
(1) – LOR10C and PR deposition on top of SLG glass



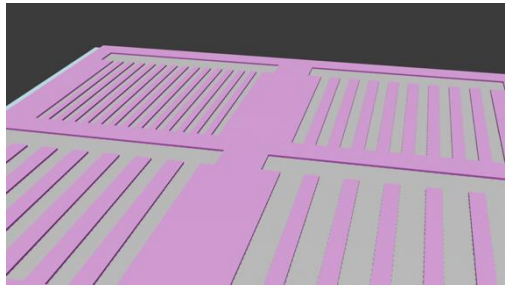
(2)– DWL pattern exposing in PR and



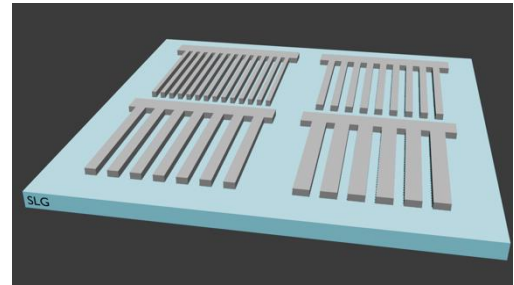
(3)–Developing exposed PR and LOR10C



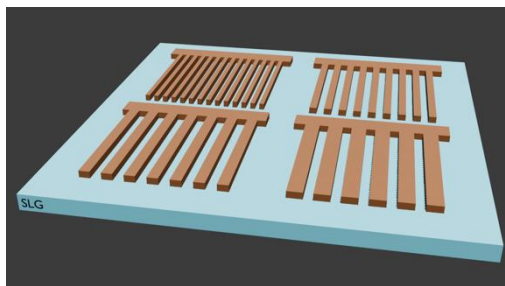
(4)– Molybdenum deposition



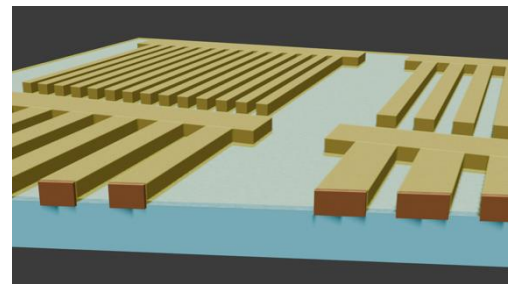
(5)–CIG layer deposition



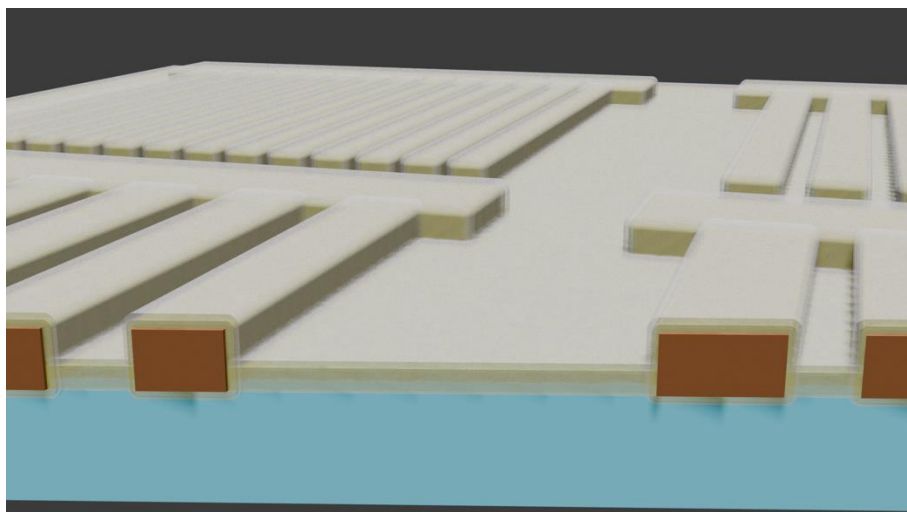
(6)– Lift off LOR10C and PR



(7)–Selenium incorporation



(8)–CdS buffer layer depositiopn



(9)– intrinsic ZnO (i-ZnO) and aluminum-doped ZnO (ZnO:Al layers depositiopn

Spin Coating LOR and PR, Exposure and Development

We begin by coating the surface of our samples with LOR and PR using a spin coating machine, which ensures uniform deposition of the desired layer thickness. Intermediate measurements are performed using a profilometer to verify that the deposited layers meet the required specifications.

Following this, the samples are processed using a Direct Writing Laser (DWL), where they are exposed to a high-intensity laser that selectively alters the solubility of the photoresist (PR) and lift-off resist (LOR). In the case of a positive PR/LOR, the exposed regions become more soluble, while for a negative PR/LOR, the exposure results in hardening of the material. The DWL system operates based on a pre-designed AutoCAD file, allowing precise patterning of the 5×5 cm² sample. This enables control over the AVT and the width of each line in our solar cell structure.

The figure below illustrates the pattern designs used in this study, where a 5×5 cm² substrate is divided into four 2.5×2.5 cm² squares. Each bus bar within these squares has a length of 17.5 mm, while the individual lines are 15 mm long, with varying widths of 400, 500, 600, and 700 μm, corresponding to decreasing AVT values while we increase the widths of the lines, illustrated by Table 1. Dividing the 5×5 cm² sample into smaller sections ensures compatibility with the graphite box used during the selenization process, facilitating controlled processing conditions. The Figure 24 presents the AutoCAD mask employed for structuring the sample.

Line Width (cm)	Opaque Area + Bus Bar (cm ²)	Total Area (cm ²)	% Opaque	AVT (%)
0.04	0.615	2.625	23.43	76.57
0.05	0.675	2.625	25.71	74.29
0.06	0.735	2.625	28.0	72.0
0.07	0.795	2.625	30.29	69.71

Table 1 - Calculated AVT values for each CIGS line width (400 μm to 700 μm), including the contribution of the bus bar area to total light blocking

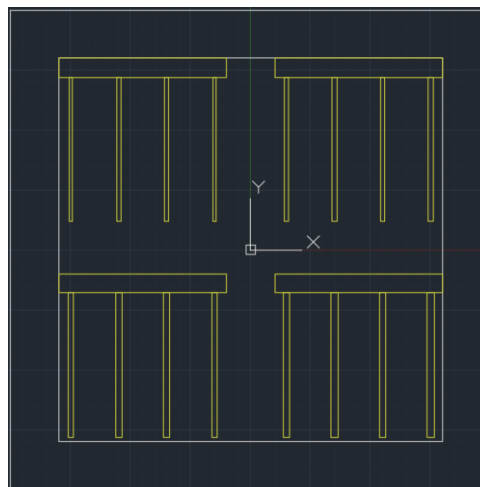
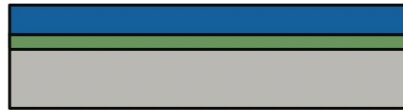
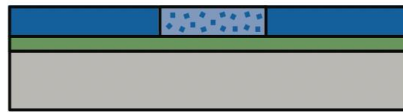


Figure 24 - AutoCAD mask used to pattern the PR-
Top left (400 μm) Top Right (500 μm)
Bottom Left (600 μm) and Bottom Right (700 μm)

After the coating and exposure, the development process is carried out. This step involves the removal of the exposed LOR and PR layers, which have become more soluble due to laser exposure, using a developing solution. This process ensures that only the desired pattern remains intact on the sample. Once the development is complete, the sample is prepared for the first material deposition, which is molybdenum (Mo).



2. Coat and soft-bake imaging resist.



3. Expose imaging resist.



Figure 25 - All 3 steps of lithography

Molybdenum Sputtering

Sputtering is the process whereby atoms or molecules of a material are ejected from a target by the bombardment of high-energy particles. [32]

In this study, a DC source is used to maintain a potential difference between two electrodes, which sustains the plasma. This plasma consists of accelerated ions of a noble gas, typically argon (Ar), which gain high energy due to acceleration. The acceleration is generated by a set of magnets surrounding the target and an additional magnet positioned at the center. The outer and inner magnets have opposite poles facing upward, creating a magnetic field directed inward through the molybdenum target. The accelerated Ar ions collide with the target, ejecting atoms of molybdenum. These atoms then travel a certain distance until they reach and deposit onto the sample, which is positioned facing the target. The deposition continues until the desired molybdenum thickness is achieved.

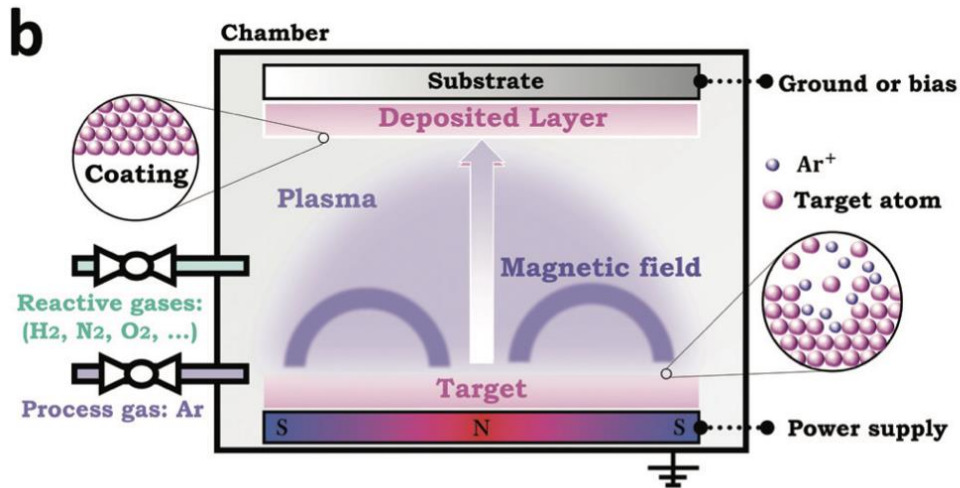


Figure 26 - Visual example of magnetron sputtering on the inside of STAR machine at LaNaSC, adapted from [33]

CIG Sputtering

The CIG layer was deposited using a sputtering process with a CIG target. The composition of the target used was 50/35/15 at% of Cu-In-Ga, and the EDX analysis performed on multiple samples showed a slightly different material composition of 49/34.5/15 at% of CIG, indicating that the target was depositing as expected.

The thickness of the deposited layer is not entirely uniform across the surface of the sample due to positional variations relative to the target. The corners of the sample are not perfectly aligned with the center of the target, leading to higher deposition in the center and lower deposition in the corner regions. However, this variation is not considered significant for the purposes of this study.

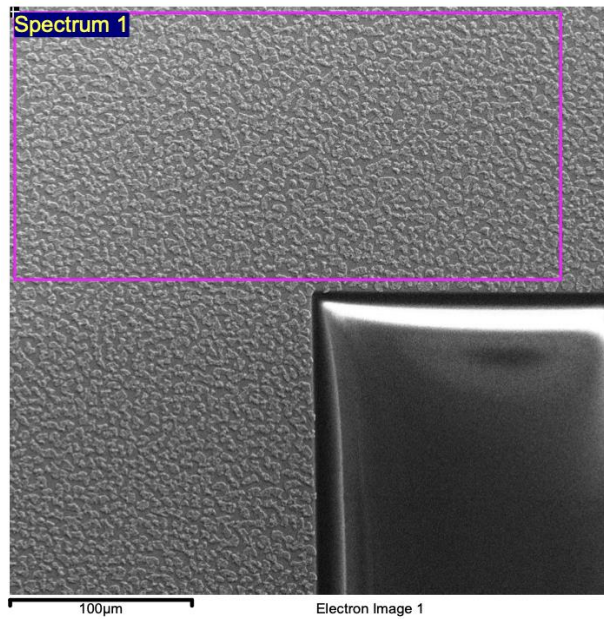


Figure 27 - SEM image of sample B

In the SEM image, small “islands” can be observed on the sample surface. EDX measurements taken inside and outside these islands revealed significant differences in composition. Inside the islands, the CIG content was measured at 47.1/38.9/14 at%, whereas outside, the composition shifted to 68.7/16.6/14.7 at%.

The sputtering process was performed using a sputtering system at INL known as Sputtering for Advanced Research (STAR) [34]. This system consists of three interconnected vacuum chambers, each dedicated to a specific sputtering process.

- The main chamber, located in the center, is used for loading the samples and depositing the molybdenum layer.
- The window chamber, positioned to the left, is used for depositing the window layer via an RF sputtering process. This is the final step in the fabrication of our solar cells.
- The CIGS chamber, on the right, is designated for depositing copper, indium, and gallium through DC sputtering, while selenium is introduced via evaporation. However, due to various issues, this process was not utilized in this study.

Each chamber in the system is separated by gate valves, which remain closed unless samples are being transferred between chambers. The system employs individual pumping mechanisms for each chamber, ensuring that vacuum conditions are maintained at approximately 1×10^{-7} mbar.

One of the strategies to enhance CIGS-based solar cell efficiency is by tuning the conduction band via control of the gallium (Ga) fraction in the $\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGS) absorber. This can be described by the compositional ratio:

$$\text{CI}_{1-x}\text{G}_x\text{S}$$

where $x = \frac{Ga}{In+Ga}$.

The bandgap varies based on the Ga fraction:

- For $x = 0$ (CIS - Copper Indium Selenide), the bandgap is 1.04 eV
- For $x = 1$ (CGS - Copper Gallium Selenide), the bandgap increases to 1.69 eV

This tunability allows for optimization of the absorption spectrum, improving charge carrier separation and efficiency in different lighting conditions. [36]

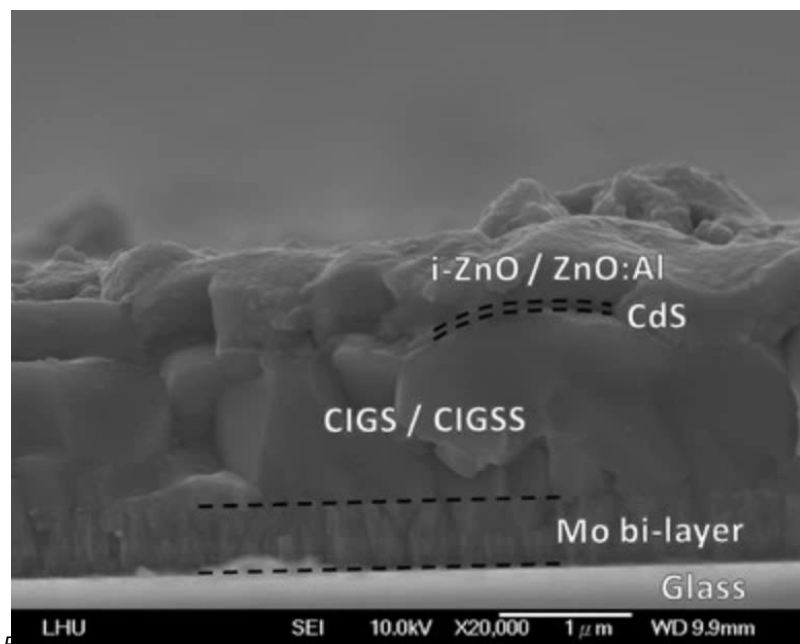


Figure 26 – SEM image of an example of thin-fabricated CIGS solar cell taken from [37]

This technique was not used because we were only using a ternary target made of Cu, In and Ga in defined percentages. Another way of enhancing the CIGS solar cells would be the sulfurization of the CIGS turning it into CIGSS as we can see in figure 28.

Lift Off

In the lift-off process, MR500 and MR700 were used to remove the layers deposited on top of the photoresist, allowing for the patterning of the deposited materials. The primary difference between the two solvents is that MR700 is less toxic and has a faster removal rate. However, no significant differences were observed in the final results between samples processed with MR500 or MR700, although no in-depth comparative analysis was conducted.

The process consists of submerging the samples in MR500 or MR700 while using a frequency generator to accelerate material removal. During this step, the solvent infiltrates the photoresist (PR) lines, dissolving the resist and stripping away the deposited material on top. For this to occur effectively, the PR layer must be thicker than the deposited material, ensuring proper undercutting and lift-off. As the solvent reacts with the PR over time, it dissolves the layer completely, leaving behind well-defined thin-film patterns.

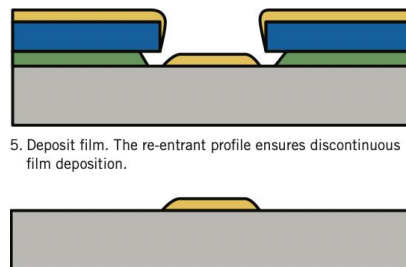


Figure 29 - Before (up) and after (down) the lift of process, blue and green is the PR and yellow as the sputtered layers of material

Selenization

To obtain CIGS, two methods can be used: selenization using selenium pellets or direct incorporation of selenium gas, as available in the STAR system. In this study, the selenization in the tube furnace was the chosen process to convert the CIG layer into a CIGS absorber layer, as the CIG precursor alone is not yet fully functional for photovoltaic applications. We chose this method because the right chamber was having problems on the selenium valve, failing to deploy the amount of selenium wanted into the chamber, making it unusable.

The selenization process takes place in a tube furnace, where the atmosphere inside is heated to 500°C, enabling selenium inside a graphite box to incorporate into the CIG material through absorption, diffusion, and reaction. The selenium reacts with the deposited CIG layer, forming the final $\text{Cu}(\text{In,Ga})\text{Se}_2$ (CIGS) absorber.

In this study, the selenization process was carried out using a tube furnace equipped with a quartz tube (Figure 30). The quartz tube contains a gas inlet (left) and exhaust (right) and is connected to a vacuum pump. During the process, the sample is placed inside a graphite box together with selenium pellets. A quartz glass square is positioned between the selenium pellets and the substrate.

Before heating the tube furnace, a purging process is performed to remove any unwanted gases and molecules in the air. This consists of three pump-and-flush cycles with nitrogen (N_2) followed by two cycles with argon (Ar). All selenization processes were conducted at atmospheric pressure with an argon flow of 100 sccm, ensuring a controlled reaction environment.



Figure 30 - Tube Furnace inside the LaNaSC group lab at INL

CdS Chemical Bath Deposition

In this part of the process we deposit the buffer layer of cadmium sulfide through a chemical bath deposition. This process is used to deposit a layer of CdS and form the p-n junction. This process is widely used in CIGSe solar cell fabrication also because of the good band alignment with CIGS and the process was optimized to deposit an homogenous layer, forming a consistent deposition [35].

To deposit this layer, a chemical bath deposition (CBD) process is used, requiring cadmium salt, ammonia, thiourea, and water. The first step involves measuring the precise quantities of each reagent, which were previously calculated to achieve a 50 nm thick layer.

Once the required amounts are determined, the chemical agents are mixed in a specific sequence to ensure proper reaction and formation of the final deposition solution. The sample is then introduced into the solution using a substrate holder, which keeps it properly still for uniform deposition.

The deposition process takes place inside a water bath heated to 60°C, ensuring that the reaction conditions remain stable. The substrate holder, containing the sample, is immersed in the deposition solution and the beaker containing the sample and deposition solution is placed in the water bath, which remains separate to maintain temperature control and to not mix both water and the solution. At this point, a timer is started, and the reaction is allowed to proceed for approximately 8 minutes, the duration was calculated to achieve the desired 50 nm thickness.



Figure 31 - Beaker containing the sample holder (white) and the solution that deposits the window layer (yellow)

Window Layer Sputtering

To finalize the fabrication of the solar cell, the window layer is deposited to act as the top contact, ensuring efficient charge collection while allowing light transmission to the absorber layer. This layer is composed of 50 nm of intrinsic zinc oxide (i-ZnO) and 200 nm of aluminum-doped zinc oxide (ZnO:Al). The deposition process is performed using the Sputtering for Advanced Research

(STAR) system, utilizing RF sputtering due to the insulating properties of ZnO, which prevent it from being deposited using a DC source.

The objective of this step is to form a transparent and conductive contact that facilitates current extraction from the absorber layer. Since this layer serves as the top contact, it plays a crucial role in determining the overall performance of the solar cell by optimizing both electrical conductivity and optical transparency.

Characterization

Scanning Eletron Microscopy (SEM)

SEM is a microscopy technique that produces images of solid materials by scanning the sample with a focused, high-energy electron beam. These images are acquired by the interaction between the eletron beam and the sample. When the incident eletrons are deflected by the sample at an angle higher than 90° then we call them backscattered eletrons (BSE). These electrons yield a useful signal for imaging the sample because they are part of the elastic scattering, which means they keep a high percentage of their initial energy. Inelastic scattering on the other hand occurs when the electrons of the beam lose substantial energy to the sample atoms, causing their ionization. This transfer of energy causes eletrons from the sample to excite, leaving the sample, which are called secondary eletrons (SE). These electrons possess low energy, around 3–5 eV, therefore, those generated at deeper sample regions are absorbed, and only SE from a region within a few nanometres of the material surface can escape. Characteristic X-rays are also formed when an outer orbit electron drops to a lower energy level to fill the vacancy of a SE. Thus, by the emission of an X-ray photon, the ionized atom returns to the ground state. The analysis of the X-rays provides chemical information of the samples materials and stoichiometry. Such analysis is called energy-dispersive X-ray spectroscopy (EDX). In Figure 32 we can see different signals obtained by using SEM.

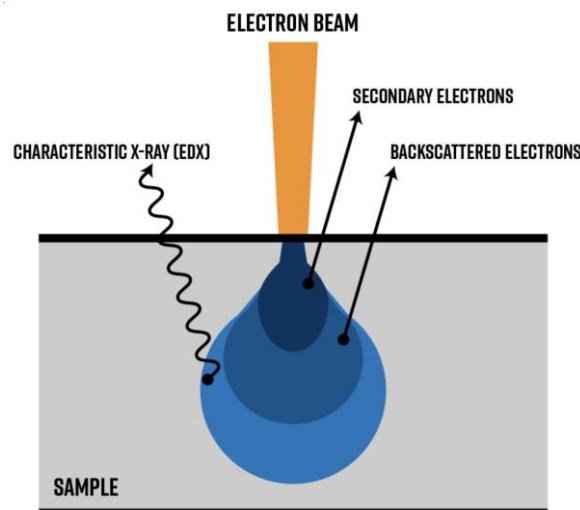


Figure 28 - Several interactions that can occur when using SEM

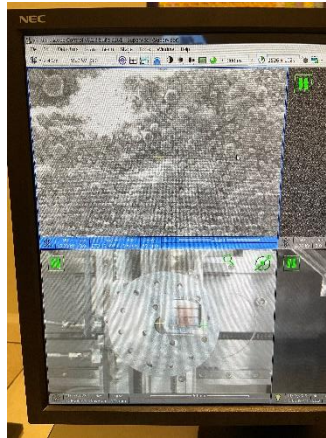


Figure 29 - Topographic visualization of a sample magnified 2474x in SEM



Figure 30 - topographic visualization of a sample magnified 424x in SEM

X-Ray diffraction

X-ray diffraction (XRD) is an analytical instrument that analyzes the crystalline structure of a material. When a beam of X-rays is directed toward a crystalline material, the X-rays are scattered in every direction, interfering constructively or destructively, depending on their phase and producing a diffraction pattern. This diffraction pattern is a result of the interaction of the X-rays with the crystal lattice and can be described by the Bragg equation:

$$n\lambda = 2d \sin \theta$$

The positions, intensities, and widths of the diffraction peaks provide information about the crystal symmetry, the lattice parameters, and the orientation. The intensity of the diffraction peaks is related to the number of atoms in the crystal, and the position of the diffraction peak is related to the interatomic spacing of the crystal. The width of the peak is related to the degree of crystalline perfection and can provide information about the size and distribution of the crystallites.

Solar Simulator

Solar simulator is essential for the characterization of solar cells. It is a device that imitates the solar spectrum, providing a controlled and repeatable test environment for solar cells. After finishing producing a solar cell, it is necessary to evaluate the electronic characteristics to understand the impact the different approaches had on the final cell. The main parameters studied are power conversion efficiency (PCE), the IV curve, open-circuit voltage, series and shunt resistances, short-circuit current density and fill factor (FF). We use a four-point probe technique, where two probes are connected to the back contact of the solar cell, and the other two are connected to the top contact. This technique involves applying a voltage to the solar cell through the two outer probes and measuring the current between the other probes. It allows for accurate measurement of the cell electrical parameters, such as resistivity and conductivity.



Figure 31 - Solar simulator used for the electrical measurements, at the right side we can see the 4 wires used by the 4 probes and the reference solar cell in the back

We can look at the equation (2) and we can see that the current appears on both sides of the equation and thus we can't solve it analytically, instead numerical methods are used, such as the JV curve where we can vary the applied

voltage through the solar cell and measure the current, obtaining a graphics like Figure 36 and Figure 37.

$$I(V) = I_{ph} - I_D - I_{Sh} \quad (1)$$

$$I(V) = I_{ph} - I_S \cdot \left(e^{\left(\frac{V + I \cdot R_S}{V_T} \right)} - 1 \right) - \left(\frac{V + I \cdot R_S}{R_{Sh}} \right) \quad (2)$$

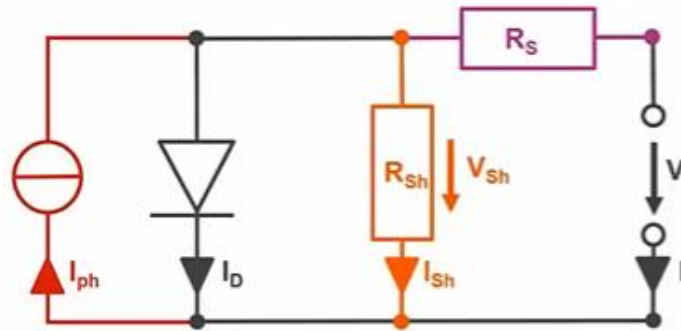


Figure 32 - Solar cell model with one diode (I_D)

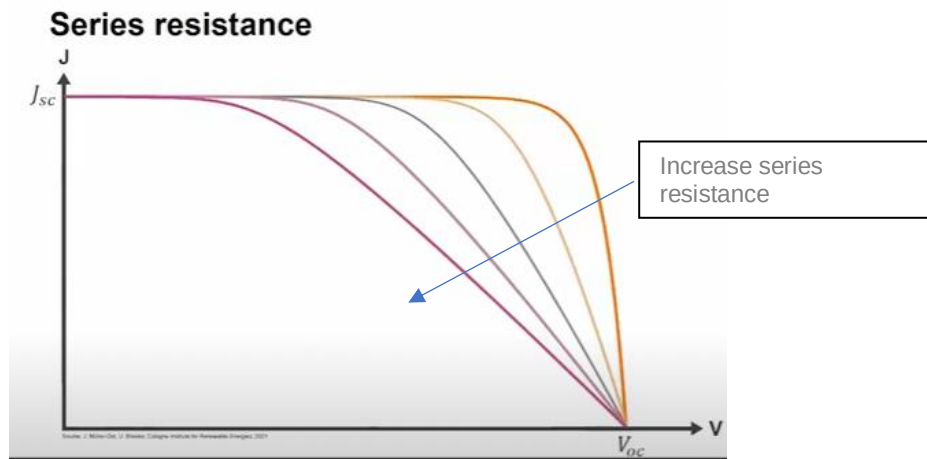


Figure 33 - Series resistance influence on the JV curve

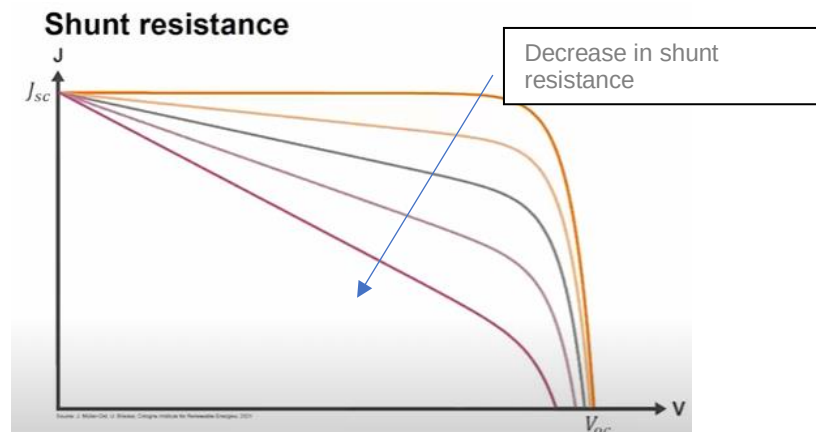


Figure 34 - Shunt resistance influence on the JV curve

To increase the fill factor (FF) of our solar cell is necessary that the shunt resistance is high and the series resistance is low, since we can calculate the fill

factor as the square below both graphics and thus, the larger the graphic curve is, the larger the square and fill factor.

Results and discussion

The main objective of this thesis was to produce line-shaped CIGS solar cells to test how they work with different light focus from different lenses and improve the production parameters. In some of the samples it was tested different approaches to two main problems the group was facing regarding the production parameters, which is the amount of selenium we should use and the heating and cooling temperature ramps used in the selenization process.

In total, nine full samples with an area of $5 \times 5 \text{ cm}^2$ were processed. Each full sample was further divided into four smaller samples of $2.5 \times 2.5 \text{ cm}^2$, as shown in Figure 39. This resulted in a total of 36 smaller samples, of which 16 were fully processed and used for analysis.



Figure 35 - Full $5 \times 5 \text{ cm}^2$ sample and the 4 divided smaller sections of $2.5 \times 2.5 \text{ cm}^2$

In the following sections, we will discuss the selenization results, including the heating and cooling ramp data as well as the amount of selenium tested. Finally, we will present a new paragraph with simulations that further explore how semi-transparent technology could benefit APV. Samples A and B were used to replicate, learn and train the processes used by the group to fabricate solar cells. Samples C to I were fully developed, with supervision of other members of the group in some processes (sentence)

- Samples H and I underwent only the lithography process.
- Sample F encountered issues during lithography and was excluded from further analysis.
- Samples C, D, E, and G were used to test different selenium concentrations and temperature profiles during selenization.
- Sample G was the most advanced sample, having undergone full device fabrication. However, it exhibited performance issues during EQE and efficiency testing, preventing reliable electrical characterization.

Sample ID	Use Case	Included in Final Analysis
A	Training and replication	No
B	Training and replication	No
C	Selenization test (Se/Temp profile)	Yes
D	Selenization test (Se/Temp profile)	Yes
E	Selenization test (Se/Temp profile)	Yes
F	Excluded - lithography failure	No
G	Fully developed - EQE and efficiency failure	Yes
H	Lithography only	No
I	Lithography only	No

Table 2 - Summary of experimental samples used throughout the development of the semi-transparent CIGS devices.

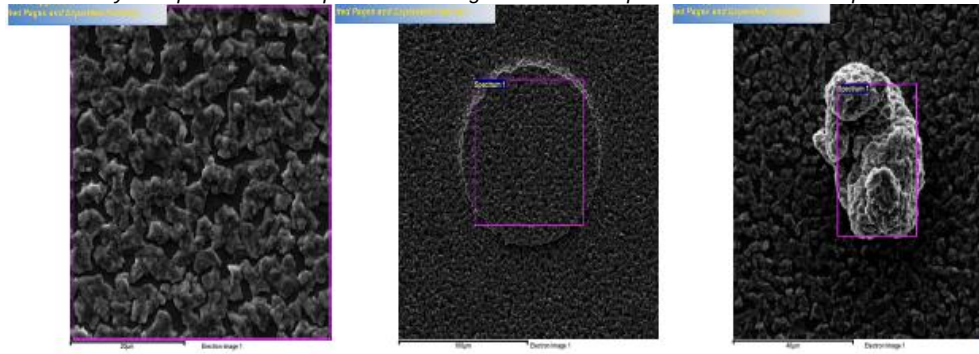


Figure 36 - Several examples of SEM possible analysis within the same sample (A) at different spots and with different magnifications

The images shown above are examples of images we can get before the selenization process, with the composition determined by the EDX. Although this method is not 100% accurate it's a very good approximation of the stoichiometry of the sample. It can also show how the sample structure was formed and how it changes after selenization. This images and the elemental percentages can give us some idea how the selenization process went and then allows us to make conclusions about how the amount of selenium used in the selenization process actuated, based on all the data we got from EDX. We can also deduce conclusions for the heating and cooling parameters based on the visualization of the sample's CIG and CIGS layers, comparing the before and after selenization.

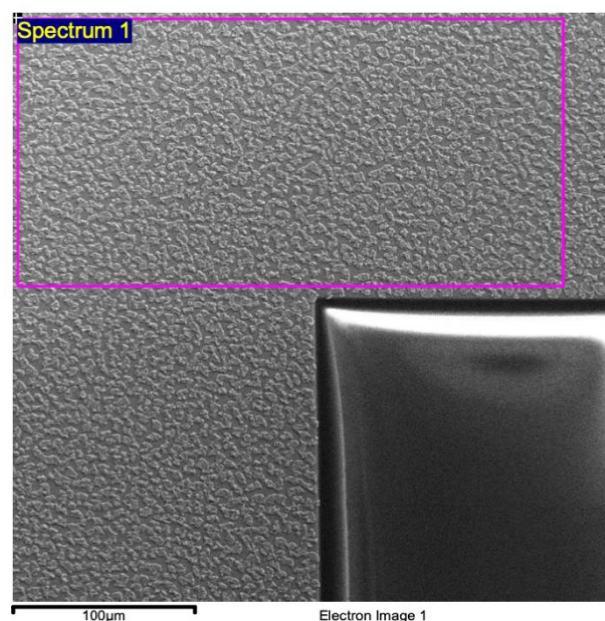
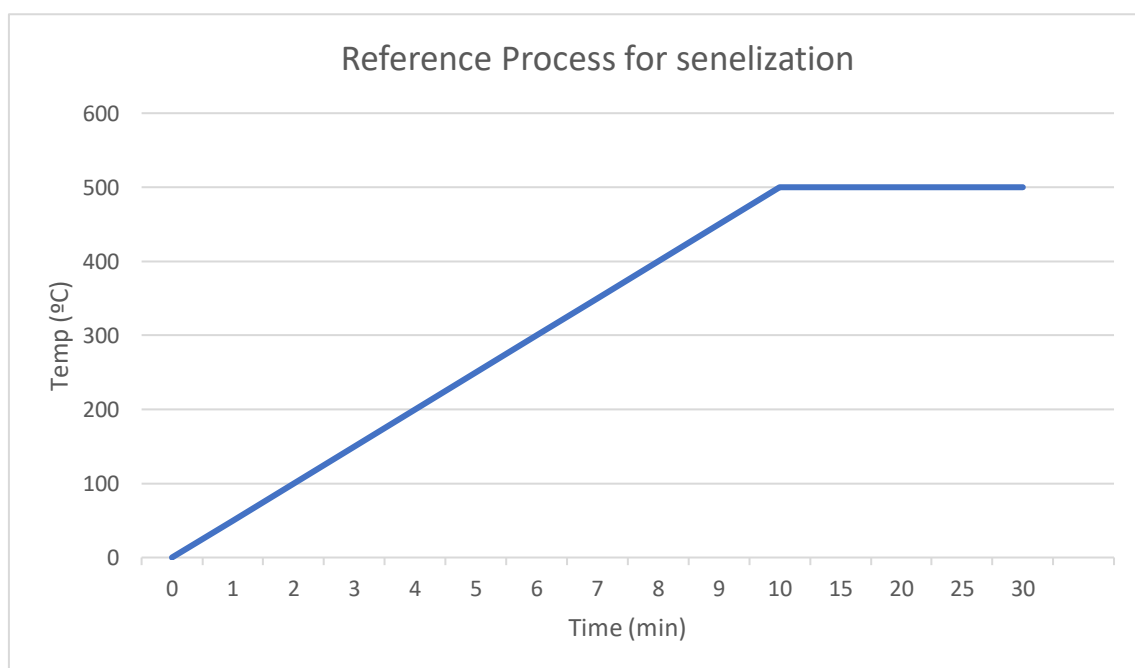


Figure 37 - SEM image showing the CIG layer of sample B

Selenization Results

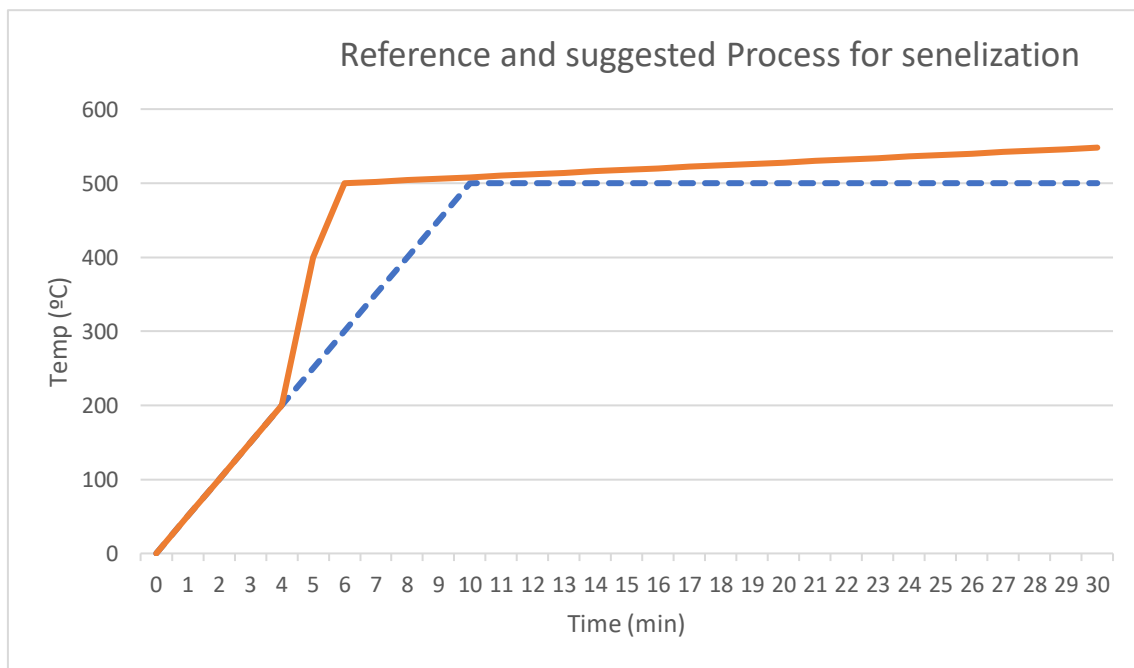
For the selenization process, we used the tube furnace at high temperatures to vaporize Se pellets to incorporate Se into the CIG substrate that was deposited in the previous process. We use a graphite box which contains both the Se pellets and the CIG sample ($2.5 \times 2.5 \text{ cm}^2$), leading to a selenium rich atmosphere at high temperatures which makes the CIG sample absorb the selenium. The group had a reference process for this selenization process which was to heat the tube furnace until 500°C using a ramp of $50^\circ\text{C}/\text{min}$, then leaving it for 30 min at 500°C until letting it cool down slowly with the tube furnace lid closed.



Graph 1 - Graph showing the reference selenization process at LaNaSC

In [38] a very similar approach was used, giving insights about the gradient of crystalline quality along the sample. The same is visible in our samples just by looking at the different color gradient shown in the cells (Figure 43). The color gradient is caused by variations in the crystalline structure across the sample, which reflect light differently from one area to another. Interestingly, this occurs even though the sample is not large enough for such variation to be expected, indicating a gradient in the deposition of the underlying CIG layer. Another way to prove this would be by doing extensive EDX measurements along our sample. Some EDX measurements and SEM images were obtained and showed differences in the grain size of the sample. According to [38] we know that the different elements (Cu, In and Ga) have different mobilities resulting in non-optimal reactions between the elements and Se, this is the result of different heating and cooling ramps temperatures and also the position of the sample related to the Se source, the amount of Se used and the distribution of CIG elements in the sample. Due to the process of CIG deposition by DC sputtering

we have a slight gradient along our samples, and that means we have different percentages of the CIG elements in the sample, which also cause different crystalline quality when reacting with Se during Selenization. But the 3 main effects would be heating ramps and temperature, as well as the amount of selenium used. In [39], we can take that in the initial stage of the selenization process, the formation of intermediary phases start to occur, roughly between 170°C to 220°C for CuSe and from 200°C to 400°C for InSe. This will always happen but it is undesirable due the detrimental eletrical properties of both phases. With this in mind it would be optimal for us to insert selenium only after the sample of CIG is heated to about 400°C, which in the tube furnace is not possible, so the solution lies in using high heating ramps, ideally above 200°C/min, but in the tub furnace the max heating ramp available is of 100°C/min. The paper also reffers that after the initial stage is important to let the sample and selenium rich atmosphere heat slowly, around 1°C/min until a temperature of 500°C so that the process of selenization can occur without the formation of undesirable phases. That said, the heat ramp in orange, presented in the graph 2 represent the ideal scenario achievable within the operational limits of the tube furnace used in this study.



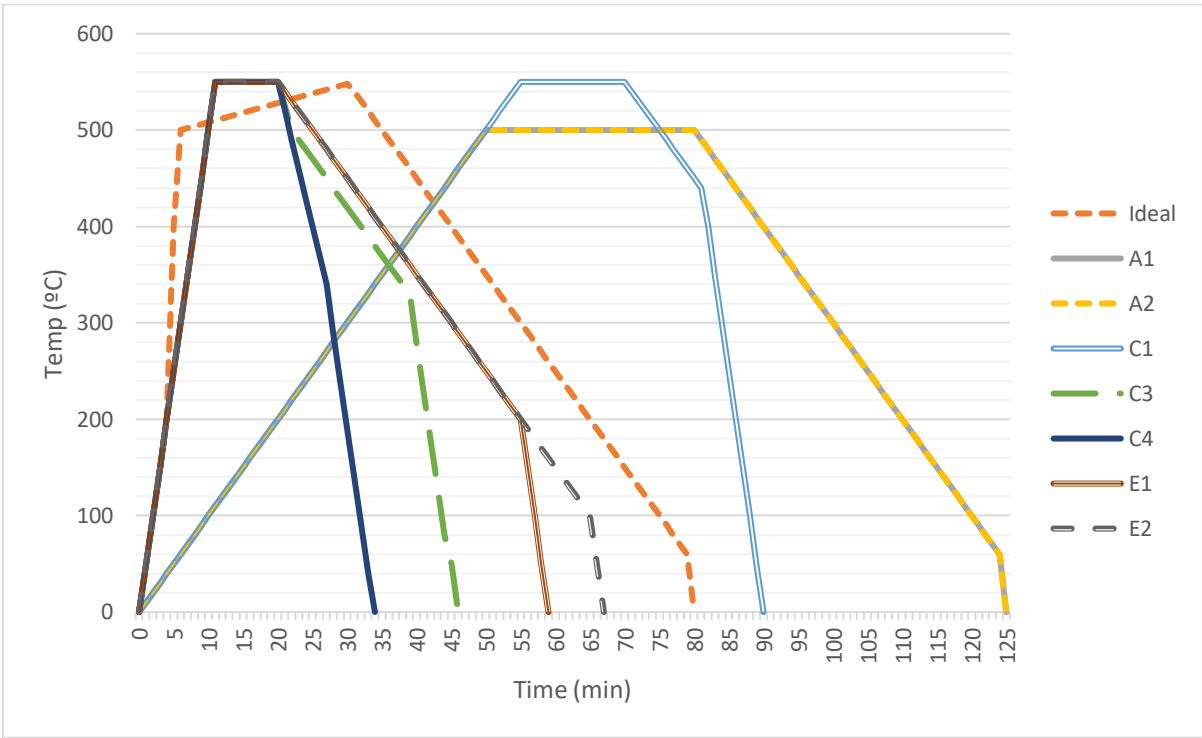
Graph 1 - In blue we have the reference procedure and in orange we have the procedure according to [39]

To clearly illustrate the different approaches used for the heating and cooling ramps in testing this hypothesis, a table was prepared for each method explored.

Sample	CIG	Heating ramp	Time at max temp	Max Temperature (°C)	Cooling method
A1	47.1/38.9/14	10°C/min	30min	500	Lid closed until 60°C

A2		10°C/min	30min	500	Lid closed until 60°C
C1	54.9/28.6/16.5	10°C/min	20min	550	Open lid at 440°C
C3		50°C/min	10min	550	Open lid at 330°C
C4		50°C/min	10min	550	Fast cooling, lid open
E1	55.3/28/16.6	50°C/min	10min	550	Open lid at 200°C
E2		50°C/min	10min	550	Open lid at 100°C

Table 3 - Process of heating and cooling ramps



Graph 3 - Graphical visualization of heating and cooling ramps shown in table 3

A quick explanation of the graph 3 to help better understand it, in orange we can see the suggested process from start to finish, this will be our guideline. Samples C3, C4, E1, and E2 were subjected to the most similar starting conditions achievable with the tube furnace. In contrast, samples A1, A2, and C1 followed a different heating ramp to evaluate the potential impact of varying heating profiles. The duration of the high-temperature stabilization phase was adjusted individually for each sample. For the final cooling stage, the same ramp was applied across all samples, but with varying end temperatures. After reaching these temperatures, the lid was opened to assess whether a faster cooling process could be achieved without compromising sample integrity

After analyzing the samples and the data from EDX, it was concluded that a slow cooling is needed before opening the lid, or abruptly reducing the temperature, so the sample does not get a thermal shock like sample C4, and have a "burnt" aspect as we can see in Figure 43. A good sample was obtained in C1, even though the initial heating ramp was not near the ideal.

After, the lid was open at 440°C in order to try to make the process of selenization faster and without compromising the sample integrity and formation of harmful secondary phases when cooling down at not ideal temperatures, and it showed good signs for the selenization final step. Both coolings of the cells, C1 and C4, were done in the effort of trying to cut the formation of harmful secondary phases obtained in the 170-400°C temperature range, like CuSe and InSe but this abrupt change of temperature was harmful in sample C4 when the temperature was around 540°C inside the tube furnace, as for C1, when opening at 440, no harm was observed and a faster cooling process was successfully achieved. Another observation was that the heating ramps and time on a fixed high temperature, annealing, will affect the final sample topology. This annealing can be done prior to the selenization as well, showing good results. Normally a longer period of time at high temperatures, or annealing, (>400°C) will be beneficial for the solar cells as described in several papers as observed in samples C4 and C1, even though we only have a 10 min difference in the annealing part of the selenization we can see in Figure 42, that the grains on the right sample C1 are more evenly distributed and homogeneous than the ones on sample C4 which are very irregular in size and non-uniform in shape. This observation was also obtained by other group members measurements when annealing the CIG before the selenization process.

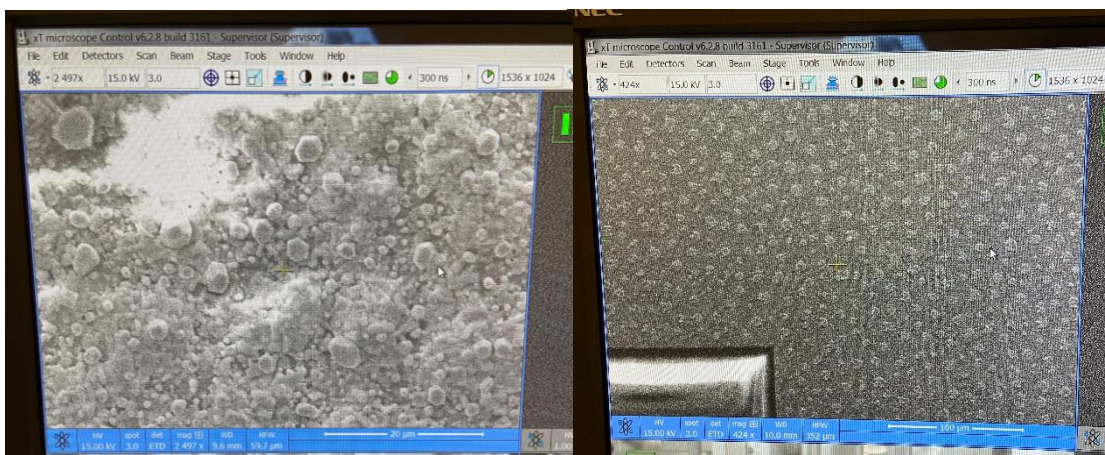


Figure 38 - EDX topographic image of Sample C4 (left) and C1 (right)

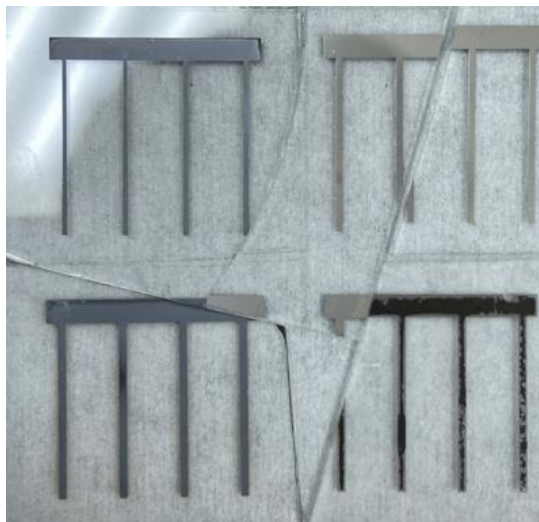


Figure 39 - Sample C shows different results after different selenization processes on sample C: C1 (top left), C3(Bottom Left) and C4 (Bottom Right)

Although all the constituent layers of the CIGS solar cell were successfully deposited, it was not possible to obtain operational devices. Electrical measurements consistently showed short-circuit behavior, with near-zero open-circuit voltage (Voc) and extremely low current density (Jsc), indicating that no functional p–n junction was formed. SEM analysis of the selenized samples revealed changes in surface morphology, suggesting possible recrystallization effects or the presence of secondary phases. In addition, EDX mapping confirmed the presence of selenium in the treated samples, though its distribution appeared uneven in some regions, which may point to incomplete or non-uniform selenization.

As shown in Table 4, EDX elemental analysis confirmed the presence of copper, indium, gallium, and selenium in the selenized samples. The analysis also provided composition ratios that align well with literature-recommended values. Specifically, the calculated CGI ($\text{Cu}/[\text{In}+\text{Ga}]$) ratios ranged between 0.85 and 1.0, consistent with optimal absorber formation, although some samples showed a slight excess of copper, expected from the use of a Cu-rich target during co-evaporation. The GGI ($\text{Ga}/[\text{In}+\text{Ga}]$) ratios were between 0.2 and 0.4, which is within the ideal range for tuning the CIGS bandgap between approximately 1.1 and 1.2 eV, suitable for single-junction photovoltaic applications.

Sample	CIG ratio	GGI ratio	Se amount used (mg)
A1	0.85	0.26	47
A2	0.85	0.26	77.5
C1	1.04	0.37	50
C3	1.04	0.37	50
C4	1.04	0.37	37.5
E1	1.05	0.37	25
E2	1.05	0.37	25

Table 4 - CIG, GGI ratios and Se amount used for the samples

As shown in Table 4, the GGI and CIG ratios suggest that the metallic precursor layers were deposited with reasonably controlled stoichiometry. These values fall within expected ranges for CIGS absorbers, indicating that the initial composition was appropriate for successful phase formation, although values of CIG greater than 1 are Cu rich which leads to the formation of Cu_xSe . However, no photovoltaic response was observed, which points toward issues arising during the selenization step. Based on the processing conditions and the relative amount of selenium used, it is plausible that the Se concentration was excessive for the available precursor mass.

In over-selenized cases, it is known that the formation of secondary phases such as Cu_xSe , as well as the possible condensation of elemental selenium on the surface, can occur, particularly when selenium vapor pressure is not carefully balanced with the metal content. These conductive phases can

disrupt junction formation and act as shunting pathways, effectively rendering the device electrically inactive. In microstructured samples, such effects may be further amplified by local geometrical factors that promote uneven selenium reactivity at line edges or interfaces.

Therefore, while the metal ratios shown in Table 4 indicate adequate control at the deposition stage, the lack of electrical response is consistent with over-selenization effects. This highlights the sensitivity of the selenization process to precursor thickness and geometry, and suggests that further optimization of selenium dosage and thermal ramping conditions will be essential to achieving functional devices in the future.

According to the literature, both insufficient and excessive selenium can negatively affect the absorber quality, either by leaving residual metallic phases when Se is lacking, or by forming conductive Cu_xSe compounds when in excess, which can create shunt paths in the device. Given the segmented architecture of the samples, it is also possible that selenium was distributed unevenly, particularly near the edges defined by the photolithographic pattern. [40], [41]

The role semi-transparent CIGS technology can play in APV

The idea behind this thesis was to understand how the semi-transparent technology of solar panels made with CIGS technology could influence the growth of plants in greenhouses and how it would affect the earnings/returns of such investment. This idea is called agriphotovoltaics, which is the mixing of both agriculture and photovoltaics.

The main objective of my work at INL was to fabricate functional CIGS-based solar cells to obtain concrete values for electricity production at different AVTs. However, due to the lack of working devices caused by several issues previously discussed, tabulated efficiency values from working CIGS solar cells will be used instead. For this study, an efficiency of 15% is considered, based on typical performance values reported for CIGS technology. Based on this we can make some other assumptions such as the area used and the amount of sunlight that hits a certain region in the world. CIGS efficiency, AVT and irradiance (direct and indirect light conditions) are the 3 main values needed to calculate the total energy production from a solar cell in a determined area of the globe. In reality, additional environmental factors such as temperature variations and panel cleanliness can influence performance. However, these external factors are neglected in this analysis as their impact on the overall energy yield is considered minor compared to the primary parameters. We will use INL, Braga as our location in the globe to get the irradiance values we need. According to Photovoltaic Geographical Information System (PVGIS), a European website that offers this type of data, to obtain a graph of the Direct Normal Irradiation (DNI) in the month of July, where we can see the peak irradiance at 13h with 846 W/m² for the Global irradiation and 609 W/m² for the DNI.

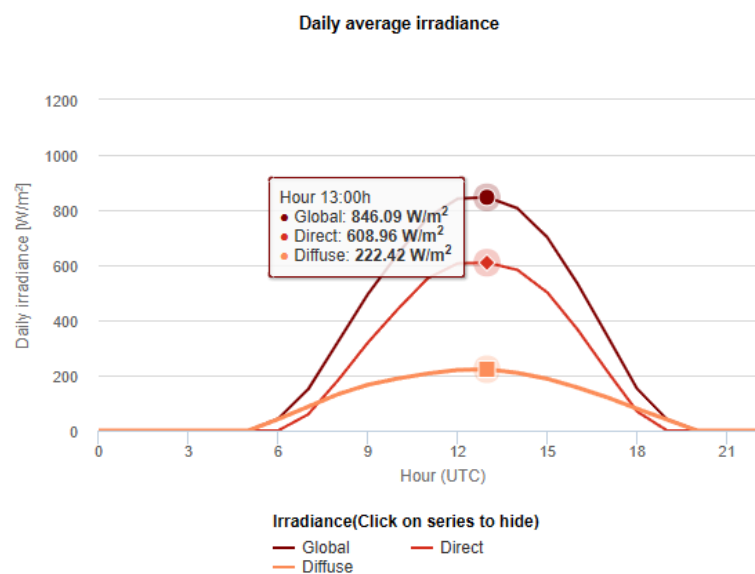


Figure 40 - Hourly W/m² at INL, Braga for the month of July

The values of AVT used in simulation will be 70%, 55% and 40%. We will use 1m² of total area used by the solar cell in order to simplify the calculations. Having all of these values we take that in the 30%, 45% and 60% AVT greenhouse, we would produce 27.4 Wh/m², 41 Wh/m² and 54.7 Wh/m² per day, respectively. This calculations can be made to every part of the globe, using the

same method but different values according to PVGIS. To generalize the calculations, let TP represent the total energy production of a full square meter of CIGS solar cell with no line pattern (Wh/m²), and PA as the production after applying a certain AVT. The production can be determined using the equation:

$$PA = TP * Area\ used * Efficiency$$

To provide a clearer perspective on how our technology compares with other solar cell technologies discussed in the State of the Art, a comparative table will be constructed. This will allow for a better understanding of where CIGS-based semi-transparent solar cells stand in terms of efficiency, transparency, and energy production potential relative to other available solutions.

Technology	Efficiency	Area (m ²)	Production	Production (Wh/m ²)	Production/year (kWh)	Location
Polysilicon	14-19% (est.)	4700.0	200 kWh	42.55	280000	China
Crystalline Silicon	4.5%	0.0275	540 mW	54.59	110	Japan
Crystalline Silicon	1.6%	0.0092	202 mW	19.41	74	Japan
Amorphous Silicon	6-7% (est.)	15.0	1.3 kWh	86.0	900	Valladolid
CIGS (0.3 m ²)	15%	0.3	27.4 Wh	91.2	240	Portugal
CIGS (0.45 m ²)	15%	0.45	41 Wh	91.2	359	Portugal
CIGS (0.6 m ²)	15%	0.6	54.7 Wh	91.2	479	Portugal
OPV	9.4%	0.94	3.36 Wh	3.57	6652	Australia

Table 5 - Technologies and energy production in APV real life examples

Polysilicon- Xue, 2017 – PV agriculture in China doi: 10.1016/j.rser.2017.01.098
 Crystalline silicon- Yano et al., 2014 – Semi-transparent PV for greenhouses doi: 10.1016/j.biosystemseng.2014.04.003
 Amorphous silicon. - Aira et al., 2021 – a-Si PV greenhouse viability doi: 10.3390/agronomy11061097
 Organic PV - Dipta et al., 2022 – Organic PV potential in greenhouses doi: 10.1016/j.apenergy.2022.120208

CIGS- Experimental/theoretical Values

From the comparative table 5, it is evident that our CIGS-based semi-transparent solar cell technology demonstrates strong potential for efficient electricity generation per square meter, making it particularly well-suited for agrivoltaic (APV) applications where land availability is a critical factor. The production per square meter is the important factor of this table, because it demonstrates the potential of our solar cell compared to market implemented technologies like silicon based technologies. This good production per square meter can be achieved by either maintaining a high efficiency percentage or deploying a large surface area of solar panels while ensuring minimal interference with agricultural productivity. While crystalline silicon panels achieve high efficiency, their significant harm to plant growth means only a very small area could be covered with such panels without affecting crops. As a result, the electricity produced in an agrivoltaic setup would be limited compared to what could be generated using larger areas of semi-transparent CIGS panels.

As discussed earlier, one of the main challenges in APV systems is the shading effect, which can significantly impact plant growth. Another objective of this thesis was to evaluate how our structured solar cells influence shading by visually analyzing the shadow projection using both a solar simulator and natural sunlight. Unlike traditional opaque solar panels, which create sharp, well-defined

shadows that block light entirely, our technology is designed to produce a more diffuse shading effect.

Due to the microstructured line pattern of our solar cells, the resulting shadow behaves differently compared to conventional PV systems. Instead of casting a solid dark shadow that completely blocks light and more important, Photosynthetically Active Radiation (PAR), the thin CIGS solar lines allow for a more gradual reduction in light intensity across the shaded area. This effect can be observed in Figure 46 a) and b), which compares a typical solar panel shadow (Fig 45) to the gradient-like light reduction produced by semi-transparent solar cells (Figure 46 a and b).

This characteristic is particularly relevant in agrivoltaics, where maintaining partial light exposure is essential for sustaining photosynthetic activity. In conventional PV shading scenarios, plants under full shadows receive insufficient light to activate photosynthesis, leading to reduced growth rates or even plant stress. However, with our semi-transparent, structured CIGS solar cells, plants would still receive a portion of the incident light, enabling them to continue photosynthetic activity at a reduced but functional rate.



Figure 41 - Example of black shadow cast by normal solar panels from [42]

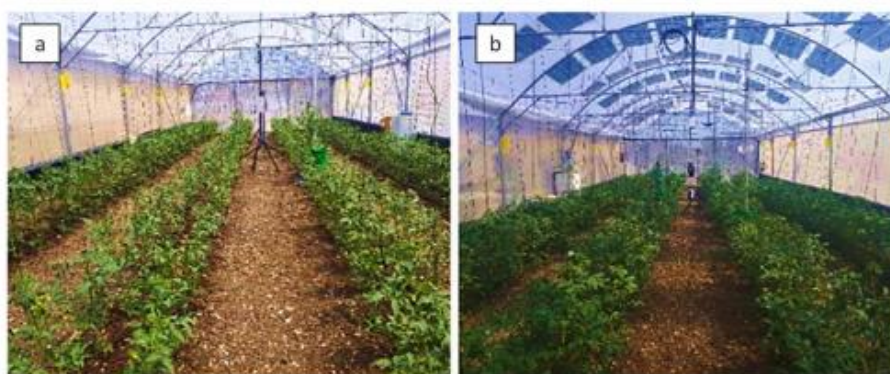


Figure 42 - Example of placing a semitransparent solar cell on top of a greenhouse (b) and normal sunlight (a)

In our CIGS spacial segmented lines we will be counting on our easily attainable AVT percentage and small lines to create a good trade between DNI and diffuse light, so we can benefit from our good efficiency and low space usage

to compete with other technologies, as well the low shadow impact they have on agriculture.

From [43] it has been shown that high-light plants, which are plants that require a lot of light to grow, will experience a reduction in photosynthesis if they have less DNI shun upon them, low-light plants on the other side show no difference when shun with DNI or diffuse light. Although no direct studies exist on this topic, it is reasonable to assume that low-light plants would still grow under the conditions of our implementation, given their natural adaptation to reduced light environments and their ability to derive benefits from the diffuse light generated by our technique, which enhances light distribution and improves photosynthetic efficiency in shaded areas. For example, instead of experiencing a binary state of light or no light, as seen in opaque solar cell technologies, our approach allows for continuous light transmission, even though at a reduced intensity, which can be determined by the density of lines per m^2 . In the table of Figure 47 we can compare (a) and (c), both having the same AVT and thus, having the same light intensity reaching the plants. But in (a), the checked patterns create a binary light distribution, meaning that if this pattern were to be placed above a greenhouse, the shadows cast by the panels would be extensive, potentially harming crops that remain shaded for longer periods. In contrast, our approach uses spatial segmentation with small lines (Figure 47 (c)). Although this also creates a binary light pattern as well, the segmentation is so fine and small that the light reaching the plants appears continuous, just like it would work to our eyes when facing such patterns in windows, minimizing any direct impact on photosynthesis. However, it still reduces the total amount of DNI reaching the crops. Ideally, this reduction is mitigated by the increased diffuse and scattered sunlight passing through, facilitated by the small gaps between the lines. An example can be seen in Figure 48, where its compared a normal opaque panel configuration.

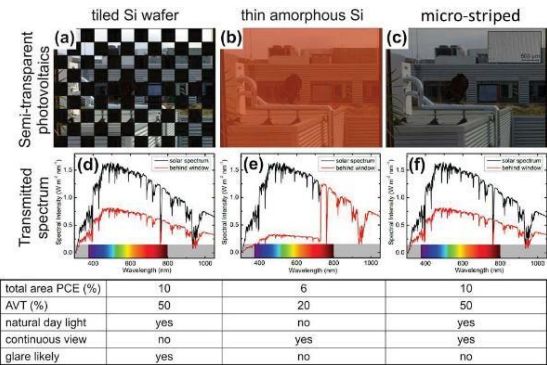


Figure 43 - The image compares a checkerboard opaque PV pattern (a), which creates sharp shadows, with a microstriped CIGS STPV design (c), which allows light transmission. Both reducing light intensity equally as we can see from the red line in both graphs

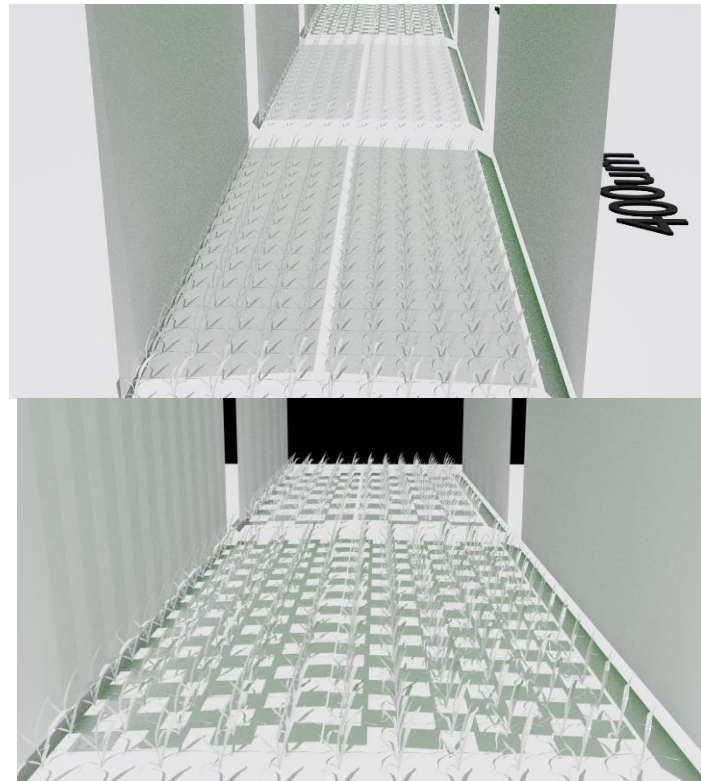


Figure 44 - The image shows a simulation of sunlight passing through semi-transparent solar panels (top) and opaque solar panels (bottom), illustrating how diffuse light is distributed in the semi-transparent case

Studies suggest that providing some level of shade or a heat barrier can be beneficial for both plant growth and overall water usage. However, we assume this is primarily advantageous during the hottest and sunniest days, as at other times, excessive shading could reduce the light and heat necessary for photosynthesis. Our approach has the potential to increase total harvest yield or, at the very least, have close to no negative impact, both of which are favorable outcomes, as they enable simultaneous food and energy production. The key challenge lies in determining the amount of light required by the selected crop to ensure healthy growth without adverse effects. Most previous studies have focused on tomatoes and lettuce due to their fast-growing nature, but further research is needed to evaluate the impact on a wider variety of crops. However, for plants that do not require intense sunlight or direct normal irradiance (DNI), our approach presents itself as one of the most promising solutions. Additionally, it is well established that each plant has a specific daily light integral (DLI) requirement. Keeping this in mind, we can estimate the feasibility of integrating our solar cells with different crops by analyzing past solar irradiation data for a given location.

For instance, let's consider the case of growing strawberries in Braga year-round. Since strawberries require 6-8 hours of sunlight per day, this corresponds to a certain DLI value. To maintain optimal growth throughout the year, we would need to adjust the average visible transmittance (AVT) for each stage of the strawberries' gestational period, as solar irradiation levels vary across seasons. During summer, we could implement a lower AVT, maximizing energy production while ensuring adequate sunlight for the crops. Conversely, in winter, a higher AVT would be necessary to make full use of the available daylight. This can be

achieved using our spatial segmentation techniques, allowing us to precisely control AVT levels and facilitate year-round agricultural production alongside electricity generation.

Ultimately, by determining the DLI requirements of the target crop and analyzing seasonal irradiation data, we can establish the optimal balance between maintaining unaffected crop yields and maximizing energy production, ensuring the best trade-off between food security and renewable energy generation.

Greenhouse Simulation

1. *Introduction to simulation approach*

In this section, a simulation-based approach is adopted to evaluate how semitransparent CIGS photovoltaic technologies can be integrated into agrivoltaic (APV) systems, with particular emphasis on their optical interaction within greenhouse environments. The analysis focuses on the spatial distribution of shadows cast and their interaction with direct light causing diffuse light, by two distinct photovoltaic configurations: conventional square-shaped opaque panels and the linear semitransparent structures proposed in this work. Opaque square panels are selected as a reference case due to their well-defined and predictable shadow projection, which serves as a baseline for comparison. By contrast, the semitransparent linear designs are hypothesized to enable a more diffuse and spatially heterogeneous transmission of light, potentially optimizing the balance between solar energy conversion and plant photosynthetic requirements. This simulation aims to provide insight into how panel geometry and transparency influence light availability at the crop level, a critical factor in the design of effective APV greenhouses.

Although originally developed as an open-source platform for 3D modeling and animation, Blender has evolved into a sophisticated environment capable of simulating photorealistic light material interactions with a medium degree of physical accuracy. Its ray-tracing rendering engine, Cycles, is grounded in the principles of physically based rendering (PBR). Cycles employs a path-tracing algorithm to calculate the trajectories of light rays as they interact with three-dimensional geometry, accounting for critical physical properties such as specular and diffuse reflection, refraction, transmission, subsurface scattering, and volume absorption. These characteristics are especially relevant in the context of semi-transparent photovoltaic technologies, where understanding how light is distributed and attenuated through complex structures is fundamental to assessing performance.

Moreover, Blender enables detailed control over light sources including solar-type directional lights and physically informed sky textures with parameters such as intensity, angular spread, and spectral contribution. These features allow for the approximation of natural daylight conditions and the evaluation of how design variables (e.g., panel geometry, material transparency, angle of incidence) affect light availability in target zones such as agricultural crop layers.

Taken together, these capabilities render Blender a valuable and versatile tool for exploratory simulation in fields that require detailed study of light behavior particularly in agrivoltaic system design, where visual and quantitative assessment of solar radiation distribution plays a crucial role in optimizing energy yield and crop viability simultaneously.

While Blender offers a powerful and accessible framework for simulating the interaction of light with materials and geometry, it is important to acknowledge that it does not achieve perfect physical fidelity when compared to real-world optical measurements. Nonetheless, its level of accuracy is sufficiently robust to provide a reliable approximation of how light would behave in practical scenarios.

For design exploration and comparative analysis such as evaluating shadow patterns, transmission characteristics, or relative light availability in agrivoltaic systems Blender offers a scientifically meaningful and visually intuitive platform that supports informed decision-making, even if it does not replace high-precision photometric instrumentation or wave-optics simulation.

2. Simulation setup in Blender

The simulation setup involved four distinct photovoltaic configurations placed on top of an identical greenhouse structures: 400 μm -wide lines, 700 μm -wide lines, 25 cm square panels, and 50 cm square panels. All configurations were designed to achieve an Average Visible Transmittance (AVT) of 50%, with the exception of one side of the section using the 700 μm lines, which had an AVT of 75%. This intentional variation allowed for a more clear comparison of how light intensity and shadow patterns change with different levels of transmittance.

Simulations were performed using the Cycles rendering and the solar trajectory was animated to replicate the sun movement from sunrise to sunset, capturing the dynamic changes in shadow position and intensity throughout the day. However, for the purposes of comparison, all rendered images were taken at 12h, when the Sun is at its highest point and shadows are most vertically projected. This moment was chosen to maximize the clarity of the shadow patterns and to facilitate direct visual comparison between panel types.

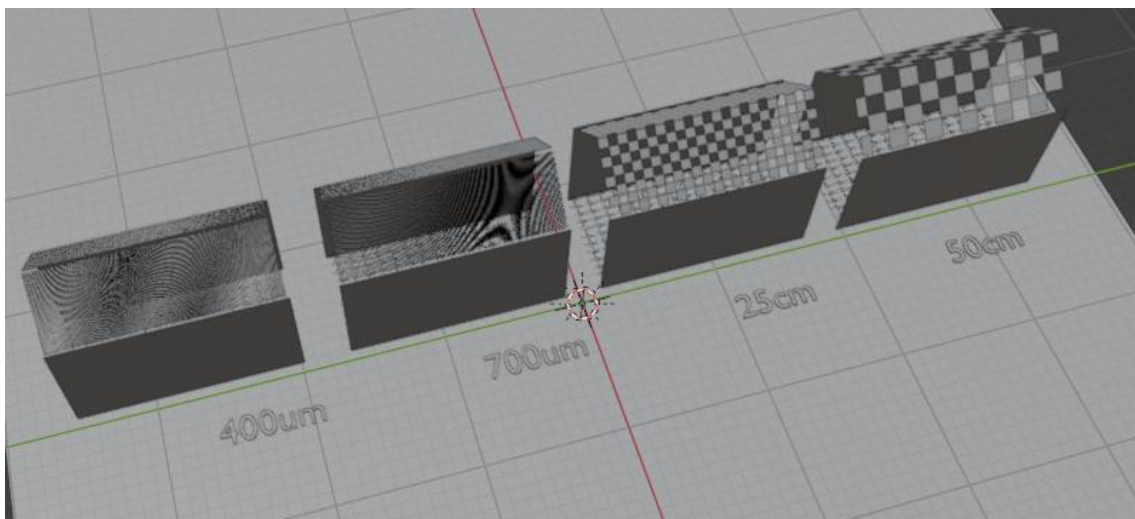


Figure 45 -Different greenhouses simulated on Blender

It is also possible to control both the number of light bounces and the type of surface interactions in the simulation (Figure 50). This is important so that we can only see the type of reflection wanted. In this simulation, only diffuse reflection is going to be considered, that is, light that is reflected without adhering to Snell's law. Unlike specular reflection, where the angle of incidence equals the angle of reflection, diffuse reflection results in scattered light due to surface irregularities, meaning the exit angle is generally different from the entry angle.

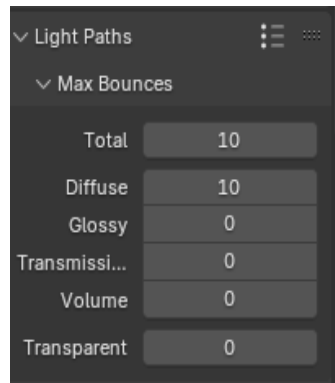


Figure 46 - Blender Definitions on Max Light Bounces

In this simulation, we also utilize the Light Path node within the shader editor (Figure 51), which enables control over the material's output color based on the type of incoming light. To visualize the light's origin, we assign red to light that comes directly from the sun, this means the light that has not undergone any scattering or redirection. And green is used to represent all other types of light. However, since our setup considers only diffuse reflections (Figure 50), the green component will exclusively be the diffused light contribution.

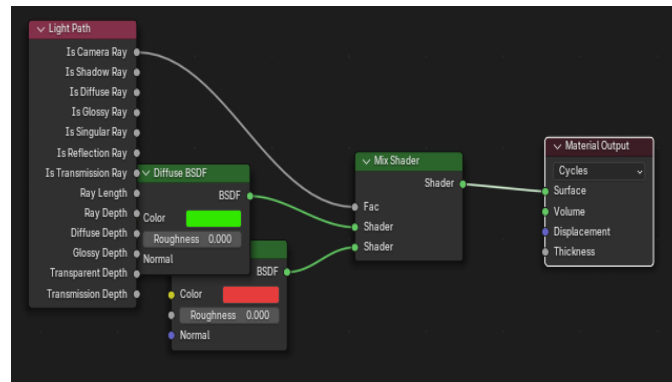


Figure 47 - Material output on the shader editor in Blender

By adjusting the parameters in Figure 50 to exclude bounced light, the resulting output corresponds solely to the red component, representing the direct sunlight in the rendered image, as illustrated in Figure 52.

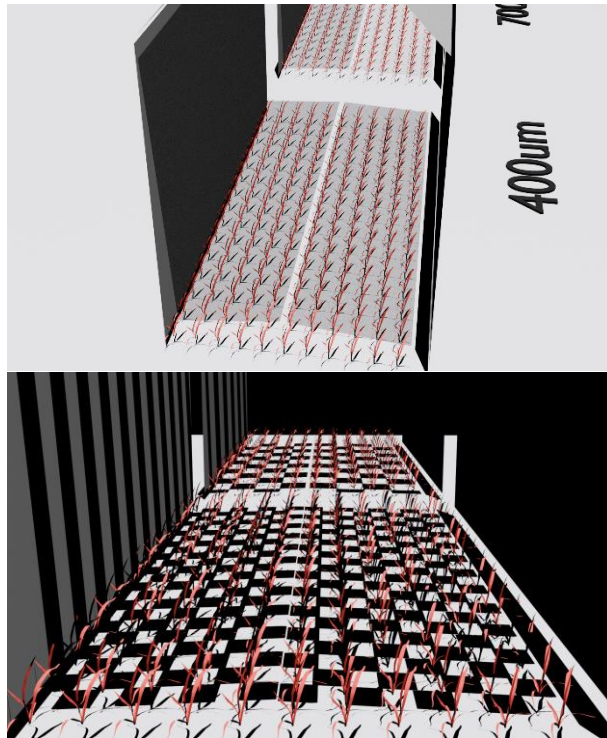


Figure 48 - Total bounces of 0, meaning only direct light (red) is being rendered

3. Optical behavior under direct and diffuse light

While both PV geometries may share an equivalent AVT value, their impact on light behavior within the greenhouse differs significantly due to geometry and optical accessibility. Under direct sunlight, square panels cast broad, high-contrast shadows, leading to uneven light distribution. In contrast, narrow PV lines spaced millimeters apart allow alternating bands of light and shade, softening shadow edges and promoting a more homogeneous light environment (Figure 53).

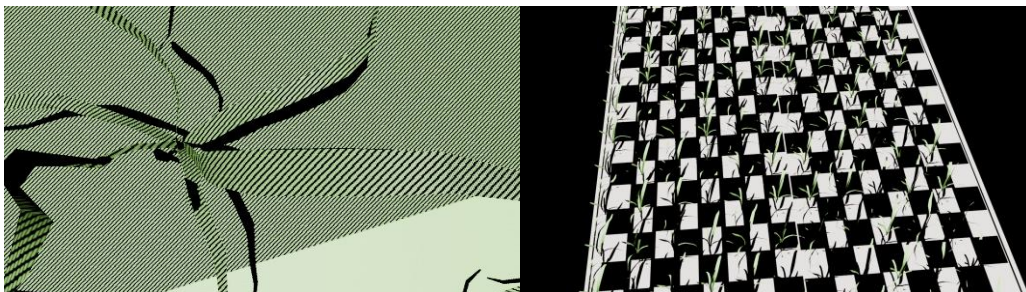


Figure 49 - Left side we can see a single plant with a pattern shadow caused by the lines (400um) and on the right side we can see a squared pattern, both at 0° sun angle meaning no diffuse light

When solar radiation becomes diffuse, for instance, under cloudy skies, the angular distribution of incoming light becomes wide. In this context, geometric transparency matters more than vertical AVT. Large square panels block not only

vertical rays but also many oblique ones while fine lines, have minimal lateral obstruction, allowing diffuse light to penetrate from more directions. As a result, more usable light reaches the crops under the same AVT.

A preliminary simulation was conducted with the sun angle of 0° , this parameter ensures the presence of exclusively direct sunlight. Under these conditions, shadows are sharply defined, allowing for a clear and controlled comparison between the different photovoltaic configurations under analysis.

By visually analyzing the rendered images under direct sunlight, the contrast in shadow behavior between the two types of photovoltaic modules becomes immediately evident. The large, well-defined shadows cast by conventional opaque panels may significantly hinder plant growth by obstructing direct sunlight and reducing photosynthetically active radiation (PAR) reaching the leaf surface. In contrast, the semitransparent solar panels generate much lighter shadow patterns, which allow for continued light penetration and enable photosynthesis to proceed with minimal interruption.

Conversely, when the simulated sky conditions are altered to lower cloud cover degrees, specifically 2° and 5° (with 10° representing maximum cloudiness), distinct light distribution scenarios emerge, as illustrated in Figures 54 and 55. Under such conditions, the increased cloud presence causes a substantial rise in the number of incident light directions due to enhanced scattering happening after the light from the sun passes through the clouds, leading to a marked increase in diffuse irradiance reaching the greenhouse roof. As a consequence, shadow boundaries become progressively blurred. Rather than sharply defined contrasts, we observe an expansion of shadows into illuminated regions and vice versa. This interaction results in the formation of

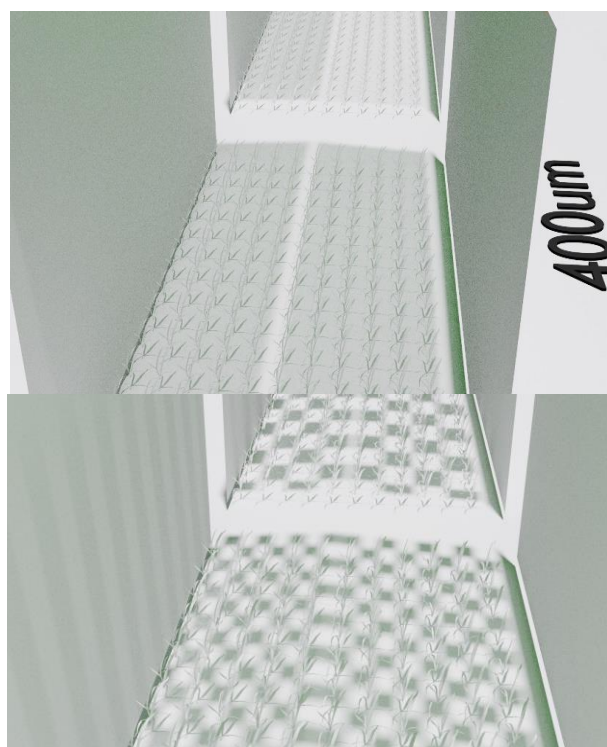


Figure 50 - Diffuse light response to a less cloudy day (2° Sun angle on Blender)

intermediate zones with mixed light intensity, a “grey area”, which can be understood as the superposition of diffuse light and partial shading.

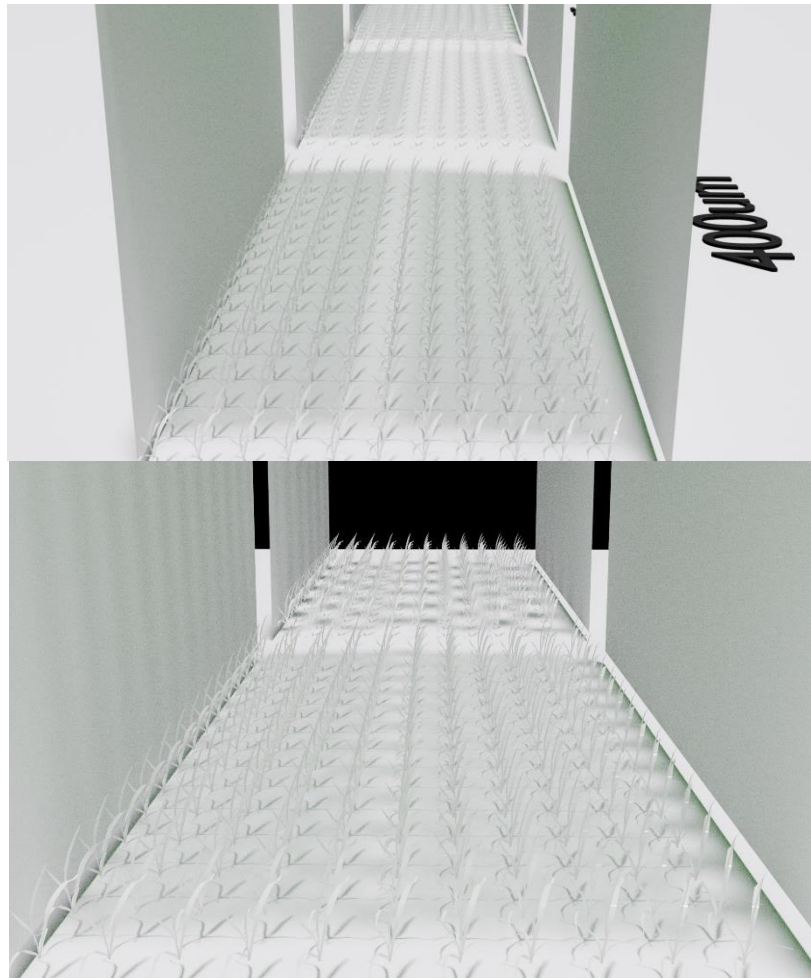


Figure 51 - Diffuse light response to a less cloudy day (5° Sun angle on Blender)

Another observation drawn from the images is that the side walls reveal a distinct pattern of diffuse light caused by the square panel configuration. In contrast, the line-pattern configuration demonstrates a more uniform light distribution. This indicates that the linear geometry promotes a more even dispersion of light, even under overcast conditions. Furthermore, a slight reduction in shadow intensity is noticeable in the 5° cloudiness scenario compared to the 2°, suggesting that the greenhouse with narrow line patterns benefits more from diffuse illumination under cloudy skies, thereby enhancing light availability for the crops below. This outcome is expected, given the higher number of reflective surfaces introduced by the increased segmentation, as well as the smaller feature size, both of which contribute to greater light scattering and distribution.

Although real-world experimental validation is required to confirm or challenge the trends observed in this simulation, the simulations strongly suggests that both well-defined and blurred shadow patterns under semi-transparent CIGS line structures offer a more homogeneous light distribution for

the crops beneath. This enhanced uniformity is particularly advantageous in agricultural environments, where light consistency directly impacts plant health and yield.

The microstructured linear design of the CIGS layers, as explored in this work, not only improves the spatial distribution of photosynthetically active radiation (PAR) under variable sky conditions, including diffuse light on cloudy days, but also presents a compelling case from an energy and economic standpoint.

Conclusion

Agrivoltaic (APV) technology has emerged as a promising approach to optimizing land use by combining solar energy generation with agricultural production. However, selecting the most suitable photovoltaic technology for APV requires balancing electricity generation, light transmission for plant growth, and economic feasibility to ensure both agricultural productivity and cost-effective energy production.

The ideal technology should provide high energy efficiency, selective light transmission, minimal thermal impact, economic feasibility, and durability in agricultural environments. Among the different PV technologies, Organic Photovoltaics (OPV) and Dye-Sensitized Solar Cells (DSSC) offer wavelength selectivity, allowing controlled absorption of non-PAR wavelengths while transmitting the necessary light for photosynthesis. However, their low efficiency, degradation under UV exposure, and limited long-term stability make them less viable for large-scale APV integration. Crystalline Silicon (c-Si) and Bifacial PV technologies, while offering high efficiency and long-term durability, present challenges in light transmission, as their opaque structure blocks most PAR wavelengths, limiting their direct applicability to APV unless modified through spacing or transparency adjustments.

Cu(In,Ga)Se₂ (CIGS) thin-film PV emerges as one of the promising candidates due to its moderate to high efficiency combined with the ability to be engineered for partial transparency. Compared to silicon-based PV, CIGS requires less material, reducing costs and environmental impact, while maintaining better thermal stability than OPV/DSSC. However, optimization challenges remain.

During the research, unforeseen challenges arose primarily from the difficulty in achieving a functional semi-transparent solar cell device, related to the fabrication processes and, more specifically, to the integration of selenium into the CIG layer, which proved essential for the performance of the solar cells. Despite the testing, the results specifically related to the selenium quantity were lost, preventing a definitive analysis of its impact. Nevertheless, based on the process and observations made during the work at INL, the selenium quantity used, around 25 mg, appeared to be excessive, particularly considering the lower total amount of CIG in the fabricated cells. This imbalance may have hindered the proper formation of the absorber layer. The main conclusions drawn from this study relate to the heating ramp and simulation. The results indicate that a higher heating ramp led to better grain size and a more homogeneous distribution. However, further in-depth research is necessary to accurately determine the optimal selenium amount and refine these findings.

In the simulation section, it was concluded that the presence of diffuse light, enhanced by the fine and narrow line geometry of our spatial design, significantly contributes to the mitigation of shadow effects on plant growth and photosynthesis. This optical behavior improves light homogeneity beneath the

panels, highlighting the strong potential of this technology for agricultural applications, particularly due to its favorable energy yield per unit area.

The assumed shadow mitigation effect, while promising, should be thoroughly validated through experimental studies. Furthermore, to optimize both plant development and photovoltaic performance, the average visible transmittance (AVT) of the solar cells should be carefully calibrated according to three key parameters: the global geographic location (solar irradiance levels), the specific crop species used (daily light integral requirements), and the time of year (seasonal variation in daylight hours). With accurate data on these three variables, it becomes feasible to calculate the ideal balance between light transmission for photosynthesis and light absorption for energy generation, thereby maximizing both crop productivity and electricity output within agrivoltaic systems.

Future work

As part of a discussion at INL group it seems that one of the potential reasons for the malfunctioning devices is the excessive formation of the MoSe_2 layer, we realized that to address this issue in future work, studies [44], [45] indicate that temperatures above 550°C significantly accelerate MoSe_2 growth. Thus, it would be beneficial to explore processing conditions that maintain the sample temperature below this threshold to prevent unwanted thickening of this layer. Additionally, since the total amount of selenium is directly correlated with the MoSe_2 thickness, future research should focus on a detailed investigation of lower selenium quantities and how partial pressure influences its formation. This analysis will be crucial for optimizing the fabrication process and improving device performance.

Another approach to introducing selenium into our samples is through the STAR system, which utilizes Se vapor in a controlled chamber with pulsed delivery to regulate both the selenium quantity and pressure. This method offers a high potential for mitigating MoSe_2 formation issues by ensuring a more controlled and uniform selenization process. Additionally, it enables the use of significantly smaller selenium quantities, which may greatly improve the proper formation of the absorber layer, especially in devices with reduced CIG content.

Future research should focus on the integration of light management systems to optimize the balance between electricity generation and plant growth in agrivoltaic (APV) applications. This includes the development of spectrally selective optical components, such as mirrors and lens-based microstructures, designed to redirect non-PAR wavelengths toward solar cells while ensuring optimal light transmission for crops. Experimental validation of hybrid APV systems that combine CIGS technology with advanced light management techniques will be essential to assess their effectiveness in improving both energy conversion efficiency and agricultural productivity. Additionally, further environmental and agronomic studies are needed to evaluate the impact of APV systems on different crop types, optimizing light distribution and microclimate conditions. From an economic perspective, a comprehensive lifecycle cost assessment of CIGS-based APV systems is crucial to determine their long-term feasibility, focusing on return on investment, performance stability, and material sustainability.

Future research should also focus on exploring how Average Visual Transparency (AVT) and Daily Integral Light (DLI) affects different plant species across various seasons and geographic locations. Since these factors are highly situational and variable, understanding their correlation could provide a more refined framework for optimizing APV systems, based on specific environmental conditions.

Furthermore, future work should also focus on evaluating the real-world effects of partial shading caused by semi-transparent PV structures on plant development. Although simulations and controlled environments provide useful

insights, field studies in actual greenhouses or open-field agrivoltaic setups are essential to understand how crop yield, growth rate, and photosynthetic efficiency respond to the dynamic and heterogeneous shading patterns created by these devices.

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