RESULTS FROM A PV SYSTEM WITH LINEAR FRESNEL LENSES INTEGRATED IN A GREENHOUSE.

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ABSTRACT: In this paper we give an overview of the results and experiences with a PV system consisting of linear Fresnel lenses mounted in the roof of a greenhouse. The concept of the system is defined in Sonneveld *et al* 2011. The Fresnel lenses project a focal line on a linear PV collector. To keep track on the focal line, a control systems moves the collector according to an accurately pre-computed path.

For electricity production from the high density light in the focal line, a series connection of PV-cells along the linear collector is wanted. However, glazing bars that support the glass panels cast shadow lines on the collector, which seriously hamper the possibilities of coupling PV-cells in series (see Janssen *et al* 2011).

To solve this problem, PV cells are switched in parallel to form modules with a length equal to the (regular) distance of the shadow lines. Then these modules can be connected in series because each module is affected equally by the shadow-lines.

To check the internal resistances and reverse bias of individual modules we short circuited modules, but this practice appeared to be catastrophic if applied to a long chain of modules. In such a short circuited chain, the modules that happen to have a slightly lower current production gets reversed biased with a voltage of almost the open chain voltage. When building an accurate simulation model of the electrical scheme this mechanism was confirmed.

Despite the drawbacks in the first experiments with the system, the perspectives were encouraging enough to continue the project and to reassemble the collector with new PV-modules.

The results up to now are:

Fresnel lenses can be incorporated in the roof of a greenhouse with sufficient focusing. The tracking system is sufficiently accurate and is realized with constructions applicable in practical greenhouses. The calculation of the position of the focal line is very accurate and needs after calibration almost no fine tuning in position. The PV collector needs to be improved, less spreading in performance of the PV cells and better reverse voltage resistance. The generated electrical energy can be delivered to grid.

A spin off effect of the capture of direct light is that the remaining light in the greenhouse is fully diffuse. This showed to be very positive on the growth of ornamental flowers. The collector can be positioned very fast in and out of the focal line and forms in fact a very sophisticated shadow system.

Keywords: Building Integrated PV, Fresnel Concentrator, PV Modules, Grid Connection, Shading, Parallel Inverters

1 INTRODUCTION

In Dutch greenhouse horticulture the target is to use 20% more sustainable energy sources in 2020 as formulated in the energy research program [1] “Kas als Energiebron 2011” . Two new greenhouse concepts have been developed first by model calculations, later by small scale experiments of different elements of the concepts and finally by the realisation of medium scale demonstration greenhouses of 100 and 500 m2. Two different principles are used to divide solar energy into a part for crop and a part for energy production. The methods of dividing the solar light in direct/diffuse part and a spectral part are compared in [2].

In this paper we give an overview of the results of the demonstration greenhouse with a PV system based on linear Fresnel lenses mounted in the roof of a greenhouse. The concept of the system is defined in [5-11]. Fresnel lenses project a focal line on a linear PV collector. To keep track on the focal line, a control systems moves the collector in accordance an accurately computed path. For electricity production from the high density light in the focal line, a series connection of PV-modules along the linear collector is installed. However, glazing bars that support the glass panels cast shadow lines on the collector. To solve this problem, PV cells are switched in parallel to form modules with a length equal to the (regular) distance of the shadow lines. Then these modules can be connected in series, each module is affected equally by the shadow-lines. This is simulated in [3]. One of the project demands was that the total system with all of its components is a practice nearby solution. Basic and practical knowledge about PV was found at [12] PVEDUCATION.

2 MATERIALS AND METHODS

The total system consists of four main components, a greenhouse with Fresnel lenses in the roof, a solar CPV collector, a sun tracking servo system that moves the solar collector into position and set of inverters to deliver the energy to the grid. All these components will be discussed.

2.1 The construction of the Fresnel Greenhouse.

Fig. 1 gives an overview how the collector is suspended in the roof of the greenhouse. Also the shadow lines can be seen clearly. The inside floor area of the Fresnel Greenhouse is 20*25=500m2. The greenhouse has an asymmetric roof with double glazed panes of 3m20 high and 1m24 wide. The glazing bars have a distance of 1m25 hence is the distance of the shadow lines. The Fresnel lens tiles are mounted between the two layers of glass. Underneath each south roof CPV collectors with a length of 20 m were installed in two rows (Fig. 1), suspended with steel cables. A short collector consisting of two modules in series is installed for testing purpose and for performance comparison. A servo system positions the collector in the focal line of the sun by means of motors and cables. The servo system and all additional measurements are realized with an I/O system based on the Beckhoff TwinSafe System. All the software for calculation of the tracking, measurement and control of the PV collector, data analyses and user interface was developed by Wageningen UR. The greenhouse climate was controlled by a commercial climate computer (Hoogendoorn). The global and diffuse radiation was measured with a SPN1 Pyranometer from Delta-T, a solid state sensor that requires no correction in time like shadow rings.

Fig. 1 PV collectors mounted in the roof of the green-house

The set point for temperature, relative humidity and max-imum PAR light were 30ºC, 80% and 500µmol.m^{-2}.s^{-1} respectively. Different types of tropical ornamental flowers were grown inside the greenhouse.

2.2 The Full CPV collector

The Full CPV collector consists of 4 rows with each 16 PV modules of 1.25 m length. Each PV module consists of 11 parallel PV cells. The PV cells are from NAREC U.K type V grove, size 4*11 cm (w*l). The 11 PV cells and the tempered glass layer are laminated with EVA on a black aluminum profile. The carrier of the collector consists of a square steel tube which is cooled with water. These profiles are attached to this carrier with click on plastic mounting brackets. Heat conducting paste is applied to improve the heat transfer and its uniformity. Each PV cell has 4 contact fingers on each side. Within the module all these fingers are electrical connected in parallel to an aluminum bar. At each side of the module these bars connect to the next/previous module, in this way all the modules (not cells) are switched in series. The aluminum connection bars are also clicked to the plastic mounting brackets and isolated is this way. Each contact finger of the PV cell is clamped to the aluminum bar with a long plastic stripe. In order to reduce the contact resistance and pressure the aluminum bars are coated with an alloy of lead/zinc. Extra mirrors to catch the stray light are also fixed to these mounting brackets. The aluminum bars and the copper connection cables including the flexible wiring between the moving collector and the gutters in the greenhouse are designed to meet the project demand that the power losses should be lower than 10%. The I_{MP} of the full collector correlates with the I_{SC} of a test module with a factor $C_{SC,MP}$, derived from the measurements of the IV curve. The 4 rows of 16 PV modules in series generate a total U_{MP} of 4*16*0.52= 33.2 V. At an irradiance of 1000W global (800W direct/200W diffuse) the typical short circuit current of the Narec PV cell I_{SC}=1.2 A. In this case $C_{dir,glob}$=0.8.

$$I_{MP}=N_p*I_{sc}*C_{SC,MPP}*C_{dir,glob}*C_{geo}*C_{gap}*C_{shade}*C_{glass}*C_{pln}$$
$$=11*1.2*0.94*0.8*25*0.9*0.9*.95=245A$$

I_{MP}	current at Maximum Power point
N_p	no of parallel cells within the module
I_{SC}	typical short circuit current of a single PV cell
$C_{SC,MP}$	factor between the I_{SC} and I_{MP} current
$C_{dir,glob}$	factor between Global and Direct Irradiance
C_{geo}	geometric concentration factor of the Fresnel lenses
C_{gap}	losses of the gaps between Pvcells and modules
C_{shade}	factor of unshaded part of the module
C_{glass}	transmissivity of the glass at perpendicular radiation
C_{pln}	pollution of the glass panes and collector

$$P_{MP}= U_{MP}*I_{MP} = 33[V]*245[A] = \pm 8KW.$$

This estimation assumes that all PV cells are 100% equal, in practice there will be a spreading in performance so the cells will not work at their individual MPP, this loss in performance is described in [4] .

2.3 The Test Collector.

The Test Collector is used for testing purposes and for reference measurements for the full collector. It consists of 2 modules in series, and is periodically short circuited for a very short time (10 mS) The open voltage V_{OC} and the short circuit current I_{SC} are registered. The power can be calculated from $P=V_{OC}*I_{SC}*FF$. The fill factor FF is determined from the IV curve measurement.

2.4 Measuring the IV curve.

The IV curve gives a lot of information about the properties and condition of the PV modules. Within a parallel project described under [3] an IV tracker was developed for this specific application. The principle of this IV tracker is simple, a capacitor is charged by the current of four PV modules in series (Fig. 2). Initial the capacitor is discharged, the voltage is zero. During charging the voltage increases to the level of the open voltage V_{OC} of the PV modules. The initial current starts at I_{SC} and decreases to zero. In this way the complete range of I and V is scanned. At the end of the charge cycle the capacitor is discharged and the tracker is ready for the next run. Switch S1 controls the charging and S2 the discharging of the capacitor. Super capacitors can handle high currents and have low internal resistance, chosen is a Maxwell BCAP650. At the start of the charge cycle the voltage U_{PV} is not zero and determined by I_{SC} and R_S, the accumulation of the internal resistances in the capacitor, the electronic switches, the wiring and the connections. At t=0 $U_{PV}=I_{SC} * R_s \approx 300$ mV. The digital and analogue in- and output signals are handled by the I/O system. To compensate the step t=0 the capacitor can be charged to a negative voltage equal to the step.

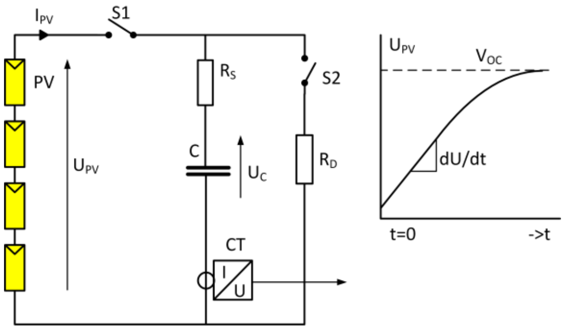

Fig. 2 Principle of the experimental IV tracker.

PV 4 modules of 11 parallel switched PV cells (type NAREC V grove)
C capacitor 650F (type Maxwell BCAP650)
S_1,S_2 4 parallel MOSFET switches (type IRFP4468PbF)
R_s $R_{cap}+R_{switch}+R_{wires}+R_{connect}$.
CT Current Transducer translates currents to voltages that can be measured (type LEM HAL-200S).

The missing values of I and V at the start of the measurements were added by linear extrapolation. Fig. 3 shows a sample IV curve obtained with the developed device.

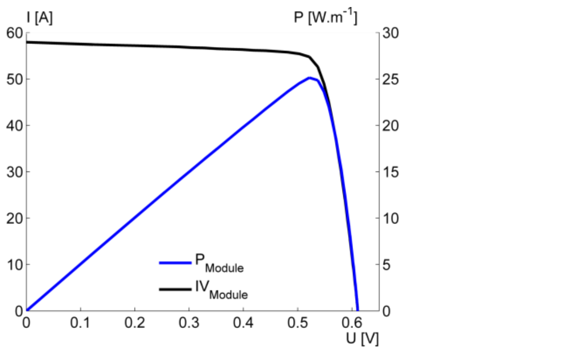

Fig. 3 Current and Power per meter PV module.

2.3 The Sun Tracking System

The CPV collector consists of 4 rows suspended with steel cables that can vary in length such that the focal line can be tracked continuously.

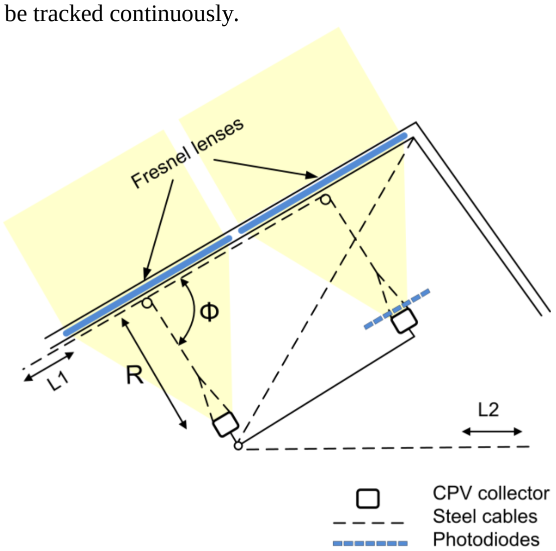

Fig. 4 Greenhouse roof with the CPV collector.

The position of the focal line changes during daytime and during the year. For every point of time the position is calculated that gives the maximum capture of radiance on the PV collector with a width of 4 cm. This calculation is done for a year around with practice data from several years. These calculations are done with the ray tracing program RAYPRO form WUR. For any angle of incidence the power is calculated for a set of positions, shown as black lines in Fig. 5. These black lines represent the 4 cm wide PV collector. The maximum power (point P in Fig. 5) is kept and the next angle is calculated. For every day of the year a track is calculated (Fig. 6). For clearance the number of positions has been strongly reduced, in practice over 2000 steps.

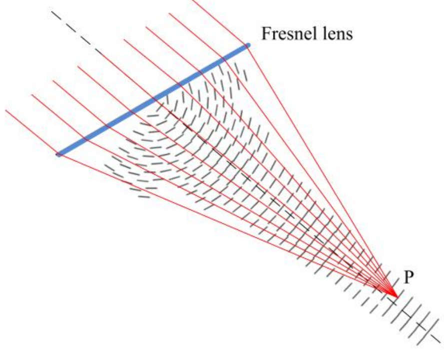

Fig. 5 Positions for which the power is calculated.

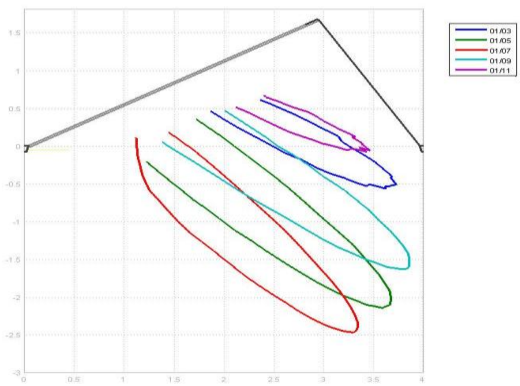
Fig. 6 Calculated tracks for the dates 1-mar, 1-may, 1-july, 1-sept and 1-dec.

The center of the focal line is expressed in angle Φ with respect to the perpendicular line and radius R the distance to the Fresnel lens (Fig. 4). Φ,R are translated with trigonometry to a change in length L1 and L2 of the steel suspension cables. Pull wire resistors give the position feedback needed for the servo system. A linear array of photodiodes (Fig. 4) gives the transverse irradiance distribution for fine tuning of the focal line. The deviation relative to the calculated track is used as a correction for the next position cycle.

2.4 The configuration of the inverters.

A demand from the project was to deliver the electrical energy to a 3 phase grid in order to realize a practice nearby application. During the design phase there were no commercially available inverters that could handle the combination of low voltage and high current. Almost no available low voltage inverters could be switched in parallel to comply the high current. At first instance the maximum electrical power of the PV was roughly estimated on 9kW at U_{MP}=30V and I_{MP}=300A. The chosen Changetec EL 700-35 can be switched in parallel, the maximum input power is 700W at a nominal input voltage of 35V and a nominal input current of 20A, so 15 inverters were needed. According the manufacturer the MPP tracker starts at a voltage of about 29V and the maximum input current varies from 22 to 26A. At a rising irradiance all the inverters start consecutive. A current transducer (type LEM HAL-200S) is used for monitoring the output current of the collector. The output voltage is measured via an voltage isolation module. The inverters are connected in 3 groups of 5 inverters to the 3 phase grid. A safety relay can disconnect the PV collector from the inverters, every inverter is secured with a maximum current switch at the input and output side. The PV collector is not grounded to prevent ground loops especially at accidental short circuit conditions.

3 RESULTS AND DISCUSSION

3.1 The green house

Fresnel lenses can be incorporated in the roof of a greenhouse with sufficient focusing. For growers this greenhouse is as functional as a normal greenhouse.

3.2 The PV collector

In 2012 a full PV collector was build and tested, the collector was connected to the configuration of inverters and power could be delivered to the grid. Fig. 7 shows the current yield of the full collector I_{MP} (max. power) and the test collector I_{SC} (short circuit). The graphs from Fig. 7 to Fig. 9 show data from 2-june-2013 time in GMT.

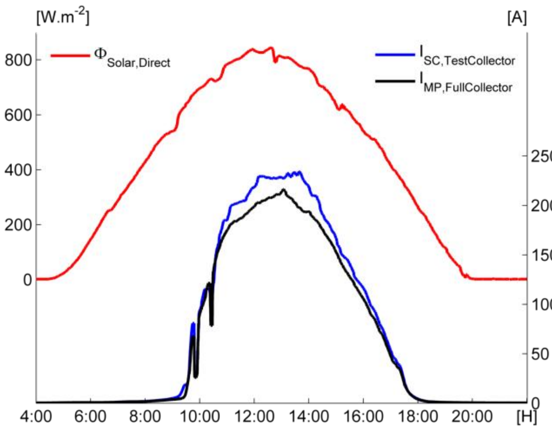

Fig. 7 PV currents as result of the incoming radiation

$\Phi_{Solar,Direct}$ is the direct global radiation in W.m^{-2}, the power is calculated from: $P_{FullCollector}=U_{MP}*I_{MP}$ and $P_{TestCollector}=V_{OC}*I_{SC}*FF$ (Fig. 8). Expressing the power/energy yield per m^2 greenhouse floor makes interpretation and estimations of the yield easier.

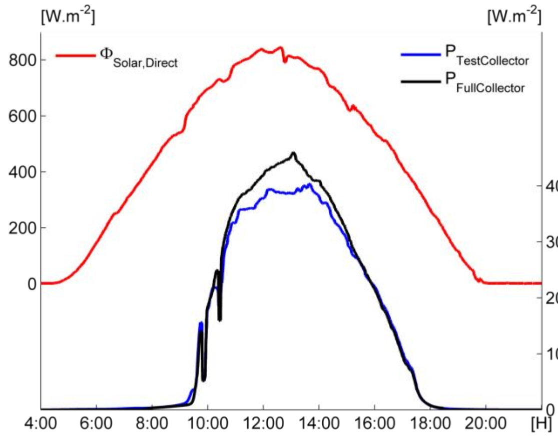

Fig. 8 The power of the full collector and test collector.

The next step is to calculate the energy production per day per m^2 greenhouse floor and compare this with the cumulative irradiation (Fig. 9).

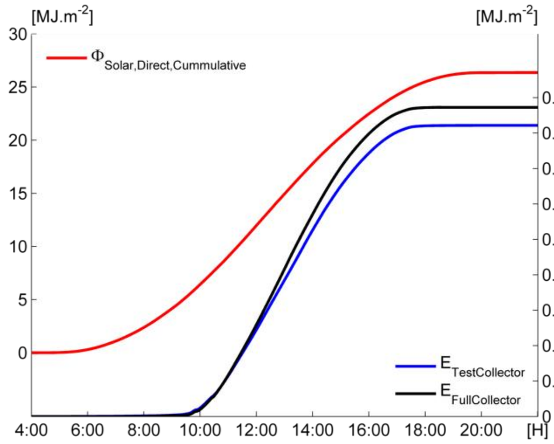

Fig. 9 Energy yield vs. cumulative direct irradiation.

The energy yield of the full collector and the test collector are measured over a period of 132 days from 18-apr-2013 till 1-sep-2013 (Fig. 10). The efficiency is calculated from the ratio of the output energy and the cumulative irradiance. The efficiency of the full collector is 2.9 % or 8.1Wh/MJ and from the test collector: 3.13 % or 8.7Wh/MJ, the blue and black line in Fig. 10. The full collector showed a degradation of 0.8% over the whole period. In the Netherlands the cumulative direct radiation is 1800 MJ.m^{-2}.y^{-1}. With an efficiency of 3% the energy yield will be 57,6 MJ.m^{-2}.y^{-1} or 15 kWh.m^{-2}.y^{-1}.). The graphs in Fig. 7,Fig. 8 &Fig. 9 show that the full collector performs very well compared to the test collector, so the alignment and the quality of the electrical wiring over the full length must be good.

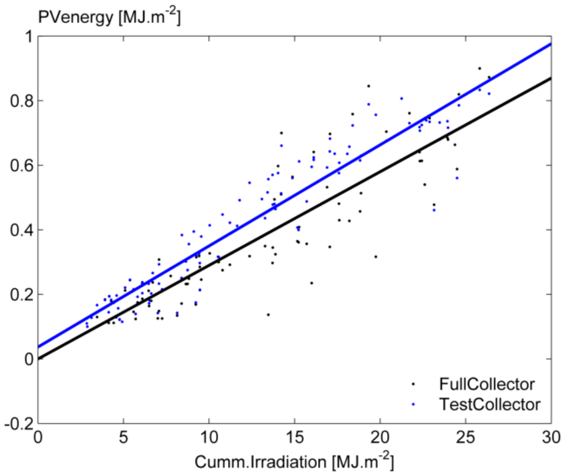

Fig. 10 Energy yield of the full collector and the test collector as a function of the irradiance.

The PV modules were manually short circuited in groups of two to get an overview of the spreading of the individual modules. The short circuit currents were compared to the current of the double reference module. The results in Fig. 11 show that the average performance is comparable to the reference module but the spreading is too high**.**

Fig. 11 Performance of the full collector related to the test collector.

The total performance is delimited by the weakest module and can be significantly increased by sharper selection of the PV modules before the assembly. An improvement up to 25% could be possible. A mobile IV tracker, based on the principle in chapter 2.3, could measure the IV curve of each module individual.

3.3 The Sun Tracking System

All pre calculated positions at any time of day and day of year showed to be very accurate. Every position was translated to a displacement of the two sets of suspension cables. These displacements formed the set point for the servo system. The sun tracking system, hard- en software, performed reliable and accurate. Fine tuning of the position with the aid of a linear array of photo diodes was hardly necessary. Fig. 12 shows the distribution of the focal line in the transverse direction at the CPV collector during the day. The white dotted lines denote the width of the collector. The position of the focal line is exact on the center of the collector. Before 11:00 and after 17:00 there was no harvest of energy, this complies with Fig. 7- Fig. 9.

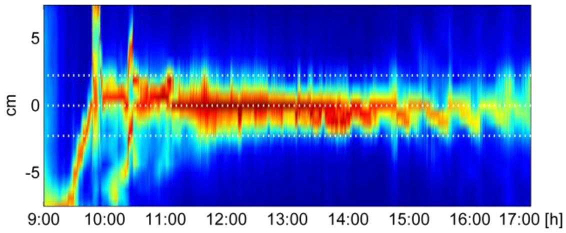

Fig. 12 Transverse light distribution on the collector**.**

3.4 The configuration of the inverters.

The fifteen Changetec inverters could be simply switched in parallel to the output of the PV collector. This switching in parallel works but the 15 independent MPP trackers do influence each other, which causes a certain instability. Especially at rapid changing irradiance the inverters switch on and off with difference in hysteresis so the total stability and efficiency is not optimal. The input currents of all inverters are not equally spread. The CEC efficiency is 94%, towards the low and high end this efficiency decreases. A point of improvement would be one master MPP tracker and multi slaves, in that case the inverters have to communicate via a network. Another advantage would be that that every inverter is loaded up to its maximum efficiency and consecutive the next inverter is switched on/off. As a result the total efficiency would be at maximum over almost the full range. Diagnostic tools embedded in the inverter are necessary to monitor the condition, performance and degradation over time. Tools such as measuring the IV curve.

4 CONCLUSIONS

☺ The smart parallel/series connection makes that the shadow lines cause only the inevitable permanent loss of about 10%. ☺Fresnel lenses can be very well incorporated in the double glass roof of a greenhouse. ☺The sun tracking system, hard- en software, performed reliable and accurate, fine tuning of the position with linear arrays of photodiodes was hardly necessary.☺ The suspension of the collector was realized with components common in greenhouse installations. Comparison in energy yield with the test collector shows that the alignment of the focal line over the full length of the collector was very good. ☺The total mechanical system and electrical wiring and connections could be kept simple and robust.

☺The NAREC PV cells performed very well at high irradiance levels (>20 suns), a measured fill factor of 0.8 is satisfactory. Reducing the high spreading in PV cells could significant improve the overall efficiency.

☺Omitting bypass diode requires that the cells must be able to resist a reverse voltage of almost the V_{OC} of the total collector, in the present case 40V.

☺Energy delivery to the grid at low voltages and high currents with parallel switched inverters is possible. Changetec inverters can be simply switched in parallel but the performance and efficiency is not optimal at all conditions. The Changetec inverters did withstand the high temperatures and humidity's in the greenhouse (30°C 100% RH). A central MPP tracker that controls the whole group of inverters would improve the stability and efficiency. In case of up scaling spreading the inverters could reduce the heavy cabling. ☺A side effect is that interception of the direct light which is focused on the collector gives very high diffuse light levels in the greenhouse. These high diffuse light levels showed to be very positive on the growth of ornamental flowers. The collector can be positioned very fast in the focal line and forms in fact a very sophisticated shadow system.

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