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Electricity generation and quality food production over the same land area





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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Zusammenfassung

Das Projekt beschreibt ein Solar-Sharing-Konzept, bei dem transparente, farbige Sonnenkollektoren zur Stromerzeugung verwendet werden und das Restlicht die Landwirtschaft unterstützt.

Das Konzept würde eine erneuerbare Stromversorgung in Gewächshäusern ermöglichen, die in Verbindung mit laufenden Projekten zur Reduzierung des Energieverbrauchs zu energieautarken Gewächshäusern führt. Der Start erfolgt zu einem Zeitpunkt, an dem neue internationale Gesetze zur Wärmedämmung und zum Kraftstoffverbrauch eingeführt werden, um den Energieverbrauch und die Kohlendioxidemissionen in gewerblichen Gewächshäusern zu senken.

Für das Projekt wurden zwei Demonstrationseinheiten in einem Gewächshaus installiert, ein mit DSC Modulen bedeckt und eine mit Glass bedeckten Referenzeinheit. Über einem Jahr wurde das Wachstum von Tomatenpflanzen verfolgt. Auf Grund der erhaltenen Ergebnisse wurde anschliessend der Farbstoff in den DSC Modulen und deren Transparenz optimiert.

Résumé

Le projet décrit un concept de partage solaire dans lequel des capteurs solaires transparents et colorés sont utilisés pour produire de l'électricité et la lumière résiduelle soutient l'agriculture.

Le concept permettrait un approvisionnement en énergie renouvelable dans les serres, ce qui, dans le cadre des projets en cours pour réduire la consommation d'énergie, conduit à des serres autosuffisantes. Cela commence à un moment où de nouvelles lois internationales sur l'isolation et la consommation de carburant sont introduites pour réduire la consommation d'énergie et les émissions de dioxyde de carbone dans les serres commerciales.

Pour le projet, deux unités de démonstration ont été installées dans une serre, une couverte de modules DSC et une unité de référence recouverte de verre. La croissance des plants de tomates a été étudiée durant plus d'une année. Sur la base des résultats obtenus, le colorant dans les modules DSC et leur transparence ont ensuite été optimisés.

Summary

The project describes a solar sharing concept in which transparent, coloured solar collectors are used to generate electricity and the residual light supports agriculture.

The concept would enable a renewable power supply in greenhouses, which in connection with ongoing projects to reduce energy consumption will lead to self-sufficient greenhouses. It starts at a time when new international laws on insulation and fuel consumption are being introduced to reduce energy consumption and carbon dioxide emissions in commercial greenhouses.

For the project, two demonstration units were installed in a greenhouse, one covered with DSC modules and one reference unit covered with glass. The growth of tomato plants has been tracked for over a year. Based on the results obtained, the dye in the DSC modules and their transparency were then optimized.



Main findings

The main findings of the project are:

- The red C101 DYE used for the coloration of the modules is not suitable for tomatoes due to the high blue light absorbance.
- The DSC modules installed on the inside of the greenhouse provides cost advantages as it remove the need of a safety glass but has the negative effect of high irradiation losses which impacts plants growth and energy production.
- The JD25 DYE with suitable absorption spectra and high blue transmission was specifically developed for the purpose of the project.
- A better DSC module design with a higher transmission due to a thinner TiO_2 layer and optimized electrolyte was designed.



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Abbreviations

Greenhouse (GH): for the purpose of this document the term greenhouse refers to any glass or plastic structure used for the cultivation of plants.

Photovoltaic cell (PV): a device with electrical characteristics that vary on exposure to light.

Dye sensitised solar cell (DSC): a transparent photovoltaic cell using coloured chemicals to absorb light for downstream generation of electricity.

Crystalline solar cell (CSC): A non-transparent photovoltaic cell which semiconducting material is made of crystalline silicon.

Solar Sharing greenhouse (SG): a commercial product that combines DSCs with traditional greenhouses for the cultivation of crops under glass and the production of electricity.

Demonstrator Solar Sharing greenhouse (demo-SG): state-of-the-art test centre funded by this project to allow the validation of the compatibility of DSCs and cultivation under glass.

Good Laboratory Practice (GLP): principles providing a framework for laboratory studies by which planned, performed, monitored, recorded, reported and archived to facilitate market requirements, such as CE marking.



1 Introduction

1.1 Background information and current situation

Land is a valuable resource. Currently, agricultural land accounts for about 38% of the dry land mass of the planet [1]; a figure that has remained static for several years because it is the maximum available area for this practice. Other sites are either uneconomical to farm or serve as important ecological resources and should be preserved. An increased food supply, therefore, demands higher production from existing sites, which generally requires, for example, increased direct energy, temperature regulation, irrigation and artificial lighting and indirectly nitrogen fixation technology and increased chemical treatments, including pest control due to high plant density. Yet, energy is also an increasingly strained resource. While energy demands for industrial, social and economic activities are increasing, several important economies, including that of Switzerland, plan to close nuclear power stations which will affect the current energy supply. Accordingly, renewable energy has become the focus of an expanding research effort and certain renewable energy systems compete with the same land pool as food production. An obvious competitor is the production of biofuel crops, but there is also pressure from other systems: "solar farm" is the term used for photovoltaic (PV) power stations that occupy large areas of land exclusively for energy generation. While energy and food have to remain a priority, not many solutions to achieve both on the same land exist today.

PVs are used to provide renewable energy on two scales: large plants feeding into the grid and small-scale installations, down to a single panel, to provide energy for the end-user. At the utility level, PV power stations are often sited in deserts or isolated areas. Increasingly, homeowners are investing in crystalline solar cells (CSCs) PVs positioned on roofs to provide local or end-user energy. The dark colour of CSCs camouflages their presence. For some homes, this investment can meet a significant part of the user's electricity needs. Improved energy efficiency and more devices containing independent CSCs can further narrow the gap between energy supply and demand in the domestic setting, progressing toward energy autonomy. These products are just one of several new technologies contributing towards a decentralised power supply.

In agricultural settings, the roof space available for CSCs is disproportionately small compared to energy demands. Still, farmers have invested in the technology using their house and barn roofs. Wider scale use is limited by the land required to site CSCs and the environmental consequence of glare and thermal flux that results from the high reflectivity of this technology.

Solar Sharing is a concept where agriculture land can be used for the simultaneous generation of electricity without detrimental effects on crop yields. This concept would expand the areas where PVs can be positioned, allowing progress in energy balance and towards autonomy. Several technologies have been proposed previously such as CSCs placed alternately over the roof space of greenhouses as shown in Figure 1 left and centre. In this example, heterogeneities in the intensity of the light within the greenhouse result in different growth rates for the plants and limiting application to shade-tolerant species. Plants initiate shade-avoidance strategies due to the relative intensities of specific colours of light, resulting in tall, weak growth. Alternative strategies involve placing high-tech dielectric film formed in concave dips across the greenhouse roof. The film reflects certain colours of light back to CSCs circling the perimeter of the dip, allowing other colours to pass through to the plants. Whilst the approach proves the Solar Sharing concept, the glass filter is composed of seven layers and the roof design must be altered resulting in logistical problems such as cleaning difficulties and the collection of water pools on the roof. In several areas, including Minamisoma, Japan [2], the compatibility of CSCs positioned over agricultural land has been tested (Figure 1 right). Minamisoma is contaminated by fallout from the



Fukushima Daiichi nuclear plant and illustrates the commitment of the community to invest in renewable energy. But routine cleaning of the CSCs, coupled to the difficulty of farming land punctuated with the legs supporting them mean wide scale applications are unlikely.



Figure 1: Various technologies incorporating photovoltaic systems into agricultural settings.

Left: CSC on a greenhouse roof in Hawaii (personal correspondence). Centre: an alternative approach where CSC are used to partially cover the greenhouse roof [3]; Right: Solar Sharing with CSC positioned over crops in a field [4]

The concept proposed herein exploits the dye-sensitised solar cell (DSC) technology that has recently been industrialized in Switzerland and to further develop the technology for its use in Solar Sharing greenhouses (SGs). Unlike the more familiar CSCs, the DSCs are transparent and can therefore replace glass. They may be positioned on roofs to filter light in SGs, sharing sunshine between electricity generation and agriculture. As the DSCs absorb light at all angles, they can also be positioned vertically forming the greenhouse walls without a significant loss of efficiency. DSCs are better suited with plant growth than CSCs as they do not produce inhomogeneity in light distribution within the greenhouses and can be optimised to provide plants with their light requirements while still generating electricity. They also offer the potential to use selective filtering of light within a certain wavelength range to modulate the plants and to improve growth, yield and/or quality. The light filtering effect can also be used for the temperature regulation in the greenhouse, which, combined with other technologies, could allow off-the-grid, autonomous and carbon-neutral food production.

1.2 Purpose of the project

The Solar Sharing project aims at commissioning and validating state-of-the-art greenhouse technology for demonstrating the compatibility between dye sensitized solar cells (DSC) and agriculture. DSCs filter light to generate electricity while the residual light is available to support plant growth. Briefly, the aim of the Solar Sharing project is to reduce the carbon footprint of farming by integrating energy-saving technologies into greenhouses. The main focus is the application of DSCs to greenhouses supporting the cultivation of crops that have been demonstrated as incompatible with other solar capture technologies, using tomato as a first crop.

The demonstration is made through a matched enclosure pair to be sited at Etablissement Horticole, Ville de Lausanne to allow complete scientific testing of the concept and optimisation of conditions for specific crop cultivation and electricity generation. Decommissioning of the DSCs is relatively straightforward and low cost, involving recovery of the DSCs and monitoring equipment, which would restore the greenhouses to their original state. The DSCs can be reused or fully recycled as needs require.



The demonstrator project builds on the output from a previous pilot project (Figure 2). The pilot study has tested the compatibility of standard DSCs with the tomato, *Solanum Lycopersicum*, and strawberry, *Fragaria x ananassa*. Tomato was selected as first model as it is widely grown across Switzerland under glass and is a crop of high importance. Globally, it is considered as the primary vegetable and accounts for 14% of world vegetable production (over 100 million metric tons/year \$ 1.6 billion market [5]). It is also genetically characterised with good understandings of its stress responses, including its shade avoidance response. The interactions of this plant with light have been previously characterised and some molecular details mapped. In addition to providing micronutrients, the tomato is also considered as a functional food, offering protection against cardiovascular disease and certain types of cancer. The protective effect is attributed to antioxidants, such as the vitamins C and E, and carotenoids principally lycopene [6]. These micronutrients are part of the plant's natural "stress response" to the environment, including the quantity and quality of light.

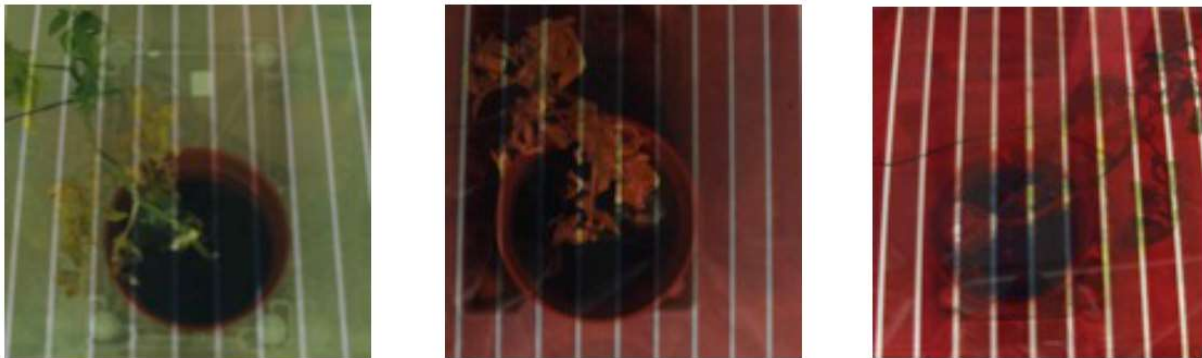


Figure 2: Photographs of some DSC modules used in the pilot study to monitor the growth of tomato plants in a pilot study. Various DSCs were selected for different colours and transparencies and the growth, development, biomass and nutrient content of the harvest were recorded. Left: Green DSC. Centre and Right: Red DSC with different transparencies.

The importance of light to plants factors both colour and intensity: plants measure both absolute and relative values of photon flux at different wavelengths to coordinate their growth and development within the local environment. Whilst a major function of light is to enable photosynthesis to convert this energy to chemical energy stored in the plant biomass, development is also regulated by light colour and intensity. Red and blue light are the major energy for photosynthesis, yet blue light is important in the regulation of flowering and some other photomorphogenic processes. The relative amounts of red and infrared light regulate the shade avoidance response and thereby the ability of the plant to support fruit. With these observations in mind, a pilot test was assembled to allow small scale testing of a series of standard DSCs for compatibility with plant growth, development and fruit yield. The results showed colour and transparency-dependent results with certain shades extending the fruiting season by several weeks.

In addition to the direct effect of light on plant growth, there are indirect effects to consider when growing plants under glass such as thermal effects. The main challenge for tomato growth in Switzerland is cooling, as the ideal growth temperature for most fruits and vegetables is around 18-25°C. Consequently, greenhouses are often shaded to reduce heating and that reduces the transmitted light as well. To make the most use of the light, the DSC system presents advantages as it acts as a light filter while generating electricity. It will favourably filter out infrared and ultraviolet light to stabilise the temperature to regulate plant growth. In addition, it will filter some visible light to generate electricity,



part of which could be employed to power heaters and/or Peltier cooling elements for further thermal regulation of the greenhouse.

The extensive research that has given scientists a clear understanding of how plants interact with their environment has been applied in the selection of DSCs for the pilot system. The electricity produced can either be fed into the grid or stored in batteries to allow autonomous greenhouse units. The system is compatible with the new drive towards hydroponic agricultural methods and filtered light systems. However, and rather than consuming energy to power LED lighting, the SGs filter the sunlight allowing a high quality of plant growth while simultaneously producing electricity. The additional cost of the DSC module integration into the greenhouse should be amortized during the usage period with the return of energy production and from the high-quality plants. The usage period of a green house varies with the construction type from some years for tunnels to 30 - 40 years for conventional green houses.

1.3 Objectives

The goal of this project is to develop an innovative solar sharing concept that allows various types of agricultural land to be used for the simultaneous generation of electricity without detrimental effects on crop yields. The project centers on adapting transparent DSC panels to cover conventional greenhouses and tunnels to increase land use efficiency by enabling the additional functionality of electricity generation on existing greenhouse and tunnel sites.

The objectives of the demonstration project are:

The optimization of module design to reach a red to blue transmission relation similar as sunlight ratio of 1.2 to 1.4. In addition to the red / blue transmission ratio the absolute light transmission of the module should be optimized for a maximum energy production without reducing the plant growth.

To demonstrate high-quality crop growths in a greenhouse covered with DSC modules

To analyse the cost of the DSC installation, including DSC modules laminated on glass substrates, cabling, inverters and mechanical structures and putting them in perspective with the resulting economic benefits coming from the energy production and increased value and yield of vegetables.

2 Description of facility

A newly launched CSCs module prototype (Figure 3) was taken as reference for the module design used in the project. The prototype used luminescent solar concentrators in a horizontal position within a greenhouse.



Figure 3: An image from the Soliculture (<http://www.soliculture.com/>) showing luminescent solar concentrators used in a horizontal application inside an existing greenhouse structure



Further evaluation including presentation to a limited customer panel, project members, and greenhouse manufacturers, identified five main benefits of the module design:

1. The internal application means that safety glass lamination is not required, reducing the cost of the DSCs.
2. The structure is independent of the greenhouse frame facilitating installation, allowing repositioning and preventing complications including invalidation of warranties on existing greenhouses
3. The internal application removes concerns regarding the DSC-installed greenhouses supporting snow.
4. Customers commented that they would be more likely to take the risk of installing a horizontal platform in polytunnels where lower value crops are often grown. A successful application would allow automation of these structures and installation in off-the-grid locations.

It was also noted that the electricity production might be reduced with an internal application due to lower incident light inside the greenhouse. It was however not considered significant enough to prevent the design change. The importance of this aspect and its integration into a full cost-benefit analysis is as well one of the objective of the project.

During the project, two test enclosures were constructed to evaluate the impact of the red C101 DSCs on plant growth as shown in Figure 4. Essentially a purpose-built frame supporting a horizontal platform of DSCs for the test unit and glass for the control. Each enclosure has a surface of 15 m² and is clad with reflective material to homogenize the light within them (Figure 5). The surface area is large enough to obtain statistically significant data and aims at being representative of the centre of an industrial greenhouse environment. The structures allowed the monitoring of plant growth and thermal parameters in the 'extreme' DSC filtered light environment (i.e. without any white light from the sides of the greenhouse).



Figure 4: Stages of greenhouse preparation. Bottom left: the DSC pod before cladding. Right: Both 15 m² greenhouse test enclosure with DSC modules and without DSC modules.

These enclosures have been installed in the greenhouses rented for the project. The units are equipped with state-of-the-art apparatus to monitor the environment and plant growth. These units were used to measure crop yield with time and to correlate it to the weather conditions.



Figure 5: Left: 15 m² control module with a glass roof. Centre: 15 m² module with red DSCs. Right: Young tomato plants growing under DSC filtered light in the module.

Table 1: Equipment of the test and control module

	<i>Test</i>	<i>Control</i>
<i>Glazing</i>	<i>DSC</i>	<i>Standard</i>
<i>Environmental control</i>	X	X
<i>Environmental monitoring in greenhouse</i>	X	X
<i>Cultivation equipment</i>	X	X

3 Procedures and methodology

Ten varieties of tomato have been screened and "moneymaker" was selected as variety for the studies due to its growth characteristics under glass such as form, time to ripening, etc. The variety demonstrated the most consistent growth profile between individual plants allowing differences due to environment to be accurately monitored. In addition, the time to ripening was found to be sufficiently slow to allow differences to be measured. The plants were cultivated in a closed-water system that minimizes irrigation requirements and the risk of pollution, and also has the added bonus, offered by the reservoir tanks, of temperature stabilization in the greenhouse environment. Growing cords were used to support the plants between the base and tip, with the cords being suspended from a frame at the top of the demo-SG. Tomato plants were planted in the controlled enclosures using a novel automated irrigation system. The irrigation system drip-feeds the plants using hydrostatic pressure, creating a zero-energy irrigation that does not waste water (see Figure 6).



Figure 6: Photographs showing the drip feed irrigation system being tested for resource-efficiency, including effects on temperature control. The reservoir structure (left panel) closely resemble the sealed water tanks previously tested at Bourdonette (right panel) and allows for temperature stabilisation and reduce energy use in thermal regulation.

The results of the experiments performed within the 15 m² enclosures in the greenhouse are summarized in chapter 4. Inside the greenhouse we prepared two experimental zones. The column labelled 'Test' depicts the area with DSC panels and the "Control" depicts the normal situation as shown in table 1 above. Tomatoes were grown in both test area and control area to monitor the effect on the plant growth of adding the DSC modules in comparison to the control. The first column of Table 1 presents the important features of the two zones and both enclosures were equipped with an environmental monitoring system.

Tomato plants have been cultivated using similar methods as used in active agricultural greenhouses, with the main difference being that rather than using energy consuming irrigations, hydrostatic pressure is used to deliver the water in a regulated way to prevent over-watering without consuming electricity.

4 Results and discussion

As a first step, the positioning of the plants has been optimised to ensure equivalency of the conditions for each tomato plant within an enclosure. The main characteristic used to characterize the tomato growth was the average number of leaves which was estimated for the plants grown in the two different enclosures from a total of 24 plants. The values are shown in the bottom left of Figure 7 which shows that there is no significant difference in the growth characteristic of the tomatoes related to its position in the enclosure (side or centre area). This was an important step to ensure that the measured differences between the growth characteristics in both enclosure reflect the effect of the DSC-modules on the light arriving to the plant.

As a second step it was found that the plants growing under the red DSCs were taller and had a narrower leaf footprint as can be observed by comparing the two top left images in Figure 7. These features are typical of shade avoidance growth and show that the impact of the light filtering on the growth of tomatoes was non-negligible. Although this type of growth results in a reduction of fruit yield, ripening of the tomato fruits was still possible under the red DSCs, as shown in the top right image of Figure 7. The comparison of the average number of leaves reported in the bottom of Figure 6 reveals that fewer leaves are present on the plants grown under the red DSC-filtered light.

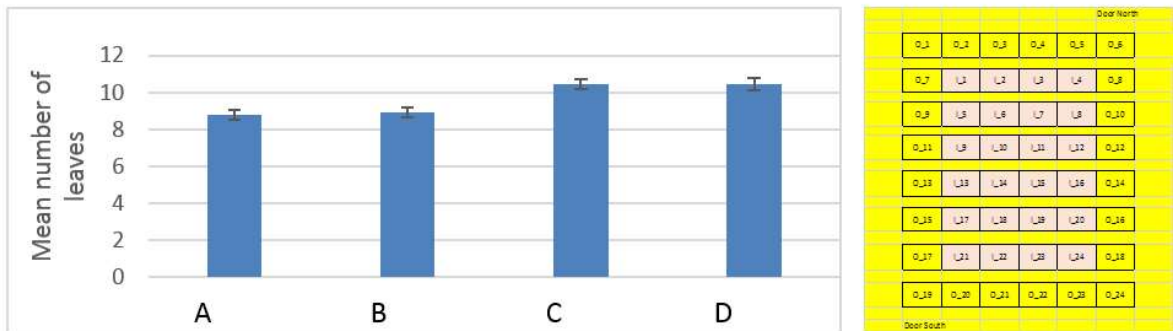


Figure 7: (Top) Photographs showing a typical example of a Money-maker tomato plant growing under red DSCs (left) and in the control module (centre). Photograph of tomatoes ripening under the red DSC-filtered light (right). (Bottom) Graphs showing the average number of leaves after 14 days (left). The columns show the mean number of leaves for 24 plants grown in (A) under red-DSCs and planted in the centre of the module; (B) under red DSCs at the edge of the module (i.e. next to the reflective coating); (C) under clear glass at the centre of the control module and (D) at the edge of the control module. The chart (right) shows the layout of the plants inside the module, indicating those in the centre and those at the edge.

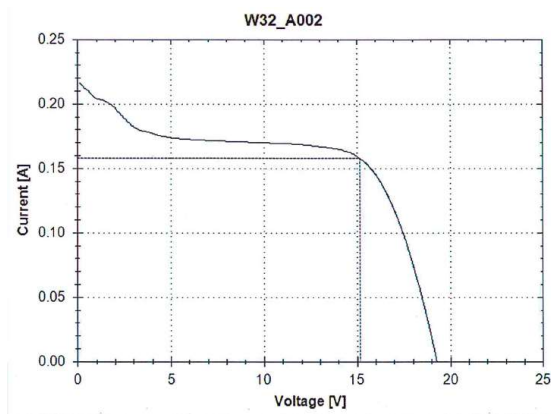
It should be noted that these results were made during winter, with full coverage of DSCs on the roof and with no stray light from sides. It thus represents the most unfavourable situation for the plant growth and the specific enclosure design allowed minimising the effects of the edges by providing an homogeneous environment for testing purpose inside.

As the first results showed that the environment in the enclosure equipped with the red DSC roof triggers a shade avoidance response in the tomato plants, an important effort was made to optimize the DSC modules to better match the optical demands of the plants and improve the quality of the growth while maintaining strong photovoltaic performances. First, LPI-EPFL developed to this end a new dye labeled JD25, which is shown on the left of Figure 8, and whose absorption spectrum is better adapted than that of the standard C101 red dye. LPI scaled up the synthesis process from milligrams to grams level and produced 10 grams for H.Glass module production line.

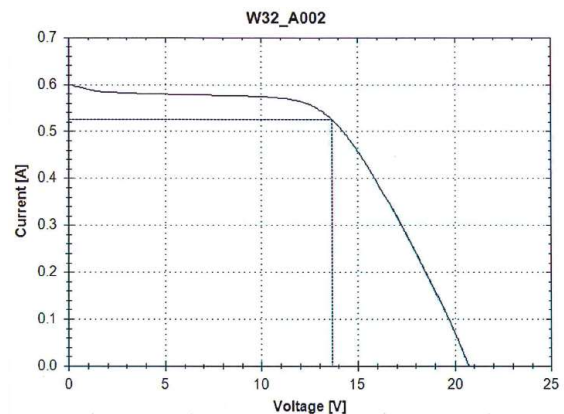


Figure 8: (Left) Structure of the salmon-coloured JD-25 dye developed by LPI_EPFL, JD-25 that has been designed and fabricated for application in the solar sharing project. (centre) Photograph of a DSC panel incorporating the new dye without electrolyte. (right) DSC panel with JD 25 DYE and Livion 14 electrolyte

In 2018 H.Glass manufactured a first batch with JD-25 DYE and Livion 14 electrolyte. The TiO₂ layer was 2.5 microns to increase the overall light transmission. The resulting aspect after coloration, but without electrolyte, of the module is salmon-like as shown in the center of Figure 8 and the right figure shows the modules after Livion 14 electrolyte filling. The average power of the modules was 7.6 watts or 1.26 % efficiency. Figure 9 shows the IV curve at 300 W/sqm and 1000 W/sqm irradiation measured with a class A LED sun simulator.



Irradiance: 300 W/sqm
 FF: 57.31 % - Vmp 15.2 V - Voc 19.28 V
 Pmax 2.4 W – Imp 0.157 A – Isc 0.164 A



Irradiance: 1000 W/sqm
 FF: 58.19 % - Vmp 13.6 V - Voc 20.7 V
 Pmax 7.2 W – Imp 0.524 A – Isc 0.594 A

Figure 9: IV curve at 300 and 1000 W/sqm irradiation for the module with JD 25 DYE, Livion 14 electrolyte and a TiO₂ thickness of 2.5 μm

As the absolute transmission of the module was low in particular in the blue range where the Livion 14 electrolyte absorbs, the electrolyte was diluted. The resulting transmission spectra are shown in figure 10.

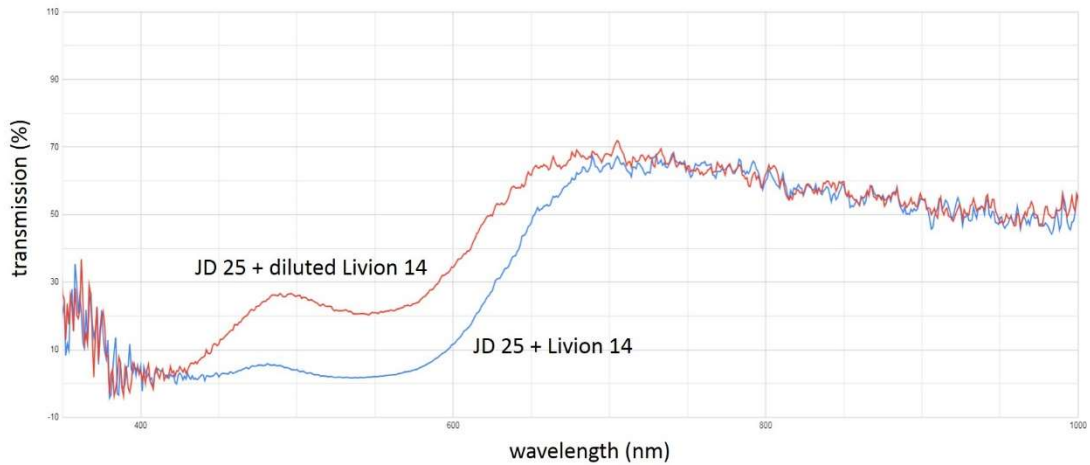


Figure 10: Transmission of modules with (blue) JD 25 Livion 14 electrolyte and (red) JD25 diluted Livion 14

For the second production batch the production line was already dismantled and nonfunctional modules with diluted Livion 14 were produced. No IV curves were carried out. As the absolute transmission of the modules with diluted electrolyte is higher, the expected final efficiency of the modules should be less than 1.26 %.

The transmission spectra of the two types of module laminated on the support glass are shown in Figure 11 in arbitrary units. The left of Figure 11 presents the transmission of the module colored with C101 DYE while the transmission of the optimized module with thinner TiO₂ layer and DYE JD25 and diluted Livion 14 electrolyte is shown on the right. By comparing the two spectra it can be observed that the optimized module presents a better ratio blue to red light, which should favor the plant growth.

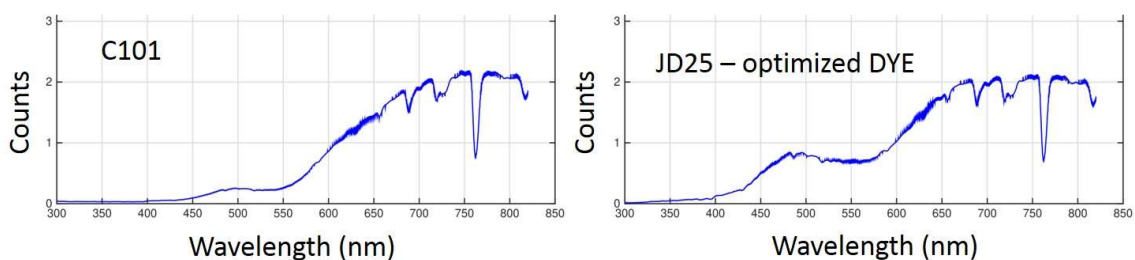


Figure 11: Transmission spectra in the blue wavelength range of modules with DYE C101 and electrolyte (left) and, optimized module with 'new' DYE JD25 and Livion 14 diluted electrolyte (right).

Another outcome of the project is related to the position of the module within the greenhouse. It was estimated that around 20% of light was lost by having the modules placed inside the greenhouse and that such irradiance losses affect too much the plant growth. Thus, and even if this configuration was thought to present advantages such as reduced costs at the beginning of the project we arrived at the conclusion that the panels will be better installed directly on the greenhouse, replacing the cover glasses in future applications.

In order to obtain more useful results and to solve the problematic of reduced light due to the position of the modules inside the greenhouse a subsequent step was planned: to partially install in the structure of a SGs optimized modules made with JD25 dye, diluted Livion 14 electrolyte and thinner TiO_x layer.



By equipping with DSC modules one section of the greenhouse, replacing the original glass and letting the rest untouched, a controlled experiment on a larger scale was planned which would reduce the detrimental effect of reduced light configuration seen in the test enclosures. This valuable step, which aimed at monitoring at the same time to power production with the plant growth, could unfortunately not be performed. The framework conditions, especially the ones related to the market chances of this specific technology has changed during the course of the project and the module manufacturer H.Glass stopped the production of DSC module making this end testing not feasible. The interest for pursuing the project has thus been altered and because of other encountered difficulties during the project such as dye delivery the project was stopped before all experiment were performed. The difficulties encountered have shown that the interest for one or for the other technology in a rash developing new field can swiftly change and that it is important to be present on the right time in the right place and, even more importantly, with the good partners. It was also observed that modifying the modules component to suit to the requirement for high quality plant growth is not trivial and a cost-intensive labour. It thus only make sense when the technology can then be applied widely and is sufficiently proofed to be stable and feasible.

5 Conclusions

Several conclusions can be drawn after a test year within the two enclosures located in the greenhouse with different top cover made either of DSC PV modules or standard glazing. As first observation it was seen that the red C101 DYE used for the coloration of the modules was not suitable for tomatoes due to the high absorbance of blue light. In order to overcome this aspect a new dye, JD25, with suitable absorption spectra and higher blue to red transmission ratio was developed. To further optimise the module for higher quality plant growth, a new DSC module design with a higher transmission due to a thinner TiO₂ layer and optimized electrolyte was designed.

It was then observed that although installing the DSC modules on the inside of the greenhouse provides some cost advantages as no safety glass is required for its production, the resulting high loss in irradiation was considered as highly detrimental both for plant growth and for energy production. The enclosures were specifically designed for experimental testing and the internal cladding material could homogenised sufficiently the light in order for each plant to be exposed to a similar amount of light in order to provide data on the plant growth quality of statistical relevance.

A cost estimate shows that the DSC technology is not yet ready for the application in green houses. A DSC module with an average efficiency of 1.5% produce in Switzerland about 10 - 15 kWh/sqm/year, equivalent to 2 - 3 CHF/year in comparison to the production cost in 2018 of over 150 CHF/sqm.

It was initially planned to go a step further and to demonstrate and test an optimised SGs with optimised modules installed on top of the greenhouse. The goal was to overcome the limitations observed with the initial experiment set-up and to provide a full-scale demonstrator to provide testing possibilities on a real application scale. This final step could however in the end not be performed as, at the end of year 2018, H.Glass decided to discontinue the production of large DSC modules due to low module efficiency and stability problems of the technology.



6 Outlook and next steps

The project showed that the optical properties of DYES can be optimized for plant growth but today the technology is not ready for large scale industrial application. The module costs should be reduced drastically, and the efficiency increased to cover the additional installation costs on greenhouses.

7 National and international cooperation

This project is conducted with direct collaboration with Lausanne City, Etablissement Horticole. Besides Lausanne City, the team established the first collaboration contacts with AgroScope, Monthey.

8 Communication

No communication activities.

9 Publications

C. S. Allardyce, C. Fankhauser, S.M. Zakeeruddin, M. Grätzel, and P.J. Dyson, *The influence of greenhouse-integrated photovoltaics on crop production*, Solar Energy, Volume 155, 2017.

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