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Spectral Filtering Agrivoltaic Solution for Glass Greenhouses.

Pilot Installation at Serre des Marais (GE)

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Zusammenfassung

Gewächshausproduzenten verbrauchen eine erhebliche Menge an Energie, die hauptsächlich aus fossilen Brennstoffen stammt, um ihr Gemüse anzubauen. Solarmodule helfen den Produzenten, auf eine nachhaltigere Energieversorgung umzusteigen. Bestehende Standardlösungen beschatten die Kulturen und haben einen erheblichen Einfluss auf den agronomischen Ertrag der Gewächshausproduzenten. Voltiris hat neuartige Solarmodule entwickelt, die durch das Filtern des Sonnenlichts funktionieren, sodass die für das Pflanzenwachstum notwendigen Lichtkomponenten zu ihnen durchgelassen werden und das verbleibende Licht zur Stromerzeugung genutzt wird. Dies sollte den Gemüsebauern ermöglichen, ihre Energieunabhängigkeit zu erhöhen, ohne Kompromisse bei der landwirtschaftlichen Produktion eingehen zu müssen. Dieser Bericht präsentiert die Ergebnisse der ersten Implementierung von Voltiris-Modulen in einem kommerziellen Produktionsgewächshaus, dem Serre des Marais in Genf, auf einer Makroskala (1000 m² Bodenfläche). Der Bericht zeigt Ergebnisse zur Entwicklung der Stromausbeute über die Lebensdauer, zur Umwandlungseffizienz der Voltiris-Module mit einem speziell entworfenen Spektralfilterund zu beschleunigten Alterungstests der Leistungskomponenten. Zusätzlich wird der agronomische Einfluss der Voltiris-Module auf das Wachstum der Kirschtomatenkultur untersucht.

Résumé

Les producteurs de serres utilisent une quantité significative d'énergie, principalement issue des combustibles fossiles. Les panneaux solaires peuvent permettre aux producteurs un apport d'énergie plus durable. Les solutions solaires existantes ont pour effet d'ombrager les cultures impactent significativement le rendement agronomique des maraîchers. Voltiris a développé de nouveaux modules solaires qui fonctionnent en filtrant la lumière du soleil, de sorte que les composants lumineux nécessaires à la croissance des plantes leur sont transmis, et la lumière restante est utilisée pour générer de l'électricité. Cela devrait permettre aux maraîchers de gagner en indépendance énergétique sans faire de compromis sur la production agricole. Ce rapport présente les résultats d'une première mise en œuvre à l'échelle macro (1000m2 de surface au sol) des modules Voltiris à l'intérieur d'une serre de production commerciale, la Serre des Marais à Genève. Le rapport présente des résultats sur l'évolution de la production d'énergie au cours de la durée de vie, l'efficacité de conversion des modules Voltiris utilisant un filtre spectral spécialement conçu, les résultats des tests de vieillissement accéléré des composants de puissance. De plus, l'impact agronomique des modules Voltiris sur la croissance de la culture de la tomate cerise est étudié.

Summary

Greenhouse growers use a significant amount of energy, mainly sourced from fossil fuels, to grow their vegetables. Solar panels help growers shift to a more sustainable energy supply. Standard existing solutions shades the crops and impact significantly the agronomic yield of greenhouse growers. Voltiris has developed novel solar modules that work by filtering the sunlight, so that the light components necessary for plant growth are transmitted to them, and the remaining light is used to generate electricity. This should enable vegetable farmers to gain energy independence without compromising agricultural production. This report presents the results of a first implementation on a macro-scale (1000m2 ground surface) of Voltiris modules inside a commercial production greenhouse, the Serre des Marais in Geneva. The report presents results on the power output evolution over the lifetime, the conversion efficiency of Voltiris modules using a specially designed spectral filter, the results of accelerated ageing tests of the power components. In addition, the agronomical impact of the Voltiris modules on the growth of Cherry Tomato crop is studied.

Main findings («Take-Home Messages»)

- **Successful combination of solar energy generation with high-tech greenhouse agriculture:** The 1000 m² pilot installation is the first large-scale AgriPV demonstration to successfully combine significant solar energy production with the cultivation of light-savvy tomato crop, without any significant total yield reduction (-4%) for the best PV modality.
- **Proven compatibility of the Voltiris system in a commercial setting:** The 1000 m² pilot confirms that the Voltiris system can be seamlessly integrated into an operational greenhouse without altering standard practices.
- **Identification of key agronomic benefits:** Research by the Swiss agronomic institute Agroscope indicates reduced leaf temperatures and potentially lower water requirements under the modules, contributing to improved resource efficiency and possibly higher yields.
- **Pathway towards viability:** Insights from pilot projects have driven enhancements in filter design, PV panel technology, and system reliability, leading to increased energy output and durability. In parallel, the price of the modules have decreased significantly during the P+D project. A clear path towards <2.0 CHF/Wp turn-key is in focus, and a potential cost reduction to <1.0 CHF/Wp is discussed.
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Contents

Abbreviations

PV - Photovoltaics

APV - Agrivoltaics

LCPV - Low Concentration Photovoltaics

EQE - External Quantum Efficiency

MPP - Maximal Power Point

PAR - Photosynthetically Active Radiation. Light between 400nm and 700nm used by photosynthesis.

DNI - Direct Normal Irradiance

DHI - Direct Horizontal Irradiance

1 Introduction

1.1 Background information and current situation

High-tech greenhouse growers are grappling with severe challenges, particularly due to the recent energy crisis of 2021-2022. Energy costs, which previously accounted for 20% of their total expenses, have surged to 40%, driven by sharp increases in electricity and gas prices. For example, electricity spot prices rose dramatically from approximately 60 CHF/MWh in July 2021 to over 400 CHF/MWh at the peak of the crisis in August 2022, while gas spot prices skyrocketed from around 30 CHF/MWh to more than 250 CHF/MWh during the same period. As a result, nearly 30% of greenhouse producers were forced to temporarily halt operations during the crisis's peak. Adding to the difficulties, energy prices have become highly unpredictable, notably due to the war in Ukraine, and there is a lack of solutions to manage this extreme price volatility. Finally, pressure from customers, retailers, and governments is pushing the agricultural sector to reduce carbon emissions. For instance, Migros, representing 40% of the Swiss market, has announced plans to exclusively purchase carbon-neutral vegetables by 2025.

Yet, high-tech glass greenhouses will be instrumental in the future of agriculture as they offer many benefits, such as enhanced climate change protection, increased yields, reduced water and pesticide usage, to name a few.

However, with more than 90% of the energy currently supplied by fossil fuels (mainly gas to heat the greenhouse), growers lack today solutions to become more energy independent and more sustainable, as current solar solutions are not tailored to greenhouse agriculture: traditional solar panels create shade and reduce yields for most of the crops, while space is insufficient around greenhouses to install enough solar capacity.

State of the Art in APV

The state of the art in agrivoltaics (APV) involves several active players in Europe, including companies, energy providers, and start-ups. These players primarily use standard opaque, or chequerboard photovoltaic modules mounted on mobile structures to limit shading effects on crops. Some startups are exploring unconventional APV systems such as luminescent solar concentrators or adaptive shading technologies. APV solutions often target crops that benefit from partial shading during periods of high solar radiation and require protection from winds, hail, and storms.

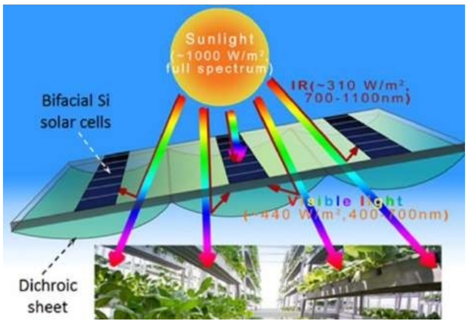
However, APV solutions face challenges related to limited crop varieties, location constraints without grid connections or significant energy consumption, and lengthy permit application processes for constructing structures on agricultural land. Despite the advantages of greenhouses for APV systems, their widespread adoption has been hindered by the fact that 95% of crops grown in glass greenhouses require high levels of sunlight. For the main greenhouse crops (tomatoes, peppers and cucumbers, e.g. 95% of glass greenhouse market), where the crop economical value is high, approaching >65CHF/m2/year, the use of semi-transparent PV panels, such as mosaique solar panels is uneconomical. Indeed, for such crops, every percent of light loss results in similar agronomical loss. For standard PV systems, capturing 1% of sunlight can generate 2Wp/m2 (200Wp for a completely black solar panel). This means that the value of the electricity ~2kWh/m2/year should be higher than the agronomical loss. For a tomato grower in Switzerland, loosing 1% of crop amounts to a loss of 0.65CHF/m2/year, while the energy generated by the light intercepted amounts to ~0.4CHF/m2/year. High value crops growers are therefore losing money by using standard PV technologies[1]

[1] https://www.wur.nl/en/research-results/research-institutes/plant-research/business-units/greenhouse-horticulture/show-greenhouse/viability-of-semi-transparent-solar-panels-on-greenhouses-is-being-evaluated.htm

Figure 1 - Greenhouse using standard solar modules covering 50% of the roofing (South side). High light losses and light level inhomogeneities results from the APV deployment.

Alternative technologies

Existing Solution	Limitation & Explanation
Standard APV solutions adapted to greenhouse	Glass-glass mosaic solar panels are mounted on the South-facing side of the greenhouse roofing. Inherently, the solar cells block parts of the light (irrespective of the crops needs), which is detrimental to greenhouse crops usually light- loving crops (tomato, cucumber, pepper = 90% of market share). The main limitation resides in a low power density per unit shading. The main actors in this field are grid operators, greenhouse constructors or installation companies, such as BayWa [DE], Sun'Agri [DE], TSE [FR], EDF [FR], Groenleven [NL], Horconex [NL]... 

Luminescent solar concentrators	Luminescent solar concentrators consist in a spectrally filtering glass that is included in the greenhouse roofing. In the glass, a layer of nanoparticles is added. Those nanoparticles capture light with wavelengths not/less needed by crops and convert them into photons that are well transformed into electricity (NIR, far-red). The emitted photons are trapped inside the glass by total internal reflection and will be guided towards conventional solar cells placed either as mosaic or placed on the edge of the glass. The main drawback resides in a low efficiency (~8% efficiency). Also, this solution also has typically a low light transmission of ~70%, which make the economics of the solution challenging for greenhouse growers. The main actors are ClearVue, Soliculture, BriteSolar. 
Spectral filtering	Spectral filtering technologies (same category as Voltiris technology) have been pushed by the following actors: DWP Energy solutions, and the research Group of Prof. Liu (Chinese UST). However, the efficiency of their solutions is low (object of our first patent), and their solution design differs significantly (no retrofit possible, or focus on outdoor use). 

Spectrally selective PV cells	Perovskites, and organic PV cells are being actively researched by a number of actors (research institutions and start-ups). However, they will suffer the following drawbacks when it comes to greenhouses: • Spectral selectivity: Most of the materials/dyes used in those types of solar cells are not as spectrally selective as dielectric spectral filters, hence blocking partly parts of the spectrum necessary for plants' growth. • Blocking radiations outside of the greenhouse. As those modules would be installed on the roof, they would block radiations at the glass level, hence decreasing the greenhouse heating effect. This results in increased heating needs in the winter . 

1.2 Purpose of the project

Voltiris has developed a solar module using spectral filtering (Figure 2 - Principle of the Voltiris technology. The whole unit is called a Voltiris solar module. The sunlight is collected by the reflector. Part of the spectrum is reflected, and concentrated onto a small PV panel. The module is mounted onto a sun-tracking or solar tracking mechanism/device.Figure 2) that is compatible with all greenhouse crops. It separates the light components needed by the plants for the photosynthesis from the unused part of the spectrum which is reflected and focused onto photovoltaic cells to generate electricity. This results in the production of renewable energy without impacting the yield of the crops underneath the modules as the light required for crops' growth is transmitted to them. Furthermore, Voltiris focuses on providing the independent, profitable, and sustainable source of energy that growers need to successfully transition to a carbon-free electrification.

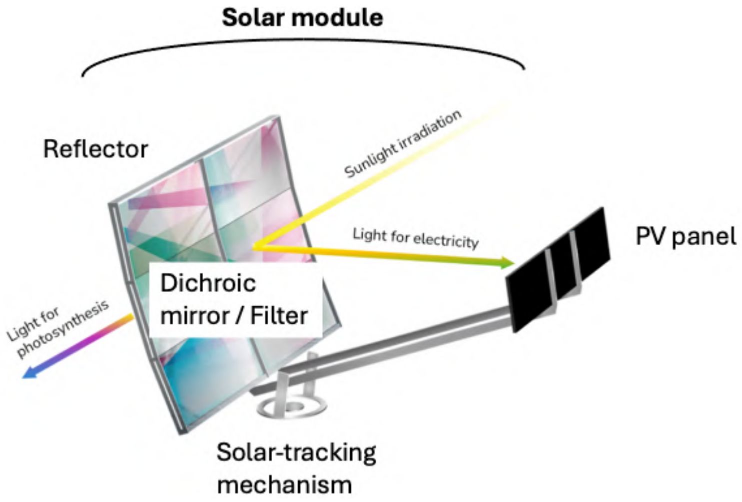


Figure 2 - Principle of the Voltiris technology. The whole unit is called a Voltiris solar module. The sunlight is collected by the reflector. Part of the spectrum is reflected, and concentrated onto a small PV panel. The module is mounted onto a sun-tracking or solar tracking mechanism/device.

Ultimately, Voltiris offers growers increased energy independence, improved sustainability, and enhanced profitability - all of this with seamless integration as no operation shutdown or construction permits are required to install the modules.

Figure 3 - Value creation for greenhouse operators of the Voltiris system.

Voltiris offers a unique solution for greenhouse growers

Compared to the state of the art in greenhouse-integrated photovoltaics, the Voltiris system offers several improvements:

1. **No shading**: Voltiris uses spectral filtering solar modules allowing the necessary light components for photosynthesis (red and blue light) to reach the crops, while concentrating the remaining sunlight onto PV cells for electricity generation. By doing so, the energy production has no impact on agricultural yields, as it selectively captures the light components not needed by the plants. In contrast, traditional PV systems used in greenhouses usually block or shade a significant portion of the sunlight, which can negatively impact crop growth and therefore, decrease the yield. The spectral filters are made by

polymer co-extrusion, which is a method already used today in solar control films in architecture and can easily be used for large scale production.

2. **Tracking system:** Voltiris modules incorporate a 2-axis solar tracking system, which optimizes the sunlight exposure for increased energy generation. This system follows the movement of the sun throughout the day, increasing the module's yield (kWh/kWp) by approximately 22% compared to fixed PV installations (Figure 4). Thanks to the tracking, the output is more constant throughout the day and better suited for self-consumption. A cost-effective 2-axis solar tracking system is only made possible as we are inside of the greenhouse. By being below the roof and sheltered from the elements, we can use lighter and more cost-effective materials such as injected polymer-based materials, significantly reducing the complexity and the cost of our patented tracking mechanism compared to standard outdoor tracking systems.

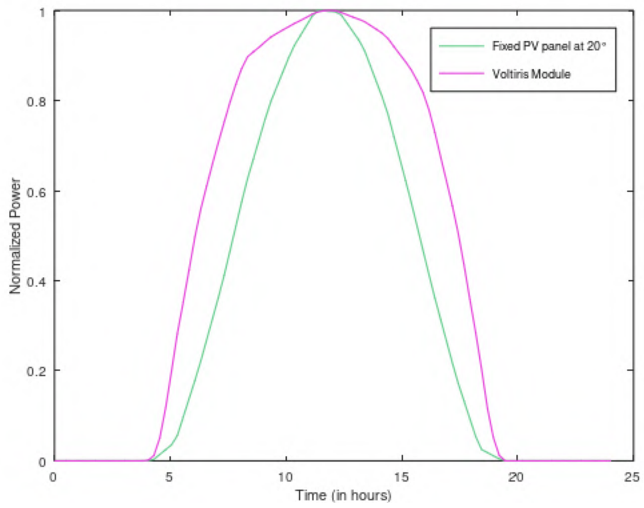


Figure 4 - Performance comparison between a standard fixed panel (South, 20°) and a Voltiris module with tracker at equal peak power for June 23rd in Geneva

3. **Retrofit**: Additionally, Voltiris modules are designed for an easy integration into existing greenhouse structures, leveraging the already available infrastructure. As the modules are built inside of the greenhouse, no building permits are required. By utilizing the greenhouse space without compromising crop production, the Voltiris system offers a practical and efficient solution to increase sustainability and profitability in the agricultural sector.

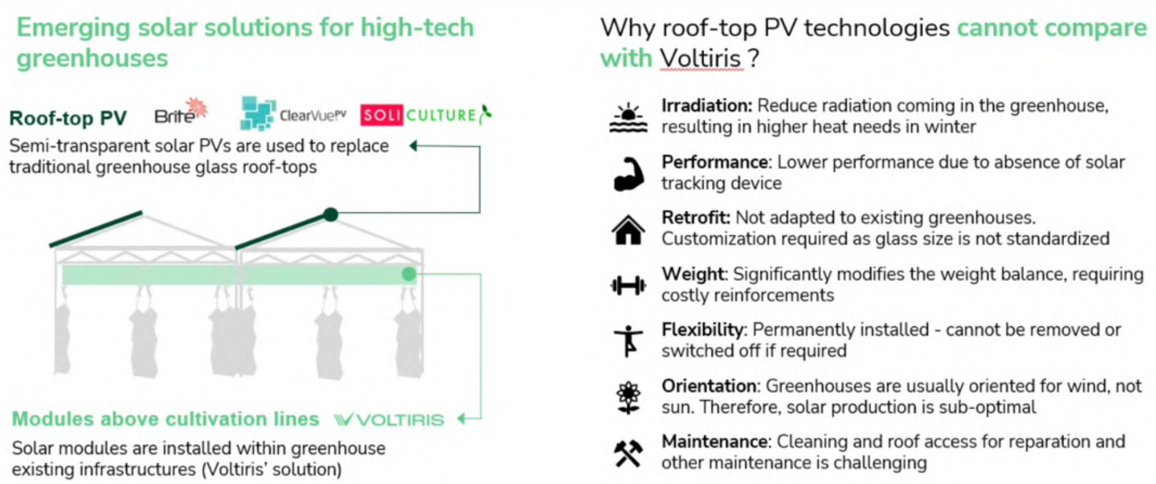


Figure 5 - Comparison of the different APV technologies applied to greenhouses. Voltiris overcomes the technical and agronomic limitations that alternative emerging solutions (roof-top PV, Brite solar, ClearVue, SoliCulture) have.

This project is a first installation at a macro-scale of the Voltiris technology, and a first deployment of the technology in a commercial greenhouse. With a scale of 1000m2, the project helps Voltiris better assess the suitability of the technology for greenhouse growers, validate the energy yield of the modules, and confirm at statistically significant scale that there are no agronomical losses due to the modules.

1.3 Objectives

The objectives of the project are the following:

- Validation of the agronomical yield, and assessments of potential agronomical benefits
- Validation of the energetic yield and units economics
- Improvement of the Voltiris modules peak power
- Validation of the validity of the Voltiris solution in the commercial greenhouse horticulture

Validation of the agronomical yield, and assessments of potential agronomical benefits

This objective will be monitored by looking at four main points:

- Yield impact: The yield below the different types of filters will be measured. The project will be a success if the yield below the Voltiris modules does not present any statistically significant yield reduction compared to the reference zones.
- Fruit quality impact. The fruits below the modules must also pass the key metrics for fruit sales (acidity-Brix index, sugar content, fruit size and weight).
- Potential agronomic benefits:
    - Water needs: By blocking partly the infrared light at the canopy, the direct leaf temperature decreases, and hence the water needs are decreased. A reduction of the water needs >10% will be considered a success.
    - The Voltiris modules act as perfect screens: the light needed by crops is transmitted, while the rest is used for energy generation. While the influence will be reduced in winter with diffuse sunlight conditions, a net climate improvement is expected in the summer. The leaf temperature will be measured by IR cameras, and a >1°C leaf diurnal temperature decrease in the period April to October will be considered a success.

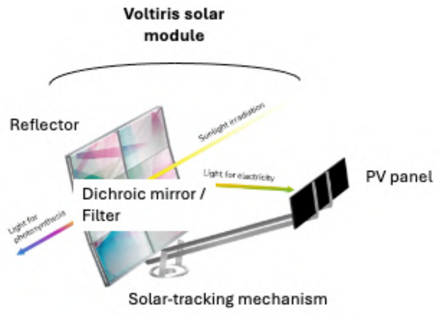
Validation of energy yield and of units economics

This objective will be monitored by looking at:

- System energetic yield. Generate >80% of the theoretical energy output of the solar energy plant (model discussed in Chapter 9). The 80% accounts for potential losses on a first project due to solar tracking errors, mis-alignment between modules wired in series, and balance of system.
- Lifetime of key components: The spectral filters and the solar modules will be tested using the standards of the solar industry. A yearly annual yield decrease < 1% due to degradation will be considered a success.
- Business model: In the project, the partner energy provider (Romande Energie), who is financing the installation, will be reviewing the business case for the solar project. The project will be considered a success if the energy provider validates the business model offered by Voltiris solution.

Improvement of the Voltiris modules peak power

- Improved spectral utilization factor. By developing a new filter in partnership with the company 3M, the goal is to increase the spectral utilization factor - i.e. the efficiency of the conversion from light power to electrical power as a function of wavelength - to >65% (see chapter 5 for more details). This means that a light concentrator made from Voltiris filters with an area of 1m2 (and a small PV panel of size 0.17m2) would yield >65% of what a fully cell-covered 1m2 solar panel would yield (see Figure 6).
- Improved PV panel peak power for Low Concentration PV. The goal of the project is to validate a new design of the LCPV PV panel to reach >31 Wp for a PV panel footprint of 1/6 m2 (see Figure 6).



Voltiris solar module	**1m2**
Reflector	1m2
Dichroic mirror / Filter	1m2
PV panel	0.17 m2 (1/6 m2)

Figure 6 - Naming convention of the components of the Voltiris solar modules, and the surface area of each component.

Validation of the validity of the Voltiris solution in the commercial greenhouse horticulture

- Ground cover ratio. A ground use greater than 30% would be considered a success. This means that we place a 1m2 solar module (module area, i.e. filter area) every 3.33 m2 of ground surface. This is a quite standard filling for modules with 2D solar tracking system (as here).

- Installation. The installation of the system in an operational environment (during the cultivation season) will be tested during this project. Also, it is necessary that the installation can be performed without disrupting the overall greenhouse operations.
- No impact on daily greenhouse operation. The grower will be involved in the design phase of the project. If the grower agrees to extend the project from phase I (<30 modules) to phase II (~300 modules), the project will be considered a success.

2 Description of facility

In this section, the overall architecture of the installation at the Serre des Marais is presented. The Voltiris system is made from 3 main parts: the reflector, the solar tracking mechanism, and the linear transmission (for actuating the solar tracking), as shown in Figure 7.

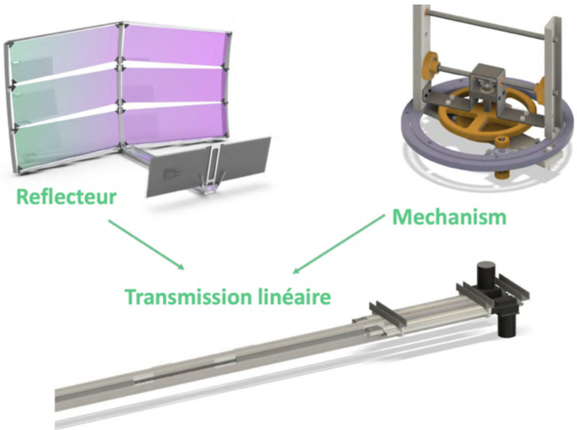


Figure 7 - Description of the Voltiris solution's hardware.

The reflector itself is made from a collector of ~1m2 made from spectral filters, and from a solar module of size ~1/6m2.

The modules are installed within the greenhouse, hanging from the structural trusses in the greenhouse (large galvanized iron profiles in a zig-zag shape), as shown in Figure 8. In Figure 9 (left), the profiles of the linear transmission are hanging from the truss bars using our "V" hangers, and in Figure 9 (right), the modules are installed on the linear transmission profiles.

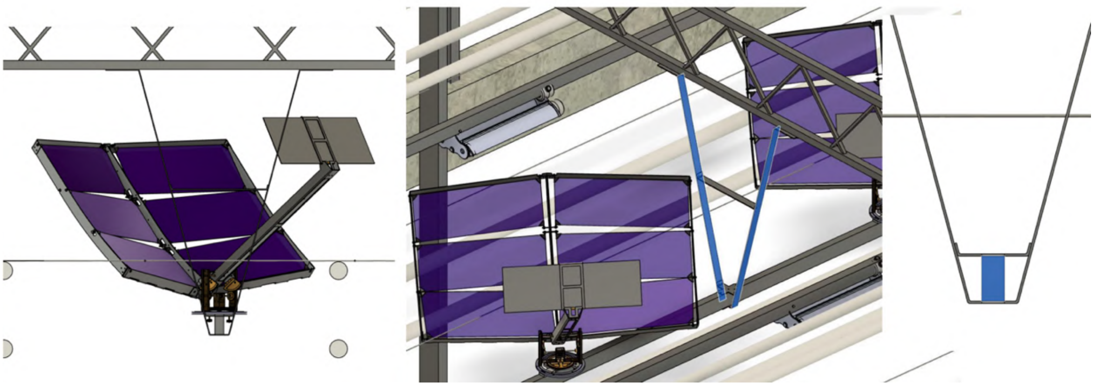


Figure 8 - Structure holding the modules in the greenhouse.

Figure 9 - Images of the holding structure at Serre des Marais.

The installation at the Serre des Marais has been performed in two phases: In Phase I, a first prototype of the solar plant has been installed (30 modules). The goal of the first phase was to test the installation process, and validate with the grower over a few months of cultivation period that our setup was not impeding on the greenhouse processes, including the cleaning (see Results part). This installation was performed in August 2023, using commercially available 3M filters (Filter 0 in Figure 10).

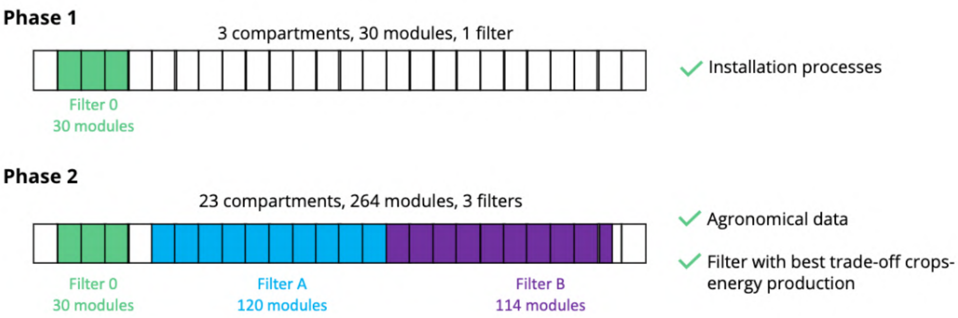


Figure 10 - Setup overview at Serre des Marais.

The installation was then further extended (Phase II) at the end of December 2023, with the addition of 234 modules. The modules of the Phase II present two modalities of filters: Filter A and filter B, with different wavelength profiles (see Results).
The image below shows the plan of the installation, as well as a close-up of one of the cell (3 compartments).

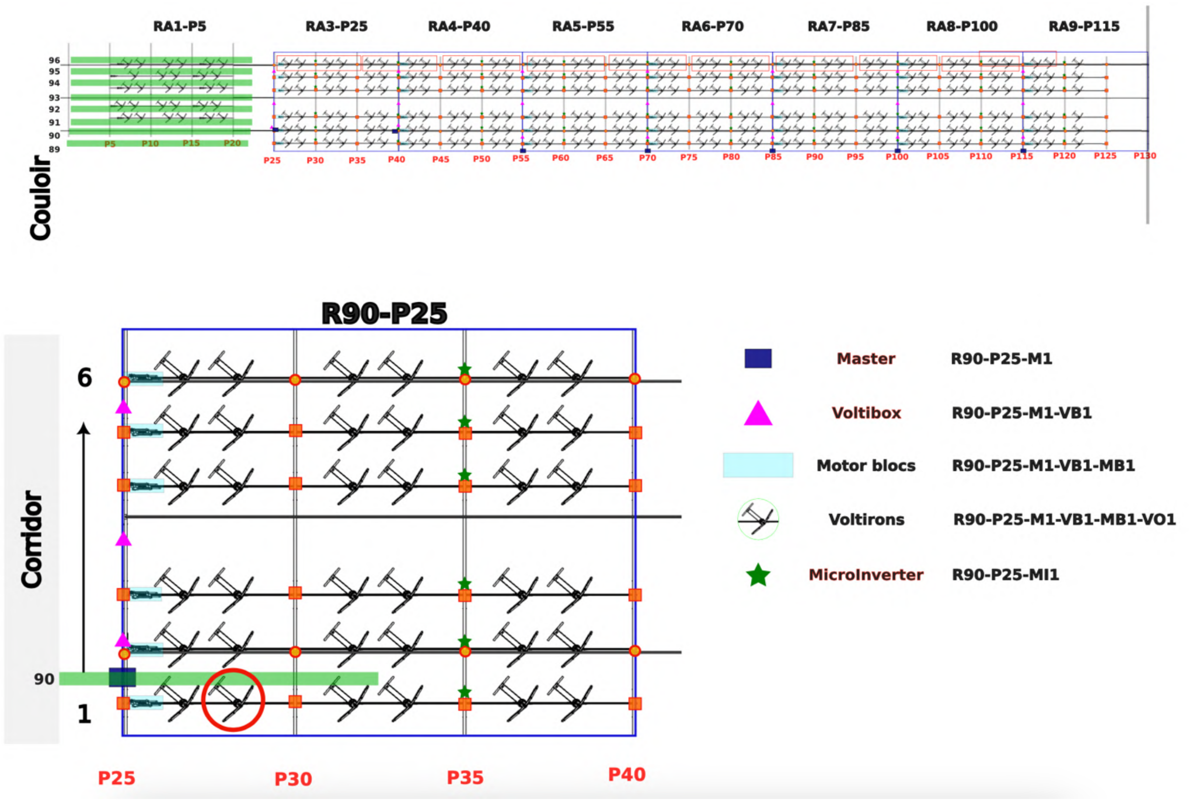


Figure 11 - Top: Overall view of the installation at Serre des Marais. In green, we highlight the modules from the Phase I. Bottom: Zoom on a single cell (3 compartments= 8meters x 15meters), where we can see the design architecture of the installation.

3 Procedures and methodology

The project has been structured in several work packages, covering the different aspects of the project. The main work packages have been:

WP1 - Design infrastructure.

WP2 - Dichroic film development and test

WP3 - Installation

WP4 - Agronomical monitoring

WP5 - Hardware test and qualification

WP6 - Energy output monitoring

In the below sections, we will list the tasks that have been performed, and the key results that were obtained.

4 Design infrastructure

4.1 Method

In this work package, the goal was to develop the mechanical design of the infrastructure, to ensure that the infrastructure does not impede on the growers' work, and it compatible with the main greenhouse processes, such as cleaning, re-hooking of the crops, basic maintenance (screen strings replacement, window change).

The design part has been carried out into several steps, as presented in Figure 12: We have first iterated the design on CAD and 3D models with the grower, before receiving the green light to install the first phase.

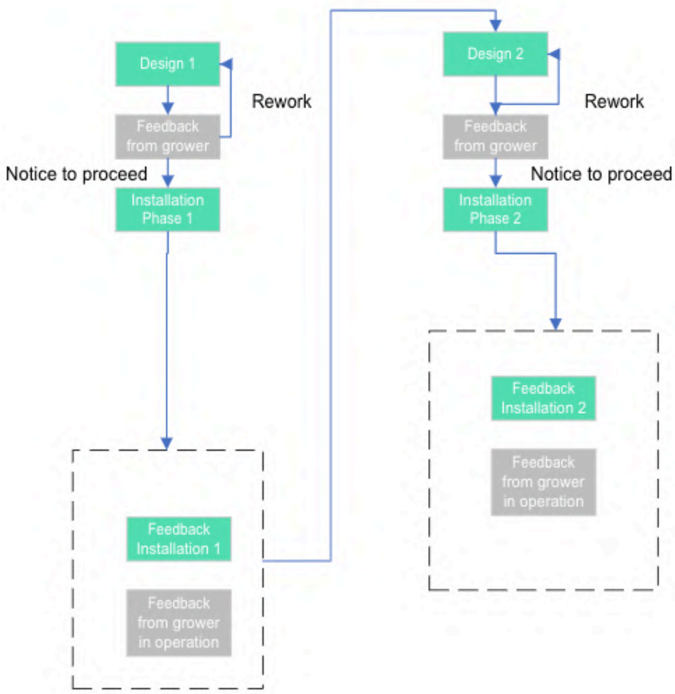


Figure 12 - Iterative approach to the design of the installation.

With the installation of the first phase, we could gather feedback from the grower on the main design issues, and stress test the technological design with some of the important greenhouse cultivation processes, such as:

- Re-hooking (process to adapt the plant head height in the greenhouse)
- Harvesting
- Cleaning

The grower was able to assess during 2.5 months the compatibility of the modules with his cultivation processes. We have then integrated the growers feedback on the design of the second phase, that was installed in December.

4.2 Data analysis and Discussion

We could validate with the first phase (30 modules), that the Voltiris technology integrate well within existing greenhouses, and that it doesn't impede on the greenhouse processes.

Learning on the implementation of the modules in a greenhouse: As a result of the first phase, we identified one point for the system improvement: there should be at least 60 cm of space between the cultivation line, and the bottom of our reflectors. It is indeed important for the re-hooking process that the workers can work with the hooks at the chest level.

The design of the modules of the Phase II has been slightly modify to offer more clearance for the workers. However, due to time constraints, the V hangers could not be adapted, and the modules are still at the same height.

Cleaning process: The cleaning is an important moment in the cultivation cycle. For phyto-sanitary reasons, it is necessary to thoroughly clean the greenhouse at the end of the season, and clean the greenhouse entirely with disinfectant solution. The cleaning is usually performed manually with high-pressure jets, or with automated cleaning robots, such as the aquajet.

The Serre des Marais has one Aquajet, and it was important to verify that the cleaning process can be performed without any hindrance. The windows above the modules was cleaned in November 2023 (see Figure 13) with special attention to the resistance of the modules to the 50 bars cleaning, and to the cleanliness of the windows located above the modules.

First, it was validated that the modules withstood the cleaning with the high-pressure jet, and that the strength of the jet does not need to be adapted due to our solution. The data presented in Figure 41 shows that the annual greenhouse cleaning with the Aquajet completely cleans the reflector, without any additional needs.

Finally, we could verify that the aquajet cleaned properly the window above the modules by verifying that all moss was effectively removed by the jet. It was however noticed that the modules need to be oriented in a cleaning position to offer the best results.

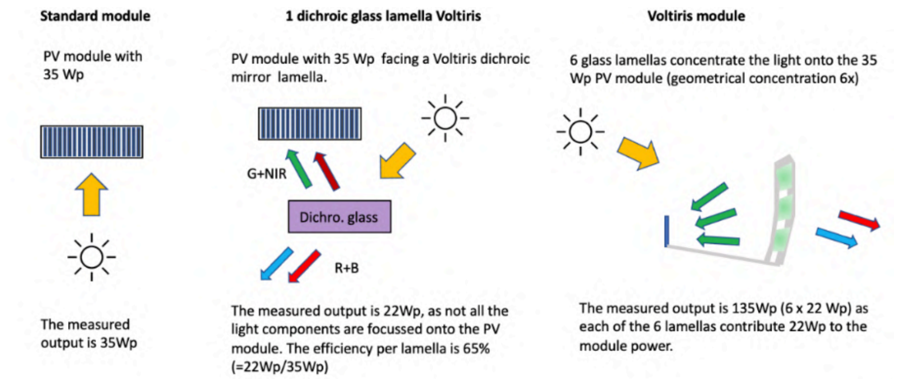
Figure 13 - Cleaning of the installation using the Aquajet machine (high-pressure cleaning).

5 Dichroic film development and test

The peak power of the Voltiris modules depends directly on the spectral utilization factor of the dichroic mirrors (see Figure 14 for an explanation of the spectral utilization factor). This means that the efficiency of the solar module can be improved by optimizing the reflective band edges of the dichroic mirror. In practice, this is achieved by tuning the thicknesses of the multiple layers of polymer forming the spectral filter (polymer co-extrusion).

The Spectral Utilization Factor quantifies how effectively dichroic mirrors filters and redirects the desired portions of the solar spectrum onto the PV cells. Without this tailored filtering—if the reflector were a perfect mirror—every relevant wavelength would be concentrated onto the PV cell, yielding a spectral utilization factor of 100%. However, the Voltiris system is intentionally designed to transmit a portion of the incoming solar radiation through the greenhouse roof to support plant growth. As a result, only a fraction of the incident spectrum is concentrated and converted into electrical energy by the PV cells. This fraction, that can theoretically reach 65%, is what we define as the spectral utilization factor: it is the ratio of the PV-useful, concentrated spectral power to the incident solar power that would be available under ideal concentration conditions.

In other words, a spectral utilization factor of 65% means that if a solar module can generate 30Wp at STC conditions, it would generate 20Wp when illuminated with the modified spectrum, while letting all the necessary light reaching the crops.



	Standard module	1 dichroic glass lamella Voltiris	Voltiris module
Peak power per unit area @ STC	220 W/m²	135 W/m²	135 W/m²
Size	0.17 m²	0.17 m²	1 m²
Power	35 W	22 W	135 W
Booster (concentration level)	1 x	0.65 x	4x

Figure 14 - Explanation of the definition of the spectral utilization factor of 65%. A perfect mirror would have a spectral utilization factor of 100%.

In the phase I, commercially spectral filters were purchased from the company 3M. For phase II, Voltiris has partnered with 3M to develop 2 optimized spectral filters for the Voltiris application : Design 1 and Design 2, which are reflecting the near infrared. On top of those filters, a commercial green reflecting filter has been laminated, making the two spectral compositions present in the Serre des Marais installation (Filter A=Design 1+ Green, Filter B= Design 2+Green). A further step in optimization will be to make a combined Green+IR filter.

The text below explains how the spectral utilization factor of the different filter recipes has been characterized based on spectroscopic measurements.

5.1 Method

Given that the Voltiris modules work by filtering out some parts of the Sun white spectrum, it is necessary to take the power distribution of each wavelength into account. The conversion efficiency of solar cells at different wavelengths (EQE) will vary on the type of cells.

5.1.1 Theoretical output and simulation of the filter:

The power generated by the panel is defined by equation (1) where f represents the power generated per electron, EQE is the ratio between the number of electron charges collected and the number of incident photons, and n is the number of photons arriving at the panel.

$$P = \int f\, EQE(\lambda)\, n(\lambda)\, d\lambda \qquad (1)$$

The number of photons can be expressed as a function of the spectrum of the incident light (see equations (2)).

$$n(\lambda) = \frac{S(\lambda)}{\frac{C}{\lambda}} \qquad (2)$$

To do this, we need to divide the spectrum by the contribution of a photon, which is the inverse of the wavelength to within one constant. Here, C and f are constants; as the results are normalized, they are neglected.

The result can be written as follows:

$$P = \int (f\, C)\, EQE(\lambda)\, \lambda\, S(\lambda)\, d\lambda \qquad (3)$$

Data required:

Some data are required to perform this calculation:

- The quantum efficiency of the cell
- The spectrum of the sun
- The spectrum reflected on the solar panel

5.1.2 Calculations:

Below are the quantum efficiencies associated with the cell types studied in this report. The graph below (Figure 15) was provided by the CSEM for 5 cell types. The data in Figure 15 does not take the encapsulant and glass of the module into account, but as the filter only reflects in the green and the NIR, this approximation does not modify the computation of the spectral utilization factor.

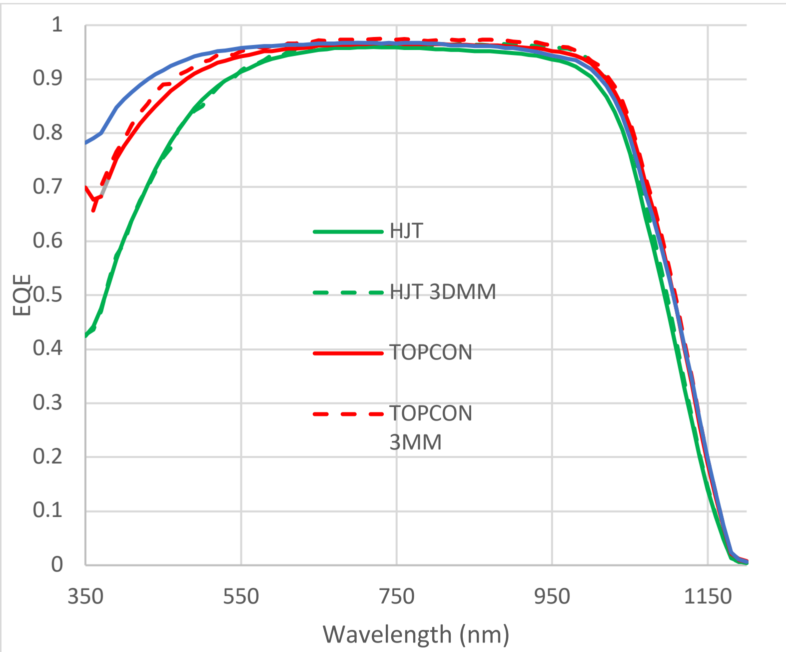


Figure 15 - Spectral efficiency of different types of solar cells.

To obtain the power distribution according to the type of cells, the weight of each wavelength must be taken into account. So, these EQE values are then multiplied by λ and by the sun's spectrum. We have taken the AM 1.5 spectrum (see Figure 16), which corresponds to the spectrum of the sun after passing through the atmosphere, with the sun at an angle of 41.8° to its zenith position. Below you can see the total AM 1.5 spectrum (left) and the part of the spectrum for which we carried out the calculations (right).

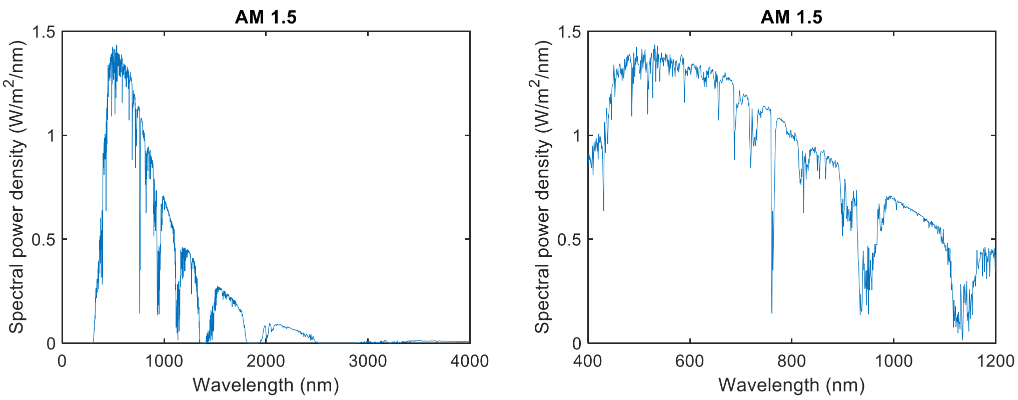
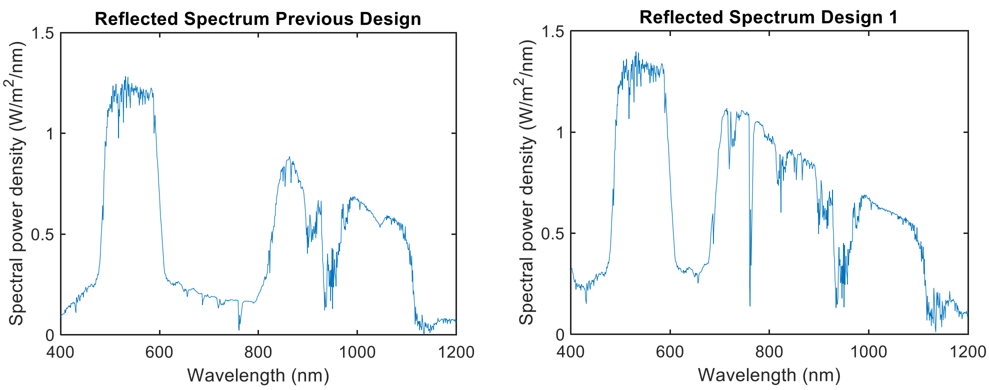


Figure 16 - AM1.5 spectral power distribution. The figure on the left shows the total spectrum of the sun from 0nm to 4000nm. The figure on the right shows the spectrum in the part we use to produce electricity, i.e. from 400nm to 1200nm.

Finally, we display in Figure 17 the spectra of the light reflected on the solar panel to generate electricity. The first corresponds to the solar module in Phase I, the next two are called Design 1 and Design 2 and are the two modalities installed in Phase II.



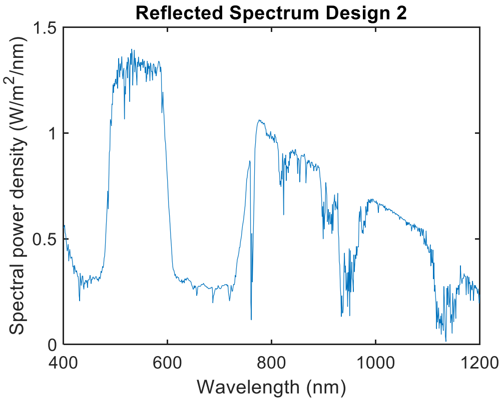


Figure 17 - Spectral power density of the reflection of a single lamella of the different filters installed at Serre des Marais.

5.2 Data Evaluation and Discussion

The solar modules used in the Phase II of the Serre des Marais project have a rated power of 26.7 Wp at STC conditions.

Once the powers have been calculated (quantum efficiency * wavelength * spectrum of the sun), we normalize them so that the total sum of the power over all wavelengths is equal to 26.7 W.

Then we use the calculated power in the case where only part of the spectrum is used (quantum efficiency * wavelength * spectrum reflected by the solar modules on the PV panel). To associate it to a power in Watt, we make a rule of three with the value for which the entire spectrum is taken into account:

Full solar spectrum	Integral of entire spectrum convoluted by the spectral efficiency of the cell	Result_total = 26.7 W
Spectrum reflected by the solar module	b = Integral of the reflected spectrum convoluted by the spectral efficiency of the cell	Result_part

Finally, the spectral utilization factor is given by: $\frac{Result\_part}{Result\_total} * 100\ (\%)$

The results obtained for a PERC G12 solar cell (as used in our modules) are summarized in the following table.

	PERC G12 bifi (Trina)
Phase I design Spectral utilization factor (%)	49.8
Filter B Spectral utilization factor (%)	78.30

Filter A Spectral utilization factor (%)	71.97

So, with this calculation method, the output power of the solar panels once the part of the spectrum transmitted to the plants is removed is 49.8% for the previous Design, and 78% and 72% for Filter B and Filter A.

In the coming months, we will validate the theoretical computations with MPP measurements of the electrical outputs of the solar modules with Filter A and Filter B.

6 Installation

6.1 Method

In order to further optimize the installation time of the Voltiris modules, the installation time of the Phase II has been measured at each steps of the installation.

6.2 Work performed and Results

This installation is the second step of the Voltiris' project in Geneva area with Serres des Marais as a partner. This installation consists of a total area of 1000m^2 and translates in the installation of roughly 250 Voltiris solar modules.

Figure 18 - Voltiris' solar installation in Geneva

6.2.1 Preparation work

To prepare and ensure smooth and efficient installation, several operations can be anticipated before the installation starts. Some other can be done in parallel of the installation.

Specifically for this installation, the V-structure had to be reworked to insure proper alignment.

The profile structure needed to be prepared on site and prior to the installation started. The preparation involved:

- Introducing the flat rods
- Marking the profiles and naming the profiles
- Clipping the solar cables
- Marking the racks

To move along the cultivation lines, we developed trolleys to transport the material along with the employees, this would significantly cut the displacement time during installation. Screws & tools were prepared and dispatched for the different workforce to be using.

Figure 19 - Several trolleys have been prepared to allow workers to move material efficiently along the cultivation lines.

Total time of the preparation, prior to the installation: **9.25h for 8 Voltiris employees**

Other operations could be performed during the installation inside the greenhouse. For instance, the mounting of the reflectors as well as the preparation of the PV panels were done while the installation was ongoing inside the greenhouse.

Figure 20 - Voltiris' team working "behind the scenes" on the preparation.

Time for reflectors: 25h for 1 Voltiris employee

- Time for solar panels: 16h for 1 Voltiris employee

The total time of preparation work for this installation account to 115 hours of work.

6.2.2 The installation process:

<u>V Structure & profiles:</u>

The installation starts with the setup of the V structure. This foundational element ensures the overall integrity of the installation. It is directly attached to the existing structure. The profiles are installed right after on the V-structure.

Along in this step, the junctions between V and profiles are tightened to ensure mechanical sturdiness. These steps are done subsequently and along the cultivation line. The cultivation line is 125m long, 21 Vs and 20 profiles are installed along one cultivation line.

Figure 21 - V-structure and profiles installed along two cultivation lines.

+	-
• U-bolts ensure an easy installation of the V	• Connections with Vs takes time. • Alignment of the profiles can be complicated due to a misalignment on the V position

Future improvements:

- Focus on process and design improvement to facilitate positioning of the V.
- Simplify the connections between Vs and profiles.
- Improve the connections between profiles.

Total time for the installation of the V-structure and the profiles: **20h for 6 Morinaj's employees**

Motors:

The next step in the installation is the positioning of the motors into the system. This goes along the connection of the linear transmission, locking in the position of the different components along it. This locking is a requirement to proceed with the installation of the mechanisms.

Figure 22 - Motors installed on the profiles.

+	-
Pre-positioning motors ensures an easy set-up of the motors	• Connection between motors and transmission is not trivial. • Allen keys are difficult to use in current setup

Future improvements:

- Simplify the connection between motors and transmission.
- Change screws type.
- Ensure proper alignment from the profiles.

Total time for the installation of motors: **5h for 3 Morinaj's employees**

Mechanisms:

The mechanisms for the solar tracking of the Voltiris solution are then positioned on the profiles. Precise alignment and connection of these mechanisms is required for their seamless functionality of the overall system.

Figure 23 - Mechanisms on the trolleys, ready to be installed on the profiles.

+	-
• Light and easy to manipulate.	• Screws and nutsteins can take some time to align and tighten. • Alignment can be tricky

Future improvements:

- Improve the connection mechanism, ideally with an autolocking mechanisms.
- Improve the "auto-alignment" of the modules.

Total time for the installation of mechanisms: **14h for 2 Morinaj's employees**

Reflectors:

To optimize light distribution onto the photovoltaic panels, reflectors are installed on the mechanisms previously installed. The placement and adjustment are simple and straightforward thanks to its design.

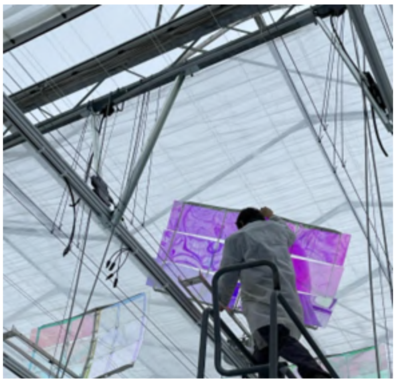


Figure 24 - Positioning of the reflectors onto the mechanisms

+	-
• Light and easy to manipulate. • Holds itself thanks to the design	

Total time for the installation of reflectors: 7h for 3 Morinaj's employees

PVs Installation:

The final step involved the installation of photovoltaic panels (PVs), harnessing solar energy to power the system.

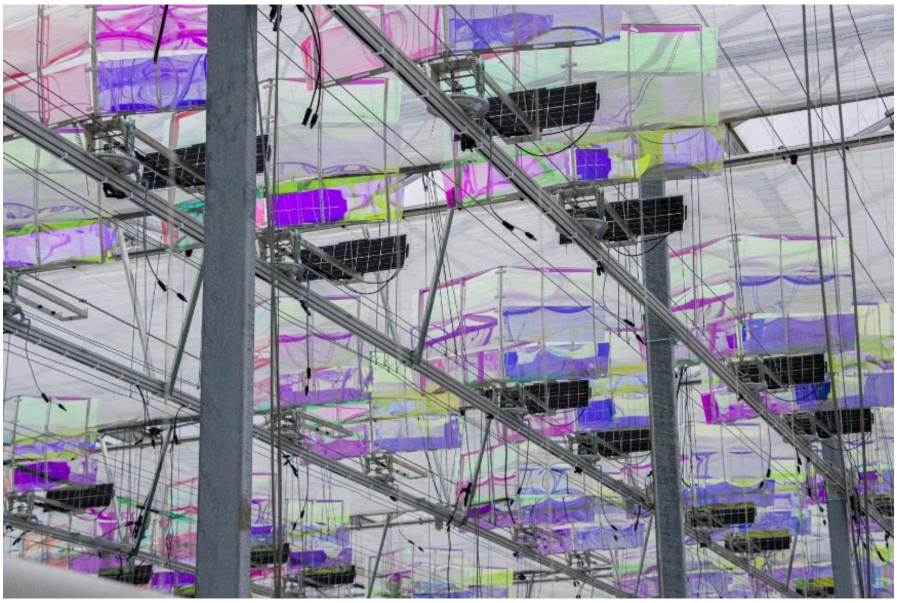


Figure 25 - Voltiris modules with the PV panels installed.

Total time for the installation of reflectors: **6h for 2 Morinaj's employees**

Cabling and wiring in general are not part of this report as it focuses solely on the mechanical aspect of the installation, a separate analysis will be performed on the electronic side of the process.

By examining the timings associated with the installation process, we can gain valuable insights into its efficiency and effectiveness. This analysis will provide a comprehensive understanding of the challenges faced during installation and help us identify key areas for improvement.

6.3 Data Evaluation and Discussion

The analysis phase of the installation process provides a comprehensive overview of the timings associated with each step. The timing of the different steps is presented in Table 1 - Breakdown of the installation time per step.

Steps	Time [h]
V-structure + profiles	120
Motors + linear transmission	15
Mechanisms	28
Reflectors	21
Solar panels	12
Total	**196**

Table 1 - Breakdown of the installation time per step.

In total, it took **196 hours** to install 250 Voltiris modules, this translates in an average time of installation per module of **47 minutes.**

By examining the duration of individual steps, we will gain valuable insights into the efficiency and effectiveness of the installation within the greenhouse environment but also on the steps where Voltiris could and should improve to reach its target installation time of <30 minutes.

7 Agronomical Monitoring

7.1 Method

The agronomical monitoring takes place in a compartment of the Serre des Marais (GE). A 1.2ha compartment is be used for the study aimed at measuring the agronomic and climatic impact of the Voltiris solar filters and panels on a cherry tomato crop (variety DRO607) grown in soilless conditions.

Two modalities PV1 and PV2 have been studied, over each a surface area of 500m2. As the test area is relatively small compared to the full compartment (500m2 vs 12000m2), the crop steering has not been adapted for the test area. This means that the temperature, humidity, and irrigation setpoints set by/to the climate computer have been made regardless of the tests.

The crop monitoring has been performed jointly by the Agroscope, and by the Serre des Marais operational team over the full season 2024.

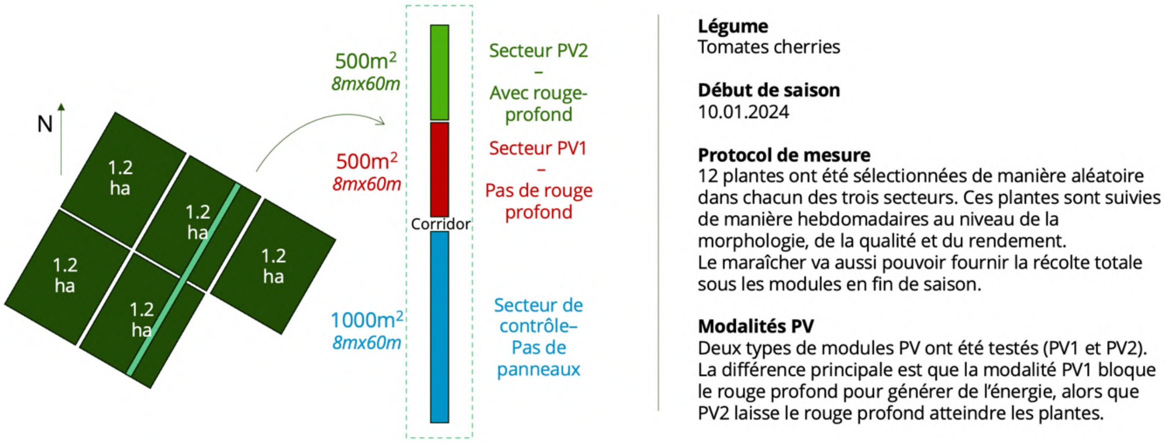


Figure 26 - Definition and position of the different modalities.

The two different modalities were equipped with different spectral filters that both filters out green light, as well as a certain portion of the near infrared. The Modality PV1 is filtering out the near infrared (700-800nm) to generate energy, while the Modality PV2 leaves the near infrared untouched, and only uses the infrared at wavelength higher than 800nm to generate energy.

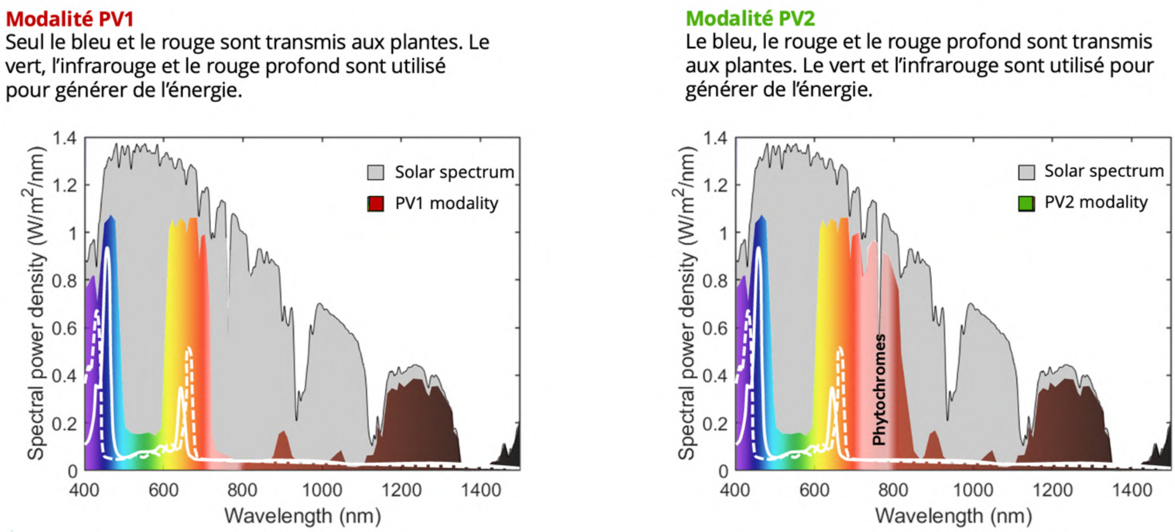
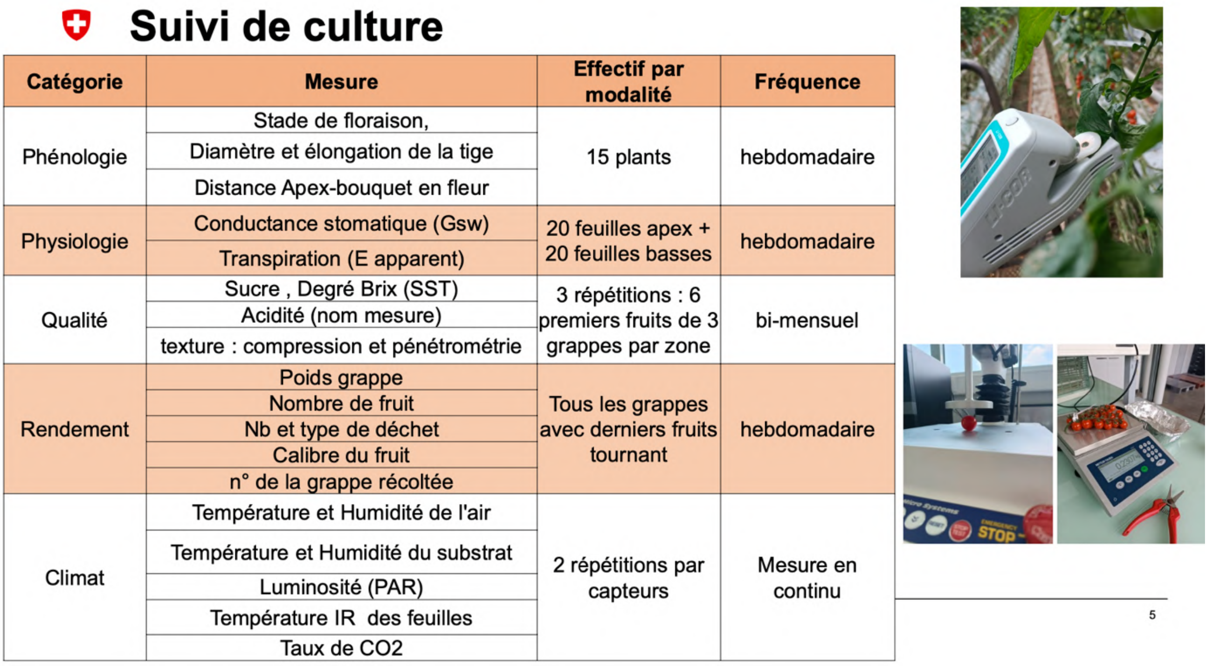


Figure 27 - Spectral characteristics in transmission of the solar modules in the PV1 and PV2 modalities.

The agronomic data have been measured by both the operational team of Serre des Marais, as well as the Agroscope.

While the data from the Serre des Marais have recorded the average yield values over the different modalities (PV1, PV2, and Control), the Agroscope has selected 15 plants in each modality and monitored them individually for quality, physiology, yield, phenology, and climate. Figure 28 presents the different variables and measurement protocol used by the Agroscope.



Suivi de culture

Catégorie	Mesure	Effectif par modalité	Fréquence
Phénologie	Stade de floraison,	15 plants	hebdomadaire
	Diamètre et élongation de la tige		
	Distance Apex-bouquet en fleur		
Physiologie	Conductance stomatique (Gsw)	20 feuilles apex + 20 feuilles basses	hebdomadaire
	Transpiration (E apparent)		
Qualité	Sucre , Degré Brix (SST)	3 répétitions : 6 premiers fruits de 3 grappes par zone	bi-mensuel
	Acidité (nom mesure)		
	texture : compression et pénétrométrie		
Rendement	Poids grappe	Tous les grappes avec derniers fruits tournant	hebdomadaire
	Nombre de fruit		
	Nb et type de déchet		
	Calibre du fruit		
	n° de la grappe récoltée		
Climat	Température et Humidité de l'air	2 répétitions par capteurs	Mesure en continu
	Température et Humidité du substrat		
	Luminosité (PAR)		
	Température IR des feuilles		
	Taux de CO2		

Figure 28 - The different metrics monitored by the Agroscope during the 2024 season.

7.2 Plant physiology

The stomata conductance and the leaf transpiration has been measured weekly by the Agroscope in the greenhouse. The data, diplayed in Figure 29 shows that there are no significant impact of the plant physiology below the solar modules, with a slight decrease in leaf transpiration below the modules in the PV1 and PV2 modalities, most probably due to the lower leaf temperature below the modules.

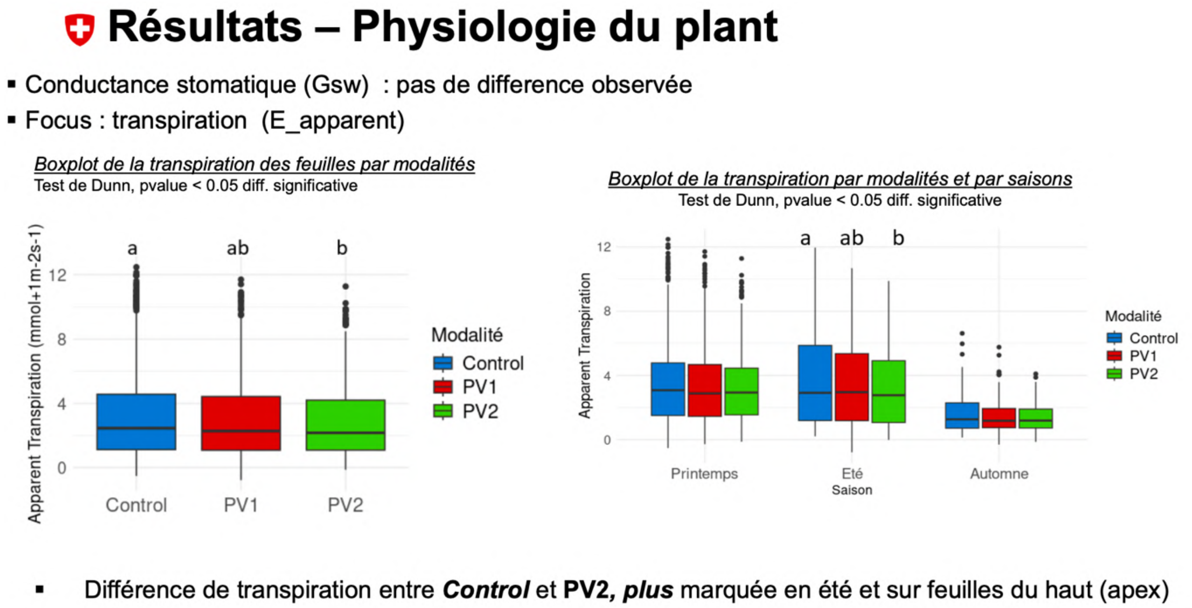


Figure 29 - Measurements of the stomatic conductance, and the leaves transpiration.

7.3 Quality

The sugar and acidity of the fruits as well as the texture of the skin has been measured on a bi-monthly frequence.
The data show that the Brix (sugar) is higher in the control modality versus the two photovoltaic modalities PV1 and PV2. This can come from slight changes in irradiance, temperature or irrigation. A crop steering specific to the modalities that could only be possible when on a large scale, can re-balance the Brix, together with an adaptation of the nutiritive solution. The Sugar/Acidity ratio is slightly lower for the PV modalities (coming directly from the lower Brix). The skin rigidity is also slightly higher for the crops in the control, but the skin elasticity is similar in all modalities.

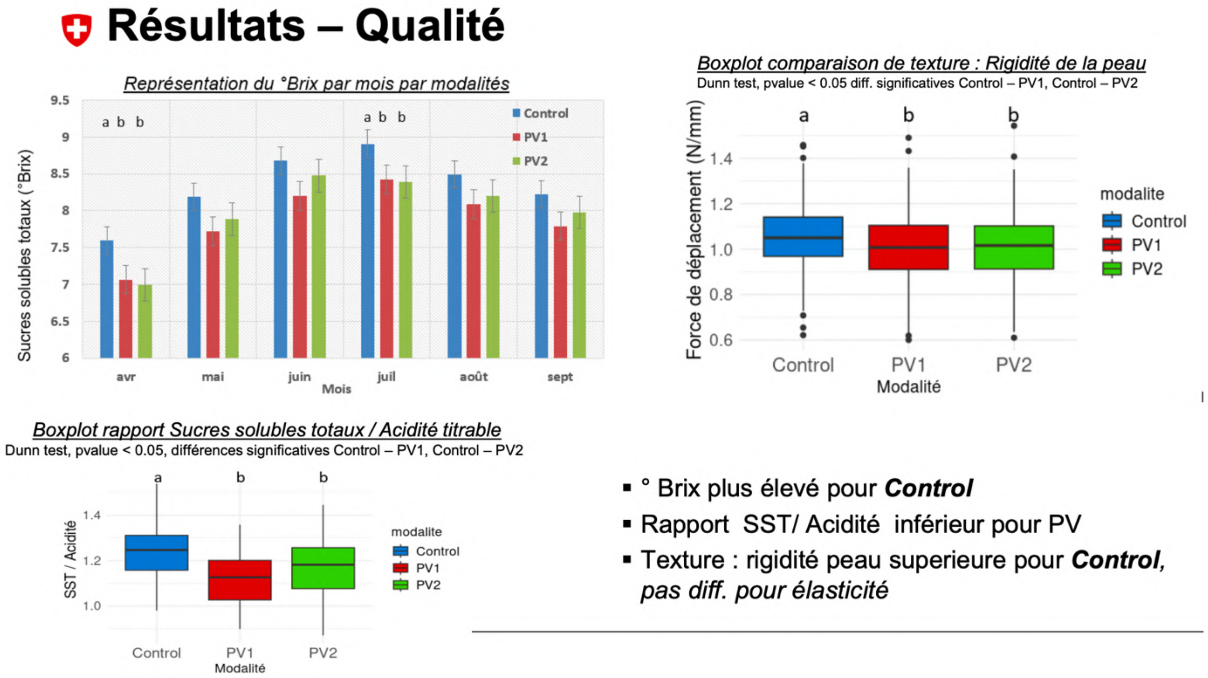


Figure 30 - Quality of the harvested crops.

7.4 Yield

Agroscope has been measuring the yield below our modules on a weekly basis, in addition to the data measured by the Serre des Marais team. The data presents two main results:

1. **Modality PV1** (far-red used for PV). The modality PV1, where the far red is used to generate electricity, tends to have an impact on the crop development. The measured yield loss is 9%.
2. **Modality PV2** (far-red sent to the crops). The impact on the total yield of the modality PV2 is only 4% far from the yield of the reference compartment.

Given that the water dripping system, the climate, and the growing practices could not be optimized to the microclimate below the modules, the results are positive. Indeed, the test zone is 1000m2 large, while the climatic zone in the greenhouse is defined in the center of 12'000m2.
Another explanation for the small yield difference is the position of the various compartments in the greenhouse. Indeed, the control zone was in the South of the greenhouse, which benefit from a warmer and brighter climate versus the zone PV2, which touches the North greenhouse wall (no light and cold wall. This behavior is best seen in the blooming/harvest cycles, where the PV2 zone lags by one bunch from the very start of the experiment, a typical feature of this greenhouse, according to the Serre des Marais head grower.

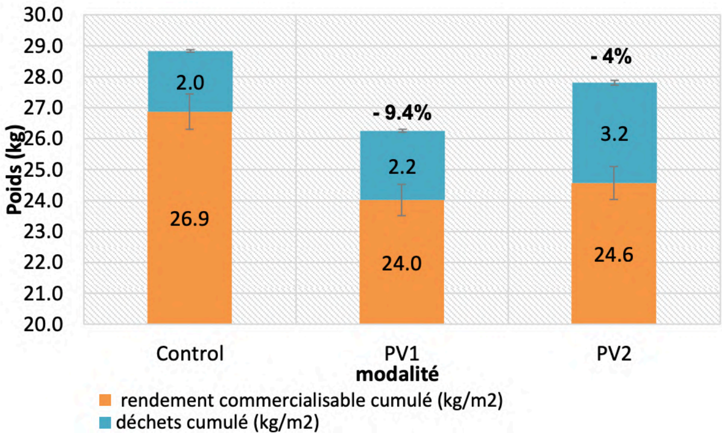


Figure 31 - Composition of the total yield with waste and quality yield.

The total yield encompasses the waste (fruits deemed not good enough for sales), and the quality yield (fruits that can be sold). Here, we see that the difference increases between the control zone and the PV1 and PV2 zones. This difference stems from early failures of the solar tracking mechanism, that have been fixed progressively between week 16 and week 20. The mechanism had indeed a manufacturing defect that blocked most panels in a position that reflected and concentrated all sunlight towards the crops. Crop burns and bunch losses resulted from the incident. The real impact of the mechanism blocking is difficult to assess, as only the waste fruits can be accounted for, while the lost bunches have potentially contributed to lowering the yield, while not measurable.

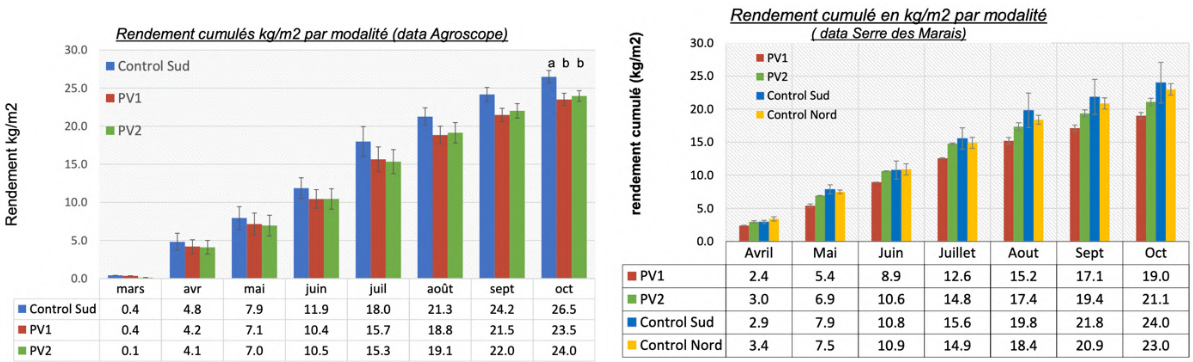


Figure 32 - Quality yield as measured by Agroscope (left and by Serre des Marais).

Tableau comparatif de différence de rendement (en %)
entre PV1, PV2, Control et Sud pour SDM et Ag

Modalité	Serre des Marais	Agroscope
	Δ/ Control Sud	Δ / Control Sud
PV1	- 20.8 %	- 11.9 %
PV2	- 12.1 %	- 8.6 %
Control Nord	- 4.2 %	

Figure 33 - Table of comparison between the Serre des Marais yield measurements, and the Agroscope data.

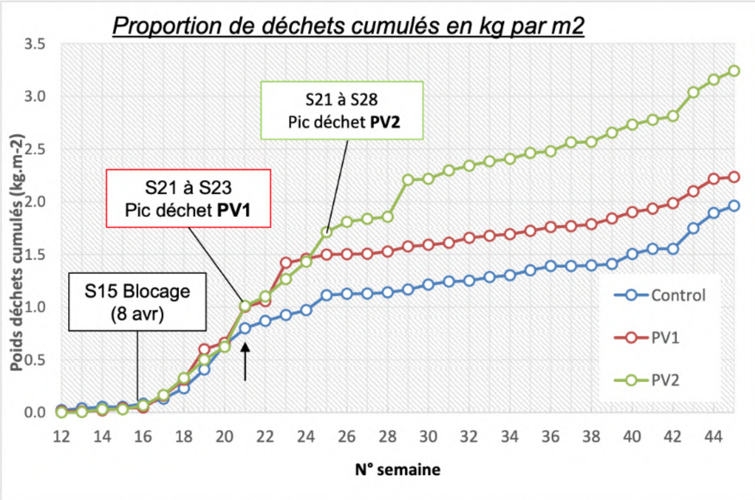


Figure 34 - Waste evolution during the season.

Figure 34 shows the evolution of the waste during the whole season. It can be seen that wastebelow PV1 and PV2 has increased significantly around week 20-26. This corresponds to ~8 weeks after the tracking system failures occurred, which is the cherry tomato cycle time (from the flower to the fruit). After week 30, the waste in all modalites stabilizes and follows a similar evolution in all modalities, demonstrating the significant impact of the tracking system failure in Spring.

7.5 Climate

Agroscope has monitored the climate below the solar modules. While no significant difference has been seen for the CO2, light and atmoshperic pressure, we see a slightly lower temperature below the modality PV2, which can be beneficial in the summer. Indeed, in the summer most greenhouse growers suffer productivity losses, as the CO2 fertilization loses in effectiveness as the windows need to be open. Thus limiting the need to open windows in summer to cool the greenhouse thanks to lower plant temperature due to Voltiris modules may limit these productivity losses.

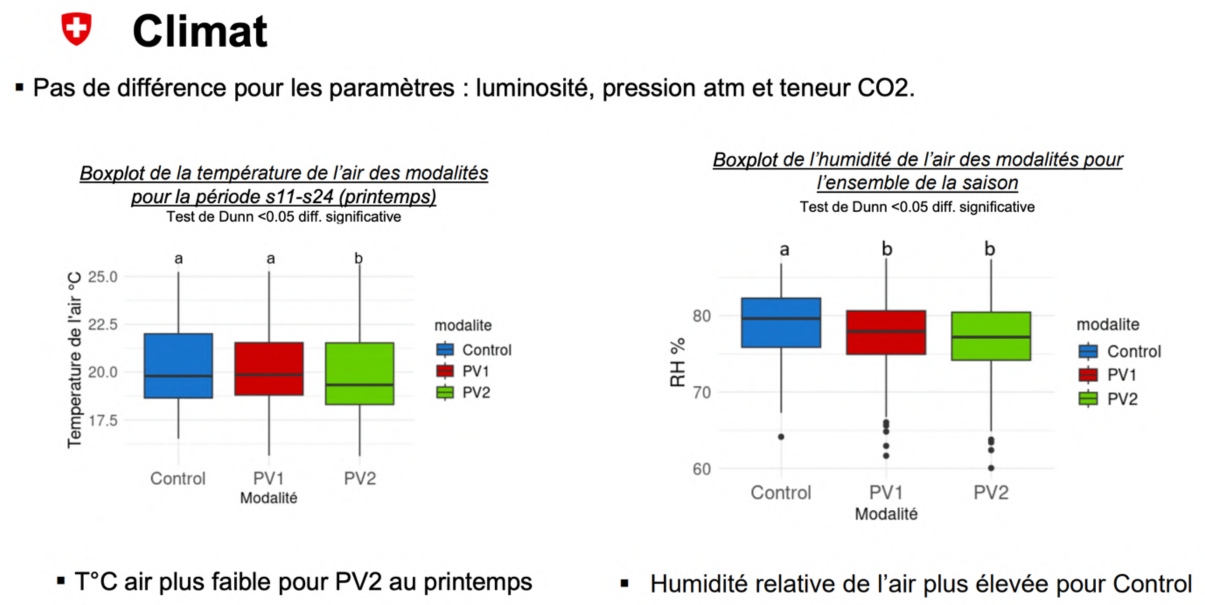


Figure 35 - Climatic data for the microclimate below the solar modules.

The humidity was also seen to be slightly lower below the solar modules, as a result of the reduced transpiration below the modules, due to a lower leaf temperature. It could bring advantages in the limitation of fungal disease development.

8 Lifetime assessment

In frame of the project at Serre des Marais, the degradation of the power components (dichroic filters and solar modules) is measured in-situ, and in accelerated ageing (climatic chambers, etc.). The goal is to be able to assess the lifetime, and measure the degradation curve of the peak power over the lifetime.

8.1 Method

The ageing and degradation of the filters and of the PV panels has been treated separately. For the PV panels and the filters, the IEC type-tests derived from the solar industry are followed.

Figure 36 presents the test sequence that is performed in the frame of the project: the CSEM has characterized spectral filters and PV panels before the installation by Voltiris. Some extra filter and PV panels stayed in possession of the CSEM for accelerated ageing (current stage). At the end of the project, the samples that have spent a full year in the greenhouse will be again characterized by the CSEM to assess the degradation, and understand how it is related to the accelerated ageing.

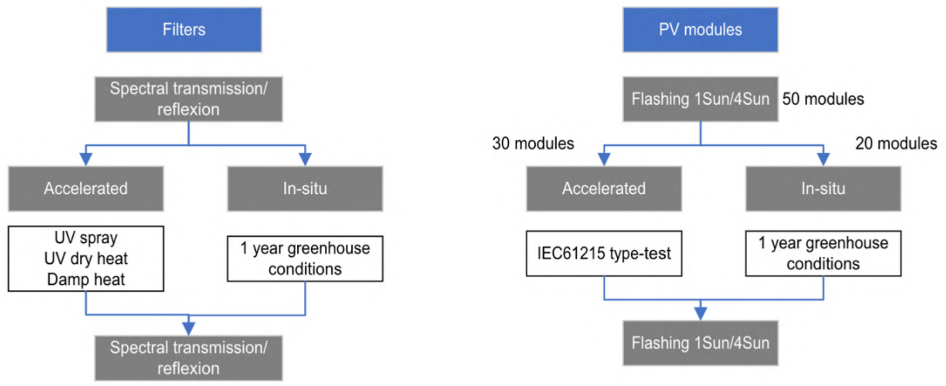


Figure 36 - Test sequence for the power components.

8.2 Filter characterization

Phase I results

8.2.1 Reference measurements

Figure 37 shows the transmission/reflectivity spectra of 17 different filter samples that were laminated onto 2mm thick PMMA (as in our reflectors installed in Phase I).

Results:

Generally speaking the spectra, as presented in Figure 37, are stable from sample to sample (random sampling). Only the reflectivity edge in the near infrared (~1150nm) varies slightly from sample to sample. Also, a thin transmission peak appears in the green, at 600nm.

However, those two small sample-sample variations are not expected to have a significant impact on the energy yield, nor on the agronomy.

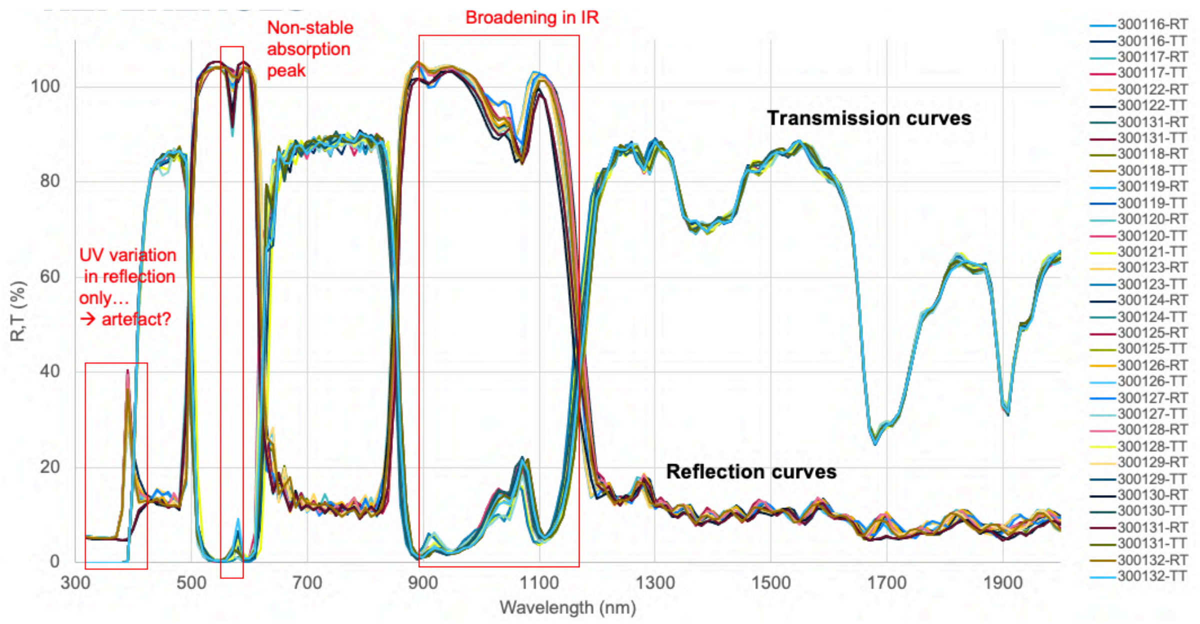


Figure 37 - Reference spectra from 17 filter samples laminated on PMMA (reflectivity and transmission spectra). The data were measured at the CSEM.

8.2.2 UV Spray results

Test parameters:

Dose A+B:	1.44 kWh/m2/day
Temperature:	T = 85°C (plate), 60°C (air)
Humidity:	50 % rel.
Cycle:	10min/cycle (4 with, 6 without spray)

Results:

First, a change of the shape of the samples have been noticed on all samples due to the humidity/heat/UV combination (similar to 43), which can impact the measurements, as the reflection/transmission spectra will be modified by the angle of incidence of the light.

Figure 38 presents the transmission and reflection spectra of the samples before and after the UV spray test. It is noticed that the cut-off of the transmission edge in the red is slightly blue-shifting after exposure to the UV spray, with a UV total dose of 48 kWh/m2 (equivalent to ~1 year Sun exposure in Switzerland).

An absorption dip appears at 1900nm due to the water absorption.

Conclusion:

We notice some degradation of the samples in the UV spray, however, it is unclear whether the effects come from the degradation of the substrate or of the filter. The mechanical deformation of the samples would suggest that it is due to the deformation of the substrate. In the coming months, the ageing of filters laminated onto glass and polycarbonate will help solve the question.

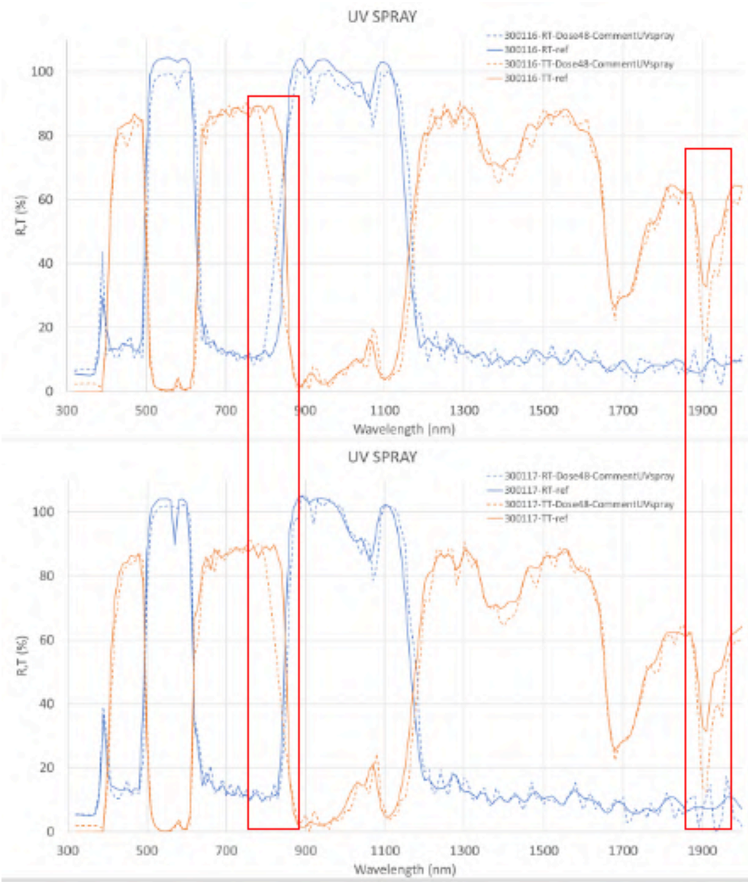


Figure 38 - Reflection and transmission spectra before and after a 48kWh UV spray dose.

8.2.3 UV dry heat results

Test parameters:

Dose A+B:	2.976 kWh/m2/day
Temperature:	T = 60°C (sample)
Humidity:	no regulation
Cycle:	no cycle

Results:

Figure 39 presents the absorption and reflection spectra after the UV dry heat. Similarly to UV spray, a small blue-shift of the band edges appear at ~800nm after the UV heat exposure. However, the absorption dip at 1900nm does not appear this time, proving that it comes from the humidity.

Conclusion:

The filter+ substrate sample seems stable in the UV dry heat, which tends to pin-point that humidity and heat is the cause of the deformation of the samples.

In the coming months, more UV ageing time will be recorded, and the ageing of the filter in UV conditions will be better understood.

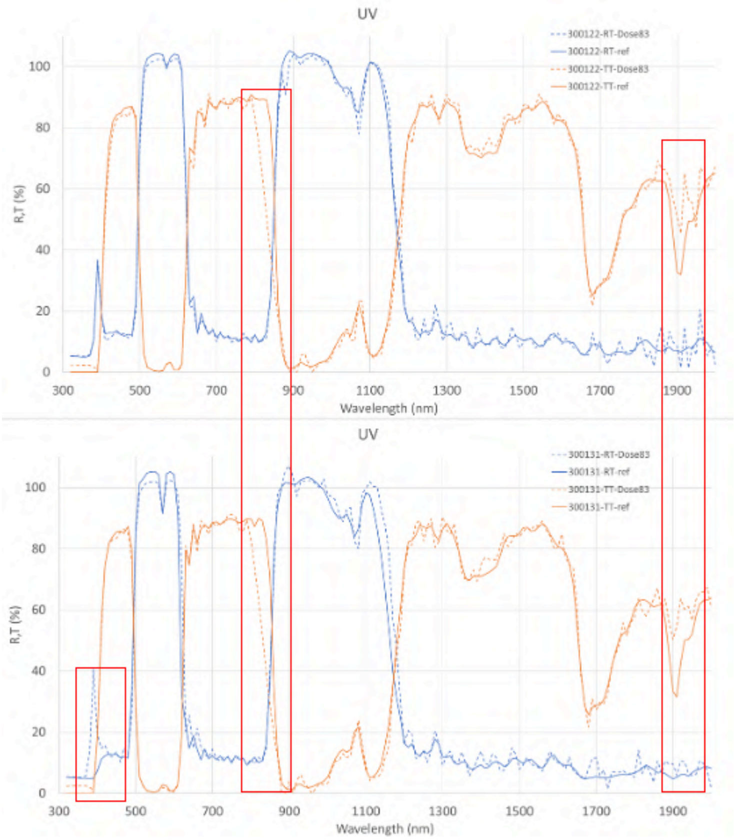


Figure 39 - Spectra of filter samples before and after the UV dry heat test (UV dose of 83 kWh), amounting to 1 year of outdoor exposure in Switzerland.

8.2.4 Damp heat results

Dose A+B:	0 kWh/m2/day
Temperature:	T = 85°C ((air)
Humidity:	85 % rel.
Time in chamber:	ongoing

Results:

Measurement is ongoing but the samples already show modification of the shape, like for the UV-spray. As this is not observed in UV only, it can be stated that the combination of humidity and heat is causing this effect.

We are currently launching new tests to better understand if it is a consequence of the substrate expanding or of the film shrinking.

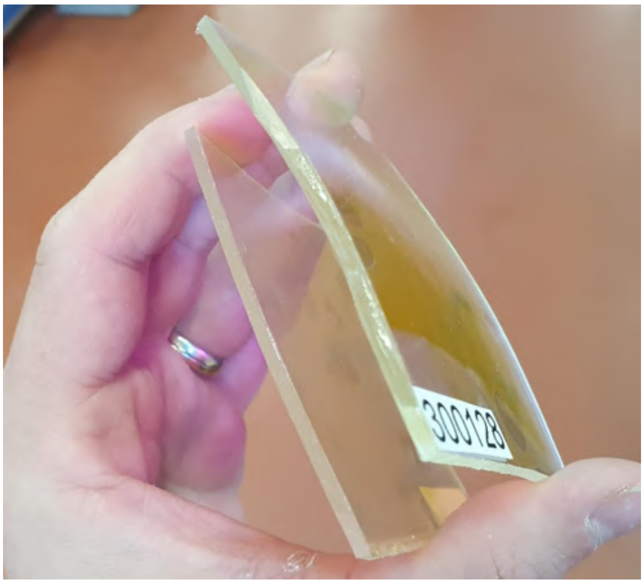


Figure 40 - Modification of the shape of the samples after the damp heat results.

Phase II results

8.2.5 In-situ ageing

After one year in the greenhouse, we have measured the reflectivity and transmission of relatively dirty lamellas in order to understand the efficiency losses after one year in operation. Also, we have collected similar lamellas after the annual clean up of the greenhouse, where everything gets cleaned with javel water.
Figure 41 shows transmission spectra for lamellas (i) before being placed in the greenhouse, (ii) after one year in the greenhouse, in a relatively dirty location, and (iii) after being cleaned during the greenhouse annual cleaning.
Based on the transmission and reflection spectra, the power conversion efficiency after one year could be measured, as in the table below (relative to the baseline of the new filter):

Filter state	**Power conversion efficiency (relative -100%)**
New	100%
Dirty /1 year	95%
Cleaned	99%

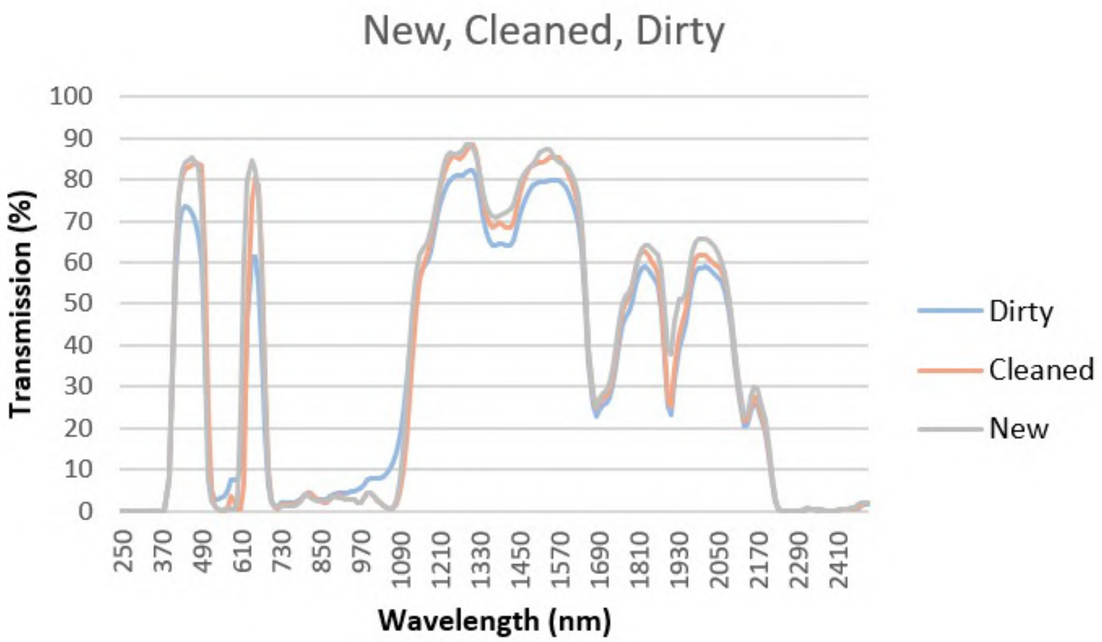


Figure 41 - Impact of the soiling on the reflectivity/transmission of the lamellas.

Unique filter data

A new filter has been developed collaboratively with 3M to replace the combination of a green and NIR filter to a single unique multi-reflection band filter. In the NIR regime, it is a compromise between filter A and filter B (see section 5.2). Its spectral utilization factor is 73%. The unique filter reduces the number of intermediate layers, which limits the absorption by the adhesive, increasing the efficiency, and the light transmission to the crops. Reflectivity measurements on this new filter were carried out at the CSEM, and the graph in Figure 42 is the result of multiplying this reflectivity (in percentage) with the AM1.5 spectrum of the sun.

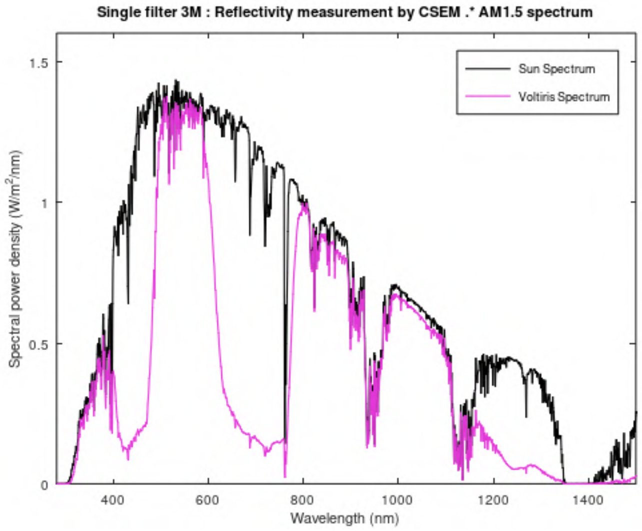


Figure 42 - Reflection spectrum of the unique filter when using the Sun as illumination.

8.2.6 Ageing of the unique filter and effect of the greenhouse glass

The ageing behaviour of the unique filter was checked with a focus on the impact of UV light. The UV degradation (UV Dry), see Figure 43, has shown that the unique filter has some yellowing (increased blue absorption). In order to better understand the ageing inside of a greenhouse, we have added a glass in front of the UV lamp in the ageing chamber to filter out the short-wavelength UV. As shown in Figure 43, the filter didn't show any degradation when exposed to the filtered sunlight, which brings some confidence that the glass-filtered sunlight in the greenhouse will not age our filters.

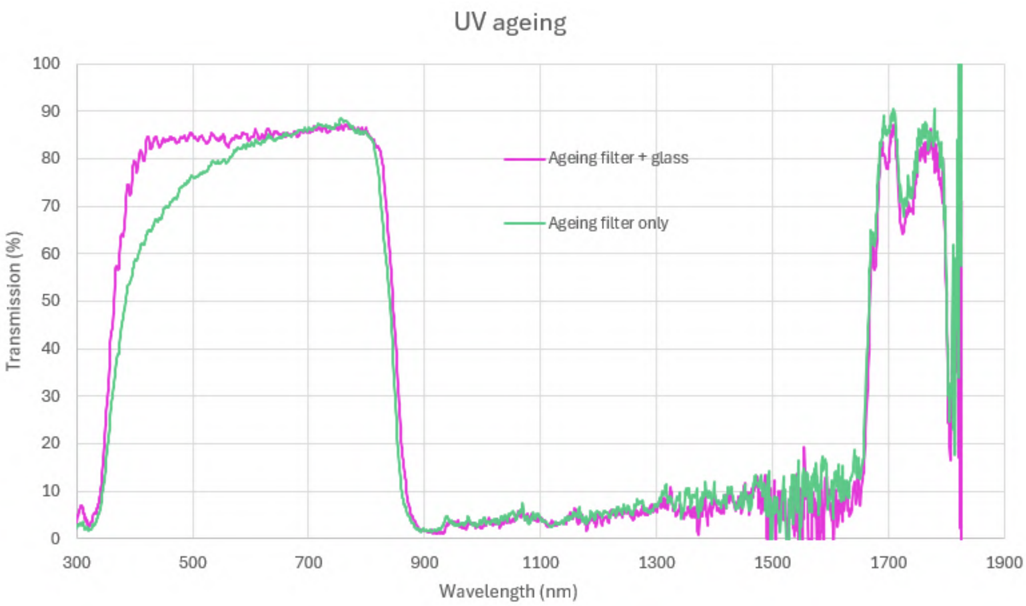


Figure 43 - Ageing of the unique filter when exposed to UV light (green) or to filtered UV light (pink) through the greenhouse roofing. The dose was 130kWh, equivalent to two years of UV exposure in Switzerland.

8.3 Solar modules characterization

8.3.1 Reference

50 solar modules installed in phase II have been measured by the CSEM in terms of IV characteristics at different illumination conditions, from 0.4 Sun illumination until 5.8 Sun (the Voltiris system works effectively with a 4 Sun illumination).

Results:

The modules installed in Phase II present a STC power rating of 26Wp, as shown in the IV curve in Figure 44. Figure 43 shows a processed output from the IV curves. It can be seen that the Fill Factor of the module decreases sharply with the concentration, decreasing from 77% at 1 Sun to 62% at 4 Sun illumination, which explains the slightly non-linear aspect of the power versus irradiance curve.

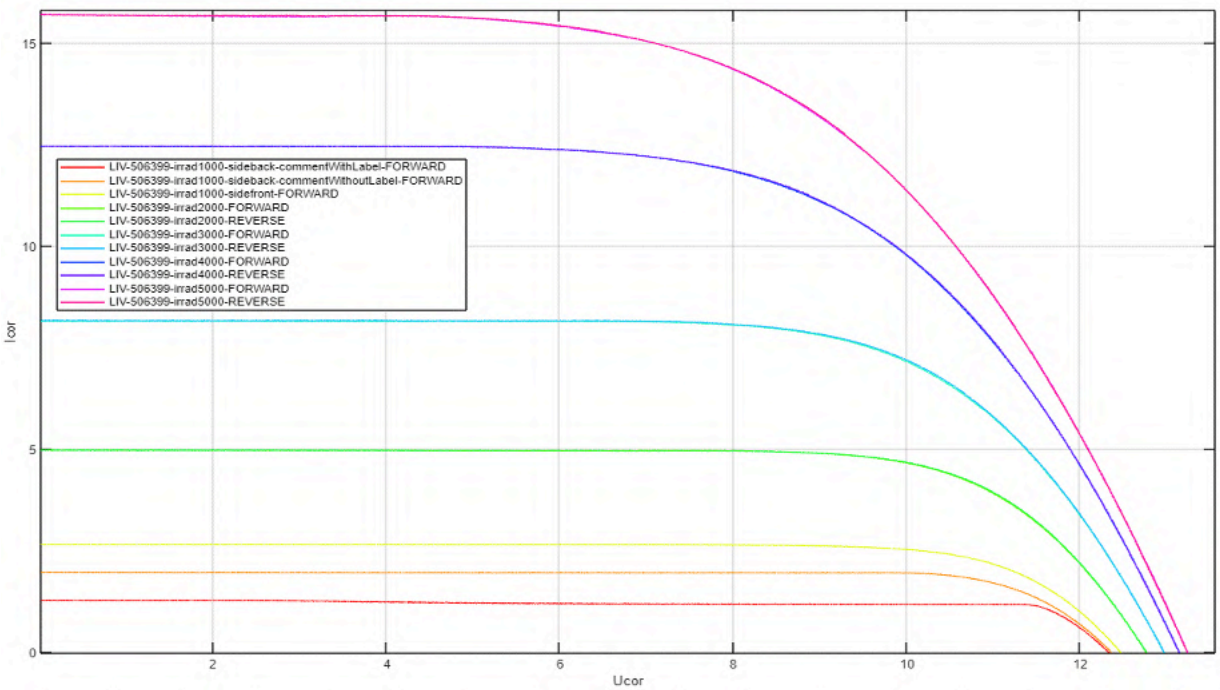


Figure 44 - IV curves of the modules at different illumination levels.

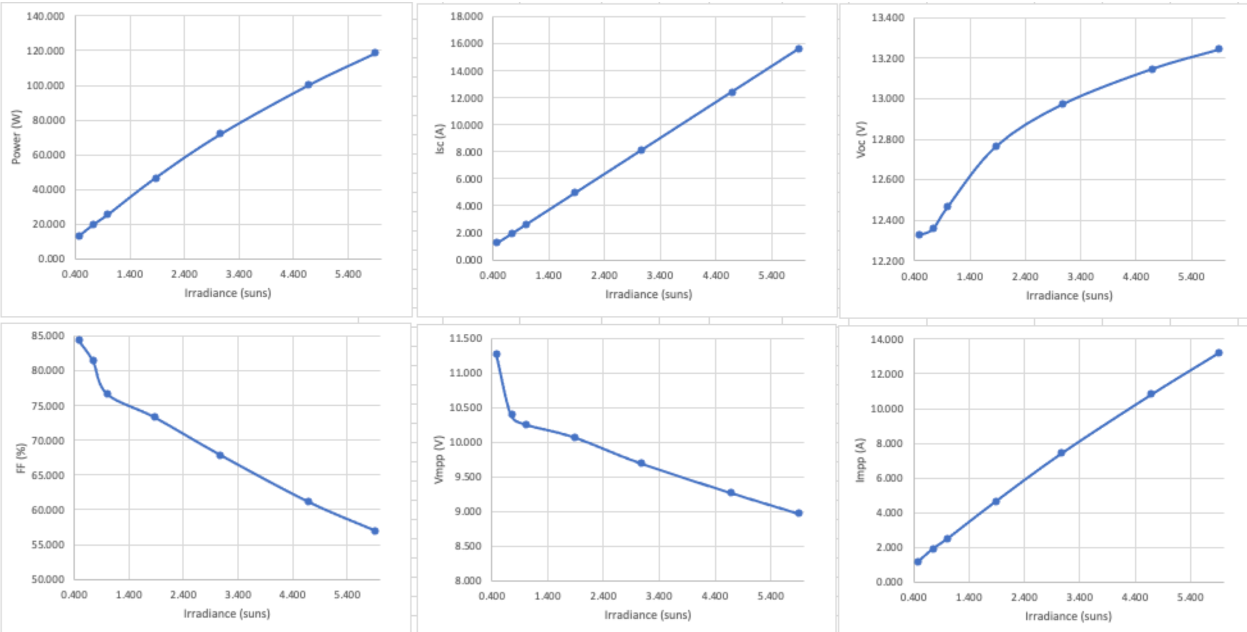


Figure 45 - Summary of the electrical characteristics of the PV panels installed in Phase II.

Conclusion:

The PV panels installed in Phase II of the Serre des Marais project have still not reached the desired peak power (26Wp vs 31Wp target), and they present a reduction of fill factor under high irradiance. To circumvent this problematic, a new optimized design of the PV panel with a potential of 32Wp has been identified, and samples should be arriving in the coming months. The new PV panel architecture will be using more busbars, which will help increase the fill factor under high concentration. Note that we expect to use PV panels with a peak power of 35Wp as soon as Spring 2025, yielding a total Voltiris module output close to 135Wp.

9 Energy output monitoring

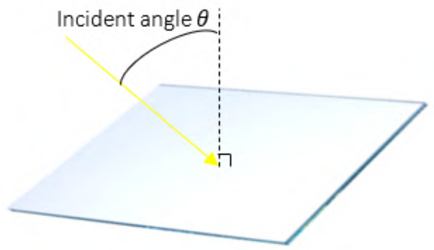
9.1 Greenhouse transmission model

In order to better understand the maximal theoretical output of our Voltiris solar modules, we have developed a tool to assess the light transmission of the greenhouse at Serre des Marais.

9.1.1 Glass transmission

To obtain the model, we first looked at the transmission of the glass.

We studied the optical transmission of glass as a function of the angle of incidence θ of the light hitting the glass using the Kramers-Kronig relation.



The evolution of light transmission for an angle of incidence θ varying from -90° to 90° in the figure below.

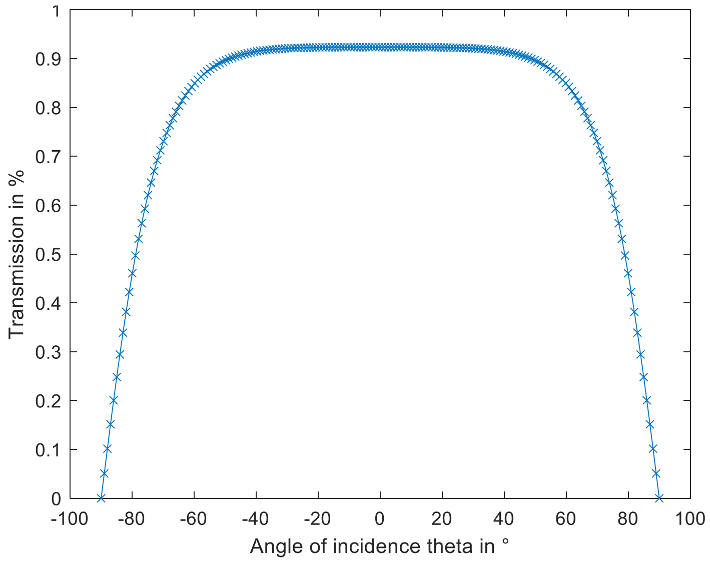


Figure 46- Theoretical transmission of glass

9.1.2 Impact of the greenhouse structure transmission

The second part influencing the light transmission of the greenhouse is the metallic greenhouse structure. In order to assess the shading due to the structure, a model of the Serre des Marais greenhouse roof was created in a 3D rendering software (Blender). This model was backed by physical measurements on site.

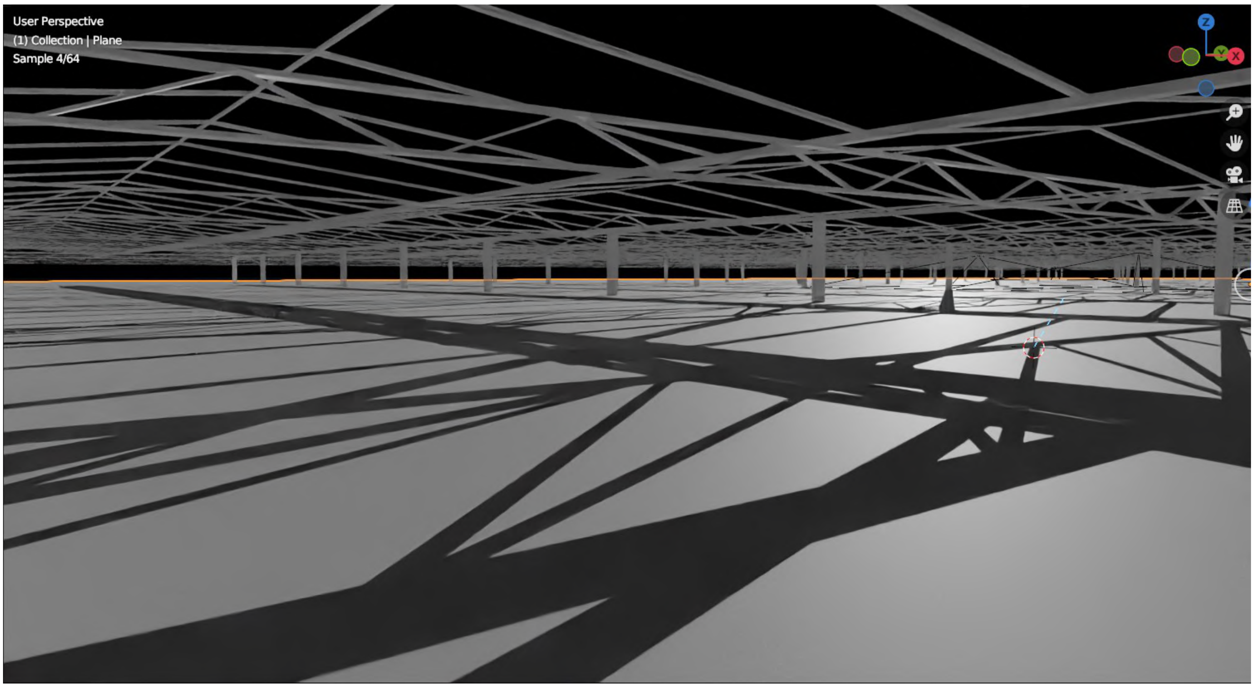


Figure 47 - Structure of the Serre des Marais in Blender

For each position of the sun, an image of the ground is taken, where the structural shadow can be seen. An algorithm interprets the images and returns the shading in %.

9.2 Evaluation of the obtained results

9.2.1 Final model and data comparison

The final model was compared with physical measurements. Two PAR meters were used in the Serre des Marais to measure the light inside the greenhouse. The average of these two PAR meters is shown in the graph below - blue curve. The red curve represents the light outside the greenhouse and was obtained using meteorological data from the nearby Meteosuisse station (Cointrin).

In the following graph, the physical transmission is shown in blue. It corresponds to the percentage of external light measured in the greenhouse. Finally, the yellow curve shows the theoretical transmission expected in the greenhouse according to the model.

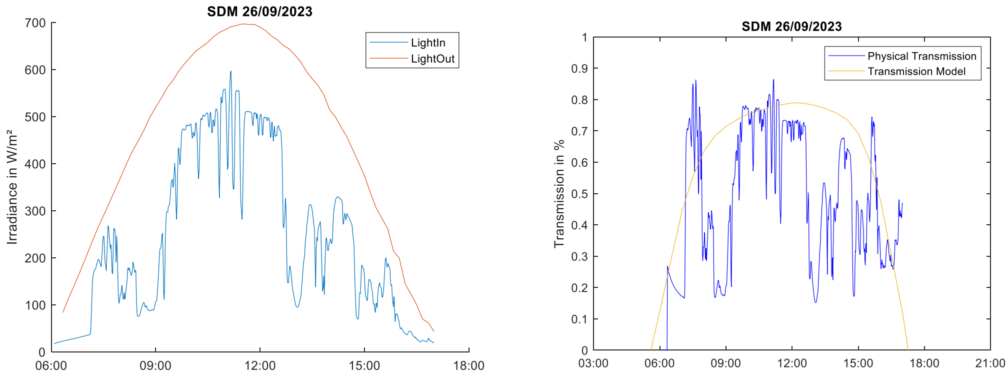


Figure 48 - Average of the two PAR sensors reading and outside radiation (left), and (right) light transmission in the greenhouse

The noise in the physical transmission is due to the small scale of the PAR sensors, that make them very sensitive to localized shading. Additional PAR would be needed to better assess the theoretical model.

The light transmitted inside the greenhouse can be extracted from our theoretical model based on the incoming radiation, as presented in Figure 48. An average light transmission of 72% was found. Figure 49 shows that there is an excellent match between the theoretical measurement (blue curve), and the experimental data (yellow curve). The dips in the blue curve are due to direct shades covering both PAR meters simultaneously.

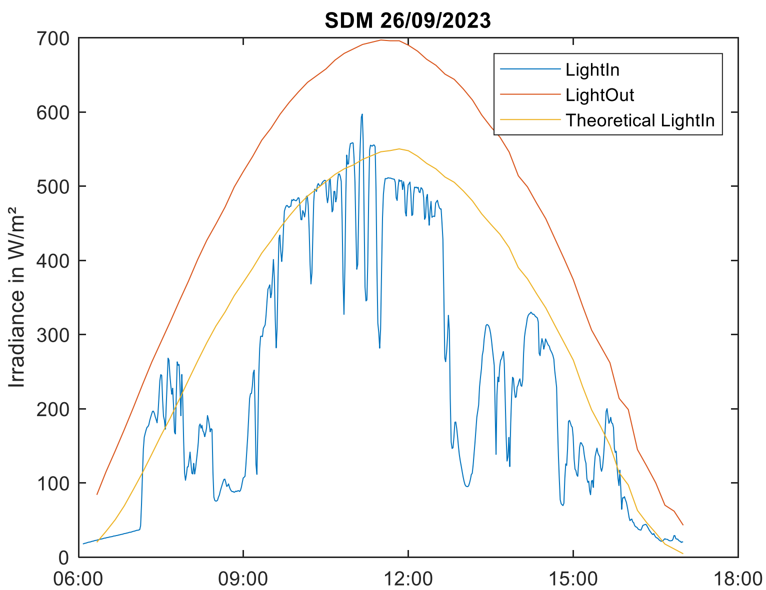


Figure 49 - Light outside of the greenhouse(red) vs light inside the greenhouse (orange), and output from the PAR meters (blue).

9.2.2 Annual model

Once this model was validated, it was generated for all days of the year with a step of 15 minutes. Here the values range from 5 a.m. to 8:30 p.m. for visibility reasons. The image below highlights the distribution of transmission during the day over the year. Green values represent high transmission values (close to 1) and red values represent low transmission values (close to 0).

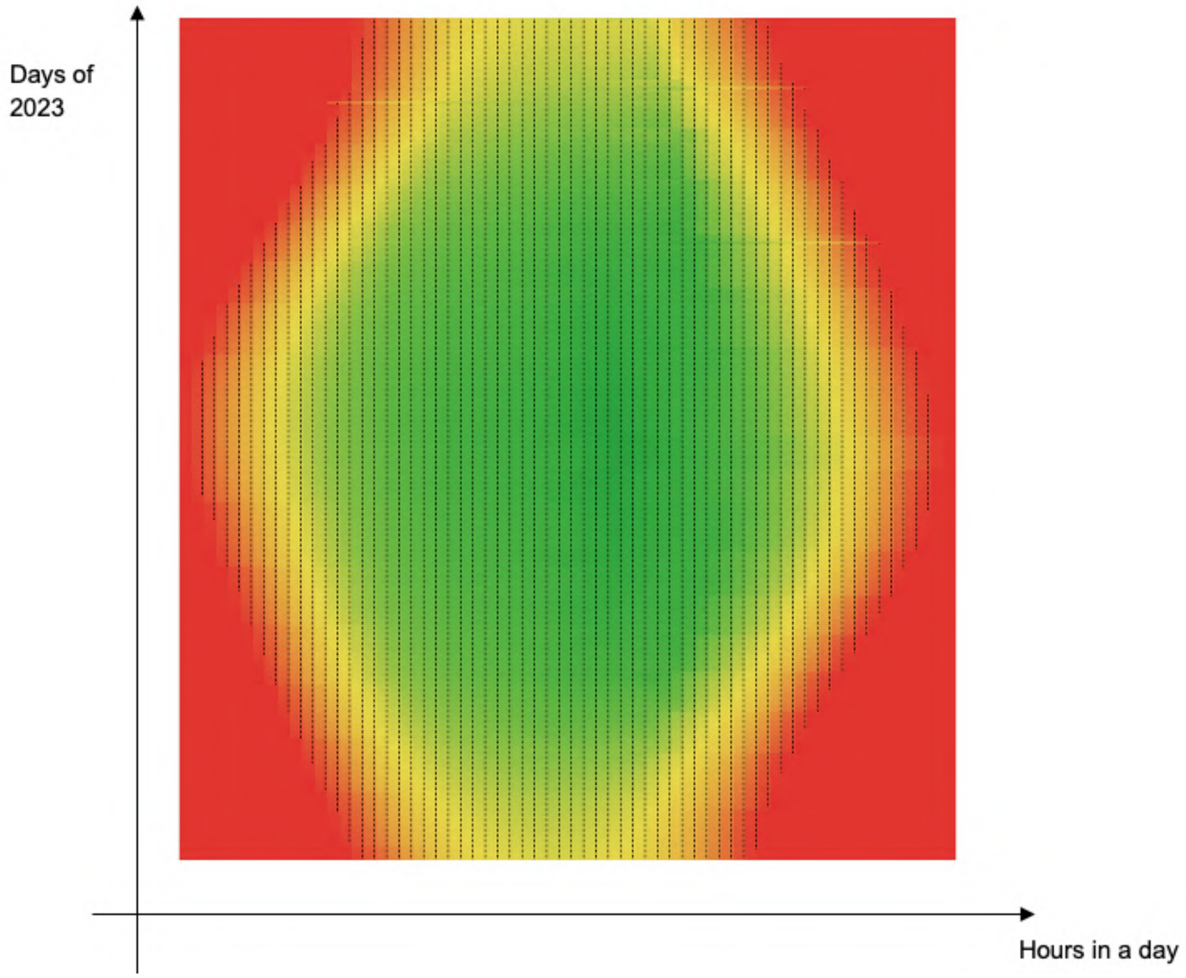


Figure 50 - Greenhouse transmission model as a heatmap over the full year.

We notice a slight increase in transmission in the afternoon. This is due to the orientation of the greenhouse. This will also be reflected in the electricity generation data presented in the latter section. These data are therefore consistent with on-site observations.

A plot of the transmission curves shown above can be seen below for the summer and winter solstices of 2023.

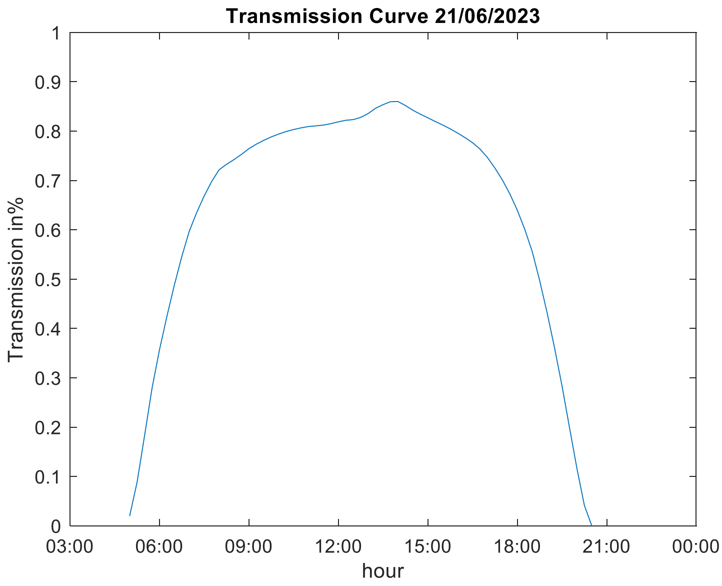


Figure 51 - Summer solstice.

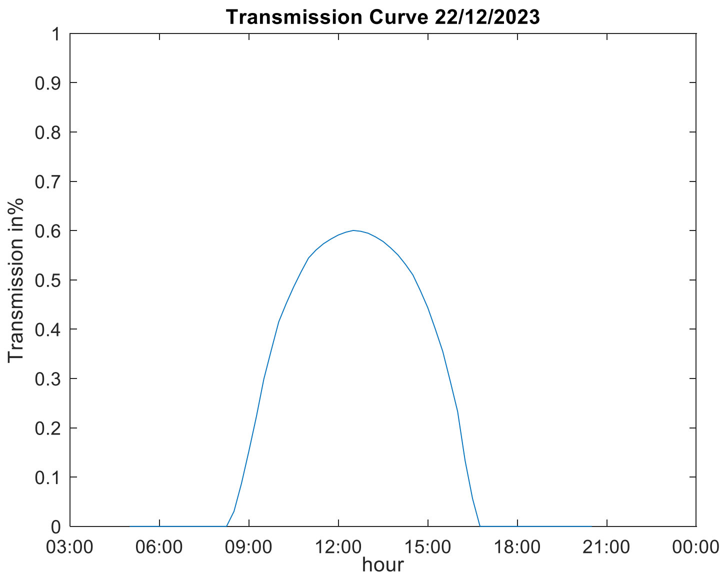


Figure 52 - Winter solstice.

9.3 Report on PV performance for phase 1

9.3.1 Theoretical model of the optimized Voltiris modules

In Voltiris modules, given the optimal spectral utilization factor of 0.65, it is possible to concentrate up to a factor of 6x to stay within the linear response range of the cells (6x 0.65 = 4).

If the light is concentrated on a small PV panel with a surface area of 0.17m2 that can produce up to 35Wp under STC conditions (~210 Wp/m2), it is therefore possible to generate 6x0.65x35Wp = 140Wp for a Voltiris module with a reflector of dimensions 6x0.17m2 = 1m2 (see Figure 14).

The theoretical power of the Voltiris modules is therefore $P_{theoretical}$ = 135Wp for modules with a surface area of 1m2.

The expected power in practice will be given by:

$$P_{Measure}=(DNI*T_{serre}*P_{theoretical}/1000+0.2*DHI*T_{serre}*P_{theoretical}/1000) \times \eta_{th}$$

Where DNI is the direct normal irradiance (W/m2), T_{serre} is the light transmission of the greenhouse (structure + glass), DHI is the diffuse horizontal irradiance. The factor 0.2 is empirical and represents the 20% sensitivity of the Voltiris modules to diffuse light. The principle behind Voltiris modules is based on a concentration system, so we use all the direct light (DNI) received in front of the sun. But only part of the diffuse light (DHI) spread over the entire surface of the sky is captured by our reflector, around 20%. η_{th} takes into account the thermal losses of approximately ~10% that are expected on the DC output (η_{th}=0.9).

9.3.2 Theoretical efficiency model of the modules installed in Phase I

In Phase 1 of the project, the modules are equipped with the following hardware:

- Green + NIR non-optimized filters. These filters have a spectral utilization factor of 0.49. Their reflection spectrum is shown in Figure 54.
- Mr.Watt PV panels, manufactured in Italy, with 25.6 Wp under STC conditions (1000 W/m2, 25°C). Their current-voltage characteristics are presented under standard conditions (1 Sun = 1000W/m2) and under concentration conditions (4 Sun = 4000W/m2) in Figure 53.

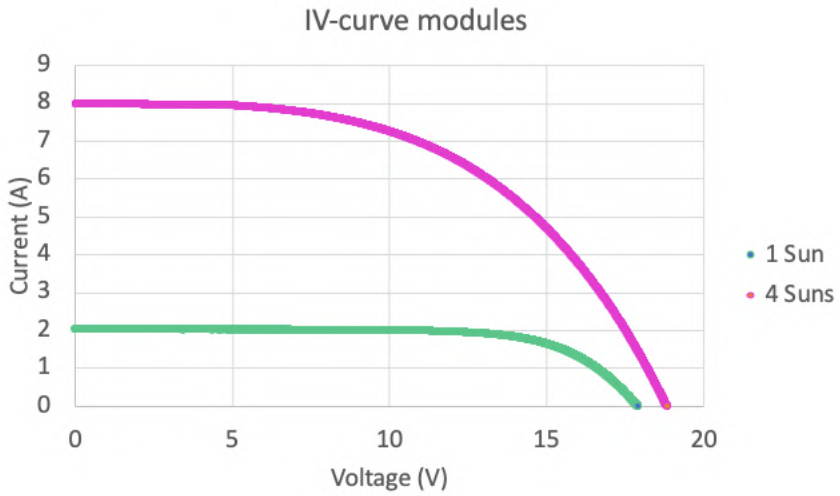


Figure 53 - IV curve of the Mr. Watt solar PV panels installed in Phase I. The fill factor is 70%.

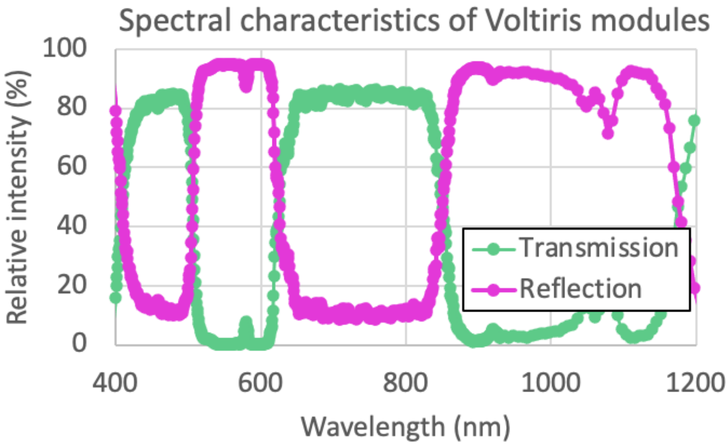


Figure 54 - Spectral characteristics of the filters installed at the Marais Greenhouse in Phase 1.

The peak power of the Voltiris modules installed in the greenhouse during Phase 1 is therefore expected to have the following characteristics (6 slats, spectral utilization factor 0.49 (see section 5.2), and 25.6 Wp for PV panels at STC)

$$P_{theoretical} = 6 * 0.49 * 25.6Wp = 75.2\ Wp$$

9.3.3 Methods

In this report, the evolution of the average yield of 4 Voltiris solar modules located in the middle of the installation is monitored over a period of 3 days, from 25.09.2023 to 27.09.2023. This period was chosen for the clarity and homogeneity of its sky.

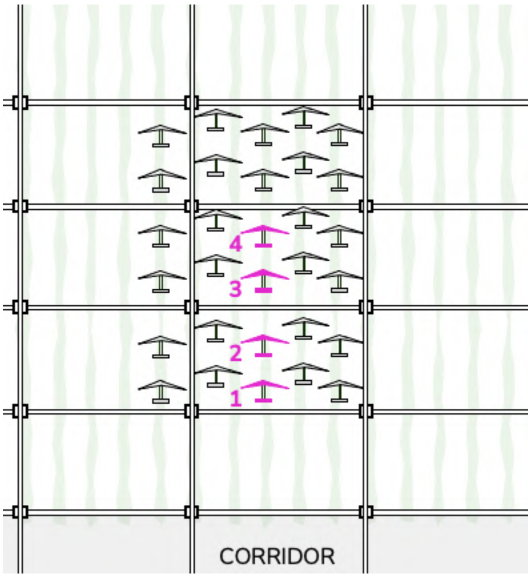


Figure 55 - Location of the Voltiris solar modules that were monitored (in magenta) during the measurement period.

The yields of the panels are extracted by measuring the short-circuit currents Isc and open-circuit voltages Voc on the panels with a multimeter and an ammeter clamp. The power was calculated using a fill factor of FF=0.7, as measured by CSEM on the Mr. Watt panels (see Figure 53).

$$P = FF * Isc * Voc$$

The irradiance was measured by Météosuisse pyranometers on the roof of Geneva Airport, approximately ~10km from the Marais Greenhouse.

9.3.4 Results

Figure 56 and Figure 57 present the average power measured on the panels monitored during the three-day period. The peak power obtained each day amounts to approximately 50Wp, with an irradiance of about 700 W/m2. Extrapolated to the complete installation (30 modules), the DC power produced corresponds to ~1.5 kWp over the days monitored.

By integrating the power data (Figure 58), the average yield of the modules and the installation is obtained. Over the monitored days, a yield of 0.2 kWh per module/day was measured, and a yield of ~7 kWh/day for the installation was extrapolated from the yield of the modules.

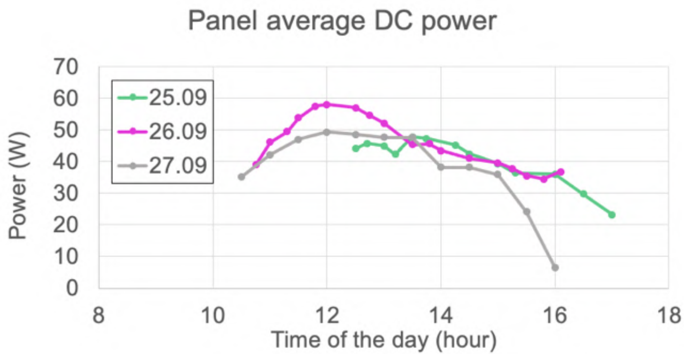


Figure 56 - Average power per panel over the three days, based on the time of day.

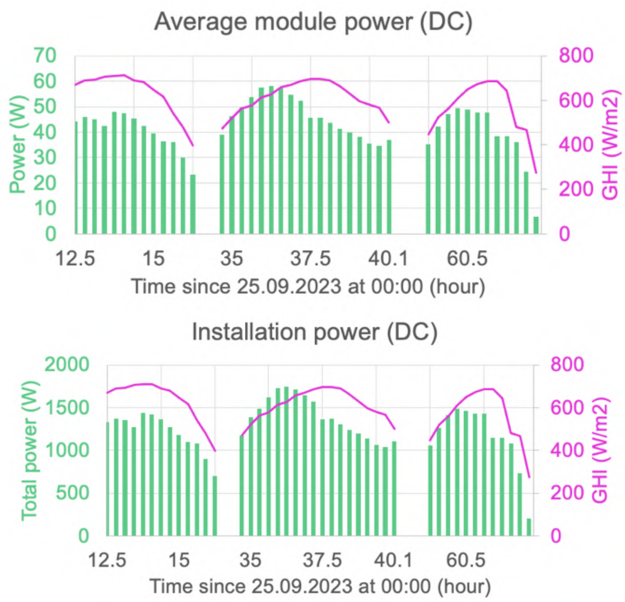


Figure 57 - Power per module (upper part) and extrapolation to the installation (below) over the three consecutive days, along with horizontal global irradiance (GHI).

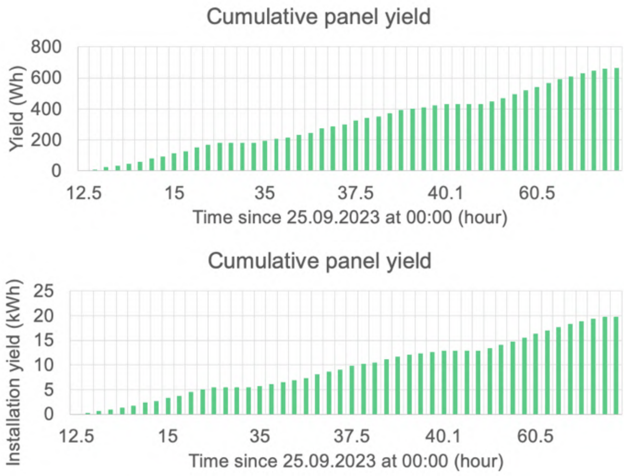


Figure 58 - Top: Average yield of one module. Bottom: DC yield of the installation by extrapolating data from individual modules.

9.3.5 Discussion

With the radiation data from the Météosuisse station on the airport roof, it is possible to determine the theoretical power of the modules on the days of measurement. The yield model:

$$P_{actual}=(DNI*Tgreenhouse*Ptheoretical/1000+0.2*DHI*Tgreenhouse*P_{theoretical}/1000) \times \eta_{th}$$

with the value $P_{theoretical}$ = 75.2Wp indeed allows us to determine the expected power in practice. Using the greenhouse transmission model discussed in the greenhouse transmission model above (Figure 50) and a thermal efficiency of 90% (ηth=0.9), taking account for the PV panel temperature (measured at ~45°C, with a coefficient of -0.3%/°C), we can establish a yield model. Figure 59 shows the comparison between the measured data and the data expected by the described model above. Besides a small discrepancy in the morning of the second day of measurement, the data closely match the model.

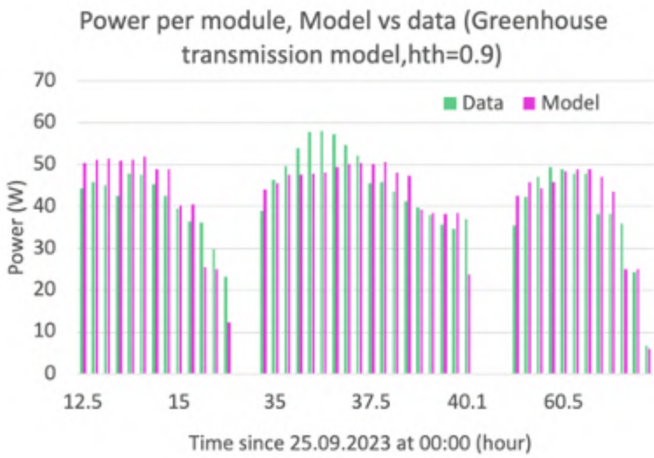


Figure 59 - Power per module: comparison between the theoretical model and the measured data.

The discrepancies between the model and the data amounts to ~5% overestimation. Here are some factors that can explain this difference:

- The design of the photovoltaic modules is not optimized and makes the module's yield highly dependent on the alignment of the reflectors and on the homogeneity of the reflection in the horizontal direction (see Figure 61).

- The design of the reflectors does not uniformly concentrate all the green and near-infrared light across the entire surface of the solar cells (see Figure 60). This design error will be corrected in Phase 2. This inhomogeneity of the reflection is due to the fixation system of the dichroic film lamella that adds a constraint in the 4 corners of the lamellas.

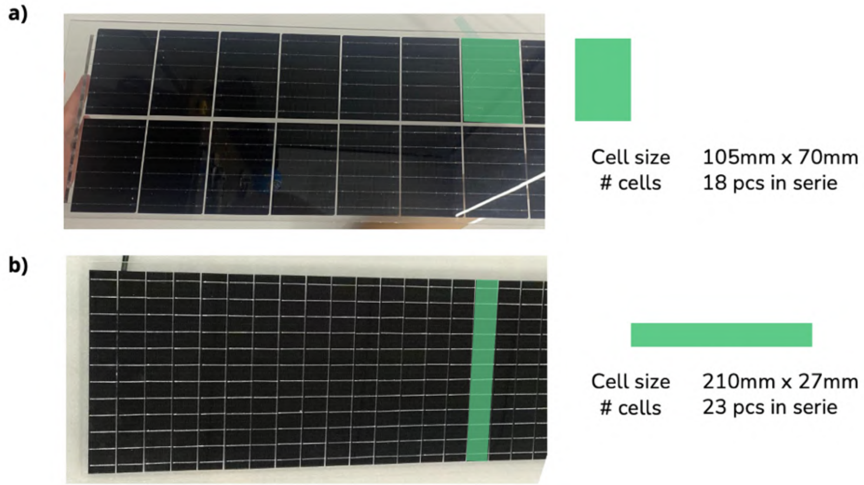


Figure 60 - Optimization of the PV panels design. During the installation of Phase 1, the PV panels (b) are made of long cells. If the reflection is shifted 1cm to the left, the yield decreases by 30%, making the design very sensitive to reflection errors

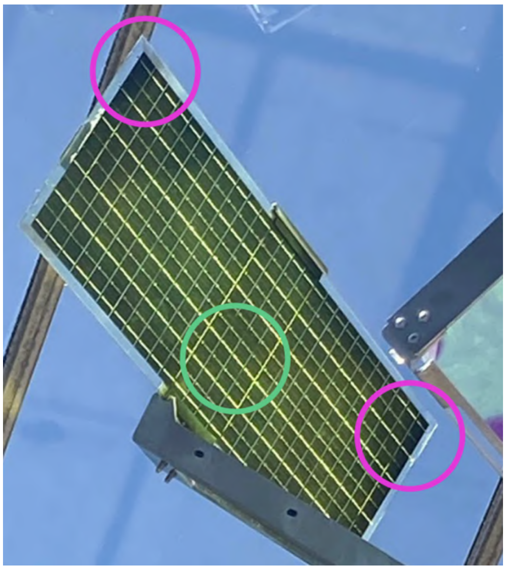


Figure 61 - The reflection of the dichroic lamellas does not occur uniformly across the photovoltaic PV panels. Since the panels are made up of solar cells (pieces of wafer) wired in series, the least illuminated cell determines the yield of the module.

9.3.6 Conclusion et outlook

The preliminary results obtained at the Marais Greenhouse are very positive: except for an 11% loss, the measured DC powers correspond to the expectations according to our theoretical power model.

The 11% loss is explained by a PV panels and reflector design that is not yet optimized. These errors was corrected in Phase 2.

The yield will also be increased by optimizing the dichroic filters, which should increase the yield by +20%. Additionally, the PV panels are expected to have an increased nominal power at STC of +5%. It is therefore expected that the average yield per Voltiris module will increase by +47% in Phase 2 of the installation (peak power module ~110 Wp).

9.4 Report on PV performance for phase 2

9.4.1 Theoretical yield of the Serre des Marais 2 Voltiris modules.

The modules of the phase 2 installation had a theoretical yield of 103Wp for the PV2 modality (leaving the far-red to the crops), and of 113Wp for the PV1 modality (as the far-red is also used for energy generation).

9.4.2 Yield data over one year

According to our yield model, the Serres des Marais (full installation-248 modules) was supposed to generate 21.3MWh/year. However, due to the challenges discussed in the next session, the actual peak efficiency was limited to 32% of the theoretical value.

Figure 62 shows the theoretical yield data (grey), as well as the measured yield (light green). The predictive yield that takes all the challenges listed below is marked in dark green. When comparing the light green with the dark green, we see that in Spring 2024, there is a large discrepancy due to the tracking errors that has also caused us burns onto the crops. Indeed, a mechanical part was not properly dimensioned, which required most of the tracking mounts to be exchanged. After replacement, starting May, we see that the two green curves are getting closer again.

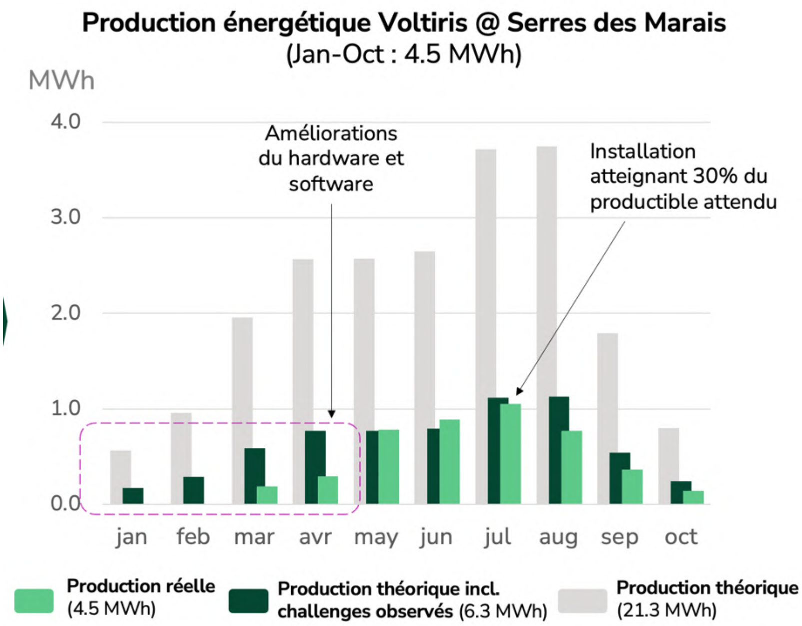


Figure 62 - Theoretical yield vs measured yield.

The main sources of differences between the theoretical yield and the practical yield are listed in Figure 63. The main problem was the so-called "batman effect". The PMMA lamellas (as a replacement of the glass lamellas in the phase 1) gained in volume due to the greenhouse humidity. As the frames were not designed for a volumetric expansion of the lamellas, the aluminium frame constrained the lamellas at the holding points, and applied stress on the lamella, causing the latter to take the form of a converging mirror, instead of having the shape of a flat mirror. Two main problems resulted from the unwanted concentration effect:

1. The light was not homogeneously covering all the PV cells. As not all the cells were covered in green light (see image below), some cells were receiving ~30% less light than the neighbouring cells, decreasing the efficiency by ~30%, and potentially causing hot spots.
2. Tracking sensitivity. The optical design was supposed to offer some unsensitivity to the tracking inaccuracy. However, as the light was concentrated closely onto the PV panel, the "illuminated area" at the PV panel level was smaller than expected, hence enhancing the sensitivity to tracking inaccuracy. An inaccuracy of 1.5° in tracking results in 25% loss at the Voltiris module level.

In addition to those problems related to the optics of the reflector, we could also make good progress and learn on the PV panel design thanks to the learnings of Serres des Marais:

1. Heat and current saturation. We have learnt that it is necessary to have as many busbars soldered onto the PV cells for our application, as we can easily suffer from Ohmic losses at 4 Sun. Also, the use of PERC technology is limited, as PERC-type cells has a high sensitivity to temperature (losses as high as -0.35%/°C). We have now moved towards the use of TopCon cells, that usually tends to offer 18 busbars per wafer (210mm), and also have a lower temperature coefficient (-0.3%/°C).
2. Mechanical stability of glass. The PV panels at Serre des Marais had a glass-glass construction, with a very thin untempered glass (2x 1mm). However, with the thermal shocks due to light concentration, and potential hot spots due to the "batman effect", many of the front/back solar panel glass broke at Serres des Marais.

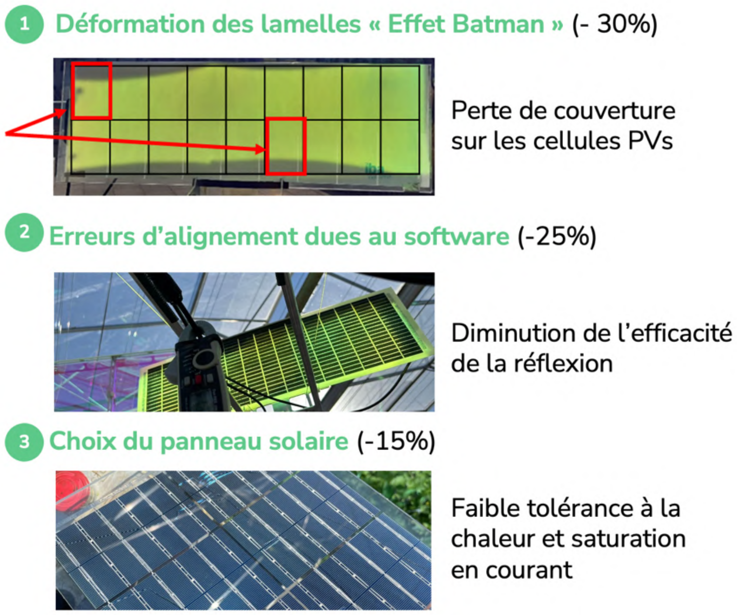


Figure 63 - Sources of inefficiencies in the Serre des Marais project.

9.4.3 Solar tracking availability

At the beginning of the phase 2, problems were encountered with the reliability of the solar tracking mount. Indeed, in the extremely humid greenhouse environment, the gears of the solar tracking, by then made from 3D printed PA6.6 GF material couldn't withstand the needed torque. During April-May, the Voltiris team needed to exchange all tracking mounts in the Serres des Marais. Starting mid-May, the tracking was seen to be operational almost all time, with an availability reaching ~95%, as seen in Figure 64.

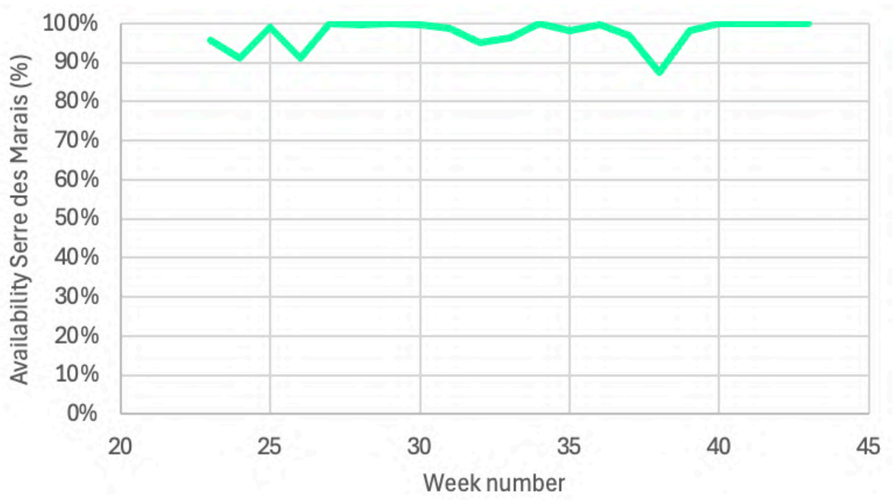


Figure 64 - Evolution of the availability of the installation (counted as %-time when the system was operational).

9.4.4 Evolution in the energy yield of the projects

A few weeks after the Serres des Marais installation, another installation was built in the Netherlands, in Delphy Research Center. There, the learnings of the Serres des Marais were put in practice. We have slightly modified the frame and reflector to accommodate better for the PMMA expansion with humidity. The result: The efficiency of the system has more than doubled, and we reached ~62% of the theoretical power efficiency.
The remaining losses were then, the frame rigidity, the Ohmic losses in the PV panel, and the heat in the PV panel.
Since then, Voltiris has been improving the power efficiency of the Voltiris modules, and we could now reach 145Wp/m2 of reflector at STC.

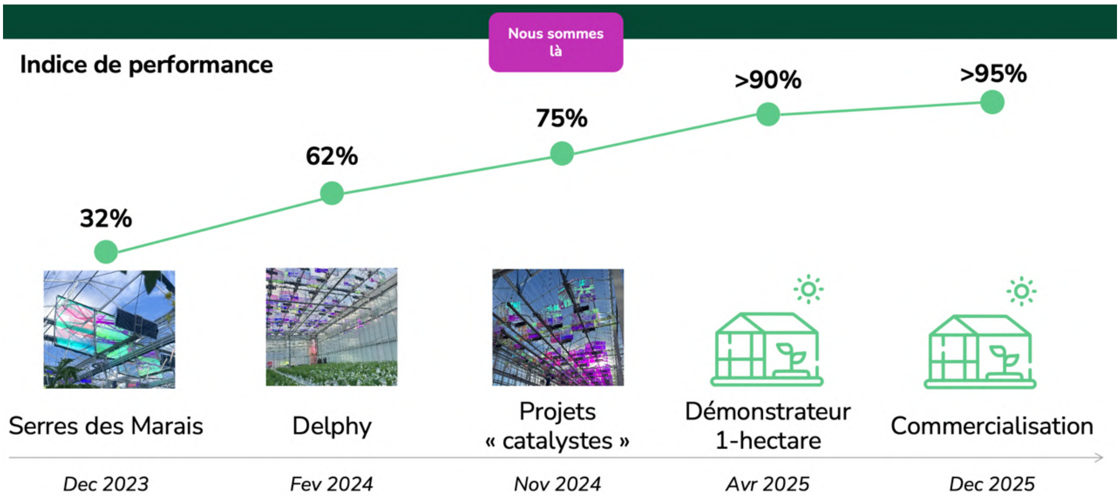


Figure 65 - The index of performance of the installations after the Serres des Marais installation.

9.4.5 Status after the SFOE support

The collaboration with the CSEM has helped to identify and qualify good suppliers for the solar PV panels of Voltiris. Using the same Bill of Material (TopCon, 18 busbars soldered), the newer solar PV panels that are used on projects have a peak power of 30.5Wp, and almost no performance degradation in concentrated light, as shown in Figure 66.

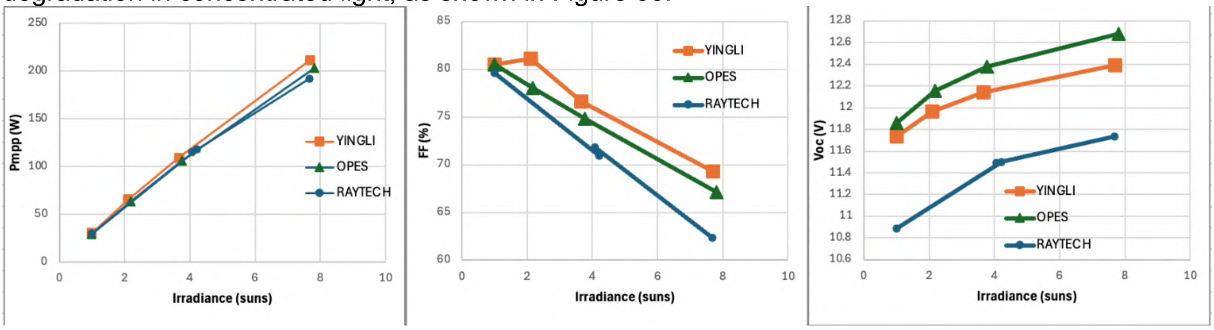


Figure 66 - Comparison of 3 different suppliers using the same Bill of Material (TopCon, 18 busbars, white backsheet).

In terms of reliability, the CSEM has performed type-tests IEC testings on the different PV panels from OPES, Raytech and Yingli. Given the importance of the damp heat behaviour in our application (greenhouses are hot and humid), the suppliers were asked to use PoE as encapsulant, as recommended by the CSEM.
The highest PV panels efficiencies were reached by Yingli with 21%. In terms of degradation, typical degradations of ~2% were measured after the damp heat, thermal cycling and humidity freeze IEC tests. While the degradations are still slightly above the pass criteria for an IEC certification, the PV panels are already much more stable than the PV panels used in the phase 2 of the Serres des Marais project.

IV PERFORMANCES AND RELIABILITY

	GENERAL INFORMATION				CURRENT-VOLTAGE MEASUREMENT							DEGRADATION (%) rel.						
	LABEL	Degrad	Nb	units	Isc (A)	Voc (V)	FF (%)	Pmpp (W)	Impp (A)	Vmpp (V)	efficiency (%)	DEG_DEff	DEG_DFF	DEG_DIsc	DEG_DVoc	DEG_DPmpp	DEG_DImpp	DEG_DVmpp
RAYTECH PERC GBS	507272 (PERC Raytech glass / transparent sheet)	ref	0		3.41	10.91	78.22	29.09	3.21	9.07	21.12							
	507272 (PERC Raytech glass / transparent sheet)	HF	10	cycles	3.33	10.89	78.28	28.40	3.16	9.00	20.61	-2.39	0.08	-2.28	-0.19	-2.39	-1.63	-0.77
	507273 (PERC Raytech glass / transparent sheet)	ref	0		3.43	10.91	78.04	29.18	3.22	9.06	21.18							
	507274 (PERC Raytech glass / transparent sheet)	ref	0		3.41	10.91	79.19	29.41	3.22	9.14	21.35							
	507274 (PERC Raytech glass / transparent sheet)	TC	205	cycles	3.33	10.94	78.35	28.51	3.14	9.07	20.70	-3.06	-1.07	-2.27	0.26	-3.06	-2.27	-0.80
	507275 (PERC Raytech glass / transparent sheet)	ref	0		3.42	10.90	79.62	29.68	3.25	9.14	21.55							
	507275 (PERC Raytech glass / transparent sheet)	TC	205	cycles	3.34	10.92	79.01	28.85	3.17	9.10	20.94	-2.85	-0.77	-2.30	0.21	-2.85	-2.40	-0.42
	507276 (PERC Raytech glass / transparent sheet)	DH	981	hours	3.33	10.88	79.31	28.73	3.18	9.04	20.85	-2.63	-0.91	-1.67	-0.06	-2.62	-1.44	-1.20
	507276 (PERC Raytech glass / transparent sheet)	ref	0		3.38	10.89	80.04	29.50	3.22	9.15	21.41							
	507277 (PERC Raytech glass / transparent sheet)	DH	981	hours	3.32	10.91	77.80	28.19	3.14	8.99	20.46	-2.66	-0.35	-2.52	0.21	-2.66	-2.21	-0.46
	507277 (PERC Raytech glass / transparent sheet)	ref	0		3.41	10.89	78.07	28.96	3.21	9.03	21.02							
YINGLI TOPCON GG	507278 (Topcon Yingli glass / glass)	HF	10	cycles	3.15	11.70	80.17	29.51	2.97	9.95	21.42	-1.69	-1.16	-0.83	0.29	-1.69	-1.51	-0.18
	507278 (Topcon Yingli glass / glass)	ref	0		3.17	11.66	81.10	30.01	3.01	9.96	21.79							
	507279 (Topcon Yingli glass / glass)	ref	0		3.20	11.66	80.41	30.03	3.02	9.94	21.80							
	507279 (Topcon Yingli glass / glass)	TC	205	cycles	3.15	11.71	80.06	29.53	2.97	9.94	21.43	-1.63	-0.43	-1.64	0.44	-1.63	-1.65	-0.02
	507280 (Topcon Yingli glass / glass)	ref	0		3.17	11.66	80.61	29.82	3.00	9.94	21.65							
	507280 (Topcon Yingli glass / glass)	TC	205	cycles	3.15	11.71	79.94	29.50	2.97	9.94	21.42	-1.07	-0.82	-0.68	0.44	-1.07	-1.06	-0.01
	507281 (Topcon Yingli glass / glass)	DH	981	hours	3.15	11.70	77.78	28.64	2.89	9.91	20.79	-4.95	-3.36	-1.98	0.33	-4.95	-4.57	-0.41
	507281 (Topcon Yingli glass / glass)	ref	0		3.21	11.66	80.48	30.14	3.03	9.95	21.88							
	507282 (Topcon Yingli glass / glass)	DH	981	hours	3.16	11.69	69.35	25.59	2.79	9.18	18.58	-15.24	-14.02	-1.75	0.34	-15.24	-8.13	-7.74
	507282 (Topcon Yingli glass / glass)	ref	0		3.21	11.65	80.67	30.19	3.04	9.95	21.92							
OPES PERC GG	507283 (PERC OPES glass / glass)	HF	10	cycles	2.95	11.08	76.89	25.13	2.73	9.19	18.24	-2.57	-1.83	-1.00	0.25	-2.57	-2.00	-0.58
	507283 (PERC OPES glass / glass)	ref	0		2.98	11.06	78.32	25.79	2.79	9.25	18.72							
	507284 (PERC OPES glass / glass)	ref	0		3.05	11.77	80.46	28.87	2.90	9.95	20.96							
	507285 (PERC OPES glass / glass)	ref	0		3.05	11.76	79.80	28.61	2.88	9.93	20.77							
	507285 (PERC OPES glass / glass)	TC	205	cycles	3.01	11.81	78.99	28.09	2.83	9.91	20.39	-1.85	-1.02	-1.22	0.39	-1.85	-1.58	-0.27
	507286 (PERC OPES glass / glass)	DH	981	hours	2.95	11.10	77.85	25.46	2.76	9.22	18.48	-1.57	0.34	-0.95	-0.96	-1.57	-1.22	-0.35
	507286 (PERC OPES glass / glass)	ref	0		2.98	11.20	77.59	25.86	2.80	9.25	18.77							
OPES PERC GBS	507287 (PERC OPES glass / transparent sheet)	ref	0		3.17	11.77	79.53	29.69	2.99	9.92	21.55							
	507287 (PERC OPES glass / transparent sheet)	TC	205	cycles	3.14	11.80	75.14	27.83	2.92	9.54	20.20	-6.26	-5.51	-0.99	0.21	-6.26	-2.53	-3.83
	507288 (PERC OPES glass / transparent sheet)	DH	981	hours	3.15	11.82	79.16	29.45	2.96	9.94	21.38	-1.61	-1.19	-0.78	0.36	-1.61	-1.54	-0.10
	507288 (PERC OPES glass / transparent sheet)	ref	0		3.17	11.78	80.12	29.94	3.01	9.95	21.73							
OPES PERC SHINGLE GBS	507360 (PERC-SHINGLE OPES glass / backsheet)	ref	0		2.81	13.77	77.43	29.93	2.64	11.36	21.73							
	507361 (PERC-SHINGLE OPES glass / backsheet)	ref	0		2.81	13.76	75.18	29.04	2.62	11.09	21.08							
OPES TOPCON GBS	507362 (Topcon OPES glass / backsheet)	ref	0		3.21	11.65	78.10	29.17	2.99	9.74	21.17							
SUNKET TOPCON GBS	507364 (Topcon Sunket glass / backsheet)	HF	10	cycles	3.40	10.59	59.80	21.51	2.83	7.59	16.26	-20.39	-19.53	-0.32	-0.75	-20.39	-7.88	-13.58
	507364 (Topcon Sunket glass / backsheet)	ref	0		3.41	10.67	74.32	27.03	3.08	8.79	20.43							
	507365 (Topcon Sunket glass / backsheet)	HF	10	cycles	3.34	10.61	60.90	21.61	2.81	7.70	16.34	-20.46	-19.95	-0.03	-0.60	-20.46	-10.62	-11.01
	507365 (Topcon Sunket glass / backsheet)	ref	0		3.35	10.68	76.07	27.17	3.14	8.65	20.54							
	507366 (Topcon Sunket glass / backsheet)	ref	0		3.43	10.72	67.81	24.92	3.01	8.27	18.83							
	507367 (Topcon Sunket glass / backsheet)	ref	0		3.44	10.71	74.39	27.36	3.14	8.72	20.68							
	507368 (Topcon Sunket glass / backsheet)	ref	0		3.42	10.70	67.95	24.82	3.02	8.22	18.76							
	507369 (Topcon Sunket glass / backsheet)	ref	0		3.44	10.69	75.38	27.70	3.16	8.77	20.94							
	507370 (Topcon Sunket glass / backsheet)	ref	0		3.44	10.72	67.99	25.09	2.95	8.50	18.97							
3 •	507371 (Topcon Sunket glass / backsheet)	ref	0		3.40	10.63	76.25	27.52	3.15	8.74	20.80							

Figure 67 - Measures of reliability of PV panels from Sunket, OPES (different BOMs), Yingli and Raytech.

Our most recent data with the identified PV panels of the same size than the ones of the Serres des Marais (the Yingli BOM in the previous Figure 67) shows that we can reach now ~84W at CSOC

(Concentrated Solar Operating Conditions), for a reflector of dimension 0.8m2, as shown in Figure 68. This corresponds to 104W for a 1m2 reflector, with a direct illumination of 900W/m2, and an operating temperature of 80°C. The data presented below were measured by the Instituto de Energia Solar in Madrid, Spain.

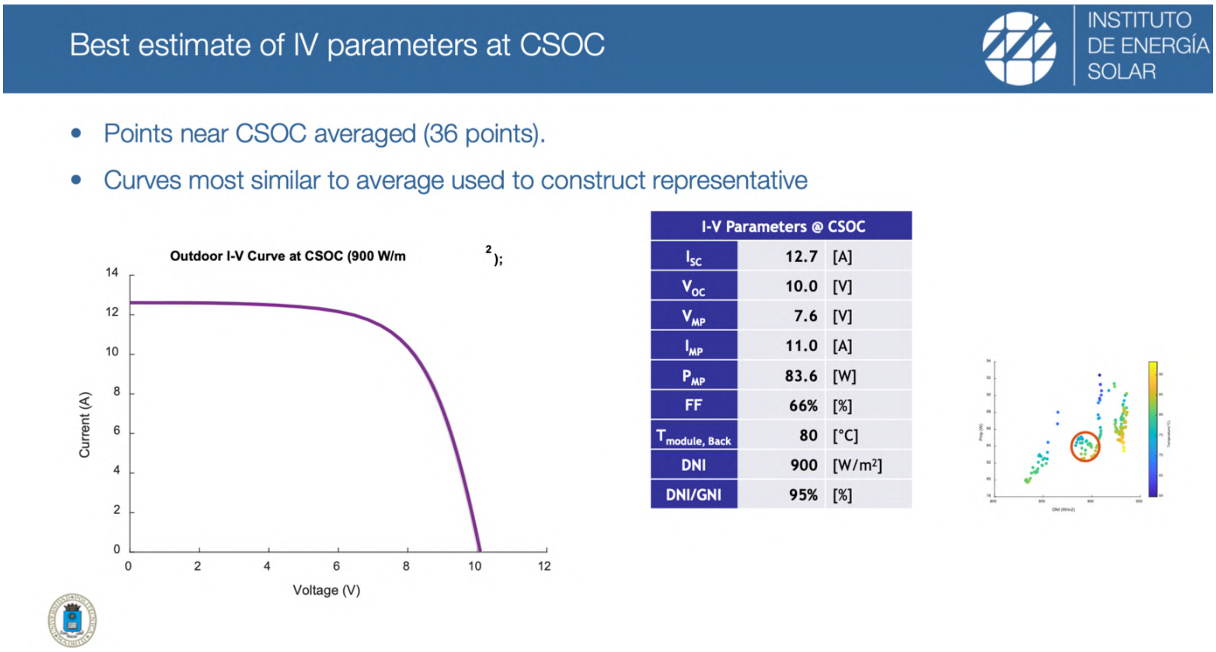


Figure 68 - IV curves and performance at CSOC conditions.

These data were obtained using TopCon PV panels from Yingli (32Wp), where 18 busbars are soldered in order to limit Ohmic losses. Also, the newer PV panels are made with a glass/white backsheet architecture, in order to limit the heating of the solar cells.

10 Economic analysis

10.1 Cost reduction and industrialization roadmap

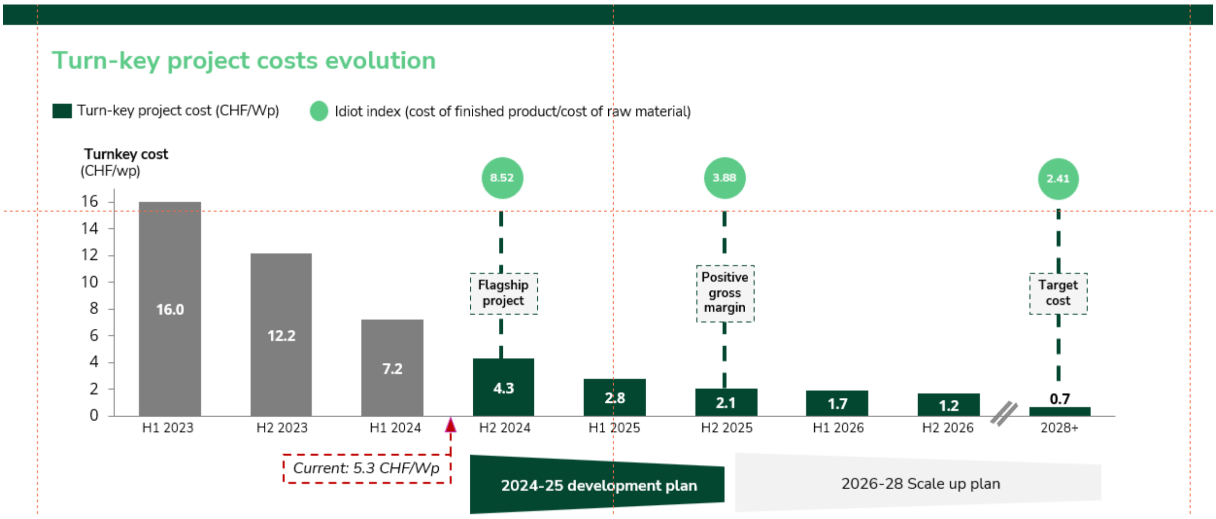


Figure 69 – Turn-key project costs evolution

The Voltiris team has outlined a clear plan to achieve economic profitability for the project. By applying insights gained from the Serre des Marais pilot to enhance the solution and establishing a well-defined roadmap for industrialization and cost reduction, the team has identified a pathway to reducing turn-key costs to below 2.0 CHF/Wp, with potential for further reduction to below 1.0 CHF/Wp.
Several factors contribute to cost reduction:
Volume Effect: Higher production volumes enable better supplier contracts and new suppliers, reducing costs.
Voltiris module Performance Improvements: Enhancements include optimized dichroic filters and photovoltaic cell designs, boosting efficiency and lowering costs.
Voltiris module Cost Reductions: Shifting from off-the-shelf to optimized components and industrialized production methods significantly cuts costs, such as using injection molding and single-film solutions.
Installation Cost Reductions: Process optimizations, like streamlining solar tracking and alignment procedures, improve installation speed and efficiency.

10.2 Case study

10.2.1 Solar energy potential

Reaching these cost targets will create significant economic value for both Voltiris and its customers. To illustrate these targets, consider the example of a Swiss greenhouse for which Voltiris accessed to the following data: historical electricity load curves, electricity tariffs, and GPS location. Using this data, we applied our in-house models and historical weather data to predict the theoretical solar energy production of 1800 Voltiris modules (7,400 m^2 of greenhouse surface) over one year, calculated at 1-hour intervals. The model shows a potential of producing 200 MWh per year leveraging this greenhouse surface. Furthermore, the results showed a self-consumption rate of 73% when comparing the predicted production with the greenhouse's actual electricity usage. It is to note that this self-consumption rate is expected to increase to 98% when the grower transitions to electric heating (planned for 2025).

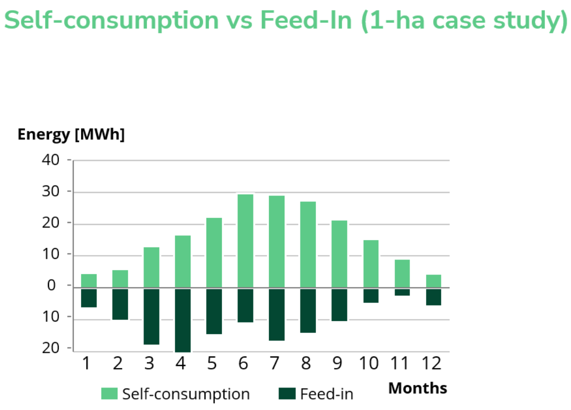


Figure 70 – Self-consumption vs Feed-in

10.2.2 Unit economics

Greenhouse growers typically aim for a return on investment (ROI) within 7 years when investing in new equipment. To illustrate the ROI for both the grower and Voltiris, we will consider two cost scenarios: 2 CHF/Wp (intermediate target costs) and 1 CHF/Wp (target costs). The following assumptions are based on the same case study:

- Size of the project: 0.74 hectares
- # of Voltiris modules: 1800
- Installed capacity: 243 kWp
- Annual energy production: 200 MWh
- Self-consumption rate: 73%
- Project costs:
  - Scenario 2026: 486k CHF (2.0 CHF/Wp)
  - Scenario 2028: 243k CHF (1.0 CHF/Wp)
- Annual Opex: 0.01 CHF/kWh
- Current cost based from the grid (2024 numbers): 0.34 CHF/kWh
- Feed-in-tariff for excess energy injection in the grid (2024 numbers): 0.15 CHF/kWh

Let's now conduct a simple payback calculation using the real numbers of this case study:

A Energy Consumption and Savings:

- **Energy consumption**
  Energy consumed on-site: 200,000 kWh * 0.73 = 146,000 kWh
  Energy sold to the grid: 200,000 kWh * (1 - 0.73) = 54,000 kWh
- **Savings for the grower**
  Savings from consuming energy on-site (avoided grid cost): 146,000 kWh * 0.34 CHF/kWh = 49,640 CHF/year
  Earnings from selling excess energy to the grid: 54,000 kWh * 0.15 CHF/kWh = 8,100 CHF/year
- **Total annual financial benefit for the grower:**
  49,640 CHF + 8,100 CHF = 57,740 CHF/year

B Annual Opex

Opex cost for producing 200,000 kWh: 200,000 kWh * 0.01 CHF/kWh = 2,000 CHF/year

Net financial benefit for the grower: 57,740 CHF - 2,000 CHF = 55,740 CHF/year

C Subsidy Impact

Adjusted project costs after subsidy
Scenario 2026: 486,000 CHF - 50,000 CHF = 436,000 CHF
Scenario 2028: 243,000 CHF - 50,000 CHF = 193,000 CHF

Note: The 50,000 CHF of subsidy is slightly lower than the values presented on the official website of Pronovo for an installation of 243kWp. However, we believe that the subsidies will lower in the near future, therefore we run the computation with a subsidie of 50,000CHF.

D Payback Period: To calculate the payback period, we divide the adjusted project cost by the net benefit for the grower.

- **Scenario 2026**:
  Payback = 436,000 CHF / 55,740 CHF/year = **7.8 years**
- **Scenario 2028**:
  Payback = 193,000 CHF / 55,740 CHF/year = **3.5 years**

As illustrated above, the following case study demonstrates the potential of the Voltiris solution to deliver attractive payback to the asset owner of the Voltiris modules. With the intermediate target costs for 2026, the payback period is around 7 years, while with the target costs for 2028, it drops to about 4 years. These payback periods are considered competitive by the many greenhouse growers we are currently in discussions with. It's important to note that, while the 2026 target costs can already generate positive results in Switzerland—where electricity prices are relatively high—the need to further reduce costs after 2026 will be crucial to accessing other markets with lower electricity tariffs. Additionally, it is expected that the demand for electricity in greenhouses will grow in the coming years, as they increasingly adopt new electricity-powered equipment to decarbonize their operations, such as heat pumps, dehumidification systems, and CO2 direct air capture. This will increase the percentage of self-consumed electricity produced by the Voltiris modules, ultimately improving the payback time of our solution for growers.

11 Conclusion and perspectives

The project at Serre des Marais represents a significant advancement in the spectral splitting low concentration photovoltaic technology from Voltiris. The project's primary objectives were to validate the agronomic and energetic performance of the modules, improve their peak power output, and assess the practicality of integrating such a system into existing greenhouse infrastructures. Throughout the project's duration, the installation underwent two phases, allowing for iterative improvements based on real-world feedback and performance data. The initial phase demonstrated the feasibility of integrating the modules without impeding standard greenhouse operations. It also provided valuable insights into necessary design adjustments, such as ensuring adequate clearance for workers during routine cultivation processes.
Agronomic monitoring yielded promising results. While the PV1 modality, which filters out far-red light for energy generation, showed a 9% reduction in yield, the PV2 modality, which transmits far-red light to the crops, exhibited only a 4% reduction. These findings suggest that optimizing the spectral filtering to balance energy production and plant growth can minimize agronomic impacts. The slight decrease

in leaf transpiration under the modules, attributed to lower leaf temperatures, indicates potential benefits in reducing water consumption and mitigating heat stress on plants.
Energy yield validation revealed that the modules performed close to theoretical expectations under optimal conditions. Challenges such as the "batman effect," caused by the expansion of PMMA lamellas in high humidity, led to uneven light concentration and decreased efficiency. These issues underscored the importance of considering environmental factors unique to greenhouse settings in the design and material selection of system components.
The project also highlighted the critical role of the solar tracking mechanism's reliability. Initial mechanical failures impacted both energy generation and crop health due to unintended light concentration on the plants. Subsequent redesigns and material improvements enhanced the system's durability and tracking accuracy, leading to increased operational availability.
In terms of improving the modules' peak power, collaboration with industry partners facilitated the development of new filter designs with higher spectral utilization factor. Advances in PV panel technology, such as adopting TopCon solar cells with more busbars, addressed issues related to ohmic losses and temperature sensitivity under concentrated light conditions. Reliability testing indicated that with the appropriate choice of materials and encapsulants, the modules could achieve acceptable degradation rates suitable for long-term operation in greenhouse environments.
The project's outcomes demonstrate the technical viability of integrating Voltiris solar modules into commercial greenhouse operations. The ability to produce renewable energy without significantly impacting crop yields offers greenhouse operators a pathway to increased energy independence, sustainability, and profitability. Moreover, the system's design allows for seamless integration into existing structures without necessitating operational shutdowns or extensive modifications.