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Projet pilote agrivoltaïque à l'Agroscope de Conthey (VS)

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Summary

This report summarises the activities and results of the P+D project " Projet pilote agrivoltaïque à l'Agroscope de Conthey (VS)", which began on 20.03.2021 and will last until 31.12.2024. The activities include the deployment and steering of a prototypal dynamic agrivoltaic installation to replace plastic tunnels over raspberry and strawberry crops, to protect them while producing renewable solar electricity on the same land. The aim of this project is to assess the techno-economic potential of the solution.

Main achievements:

- Installation of an 18 kWp demonstrator, connected to the grid, whose design allows for agronomic experimentation and comparison to control zones for agricultural production.
- Tests of light management strategies during several agricultural production cycles of different varieties of raspberries and strawberries.
- Agronomic activities and crop monitoring, with analyses of crop quantity and quality, in comparison to various reference zones (covered by two different kinds of plastic tunnels and uncovered).

Agronomical results showed varied outcomes, depending on seasons, varieties, and applied shading. Crop yields obtained under the prototypal agrivoltaic system were in some cases similar and in other cases lower than those obtained under the plastic covers. However, in several cases, larger fruit sizes were obtained under the agrivoltaic system, potentially increasing the economical return for the producer even in case of lower yield. The results allow to identify shading levels and varieties for which agricultural yields are maintained while producing solar electricity on the same land. In all cases, crop yield and fruit size were larger under the agrivoltaic system compared to an uncovered reference zone, indicating a benefit provided by the agrivoltaic cover for this type of crop.

Electrical production match expectations based on simulations for this prototypal system. However, the first months of the project enabled the authors to identify limitations in terms of industrialization potential of the technology on which the prototype is based.

A new generation solution, retaining the micro-climatic management functionalities of the original prototype, but circumventing its limitations, has since been developed and installed for extended testing on a commercial scale, in the form of a 265 kWp installation split in two parts dedicated to raspberries and strawberries. The outcomes of the 2024 commercial production and agronomic follow-up under the commercial scale agrivoltaic installation are reported.

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Abbreviations

CAN: Controller Area Network

DLI: Daily Light Integral

DNI: Direct Normal Irradiance

E-mode: Electricity Mode

GHI : Global Horizontal Irradiance

GII: Global Inclined Irradiance (aka Global Tilted Irradiance)

LCOE: Levelized cost of electricity

MLT-mode: Maximum Light Transmission Mode

PAR: Photosynthetically Active Radiation (conventionally: AM1.5 filtered to 400-700nm)

PPFD: Photosynthetic Photon Flux Density

PV: Photovoltaics

1. Introduction

1.1 Background information and current situation

In Switzerland, just like in many European countries, a double-use of land and infrastructure is required to achieve the photovoltaic deployment targets related to the energy transition. In Switzerland, the Energy Strategy 2050[1] implies the production of 45 TWh/year of electricity from renewable sources (excl. hydro-power)[2]. In Europe, the “Green New Deal” targets 27 GW_p/year (equivalent to roughly 500km^2) of new solar deployments every year until 2050.

Agrivoltaics is the combination of agricultural and photovoltaic energy production on the same land. It opens the perspective of large-scale solar deployments, while at the same time fulfilling a role of sustainable protection for the crops in a context of climate change. As a replacement of conventional protective structures such as plastic greenhouses, impact on landscape also promises to be minimal.

It is an emerging but growing sector, with 2200 systems (2.8GWp) installed in Europe between 2014 and 2022[3]. Political initiatives to support agrivoltaics are currently carried in Italy[4], France[5] and Germany[6]. In Switzerland, a recent study by ZHAW evaluates the technical potential of agrivoltaics on the category of crops “Dauerkulturen” (includes berries and orchards, which typically need protection against rain, hail, or excess irradiance) to 5.1 TWh/year.

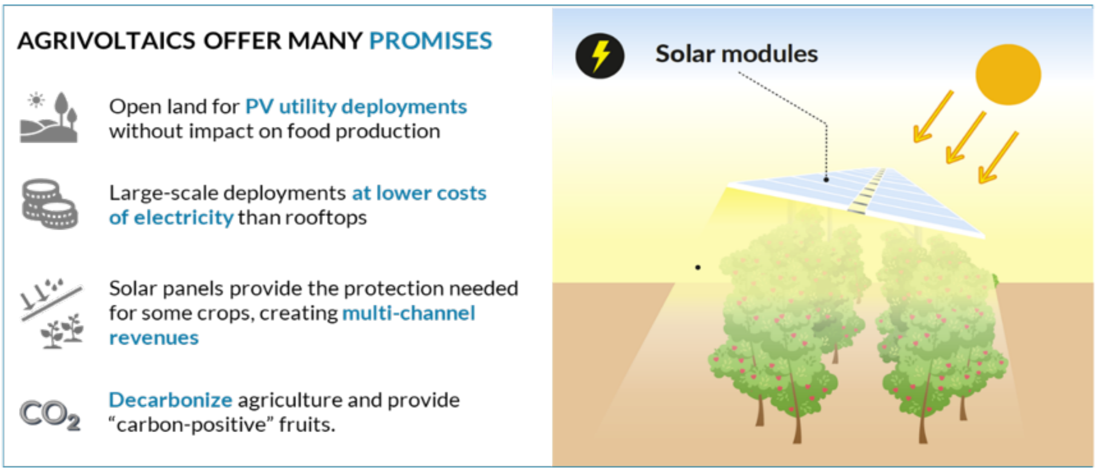


Figure 1: The promises of agrivoltaics.

[1] https://www.bfe.admin.ch/bfe/en/home/politik/energiestrategie-2050.html
[2] https://aeesuisse.ch/fr/news/communique-de-presse-une-etape-importante-dans-la-politique-energetique-le-parlement-adopte-le-decret-manteau/
[3] Roxani *et al*, A. Multidimensional Role of Agrovoltaics in Era of EU Green Deal: Current Status and Analysis of Water–Energy–Food–Land Dependencies. Land 12, 1069 (2023).
[4] "Italy devotes €1.1bn to agrivoltaics, €2bn to energy communities and storage", in PV magazine International (pv-magazine.com)
[5] "Agrivoltaics to shine in France after presidential recognition", in PV magazine International (pv-magazine.com)
[6] https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2022/forschungsanlage-der-modellregion-agri-photovoltaik-baden-wuerttemberg-von-ministerpraesident-kretschmann-eroeffnet.html

For agrivoltaics to fulfil its promise of a dual-use of the land, it is key to ensure that agricultural yields are preserved. For example, the German DIN specification[7] sets that at least 2/3 of the yields must be preserved. In Switzerland, the federal ordinance 32c (OAT)[8] requires the agrivoltaic cover to provide a positive impact on the agricultural production. To achieve that, the coverage must be carefully designed to match the crop needs. This is not achievable by covering crops with opaque silicon photovoltaic modules, as they provide too much shade and severely degrade agricultural yields.

In contrast, semi-transparent solutions can provide a viable balance for the light sharing between crop needs and electricity generation, with the opportunity to match the transparency of conventional agricultural covers. Another category of solution – known as dynamic agrivoltaics – opens the perspective of a smarter sharing, with the real-time adjustment of light transmission. In this case, light transmission can be maximized when the crops need it, and electricity generated when the light is in excess. Before the beginning of this project, dynamic agrivoltaics was realized by mounting solar modules on single-axis trackers[9] or linear rails to provide dynamic light adjustment capability, by moving the module shades onto or away from the crops. This type of solution has several limitations, such as the inhomogeneous light distribution on the crops (either full light or full shadow), the limited protection that movable panels can provide to the crops against meteorological hazards, and limited ground covering ratio.

New technological solutions are thus required to provide the right amount of light and protection to the crops, while producing enough electricity to achieve economic viability.

1.2 Purpose of the project

The company Insolight SA, based in Lausanne, has developed the innovative agrivoltaic solution Insolagrin, which combines a static protection for the crops with adjustable light transmission. In its first generation, Insolagrin is composed of a prototypal version of photovoltaic modules THEIA (Translucency and High Efficiency In Agrivoltaics), which enable a real-time control of light transmission at the module level. This module technology is ideally suited for agrivoltaic applications, since it provides the right amount of light to the crops, while converting the excess sunlight to renewable energy. Furthermore, since the modules themselves are not moving, they can easily be integrated into a static structure, providing a high degree of protection to the crops, and achieving dense ground coverage ratios. In summary, the technology enables dynamic agrivoltaics onto a static structure.

The purpose of this project is to deploy an array of THEIA prototypal modules as a replacement of plastic tunnels above raspberries and strawberries, to demonstrate the potential of the technology to provide enough light and protection to the crops, while producing enough renewable energy to make the solution economically viable. The agronomic yield of the crops cultivated below the agrivoltaic installation is compared to the yield of reference crops cultivated under various reference zones, representative of conventional berry production systems.

[7] https://www.din.de/de/wdc-beuth:din21:337886742
[8] https://www.fedlex.admin.ch/eli/cc/2000/310/fr
[9] Valle, B. et al. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. Applied Energy 206, 1495–1507 (2017).

2. Description of the facility

2.1 Key facts

Project type	Photovoltaic installation on soft fruits (berries)
Location	Agroscope, Conthey (VS)
Installation size built for the project	total: 535m^2 165 m^2 agrivoltaic, 380 m^2 control area
Solar capacity	18 kW$_p$
Electricity production	up to 18'000 kWh/year
Crop type	raspberries & strawberries
Expected crop yield	up to 2.5 kg/m^2/year

2.2 Overview

The pilot installation designed and deployed in the framework of this project is located on the grounds of the Swiss federal institute of Agronomy (Agroscope) in Conthey (Valais, CH).

Figure 2: Aerial views of the Agroscope center in Conthey and location of the pilot installation (red area).

The pilot installation is composed of a central area of ca. 165m^2 covered with the translucent PV modules (176 modules in total).

2.3 THEIA prototypal modules

The pilot installation is based on the innovative photovoltaic modules THEIA, previously developed by Insolight. Thanks to their design made of solar cells and lenses, THEIA modules provide a dynamically adjustable light transmission, as illustrated on Figure 3. In this prototypal version, the modules are composed of a PMMA front plane with embedded optics and a PV backplane with elongated solar cell strips arranged according to a custom layout. Cylindrical lenses on the front plane create a line focus on the backplane (2x concentration factor). The modules include an actuation system, enabling a translational movement of the PV backplane relative to the front plane, to adjust the ratio of direct sunlight focused on the PV cells or transmitted through the gaps between them.

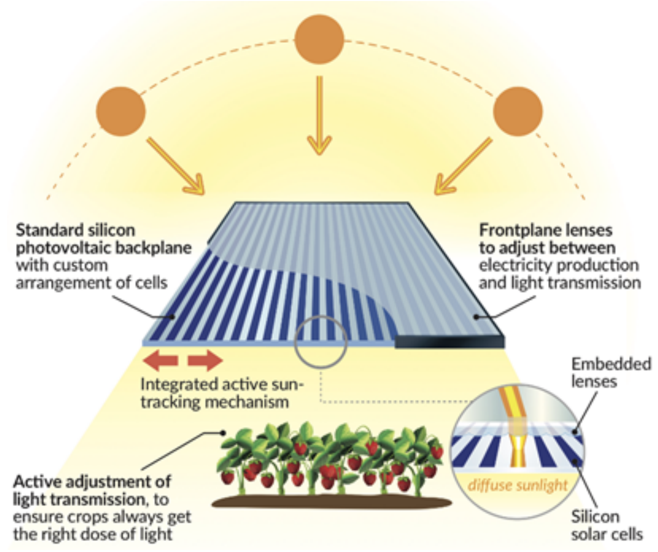


Figure 3: Principle of operation of the THEIA prototypes.

Light transmission and electricity production can thus be adjusted continuously and instantaneously at any time to match the requirements of the plants growing below. Figure 4 illustrates the minimum and maximum light transmission levels achievable with the THEIA modules, namely E-mode (Electricity mode, 15%) and MLT-mode (Maximum Light Transmission mode, 70%).

Figure 4: Illustration of the light transmission on crops in E-mode and MLT-mode.

THEIA prototypal modules used in the installation have been characterized in concentrator standard test conditions with a quasi-collimated flasher Pasan) at CSEM within the framework of the Innosuisse project ATLAS:

- Modules installed over the raspberries are assembled with PERC cells backplanes. The median backplane efficiency is 18.8% and module efficiency is 16% (in E-mode).
- Modules installed over the future strawberry section are assembled with IBC cells backplanes. The median backplane efficiency is 19.5%, backplane bi-faciality factor is 83%, and module efficiency is 17.4% (in E-mode).

An example of outdoor measurement of the module efficiency (with respect to GII, without temperature correction) is shown in Figure 5, in a condition where the Direct Inclined Irradiance to Global Inclined Irradiance ratio was 82%.

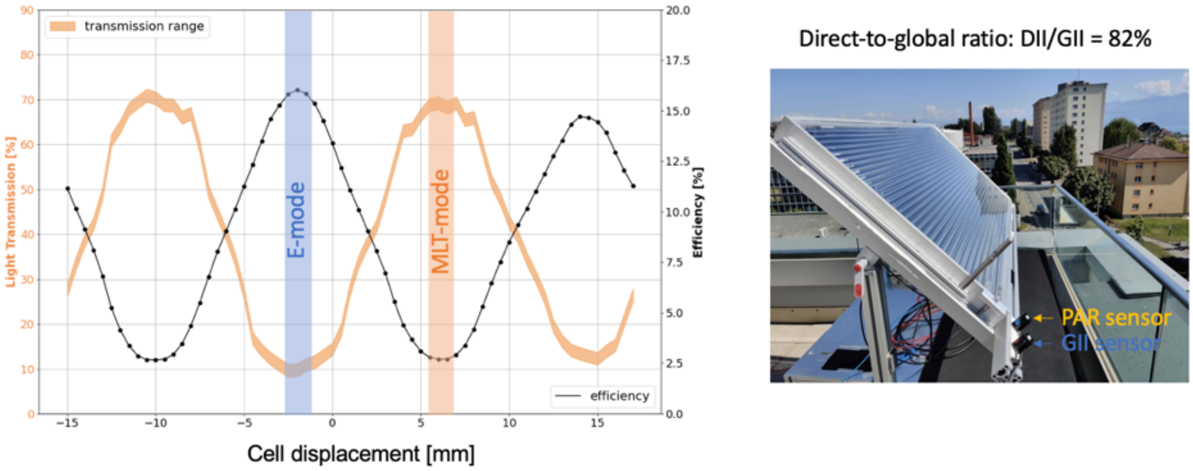


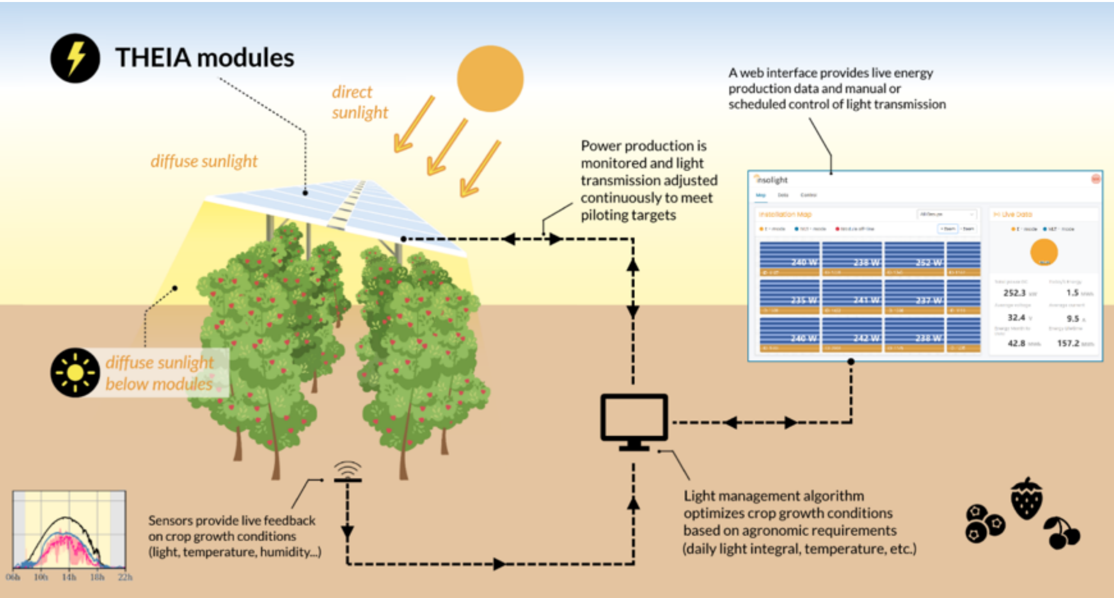
Figure 5: Example of outdoor measurement of PAR transmission and module efficiency (without temperature correction) with respect to GII, as a function of the linear backplane displacement with respect to the optical layer.

A limitation of this design is that the light transmission adjustability only acts on the direct fraction of sunlight. Diffuse light transmission is not controlled, with half of the light being captured by the cells and the other half transmitted, minus optical losses.

2.4 Monitoring and piloting hardware

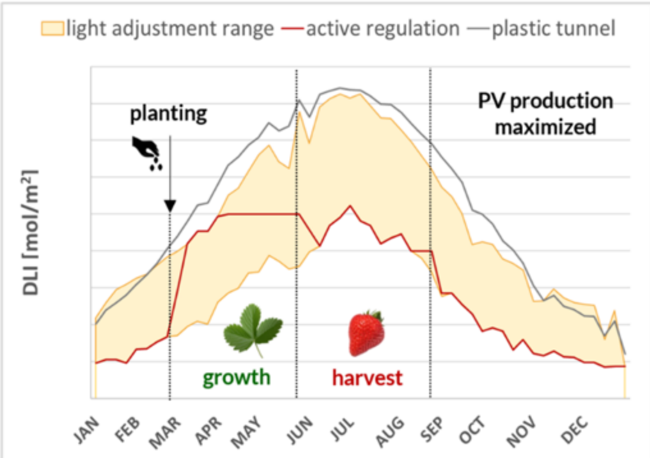
All the solar modules of the pilot installation are connected to a central gateway through a bidirectional communication bus (CAN). The bus allows the modules to log their power output, and the gateway to send commands to the modules to adjust light transmission according to an algorithm.

Several types of sensors (direct, diffuse and Photosynthetically Active Radiation (PAR), air temperature, relative humidity) have been deployed under the installation, in the control area (under plastic tunnels) and above the installation (see section 3.1 for more details). All the sensors are also connected to the communication bus and logging data every few minutes to a database.



A light management algorithm has been developed by Insolight with the aim provide optimal lighting conditions on the crops. The algorithm takes various agronomic targets as an input, such as the optimal daily light integral or temperature during the various development stages of the raspberries and strawberries. These targets have been defined in collaboration with Agroscope.

Figure 6: Example cultivation cycle and light regulation output for late strawberries in Aix-en-Provence (France). The range of light adjustment is depicted in yellow. The daily light integral (DLI) is regulated to optimal values [mol/m^2/day] during growth and harvest.



2.5 Construction

The design of the structure has been defined by the three project partners - Agroscope, Romande Energie and Insolight - taking into account the requirements of the agricultural production and trying to optimize both crop protection and electricity production. The main parameters of the resulting structure are summarized in Table 1.

Table 1: Main parameters of the agrivoltaic structure.

Layout	4 tables, each with 44 modules on 4 rows
Ground coverage ratio	ca. 72%
Module orientation	tilt: 30°, azimuth: 165°

Figure 7 shows side and front views of the construction. It should be noted that the structure is anchored to the ground with "harpoon" screws, without concrete slabs, in order to preserve the soil and facilitate dismantlement.

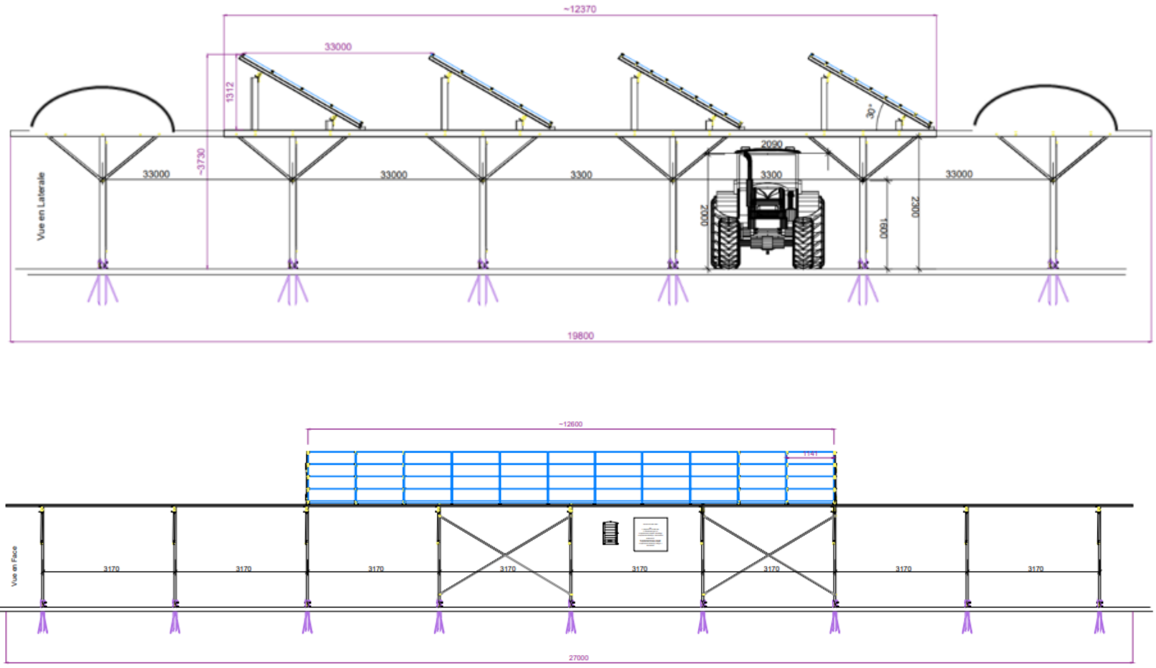


Figure 7: Lateral and front side views of the prototypal Insolagrin installation.

Construction started mid-July 2021 and took ca. 3 days.

Due to limited production capacity, modules were deployed in phases, with two batches of PV backplanes from different suppliers:

- **First phase**: 88 modules installed at the end of July 2021.
    - 82 **mono-facial** modules (PERC cells)
    - 6 **bi-facial** modules (IBC cells)
- **Second phase**: 88 **bi-facial** modules (IBC cells) installed at the end of November 2021.

Figure 8: Photographs taken during the pilot construction.

2.6 Grid connection

Since each module can be piloted independently to provide a specific light transmission level and power output, it has been decided to use one micro-inverter per module for the grid connection. In this manner, each module is operated independently at its own maximum power point. Figure 9 provides an overview of the micro-inverter strings (Enphase IQ7 series).

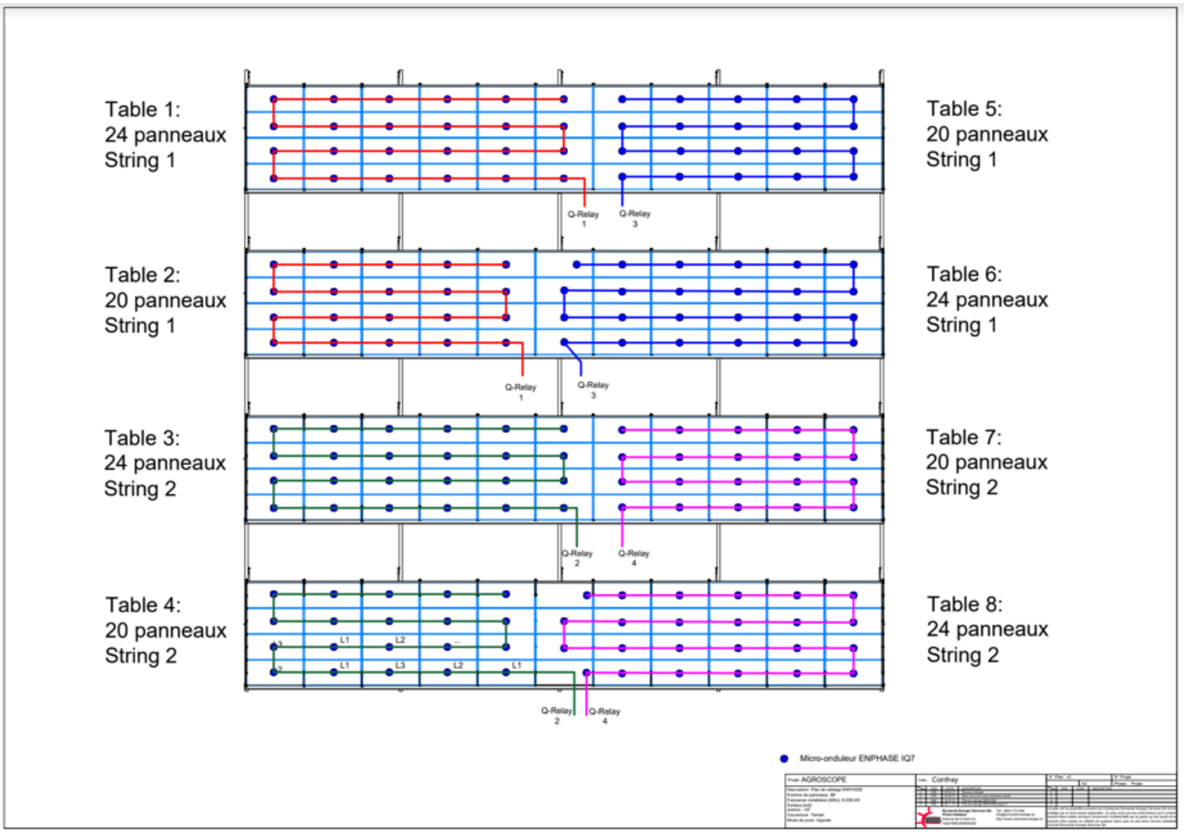


Figure 9: Layout of microinverter strings.

2.7 Communication bus and power supplies

Besides the grid connection, all the modules are connected on a CAN bus for bidirectional communication with a central gateway, which is connected to the internet and able to relay messages to and from the modules to a cloud platform. Furthermore, all modules are supplied with 15V DC to power the actuation and tracking system. Figure 10 summarizes the layout of the low voltage circuitry.

Figure 10: Layout of the communication and power supply circuitry.

2.8 Agronomic reference zones

Agronomic reference zones were used as witness for the various agronomic trials. Different reference zones were used, representative of conventional berry production systems in Switzerland (Figure 11). A zone of plastic umbrellas was built during the project, adjacent to the prototypal agrivoltaic installation. In addition, two other representative reference areas already in place at Agroscope were also used: multi-span plastic greenhouses (high end production tool with active venting and misting system) and an uncovered area.

Figure 11: Photographs of the reference zones used throughout the project. Left: Plastic umbrellas, adjacent to the prototypal agrivoltaic installation. Middle: multi-span plastic greenhouses. Right: uncovered area (outdoor).

2.9 THEIA GEN2 modules, new insolagrin solution and installations

Based on the learnings of the first two years of the project, which have enabled to establish the performance but also the limitations of the THEIA prototype modules in the field (see Sections 4 and 5), a redesign of the THEIA modules and Insolagrin solution and has been performed (Innosuisse funded project ATLAS – see Section 7). New semi-transparent bifacial panels have been developed, leveraging the use of conventional-size glass-glass laminates with spaced PERC half-cells. Two levels of transparency have been defined: THEIA-T60 (200W) with 40% of cell coverage, and THEIA-T40 (300W) with 60% cell coverage. The surface that is not covered by cells is made of a transparent diffusive glass-encapsulant-glass laminate. Drawings and a photograph are shown in Figure 12.

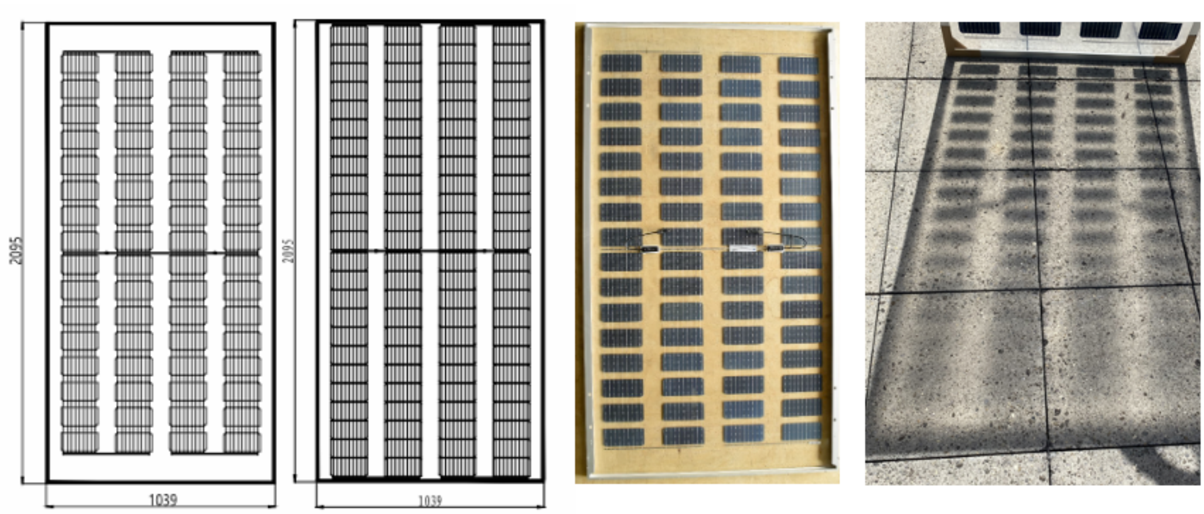


Figure 12: GEN2 THEIA modules. From left to right: (i) Drawing of THEIA-T60 module (ii) Drawing of THEIA-T40 module (iii) Photograph of T60 module (back side) (iv) Photograph of the shadow casted by a T60 module held vertically, to illustrate module diffusivity and homogenization of transmitted light with increasing distance.

With the new generation Insolagrin solution, the tuning of transmitted light for micro-climatic control is not done at the module level, but at the system level, using an agricultural shading screen with a reflective upper surface positioned under the modules (see Figure 13). The screen can be deployed fully or partially, based on a crop-specific steering algorithm, to optimize microclimatic conditions under the installation, for example in case of a heat wave when direct sunlight can damage fruits and leaves. Every time the screen is deployed, it reflects light towards the back side of the bi-facial panels to boost the electricity production. This feature can also be used when there are no crops under the installation to increase the electricity production in winter time. In summary, the new generation Insolagrin solution retains the protection and dynamic light adjustment features of the prototypal solution, while leveraging on qualified and scalable components.

Figure 13:New generation Insolagrin solution, with retracted (left) and deployed (right) shading screen.

Figure 14: Photographs of the projects based on the new generation Insolagrin solution in Conthey. Left: 16kWp demonstrator. Right: 265kWp commercial-scale installation with dedicated parts optimized for the cultivation of raspberries and strawberries.

The commercial-scale installation includes a research component in the form of different agrivoltaic modalities. The raspberry part is divided in 4 sub-parts to probe the light-sharing trade-off (see Figure 15):

- East-West oriented T60 modules (640 kWp/ha)
- East-West oriented T40 modules (950 kWp/ha)
- West-only oriented T60 modules (640 kWp/ha)
- West-only oriented T40 modules (950 kWp/ha)

The strawberry part is divided in two sub-parts: T60 and T40 modules (480 and 710 kWp/ha, respectively).

Figure 15: different modalities of the new generation commercial-scale agrivoltaic installation in Conthey. From left to right: (i) Raspberry part with East-West (EW) oriented modules. (ii) Raspberry part with West-only (WW) oriented modules. (iii) Strawberry part. Plastic tarps have been added during the year 2024 to close the gaps between modules and protect fruits against rain, except on the westernmost chapel to compare agronomic results with/without plastics between the panels.

3. Procedures and methodology

3.1 Climatic monitoring

A series of climatic sensors has been deployed on-site. They are used for two purposes: (1) Log meteorological data to provide inputs for our simulation toolbox, and compare PV output and light transmission to theoretical predictions ; (2) Provide inputs for the light management algorithm that pilots the installation. The sensors deployed include irradiance sensors: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), Global Inclined Irradiance (GII – aka Global Tilted Irradiance GTI), and Photosynthetically Active Radiation (PAR – solar radiation filtered to 400-700nm) ; temperature and relative humidity sensors. The sensors that are critical to evaluate the micro-climatic conditions of plant growth are deployed under the panels (test zone) and in the reference zones. Photographs of sensors are shown in Figure 16, and an output example is shown in Figure 17.

Figure 16: Climatic monitoring equipment deployed on site: Direct and diffuse irradiance sensor (left) ; Photosynthetically Active Radiation (PAR) sensor (middle) ; Temperature and relative humidity sensor (right)

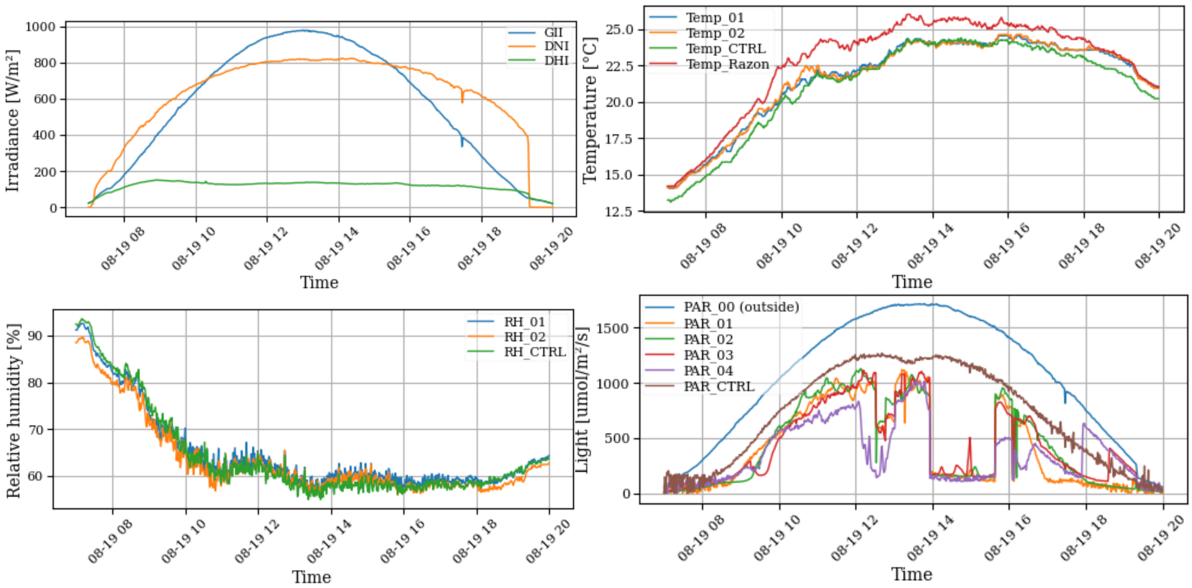


Figure 17: Example of sensor outputs on a typical sunny day (August 19th, 2021). Output of irradiance, temperature, relative humidity, and PAR sensors.

3.2 Photovoltaic energy monitoring

The operating current and voltage of every panel is probed independently. This data, along with data from irradiance, PAR, temperature, and relative humidity sensors is collected and saved on a database, which can be accessed and visualized from a web interface (Figure 18) or using an Application Programming Interface (API) for custom analysis.

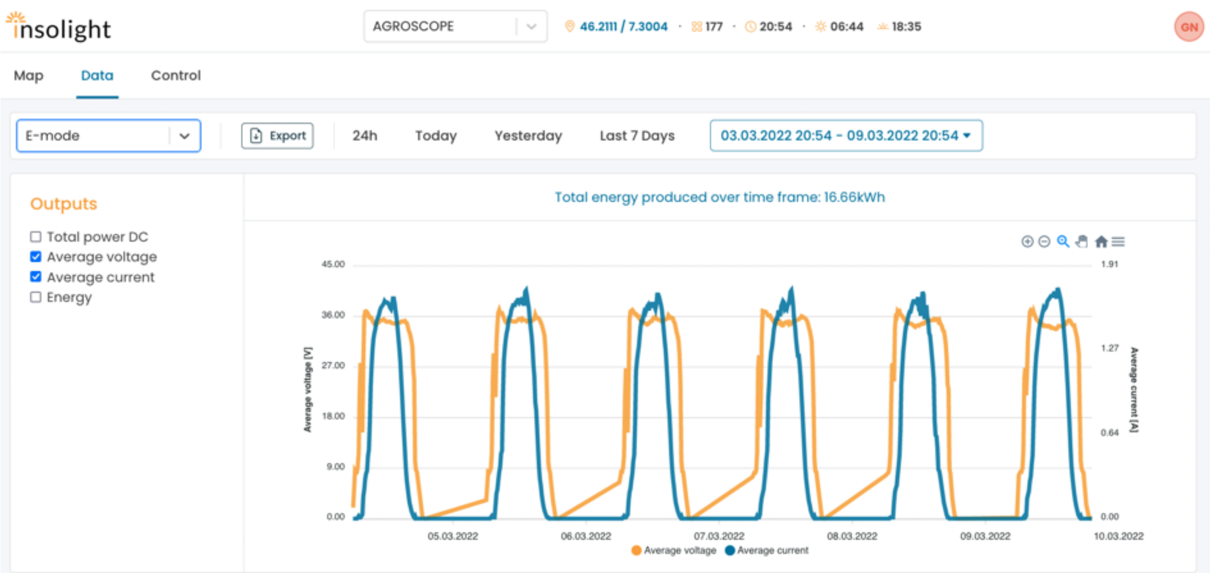


Figure 18: Monitoring of the photovoltaic output, as visible from the web interface developed by Insolight.

3.3 Piloting and light management algorithmics

During the project, a Light Management Algorithm (LMA) has been designed to take into account micro-climatic needs of the crops. The basic functions are to provide the right amount of light to the crop and protect them from excess irradiance and temperature. The LMA pilots the panels by adjusting their light transmission (between E-mode, MLT-mode and intermediate modes) to produce electricity with excess sunlight. Crop specific input parameters are expressed in terms of a target of Daily Light Integral (DLI), and limits of PAR Photon Flux Density (PPFD) and air temperature.

3.4 Photovoltaic and light transmission simulation toolbox

A simulation toolbox has been developed by insolight to predict photovoltaic electricity generation and light transmission. It is based on a ray-tracing modelling of the light propagation in the solar panel, and a separation of irradiance in its direct and diffuse components. The simulation also takes into account inter-row shading in winter. Example of PV production and light transmission over typical days are shown in Figure 19, with a good agreement between measurements and simulations. A slight excess of PV production (associated to a lack of light transmission) in MLT-mode can be noted between 9h-10h and has been attributed to light scattering in the optical layer for the angle of incidence prevailing at this hour. The simulation toolbox enables the simulation of Insolagrin performance using typical meteorological year data, satellite data or onsite measurements. Thus, it can be used to simulate the effect of installation geometries and piloting strategies in arbitrary locations.

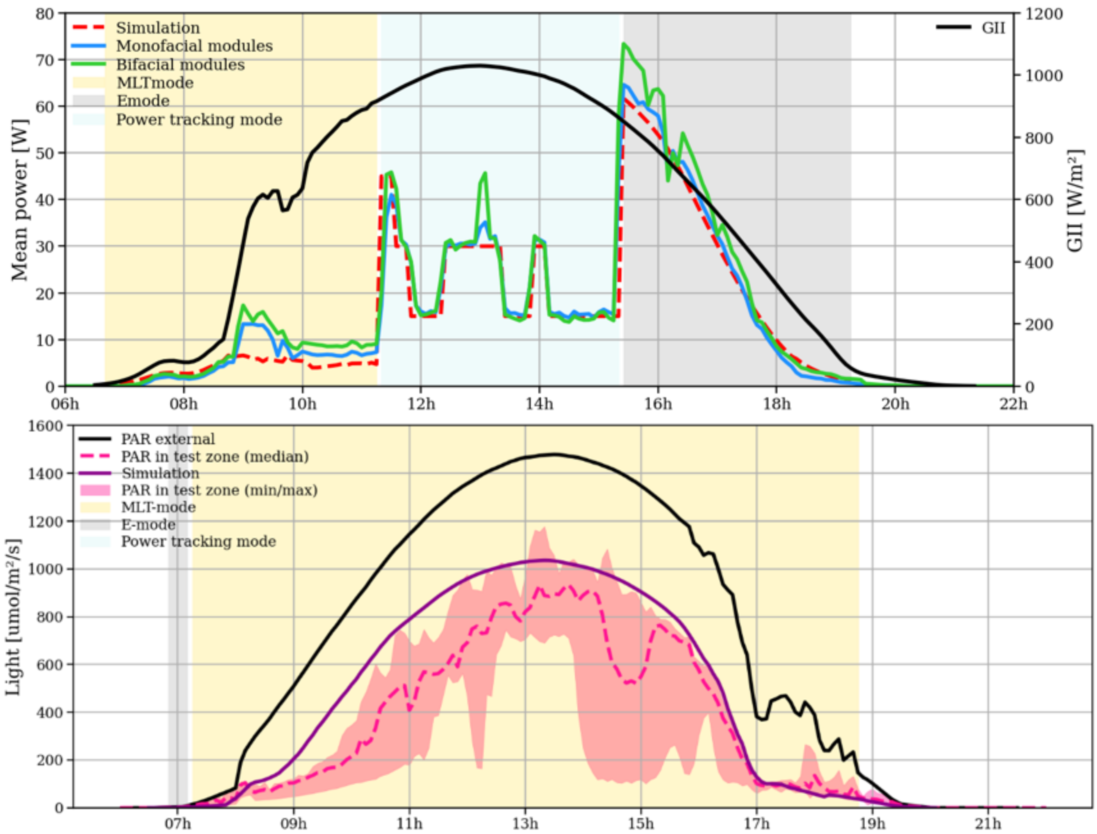


Figure 19: Examples of comparison between simulation and mean power output per module on August 8, 2021 (top) and light transmission on Sept. 18, 2021 (bottom). Simulation did not include bi-faciality, hence the better agreement with the power output of mono-facial

modules. The min/max range of PAR light measured under the panels shows the effect of local shadows. The simulation does not include calculation of structure shadows, hence the better agreement with the unshaded detectors (max of the range).

3.5 Agricultural procedures and monitoring

Pre-cultivated (also called “long canes”) raspberry plants were used. Plants were cultivated in so-called spatial repetitions, which had a length of six meters and included twelve pots. Pots had a volume of 10 L and a professional substrate (ökohum GmbH) was used (with a medium nutrient level, high pH and nutrient buffering due to adequate humus content and very good water absorption and storage, raw material: bark humus, peat (<40%), coconut, rice husks, pumice sand). In total 3 spatial repetitions per system were used.

The following trials have been conducted under the prototypal system within the project:

Species	Variety	Type	Dates	Reference zones
Raspberries	Vajolet	Long-cane, season	26.07.2021 – 12.11.2021 (late season due to set-up availability)	Umbrellas, Multi-span greenhouse (1 repetition)
Raspberries	Vajolet	Long-cane, season	29.04.2022 – 02.08.2022	Umbrellas, multi-span greenhouse
Raspberries	Glen-Ample	Long cane, season	03.08.2022 – 04.11.2022 (late season due to set-up availability)	Umbrellas
Strawberries	Karima	Everbearing	29.04.2022 – 26.10.2022	Umbrellas
Raspberries	Clarita	Long-cane, everbearing	13.04.2023 – 06.14.2023	Plastic greenhouse, uncovered
Raspberries	Kwanza	Long-cane, everbearing	13.04.2023 – 06.14.2023	Plastic greenhouse, uncovered

Table 2: Agronomic trials conducted within the project under the prototypal system.

The following trials have been conducted under the commercial-scale Insolagrin system within the project:

Species	Variety	Type	Dates	Reference zones
Raspberries	Paris	Plug plants, everbearing	11.04.2024 – 27.10.2024	NA
Strawberries	Joly	Season	13.06.2024 – 02.08.2024	Uncovered line at edge of installation

Table 3: Agronomic trials conducted within the project under the commercial-scale Insolagrin system.

Unfortunately, due to a last-minute delay in its construction (ramming machine broken), the control zone that was planned adjacent to the commercial-scale Insolagrin installation (a conventional production zone made of 4 rows of plastic umbrellas) was not ready for the 2024 planting. The trial still took place to establish a first reference point, compare the various agrivoltaic modalities between each other, and evaluate the compatibility of the infrastructure with commercial berry production practices. For the strawberries, the westernmost row at the very edge of the installation, which is not covered by plastics nor solar panels, served as an uncovered control line (Figure 21).

Figure 20: Selected photographs of the trials in agrivoltaic prototype and reference zones.

Figure 21: Selected photographs of the trials in the commercial-scale agrivoltaic installation dedicated to raspberries (top) and strawberries (bottom). Bottom right: westernmost line at the edge of the strawberry installation, serving as an uncovered control for the 2024 season.

3.5.1 *Fruit yield and weight*

Fruits were harvested and weighted 3 times per week.

3.5.2 *Fruit quality*

After harvest, fruits were classified into marketable and non-marketable malformed and discolored fruits (fruits affected by disease and pests), as performed by Swiss producers.

During the harvesting period from 29.09. until 03.11.2021, sugar content (in Brix°, two samples per block and sampling day), acidity (in g/L, one sample per block and week) and firmness of the fruits (g/mm) were analyzed six times at regular intervals. Note that berry firmness is a numerical expression whether berry is considered rather hard or soft. The unit is g/mm and indicates how much pressure (measured in gram) is needed to squeeze the berry one millimeter. In 2022, the quality of raspberries and strawberries was measured once a week.

3.5.3 *Pests and diseases*

Plants were checked for pests and diseases once per week.

3.5.4 *Irrigation and drainage management*

During the whole growth cycle, raspberries were constantly irrigated through two drip irrigation tubes per plant pot. Measurements of the irrigation and drainage water quantity were carried out at regular intervals 20 times over the whole growth cycle.

4. Results

4.1 Light management

Example of light management on a typical day are shown in Figure 22. It shows that the piloting algorithm was able to achieve its targets: (1) The installation activated a light limitation mode between 12h and 14h to prevent the PPFD to go beyond the set limit. (2) The installation activated a protection mode between 14h and 15h when the air temperature reached the set limit (temperature graph not shown). (3) The installation turned into E-mode when the algorithm estimated that the DLI target would be reached by end-of-day.

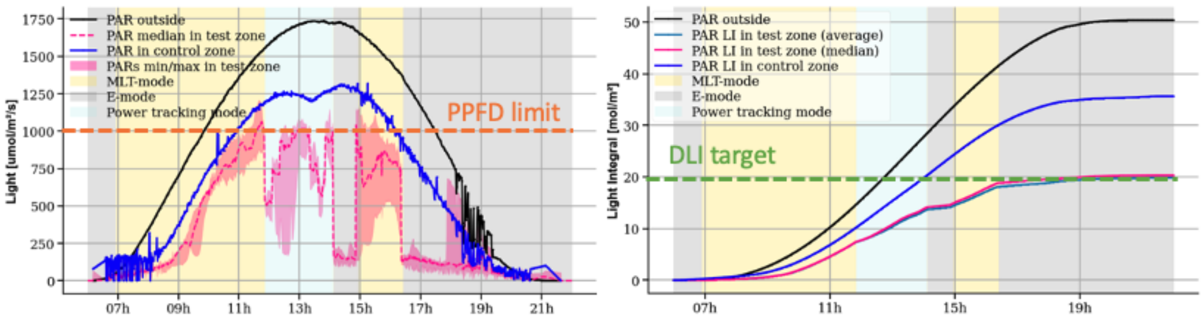


Figure 22: Example of light management under the installation on August 14 2021. Left: PAR Photon Flux Density (PPFD) is piloted to never overcome the PPFD limit parameter. Right: Accumulated light integral is piloted to reach the Daily Light Integral (DLI) target parameter. At the same time, PPFD and DLI outside and in the control zone exceed the limit and target, respectively.

4.2 Light availability

Light availability in the multi-span plastic greenhouse was measured to an average of 63% of the outdoor radiation. Light availability under the umbrellas was measured to an average of 67% of the outdoor radiation in for the Vajolet and Karima trials, and 80% in for the Glen-Ample, Clarita and Kwanza trials (different plastics were used). Under the prototypal agrivoltaic system, the light availability varied as a function of the applied light management strategy, with averages between 30 and 40%.

As discussed in Section 2.3, a limitation of the THEIA panels prototypes arises in case of highly diffuse light conditions (e.g. overcast days). In this case, the transparency of the panels can't be controlled, and averages around 30% transmission, in conditions where light availability is generally a limiting factor for photosynthesis.

Additionally, it was observed during the Strawberry trial (Karima 2022) that the position of the pots under the agrivoltaic cover was sub-optimal in terms of light distribution. Indeed, most of the leaves were directly shaded by the rain collection gutters for a large part of the season without benefitting from the light regulation by the THEIA panels, while the fruits were hanging in full sun (Figure 23).

Figure 23: Photograph from the strawberry trial (02.08.2022), showing the light distribution on the plants, due to a sub-optimal positioning of the pots.

The light availability under the new commercial-scale installation varies between the modalities (T40 or T60 modules) and whether the gaps between the modules are filled with plastic for rain protection during harvest. The raspberry zone transmits between 27% (T40 with plastics) and 45% (T60 without plastics) of the DLI, while the strawberry zones transmit between 36% (T40 with plastics) and 53% (T60 without plastics) of the DLI. Transmission is also reduced when the screen is deployed to protect crops against extreme temperature or irradiance. The low coverage of the strawberry zone makes it the most luminous agrivoltaic installation tested on strawberries to date, to the authors' knowledge.

4.3 Impact on temperature

We didn't measure any significant air temperature difference between under the agrivoltaic prototypal installation, the plastic umbrella zone, and the uncovered zone. This is attributed to the small size of the agrivoltaic and umbrella zones, where edge effects minimize impact on local air temperature despite different amounts of solar radiations transmitted by the covers.

On the other hand, temperature in the closed multi-span plastic greenhouses was significantly higher than in the other zones by 3°C. In addition, in the plastic greenhouses, an active system of venting and misting was applied whenever the temperature was above 25°C during the harvest season.

In the new commercial-scale installation, measurements performed during summer 2023 showed that the air temperature under the commercial-scale installation remained close to air temperature, while reaching temperatures up to 5-6°C higher under a plastic tunnel (see Figure 24).

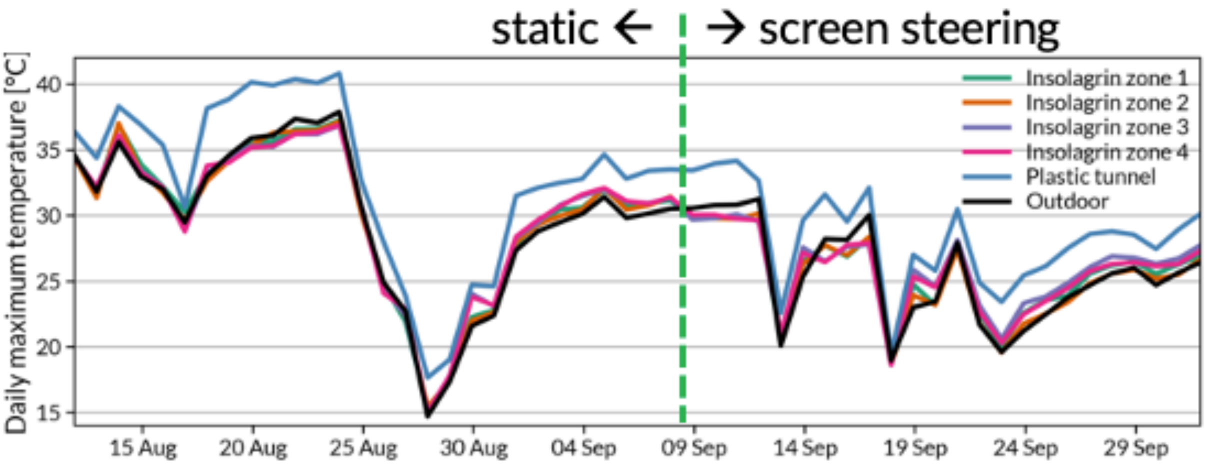


Figure 24: Maximal air temperature recorded during summer 2023 under the 4 raspberry zones of the commercial-scale insolagrin installation, and compared to a plastic tunnel. The shading screen was commissioned on Sept. 9th and was left immobile before that date.

4.4 Agronomic results

Trial	Zone	Total yield (kg/plant)	Fruit size (g/fruit)	Sugar content (°Brix)	Acidity (g/kg)	Firmness (g/mm^2)
Raspberries Vajolet Fall 2021	Agrivoltaic prototype	2.2[a]	5.9	8.7[a]	16.4	19.1[a]
	Plastic umbrella	2.7[a]	6.2	9.0[a]	17.5	19.4[a]
	Plastic greenhouse	2.2[a]	5.3	N/A	N/A	N/A
Raspberries Vajolet Summer 2022	Agrivoltaic prototype	2.2	5.0[a]	9.6[a]	18.0[a]	24.5[ab]
	Plastic umbrella	3.1	5.6	10.6	17.7[a]	26.4[b]
	Plastic greenhouse	1.9	5.1[a]	9.6[a]	16.0	24.2[a]
Raspberries Glen-Ample Fall 2022	Agrivoltaic prototype	1.3[a]	5.8[a]	9.0	19.2[a]	23.1[a]
	Plastic umbrella	1.5[a]	6.1[a]	9.5	19.3[a]	22.6[a]
Strawberries Karima Summer 2022	Agrivoltaic prototype	0.6	14.2	6.4	6.8[a]	73.0[a]
	Plastic umbrella	1.2	15.4	7.0	7.6[a]	73.5[a]
Raspberries Clarita Summer 2023	Agrivoltaic prototype	1.9[a]	5.2	8.3*	16.2*	44.3*
	Plastic greenhouse	1.9[a]	4.1[a]	9.8*	16.3*	36.4*
	Uncovered	1.7[a]	4.1[a]	9.7*	15.6*	33.7*
Raspberries Kwanza Summer 2023	Agrivoltaic prototype	1.8	4.7	9.0*	17.7*	44.4*
	Plastic greenhouse	2.2	3.8[a]	9.8*	18.0*	38.9*
	Uncovered	1.6	4.0[a]	9.8*	16.5*	35.4*
Raspberries Paris Summer 2024	Agrivoltaic EW-T60	0.28**	4,1**	***	***	***
	Agrivoltaic EW-T40	0.20**	4.1**	***	***	***
	Agrivoltaic WW-T60	0.19**	4.0**	***	***	***
	Agrivoltaic WW-T40	0.22**	4.0**	***	***	***
Strawberries Joly Summer 2024	Agrivoltaic T60 + plast.	0.16[a]	10.5	6.7	9.9	58.8
	Agrivoltaic T40 + plast.	0.14[a]	12.2[a]	6.2	9.9	57.2
	Agrivoltaic T60	0.15[a]	12.7[a]	7.2	10.4	63.2

	Edge line (no cover)	0.15[a]	11.8[a]	7.3	11.1	65.2

Table 4: Summary of agronomic results. Results that have the same superscript letter indicate that the difference between them is not statistically significative. (*) statistical significance could not be determined due to insufficient sampling ; (**) Yield from primocanes. A second harvest will occur in spring 2025 to establish the full potential of the plants. Statistical analysis in progress, will be completed for the final report ; (***) Quality analysis in progress, will be completed for the final report.

4.4.1 *Raspberry agronomic results: discussion*

From the results summarized in Table 4, we draw the following conclusions:

- There are significant differences of yields and fruit sizes between the three reference zones (plastic umbrellas, multi-span plastic greenhouses, and uncovered).
- Yields are in general similar or not statistically different for the raspberries produced under the agrivoltaic system and those cultivated under the multi-span plastic greenhouses (except for one trial - Kwanza 2023 – where the plastic greenhouse had a better yield).
- Fruit sizes are either larger or similar for the raspberries cultivated under the agrivoltaic system in comparison to the plastic greenhouse. This result is important, as harvesting costs are lower for larger fruits (per kg of harvested fruits). The economic returns for the producer can thus potentially be larger, even in the case of a similar or lower commercial yield.
- Yields and fruit sizes were better under the plastic umbrellas than in all the other systems. A probable explanation of the over-performance of this system is linked to its configuration and small size[10].
- Commercial yield and fruit size are in all cases higher under the agrivoltaic system compared to the uncovered reference. In average 12% more fruits were produced per plant under the agrivoltaic system compared to outdoor.
- Quality analyses show in general little (less than 1 °Brix) or no statistically significant difference between the modalities. Exceptions are the Clarita 2023 trial, where the raspberries cultivated under the agrivoltaic system had less sugar than in the other zones. Also, in the Clarita and Kwanza trials, the berries cultivated under the agrivoltaic system had a higher firmness than in the other zones, which is an advantage for conservation.
- The 2024 harvest results on raspberry Paris primocanes are within the expected range for yield and fruit size for a fall harvest on primocanes. This result is promising as it shows that a

[10] The plastic umbrellas feature a very high transparency (70-80%), which is an advantage for photosynthesis when temperatures are low or moderate. However, in large-scale installations, a high transparency also impacts the microclimate and heats the air, which can inhibit photosynthesis or even damage the crops. In the present small-scale experiment, the plastic umbrellas are distributed all around the agrivoltaic zone, and thus especially prone to edge effects, which prevent the modification of air temperature, thus only keeping the positive effect of the high transparency and not its disadvantages. As a conclusion, while the results of the plastic umbrellas are interesting in themselves, we believe that they are not representative of what would be obtained in a larger commercial scale installation. In contrast, the plastic greenhouses are closed on their sides, so their inner microclimate is mostly independent of the experiment size. The agrivoltaic system transparency is in average much lower (30-40%), limiting increases of air temperature independently of the system size.

commercial production is possible under the agrivoltaic installation. Difference of yield between the zones indicate that light availability may have been a limiting factor, but statistical analysis still needs to be performed to establish if the differences are significative. The 2025 spring harvest on the same canes will provide the full potential of the plant production. In addition, new long cane plants will be planted in the agrivoltaic and control zone (plastic umbrellas) in 2025 to provide a quantitative comparison with a conventional production zone.

4.4.2 *Strawberry agronomic results: discussion*

As seen in Table 4, agronomic results from the Karima trial in 2022 show a significantly lower yield, fruit size and sugar content under the agrivoltaic system compared to the plastic umbrellas. We believe that the conclusions that can be drawn from this single result are limited, for the two following reasons: (1) because of the edge effects favourably impacting the reference plastic umbrellas, as discussed for the raspberries[10] ; (2) the setting of the pots under the agrivoltaic cover in this trial was sub-optimal, as the leaves were directly shaded by the rain collection gutters for a large part of the season, without benefitting from the light regulation by the THEIA panels (Figure 23). The results confirm that strawberries are particularly sensitive to light conditions and availability. Nevertheless, we can infer from this experiment that the prototypal system is not well adapted for the cultivation of strawberries, and that it is important to design a specific agrivoltaic system for each kind of crop.

The 2024 trial on Joly strawberries under the commercial-scale installation brings mitigated results. The overall yield and fruit weight are lower than what can normally be expected for such a production (typically 400g/plant, 4g/fruit). A strong powdery mildew pressure was also observed, impacting commercial yields. The lower yields and fruit size can be due to the following factors, or a combination thereof: lower light availability, late plantation date, powdery mildew pressure, high humidity of the site (near the canal), especially in 2024. As no significant difference was observed between the modalities with different light availabilities, even with the uncovered control line at the edge of installation, it can be inferred that the light availability was not a limiting factor this year. The comparison against the control zone (plastic umbrellas) in 2025 will allow to derive a quantitative conclusion and separate the effects that are due to the agrivoltaic installation to those that are site-specific.

4.5 Photovoltaic energy production

4.5.1 *PV production – prototypal system*

Figure 25 and Figure 26 shows the daily electrical power output per unit of active module area of mono-facial, respectively bi-facial modules since their installation, and compare it with their simulation.
The agreement between actual output and simulation is generally good when modules are in maximum electricity production mode (E-mode), so generally around winter. When the modules are in maximum light transmission mode (MLT-mode), the simulation underestimates the energy production, especially for bi-facial modules. The main reasons are due to the light scattering effect mentioned in section 3.4 and to the contribution of bi-faciality.

During winter, the electrical production of mono-facial modules was slightly lower than simulated, and this discrepancy is attributed to condensation and frost on the panels during early morning (see Figure 27), and in some cases to snow cover. Overall, the PV production of mono-facial modules was ~7% higher and bi-facial 20% higher than the simulated outcome.

As can be seen, IBC bi-facial cells provide a significant boost (+13.6 %) compared to the mono-facial PERC cells.

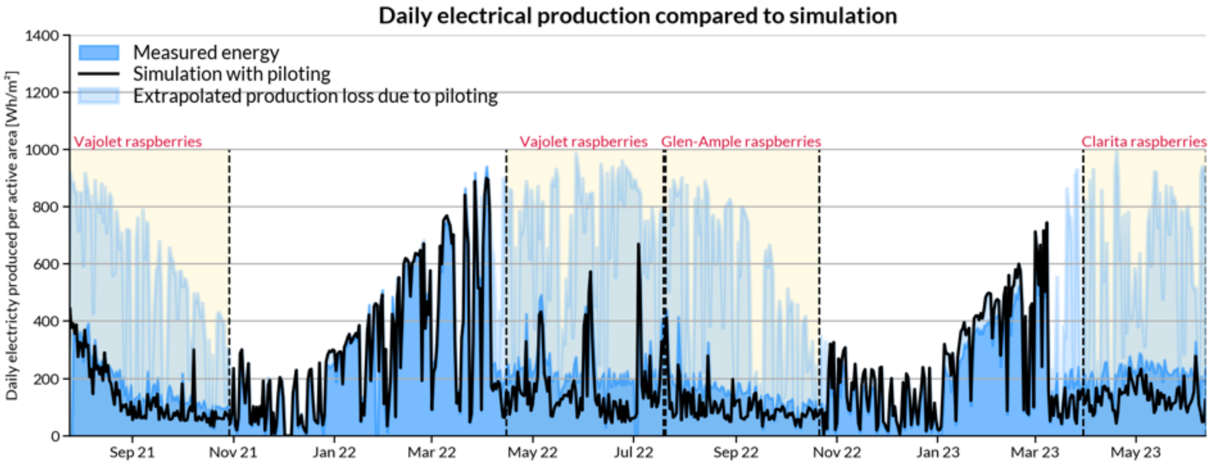


Figure 25: Daily electrical production of the pilot with mono-facial modules (energy generated per unit of active area), from installation to end of June 2023. The black line is the simulated output based on irradiance data measured on-site. During the agronomical trials, represented by the yellow areas the panels were piloted to meet the agricultural targets of light needs. Light blue area represents the electricity production sacrificed to meet the crop light needs.

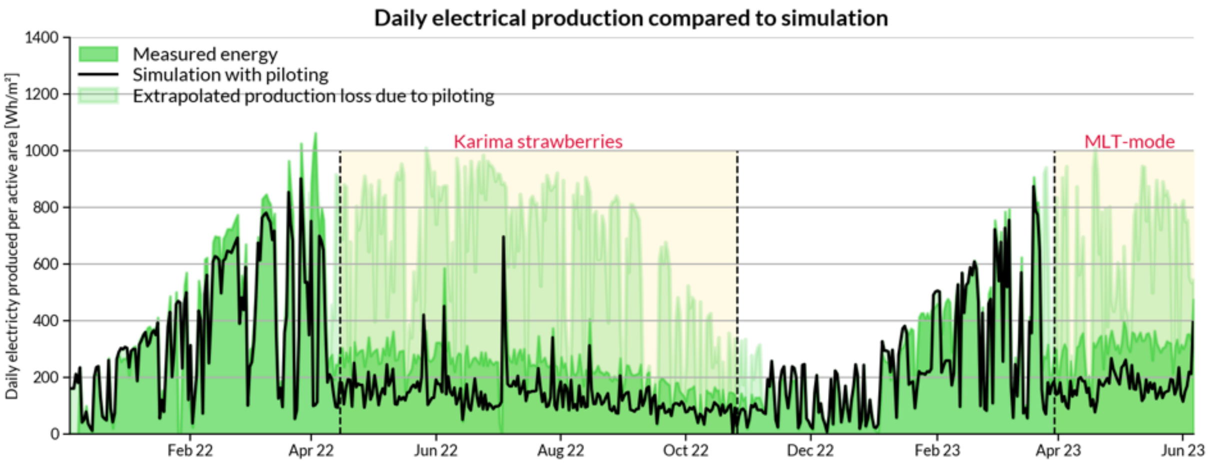


Figure 26. Daily electrical production of the pilot with bi-facial modules (energy generated per unit of active area), from installation to end of June 2023. The black line is the simulated output based on irradiance data measured on-site. During the agronomical trials, represented by the yellow areas the panels were piloted to meet the agricultural targets of light needs. Light green area represents the electricity production sacrificed to meet the crop light needs.

Figure 27: Example of frost on the panels in early morning. Frost and condensation act as absorbers and diffusers, thus lowering the amount of light reaching the solar cells.

As we have full data on the year 2022, we will compare the energy production during this year with the KPIs. As the modules made with IBC bifacial cells provide a significant improvement, we extrapolate the result for an installation made of these modules. Based on the good agreement between actual PV energy production and simulations, especially when modules are in E-mode, we use the simulation toolbox to extrapolate the production of an installation for three different scenarios.

- Scenario 1: actual piloting of 2022 (with two agronomic trials from mid-April to mid-November – can represent the production schedule of some producers)
- Scenario 2: 1 agricultural cycle of 3 months (realistic scenario for many raspberry producers of summer raspberries).
- Scenario 3: No agricultural cycle, full E-mode (limit case).

Figure 28 shows the cumulated energy output per unit of active area for the bi-facial installation, for the different scenarios mentioned above.

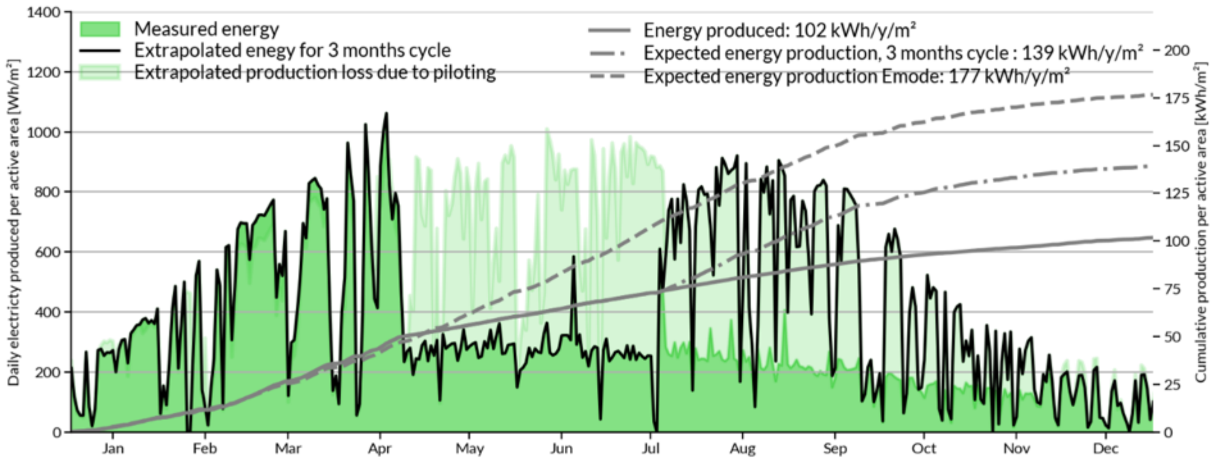


Figure 28: Daily and cumulated production per unit of active module area of bi-facial installation for the different scenarios in 2022. Full grey line is the measured cumulated energy (actual piloting of 2022 with two agronomic trials), the dash-dot line is the extrapolated cumulated energy for only 1 agronomical cycle of 3 months (realistic) and the dash line is the extrapolated cumulated energy if no agronomical cycle, so modules would be in full E-mode (limit case).

Results and corresponding specific yield are summarized in Table 5.

	Yearly production per module active area	Specific yield
Scenario 1: actual piloting (2 agronomic trials in 2022)	102.0 kWh/m^2	534.1 kWh/kWp/yr
Scenario 2: 1 agronomical cycle of 3 months. (extrapolated)	139.3 kWh/m^2	729.4 kWh/kWp/yr
Scenario 3: Full E-mode (extrapolated)	176.6 kWh/m^2	924.8 kWh/kWp/yr

Table 5: PV production in 2022 and extrapolations for other scenarios.

The annual production of this prototypal system would therefore stand between 534 kWh/kWp and 729 kWh/kWp, depending on if 1 or 2 agricultural production cycles are performed.

With an installation density (for this prototype) of 109 Wp/m2 of ground area, the yearly production per ground area is thus up to 79 kWh/m2, or 790 MWh/ha.

4.5.1 *PV production – new Insolagrin (THEIA GEN2)*

The PV production of the new Insolagrin solution is assessed using the 16kWp installation of new generation that was connected to the grid in Fall 2022. The large 265kWp installation will only be connected to the grid in spring 2025 due to additional grid connection work. Figure 29 shows the monthly AC production of the 16kWp installation of new generation for two full years, compared to its expected production simulated for a typical meteorological year (TMY). A specific yield of 1181 kWh/kWp/year is measured. Lower production in the winter months is in part due to the snow cover.

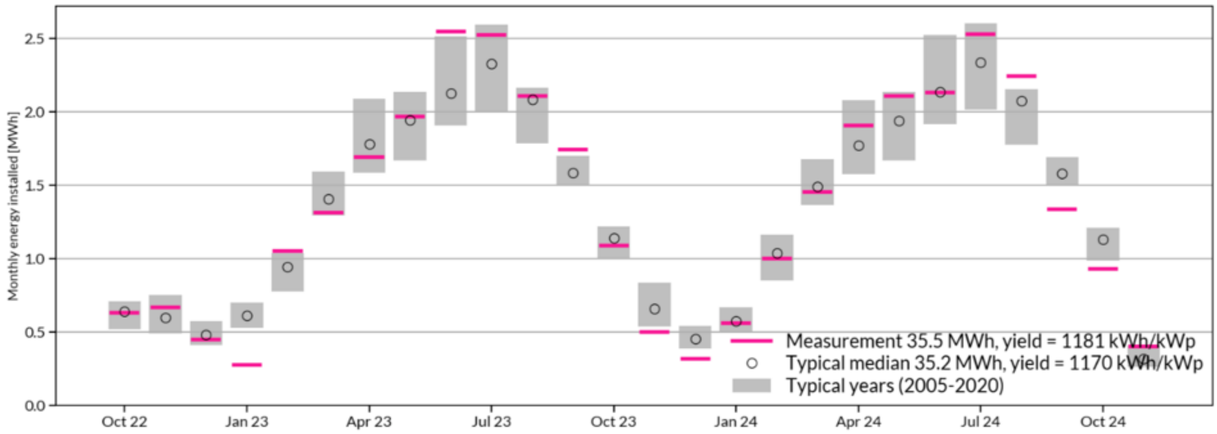


Figure 29: Monthly PV production (AC) of the new generation demonstrator (16kWp installed, of which 14.4kWp were stringed for grid injection) from Oct. 2022 to Oct. 2024.

5. Discussion: overall economic performance

5.1 Agricultural returns

As detailed in Section 4.4, commercial agricultural yields under the prototypal dynamic agrivoltaic system were in general similar to those obtained under a multi-span plastic greenhouse, lower than those obtained under plastic umbrellas (result that we ascribe to an artefact due to the small size of the experiment), and better (+12%) than those obtained in an uncovered reference zone. Fruit sizes were also in several cases larger under the agrivoltaic system compared to the other zones, which will advantageously impact harvesting costs and margins. Agricultural returns will be calculated for the various cases and presented in the final report of this project.

5.2 Electrical returns

It was shown in Section 4.5 that electrical production with the prototypal system during a year like 2022 would be in the range of 139 kWh/m^2 of module area, 730 kWh/kWp or 790 MWh/ha. It is about 25% lower than what was planned at the project beginning for this prototypal technology. Good agreement with predictions of the simulation tools developed during the project enable us to attribute this difference of to (1) optical losses within the lens plate, especially at high angle of incidence, and (2) larger-than-originally expected fraction of diffuse light, on which the lens array doesn't have a steering power. In addition to that, several challenges linked to the reliability and industrialization of the THEIA prototypes with integrated micro-tracking technology made us review our predictions of production costs (not detailed in this report), bringing the Levelized Cost of Electricity (LCOE) to ~0.4CHF/kWh for a production capacity of 100 MWp/yr. THEIA modules such as those tested in this prototypal installation are thus non-competitive for the agrivoltaic market, even when bringing benefits to the agricultural production. These challenges in terms of industrialization and competitiveness have led insolight to develop a new generation dynamic agrivoltaic solution, retaining its important features but leveraging on qualified components from the PV and agricultural industry. Higher specific yield (~1200 kWh/kWp/yr in Conthey for scenario 2) and lower production costs (<1.5 CHF/kWp installed) make the new generation solution competitive (LCOE < 0.1 CHF/kWh) for its market entry.

5.3 Overall economic viability

A complete calculation of combined economical returns (agricultural + electrical) is still a work in progress and will be presented in the final report, taking into account agricultural operation costs (depending on fruit size). The agrivoltaic cover will also enable the producer to save on plastic covers and their periodic replacement (~10’000 CHF/ha/yr).

6. Conclusions and perspectives

The completion of this 4-year project provides a first reference for agrivoltaics on berry crops. A functional 18kWp dynamic agrivoltaic installation featuring the THEIA prototypal modules has been built and shows that it can protect crops while producing solar energy.

The agronomic results gathered on long-cane raspberries show varied results in terms of marketable yield and fruit size, depending on season, variety, applied shading, and to which reference zone they are compared to. These results enable us to identify the shading strategy and variety for which the agrivoltaic system maintains crop yield in comparison to a conventional production tool. Crop yields are generally similar or lower compared to plastic tunnels, and better compared to uncovered references. In several cases, fruit size was larger under the agrivoltaic system, positively impacting overall agricultural returns. Fruit quality is in general not impacted by the modality. A trial on “Karima” everbearing strawberries showed that this prototypal system is not well adapted for the cultivation of this species.

In 2022, the bi-facial modules have produced 102 kWh/m^2/year, including production losses induced by the piloting over two back-to-back agronomic trials. The electrical production is in good agreement with simulations of the prototypal system performance.

The Innosuisse ATLAS project supported the development of a new generation Insolagrin based on the learnings and results presented in the current report. The new generation solution combines the main features of the prototypal THEIA modules: a dynamic control of light transmission with a static protection of the crops but leverages on qualified components from the PV and agricultural industry. The new solution also circumvents some of the limitations of THEIA prototypes by providing more light to the crops, especially in diffuse light conditions, with the perspective of improving agronomic performance compared to the prototypal system.

An agronomic trial was performed in 2024 in a 265kWp commercial-scale installation of the new generation, comparing 4 different agrivoltaic modalities dedicated to the production of raspberries, and 2 modalities dedicated to the production of strawberries. The size of the new installation also provides the opportunity of assessing the micro-climatic impact with negligeable edge effects, with the perspective of fully benefitting from temperature management strategies. The construction of a reference zone (4 rows of plastic umbrellas) next to the installation is in progress (Figure 30) and will enable a full-scale agronomic comparison with a conventional production system in 2025.

Figure 30: construction in progress (status as of Nov. 6th 2024) of the control zone next to the commercial-scale agrivoltaic installation in Conthey.

7. National and international cooperation

Leveraging on the infrastructure funded by the project, Agroscope and Insolight have applied and obtained, in collaboration with CSEM (Neuchâtel), an Innosuisse funding (ATLAS project - 55307.1 IP-EE) for 2021-2024. Its tasks are meant to complement the present project objectives:

- Metrology tools for PV efficiency and light transmission
- Development of the new generation Insolagrin solution
- Advanced agronomic measurements and analyses, for a finer understanding of the effect of light management strategies on crop growth and development:
    - Photosynthesis measurements
    - Leaf temperature sensors
    - Sap flow monitoring
    - Plant morphology
    - Leaf element composition

8. Publications

<u>Scientific and technical publications, contributions to conferences:</u>

- Oral presentation: “PV Modules with Dynamic Control of Transmitted Light for Agri-photovoltaics” – *Intersolar 2021, Münich, 07.10.2021*
- Invited oral presentation: “Une solution suisse pour l’agrivoltaïque dynamique” – *4. Nationale Gewächshaustagung, online, 23.10.2021*
- Invited oral presentation: “Une solution au service des cultures” – *Conférence INES Agrivoltaïsme, Gréoux-les-Bains, 30.11.2021*
- Oral presentation: “Agrivoltaïsme en Suisse ? Potentiel et solution insolagrin” – *PV Tagung 2022, Bern, 30.03.2022*

- Invited oral presentation: “insolagrin: a semi-transparent solution for dynamic agrivoltaics” – *1st International Integrated-PV Workshop, online, 7-8.04.2022*
- Oral presentation: “insolagrin : a Solution for Dynamic Agrivoltaics” – *Agrivoltaics 2022, Piacenza, 15-17.06.2022*
- Oral presentation: “Agrivoltaics in Switzerland? – Potential and insolagrin solution”, ZHAW Fachtagung Agro-photovoltaik: Agro-Photovoltaik in der Schweizer Landwirtschaft, Wädenswil, 14.07.2022
- Oral presentation: “Dynamic agrivoltaics with berry crops” – *31st International Horticultural Congress, Angers, 14-20.08.2022*
- Oral presentation: “First results from insolagrin, a novel solution for dynamic agrivoltaics” – *8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Milano, 26-30.09.2022*
- A public event on agrivoltaics has been organized by Agroscope in Martigny and Conthey on 4.11.2022, with the attendance of 70 participants from Switzerland and European countries.
- Invited oral presentation: “insolagrin: a semi-transparent solution for dynamic agrivoltaics” – *2nd International Integrated-PV Workshop, online, 28.03.2023*
- Oral presentation: “Dynamic agrivoltaics with raspberry crops: field trial results” – *Agrivoltaics 2023, Korea, 12-14.04.2023*
- Oral presentation: “Field results and simulation of a new generation dynamic agrivoltaic solution” – *40th European Photovoltaic Solar Energy Conference and Exhibition (EU-PVSEC), 18-22 Sept 2023, Lisbon*
- Oral presentation: “Heat stress and frost mitigation in a commercial-scale dynamic agrivoltaic system” -- 5th World Conference on Agrivoltaics (Agrivoltaics 2024), Denver, USA, June 13th, 2024.
- Invited oral presentation: “Mitigation of heat stress and frost in agrivoltaic installations”, INNOVATION, EXPERIMENTATION AND SUSTAINABILITY FOR AGRIVOLTAIC SYSTEMS DESIGN, Naples, Italy, October 21st, 2024
- Invited oral presentation: “Developing APV-Projects for Vegetal Agriculture: Key Learnings” -- 3rd Agrivoltaics Europe -- Vienna, Austria, November 5th-7th, 2024.