HIGH CROP YIELDS AND ENERGY PRODUCTION INSIDE A DOUBLE INFLATED ETFE GREENHOUSE USING VERTICAL BIFACIAL PHOTOVOLTAIC PANELS AND DIFFUSE PLASTIC FILMS

INTRODUCTION.

Photovoltaic solar panels are increasingly being integrated into the agricultural sector, and FILCLAIR was consulted to respond to requests for photovoltaic greenhouses. After feasibility studies, Filclair was unable to meet these demands because the structure of plastic greenhouses is not strong enough to support solar panels on the roof of the greenhouse. Therefore, it was necessary to try to find other solutions to meet this PV greenhouse market. In addition, Filclair wanted to stand out from traditional PV greenhouse offerings by proposing a solution that creates the least amount of shade possible on the crops while still allowing for energy production.

Thus, the starting point for this research was to find a viable alternative to photovoltaic panels on the roofs of agricultural greenhouses. Several ideas were explored: the first to be explored was solar tracking, which allows for greater electricity production than fixed photovoltaic panels. The initial hypothesis was that it would be possible to produce the same amount of electricity in the greenhouse with solar panels on tracking systems as with fixed panels on the roof, thanks to the production boost enabled by tracking, to compensate for the decrease in brightness caused by the plastic covering.

The main difference in the light under plastic greenhouses is that instead of being mostly direct, the light is diffused by the plastic films. Plants are the primary beneficiaries of this diffuse light, but for photovoltaic panels, it was necessary to study how this would impact the amount of light received.

Therefore, it was necessary to take into account the properties of this light in the greenhouse to estimate the amount of light that can be expected to be received on panels installed inside a double-layered inflatable plastic greenhouse, which is a very interesting greenhouse model in terms of possible energy savings (see previous study by Agrithermic with Hortinergy).

I. MATERIALS AND METHOD.

The isotropic scattering material model is a simplified model that assumes that light is scattered randomly in all directions uniformly, which may not reflect reality in some cases but can provide useful results for preliminary analysis or to evaluate general trends, as is the case here.

For example, if we take a cloud cover that is crossed by sunlight, which was initially mostly parallel, the clouds deflect them from their trajectory. If the cloud cover is extensive, we then observe that there is no longer shadow of objects on the ground. Under a greenhouse, it is the same phenomenon: the greenhouse covering has a certain scattering power, just like a cloud cover, and some of the light is then irradiated into the greenhouse in a diffuse form.

When light is diffused after passing through a diffusing plastic film, it is then as if this object became a light source itself, a bit like a lamp that would illuminate the inside of the greenhouse. Therefore, in this case, we can estimate the flux of diffuse light that reaches a surface located under this diffusing object, considering that it emits in all directions.

This model assumes that two phenomena overlap: part of the light is transmitted without being deviated compared to the outside, and part is deviated (by diffusion). In the first case, it is as if the panels were outside since the light remains the same, while for the second case, the light will be emitted in a homogeneous manner in all directions, which will be different from the outside. By the principle of superposition, the total radiation that reaches panels under a diffusing greenhouse covering is then expressed as the sum of these two types of light.

To calculate the percentage of light that retains the same properties as outside, we relied on diffusion coefficients provided by plastic film manufacturers. For example, for a traditional clear plastic film, the diffusion coefficient is around 25%, and for a highly diffusing film, it is 90%. This means that 25% of the light that reaches and passes through the greenhouse covering will be emitted inside in a 100% diffuse manner, and 75% will be exactly the same as outside. For the case of a double-layer plastic film, we then calculate the percentage P_conservative of light identical to the outside as :

P_conservative = (1 - Coeff_Diffus_1) * (1 - Coeff_Diffus_2)

P_scattering = 1 - P_conservative = Coeff_scattering_1 * Coeff_scattering_2 – Coeff_scattering_1 – Coeff_scattering_2

For the first case, we relied on simulations carried out with the online tool from the European official website PVJIS (PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM) : [PVGIS Online Tool (europa.eu)](). Thanks to this tool, we were able to estimate the annual solar irradiation of panels outdoors in different configurations. These values also served as a reference for our study, so that we could later compare them to the solar irradiation calculated in the case of panels arranged inside the greenhouse.

For the second case, we had to simulate the emission of light particles (photons) from the roof and the ground. Each of these photons is assigned a random direction in the greenhouse, and we count the number that reaches a panel surface. The more photons we emit, the better we can estimate the percentage that reaches the photovoltaic panels: this is the principle of a Monte Carlo simulation. Using the convergence towards the statistical mean allowed by the law of large numbers (10 million photons emitted in the simulation provides a convergence of about 10^-2% of the number of photons reaching a panel surface), we can then obtain a good estimate of the irradiation of the PV panels in the greenhouse quite efficiently, in less than a minute.

II. RESULTS.

1. Results of simulation outside.

Below are the PVGIS simulations of the annual solar irradiation of the panels outside, in South of France.

Latitude (decimal degrees):43,530
Longitude (decimal degrees):5,451
Elevation (m):202
Radiation database:PVGIS-SARAH2

Reference Results for Outdoor Solar Panels		% Ref.
Fixed panel laid flat outside.	**1694 kWh/m²/yr**	+0
Fixed panel inclined (39°) towards the South outside	**1991 kWh/m²/yr**	+18%
Vertical bifacial panel oriented East / West	**1950 kWh/m²/yr**	+15%
Fixed East-West tracking panel outside	**2367 kWh/m²/yr**	+40%

A fixed panel tilted at an optimal angle of 39° towards the South receives +18% more light throughout the year than a horizontal panel, and a vertical bifacial panel receives +15% on both sides. When using East-West solar tracking, the light gain is +40%.

A configuration with solar panels on tracking inside the greenhouse was first tested, but the idea was eventually abandoned.

"Indeed, the diffusion of light significantly reduces the interest of tracking, while too direct light poses a significant risk of shadowing from the greenhouse structure on the panels, which could cause a dramatic drop in production. Even if we were to use two perfectly clear ETFE films (0% diffusion and 94% transmission), we could expect a maximum of 95% of the solar irradiation of fixed panels on the roof, not to mention the very likely overheating of the panels under the greenhouse, which would further limit their efficiency."

So we focused on a configuration that would take maximum advantage of the benefits of diffuse light, which are to eliminate the risks of shading and to be able to place the panels with the desired orientation without casting direct shadow on the crops.

For this study, it was assumed that the average albedo of the greenhouse floor (including the crops) was 50%, which seems achievable by maximizing the white surfaces in the greenhouse (such as white-painted poles and covering the floor with a reflective plastic sheet, as is already the case for many projects aiming to maximize light on plants).

Assuming a double-layered inflated plastic cover made of ETFE and taking into account the shading coefficient of the steel structure of the greenhouse, a global coefficient of light transmission of around 80% is achieved.

Below are the results of simulations of the relative amount of light reaching the surface of the PV panels, expressed as a percentage of the annual solar irradiation on an equivalent horizontal surface outside. The percentages in the two-dimensional table input are the diffusion percentages of each of the two layers of the covering. 0% corresponds to a completely clear film and 100% corresponds to a completely diffusing film.

2. Résults of simulations inside double inflated ETFE greenhouse.

Solar irradiation of panels expressed as a percentage of outdoor solar irradiation.

a) Solar irradiation of panels under greenhouse with East-West tracking :

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	112%	108%	105%	101%	98%	94%	90%	87%	83%	80%	76%
10%	108%	105%	102%	99%	95%	92%	89%	86%	83%	79%	76%
20%	105%	102%	99%	96%	93%	90%	88%	85%	82%	79%	76%
30%	101%	99%	96%	94%	91%	89%	86%	84%	81%	79%	76%
40%	98%	95%	93%	91%	89%	87%	85%	83%	80%	78%	76%
50%	94%	92%	90%	89%	87%	85%	83%	81%	80%	78%	76%
60%	90%	89%	88%	86%	85%	83%	82%	80%	79%	78%	76%
70%	87%	86%	85%	84%	83%	81%	80%	79%	78%	77%	76%
80%	83%	83%	82%	81%	80%	80%	79%	78%	78%	77%	76%
90%	80%	79%	79%	79%	78%	78%	78%	77%	77%	76%	76%
100%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%	76%

b) Solar irradiation on vertical bifacial panels under the gutter (9 rows of 100m x 1.3m):

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	92%	96%	99%	103%	106%	110%	113%	117%	120%	124%	128%
10%	96%	99%	102%	105%	108%	112%	115%	118%	121%	124%	128%
20%	99%	102%	105%	108%	111%	113%	116%	119%	122%	125%	128%
30%	103%	105%	108%	110%	113%	115%	118%	120%	123%	125%	128%
40%	106%	108%	111%	113%	115%	117%	119%	121%	123%	125%	128%
50%	110%	112%	113%	115%	117%	119%	120%	122%	124%	126%	128%
60%	113%	115%	116%	118%	119%	120%	122%	123%	125%	126%	128%
70%	117%	118%	119%	120%	121%	122%	123%	124%	125%	126%	128%
80%	120%	121%	122%	123%	123%	124%	125%	125%	126%	127%	128%
90%	124%	124%	125%	125%	125%	126%	126%	126%	127%	127%	128%
100%	128%	128%	128%	128%	128%	128%	128%	128%	128%	128%	128%

c) Solar irradiation on vertical bifacial panels under the gutter (9 rows of 100m x 2.6m):

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	92%	93%	95%	96%	97%	98%	99%	101%	102%	103%	104%
10%	93%	94%	95%	97%	98%	99%	100%	101%	102%	103%	104%
20%	95%	95%	96%	97%	98%	99%	100%	101%	102%	103%	104%
30%	96%	97%	97%	98%	99%	100%	101%	102%	103%	103%	104%
40%	97%	98%	98%	99%	100%	101%	101%	102%	103%	104%	104%
50%	98%	99%	99%	100%	101%	101%	102%	102%	103%	104%	104%
60%	99%	100%	100%	101%	101%	102%	102%	103%	103%	104%	104%
70%	101%	101%	101%	102%	102%	102%	103%	103%	104%	104%	104%
80%	102%	102%	102%	103%	103%	103%	103%	104%	104%	104%	104%
90%	103%	103%	103%	103%	104%	104%	104%	104%	104%	104%	104%
100%	104%	104%	104%	104%	104%	104%	104%	104%	104%	104%	104%

d) Solar irradiation on vertical bifacial panels under the gutter (9 rows of 100m x 3.9m):

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	92%	92%	92%	91%	91%	91%	90%	90%	90%	90%	89%
10%	92%	92%	91%	91%	91%	91%	90%	90%	90%	90%	89%
20%	92%	91%	91%	91%	91%	90%	90%	90%	90%	90%	89%
30%	91%	91%	91%	91%	91%	90%	90%	90%	90%	90%	89%
40%	91%	91%	91%	91%	90%	90%	90%	90%	90%	90%	89%
50%	91%	91%	90%	90%	90%	90%	90%	90%	90%	90%	89%
60%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	89%
70%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	89%
80%	90%	90%	90%	90%	90%	90%	90%	90%	90%	89%	89%
90%	90%	90%	90%	90%	90%	90%	90%	90%	89%	89%	89%
100%	89%	89%	89%	89%	89%	89%	89%	89%	89%	89%	89%

e) Solar irradiation on vertical bifacial panels under the gutter (9 rows of 100m x 5.2m) :

	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0%	92%	91%	89%	88%	87%	86%	84%	83%	82%	80%	79%
10%	91%	90%	88%	87%	86%	85%	84%	83%	81%	80%	79%
20%	89%	88%	87%	86%	85%	84%	83%	82%	81%	80%	79%
30%	88%	87%	86%	85%	85%	84%	83%	82%	81%	80%	79%
40%	87%	86%	85%	85%	84%	83%	82%	81%	81%	80%	79%
50%	86%	85%	84%	84%	83%	82%	82%	81%	80%	80%	79%
60%	84%	84%	83%	83%	82%	82%	81%	81%	80%	80%	79%
70%	83%	83%	82%	82%	81%	81%	81%	80%	80%	79%	79%
80%	82%	81%	81%	81%	81%	80%	80%	80%	80%	79%	79%
90%	80%	80%	80%	80%	80%	80%	80%	79%	79%	79%	79%
100%	79%	79%	79%	79%	79%	79%	79%	79%	79%	79%	79%

III. DISCUSSION.

For a total surface area of 1170m² of panels for a greenhouse of 1 hectare (10 rows of 9.60m x 100m), one can expect to obtain up to 128% of the amount of light captured by an equivalent horizontal surface outside. When stacking 2 panels to double the height of each row, there is still more light compared to the outside solar irradiation. By tripling the height, it is less advantageous, but we still retain 89% of the outside solar irradiation. We also note that the higher the height, the less beneficial diffuse light is. For a height of 3.9m (3510m² of panels for 1 hectare), we achieve a balance with only a 3% difference between 100% direct light and 100% diffuse light.

What is remarkable is that if we compare the amount of light reaching a bifacial panel outside versus inside the greenhouse, the higher amount of diffuse light inside the greenhouse compensates for the 20% loss of brightness due to the greenhouse cover and structure. Of course, this assumes that the ground and vegetation have an average albedo of 50%, and that ETFE plastic films are used which have both excellent light transmission and good light diffusion.

This can be explained by the fact that the more panels are placed under the greenhouse, the more the light will have to be shared among the panels, which allows less light to reach the ground to be reflected onto the panels. Indeed, the albedo is an important factor for the efficiency of vertical bifacial panels. By optimizing the albedo of the greenhouse floor with white surfaces, this can be made possible.

In addition, the fact that there is a maximum of diffuse light in the greenhouse is not only beneficial for the panels, but also for the vegetation, allowing for very homogeneous lighting and no shadow from the panels. Moreover, the panels are located in a position that does not interfere with activities inside the greenhouse. It can be assumed that the decrease in yield caused by the overall decrease in luminosity in the greenhouse can be partially compensated by this more homogeneous light on the leaves, making it more profitable than a traditional photovoltaic greenhouse with panels placed on the roof.

In addition, it would remain to be seen whether this solution would be a good alternative economically compared to photovoltaic glass greenhouses with panels installed on the roof. According to a 2021 study published in the journal Solar Energy, the additional cost of bifacial solar panels can vary from 5% to 30% depending on the size and power of the panels, installation conditions, and material costs.

Indeed, the high temperature inside the greenhouse can lead to a decrease in the efficiency of the solar panels. This is known as the temperature coefficient, and it is usually expressed as a percentage of power loss per degree Celsius above a certain reference temperature. The temperature coefficient varies depending on the type of solar panel, but it typically ranges from -0.2% to -0.5% per degree Celsius. However, this effect can be mitigated by using proper ventilation and cooling systems inside the greenhouse. It is also important to consider the cost-effectiveness of this solution compared to traditional solar panel installations on rooftops or open fields. This would depend on various factors such as the cost of materials, installation, maintenance, and the local energy market conditions. Nonetheless, the use of bifacial solar panels in greenhouses has the potential to provide multiple benefits such as increased energy production, improved crop yield, and reduced environmental impact.

Conducting real-world experiments is essential to validate these hypotheses and gather more data on the performance and efficiency of bifacial solar panels under ETFE greenhouses. It would also allow us to study the effect of different factors such as temperature, humidity, and weather conditions on the panels' performance. This data can be used to optimize the design and placement of solar panels in greenhouses, which can ultimately lead to higher energy yields and improved cost-effectiveness.

IV. CONCLUSION AND PERSPECTIVES

The initial objective was to propose an alternative solution to traditional glass photovoltaic greenhouses, in which the photovoltaic panels are placed on the roof, by imagining a solution that would allow for maintaining good agricultural yields.

After an initial study on a solar panel tracking solution in a double-layer inflatable plastic greenhouse, the idea was ultimately abandoned as its performance was deemed uncompetitive compared to panels installed on the roof.

Another solution that appeared more interesting in these conditions was studied: double-sided vertical panels, which allow to capture light on both sides. We therefore developed a model to calculate the amount of light that can reach these panels, varying the diffusion rates of each plastic film in the ETFE double-layer inflatable structure.

The results showed that a good solar irradiance could be obtained on these panels under the greenhouse, compared to the outdoor solar irradiance.

To put these results in perspective and focus on a specific case, we can refer to the study by Agrithermic using the Hortinergy software, which demonstrated that a Filclair double-inflated ETFE greenhouse can benefit from +18% more light than a Venlo glass greenhouse.

If 9 rows of vertical bifacial panels were installed under this ETFE greenhouse on a height of 1.3m, the decrease in luminosity due to the panels would exactly compensate for this surplus of +18% of light under the ETFE greenhouse, so the agricultural yield would remain the same, with the additional production of energy.

Assuming that these bifacial panels under the greenhouse could produce as much electricity as panels outside thanks to their very good solar irradiation of 128% of an external horizontal surface, we could expect an annual production of between 250 and 300 MWh of electricity in Nantes, and 300 to 377 MWh in Avignon. For Nantes, by selling all the electricity produced by the panels back to the grid and assuming a resale price of 12 cents/kWh, we could earn between 30,000 and 36,000 euros per year. For a one-hectare greenhouse of tomatoes, with double ETFE inflatable cover and a thermal screen, assuming an energy cost of 40 euros/MWh for gas, heating expenses would be around 80,000 euros per year by heating the greenhouse at 20°C during the day and 16°C at night throughout the year except in November. This would reduce the net heating expenses of such a greenhouse to about 50,000 euros per year per hectare. If we compare this configuration to the conventional Venlo glass greenhouse with a thermal screen, we are at around 100,000 euros of heating needs per year per hectare, so there would potentially be a factor of 2 between these two configurations, without impacting the amount of available light for the crop, to allow for identical agricultural yields.

Of course, to arrive at a reliable projection of electrical production for this specific configuration, experiments would need to be conducted in the field to address technical uncertainties, such as the heating of the panels inside the greenhouse. A more in-depth techno-economic analysis based on real-life conditions would therefore be essential to build a viable economic model for these relatively new agrivoltaic greenhouses.