

## GREENHOUSE WITH AN INTEGRATED CONCENTRATED PV SYSTEM

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**ABSTRACT:** The scope of this investigation is the development of a new type of greenhouse with an integrated filter for rejecting near infrared radiation (NIR) and a solar energy delivery system. Cooled greenhouses are an important issue to cope with the combination of high global radiation and high outdoor temperatures. As a first measure, the spectral selective cover material, which prevents the entrance of NIR radiation, is investigated. The special spectral selective properties of these materials have to block up to 50% of the solar energy outside the greenhouse, which will reduce the needed cooling capacity. The second measure is the integration of a solar energy system. When the NIR reflecting coating is designed as a parabolic or circular shaped reflector integrated in the greenhouse, the reflected solar energy of a PhotoVoltaic (PV) cell in the focus point delivers electric energy. With a ray tracing computer program the geometry of the reflector was optimally designed with respect to the maximum power level. The PV cells mounted in the focal point require cooling due to the high heat load of the concentrated radiation (concentration factor of 30-40). The properties of different materials, Ge, GaSb, CIS and Si cells were investigated to find the optimal cell for this application. All part are integrated in a greenhouse structure with a size of about 100m<sup>2</sup>.

**Keywords:** Ray Tracing, Concentrators, Energy Options, PV System, Solar Cell Efficiencies.

### 1 INTRODUCTION

In northern Europe, with colder winter climate conditions, energy saving is an important issue. Moreover during summer cooling is needed by natural ventilation to remove excess energy. In the southern countries with higher global radiation and higher outdoor

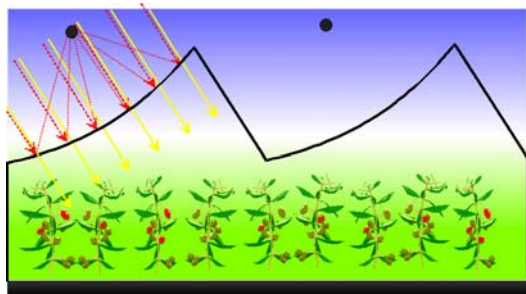


Fig. 1 Greenhouse with spectral selective cylindrical mirror and a collector in the focal point (—>) indicate visual light, (—>) indicate NIR radiation

temperatures during summer, cooling of greenhouses is even more important [1]. With the novel greenhouse design presented in Fig.1, cooling can be combined with energy supply. First developments applying linear Fresnell lenses where presented by Jirka et al. [2] and Tripanagnostopoulos et al. [3]. Fraas et al. [4] presented an illumination system with glass fibres. A schematic setup of the new design with a spectral selective mirror is depicted in Fig. 1. The advantage of this system is a very homogeneous and high illumination level in the greenhouse. The basic setup is an in a greenhouse integrated NIR filter with a parabolic or circular shape that will focus the NIR radiation. First of all, it will prevent high heat radiation load during a period with high outdoor temperatures. Secondly, the focused radiative energy can be transferred into electrical energy. This can be applied e.g. for additional cooling of the greenhouse with a pad and fan system and/or can be externally used. With a ray tracing computer program the

special geometry of the reflector was optimally designed with respect to this maximum energy yield. The PhotoVoltaic (PV) or Thermal PhotoVoltaic (TPV) cells mounted in the focal point require cooling due to the high heat load of the concentrated radiation (concentration factor of about 40). The (TPV) properties of different materials, Ge, GaSb, CIS and Si cells were investigated. All the parts mentioned before will be integrated in a test prototype greenhouse with ground area of about 100 m<sup>2</sup>.

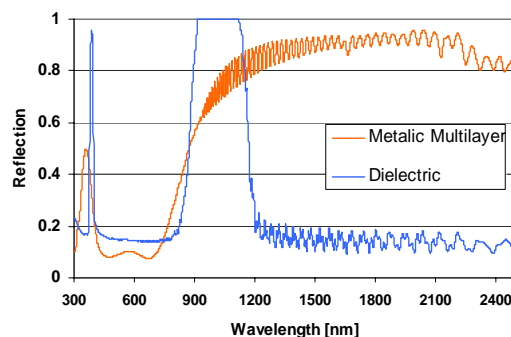


Fig. 2 Reflectance of spectral selective reflecting metallic and dielectric multilayer film

### 2 METHODS AND RESULTS

#### 2.1 Separation of visible and thermal radiation

For the separation of the visible part of the spectrum (Photo Active Radiation or PAR wavelength 400-750 nm) and thermal radiation (NIR wavelength 750-2500nm) standard and new materials were investigated with respect to light transmittance and NIR reflectance. Two materials were selected with useful material properties: one metallic multilayer and one dielectric multilayer based on plastic film. The transmission and reflection properties of these films are depicted in Fig.2. The dielectric multilayer film shows a very good transmission in the PAR region (low absorption, not in the figure) and good reflection for a limited NIR area of

900-1200 nm. The metallic multilayer film shows a somewhat lower transmission in the PAR area (higher absorption) and a good reflection for the large wavelengths of the NIR area of 900-2500 nm. For horticultural applications, we designed a special reflector that combines high PAR transmission with optimal NIR reflection up to 1800 nm. The designed spectral reflection of this film is given in Fig. 3. This film shows a total NIR reflection in the area of 750-2500 nm of 97 % combined with a PAR reflection (400-700nm) of only 7 %. Implications for the climate conditions in greenhouses with a NIR reflecting film are given by Hemming et al. [5] and Sonneveld et al. [6].

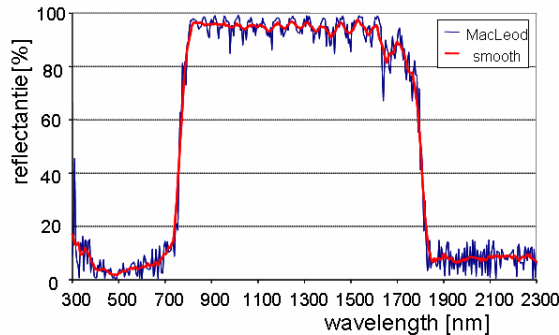


Fig. 3 Reflectance of a new developed spectral selective dielectric multilayer film.

2.2 Concentration of thermal radiation through a light-transmitting mirror.

With a ray tracing computer program (Raypro) the optimal geometry and yield of the reflector was designed. Especially the influence of the parabolic or circular through geometry was studied with respect of the yield, complexity of construction and control and the costs of the system. Fig. 4 and 5 show the different parabolic or circular trough reflector variants. An advantage of the parabolic trough reflector of Fig. 4 is a high achievable concentration ratio of up to 120 but this requires continuous adjusting of the reflector and collector combination to solar elevation to set or keep the system in the optimal focal point.



Fig. 4 Parabolic reflectors rotate in the East-West direction

With the circular trough geometry (Fig.5) the position of the focal point (line) depends on the elevation angle of the sun. The focal point moves in dependence of the position of the sun along a circle with the radius half of that of the circular reflector. The advantages of the circular trough concept are the fixed position of the circular reflector and the relative simple control mechanism for the position of the PV cells. The only moveable part is the PV cell in the focal point. A disadvantage is a reduction of the concentration factor. In Fig. 6 the yield of this concentrator is given at an angle

of incidence of 0° and 20°. At a higher angle of incidence the concentration factor drops to about 40 with a reasonable yield of the concentration system.

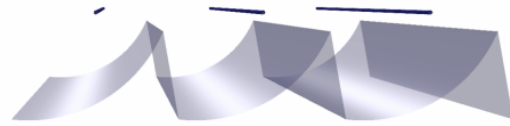


Fig. 5 Cylindrical reflectors oriented in the North-South direction

With Raypro, a ray tracing program, the total collected energy on a silicon solar cell in the focal point is calculated with climate data of a clear day (June 25) in the Netherlands (De Bilt). The efficiency of this solar cell is calculated to be 15 % for the NIR region. The result of the calculations with silicon cells is presented in Fig. 7 for the two different design cases of Fig. 4 and 5.

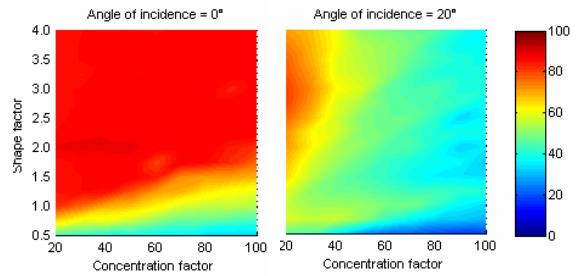


Fig. 6 Yield of a cylindrical trough concentrator as a function of the concentration and shape factor for an angle of incidence of 0° and 20°. The shape factor is defined as: radius of the cylinder divided by the chord distance

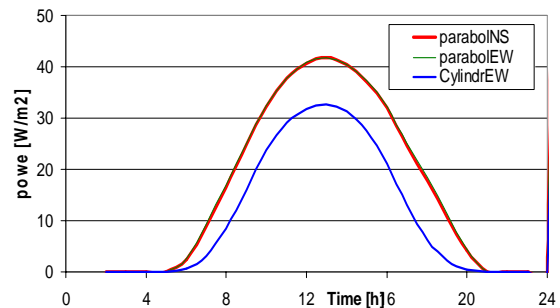


Fig. 7 Calculated results of the electrical power output on a clear day June 25 the Netherlands (De Bilt) of the Silicon PV cell in the focus point of : (—) Parabolic trough reflector with North-South orientation, (—) Parabolic trough reflector with East-West orientation and (—) Cylindrical trough reflector with East-West orientation.

The yield of the parabolic trough reflector in the East-West direction is equal to the yield of this reflector in the North-South direction. The yield of the circular trough reflector is about 30% less but the system is less complex to construct. In Table 1, some characteristic energy figures per greenhouse surface area are given for a clear summer day (25 June) in The Netherlands for the two system designs and a normal PV system used as a reference. From the absorbed energy the generated

electrical energy per m<sup>2</sup> area greenhouse is calculated. Due to the concentration factor of about 40, the required PV area is a lot smaller compared to a normal silicon PV system. The solar cells have to be cooled with air or water as described by Zondag et al.[8].

Table 1 Overview of the typical electric power and yield of the designed systems.

System	Peak Power* [W/m <sup>2</sup> ]	Daily Energy Yield* [MJ/m <sup>2</sup> ]	[KWh/m <sup>2</sup> ]
Global radiation	925	31	8,6
Reference PV	138	4,6	1,3
Parabolic reflector in E-W	41,7	1,3	0,4
Parabolic reflector in N-S	41,7	1,4	0,4
Cylindrical reflector in E-W	32,7	0,9	0,3

\*) Clear day June 25 the Netherlands (De Bilt).

### 2.3 Transformation of the NIR radiation to electric energy by TPV and PV cells.

For the conversion of the NIR radiation into electric energy PV and TPV cells can be applied. The properties of different cells, Ge, GaSb, CIS and Si cells were investigated.

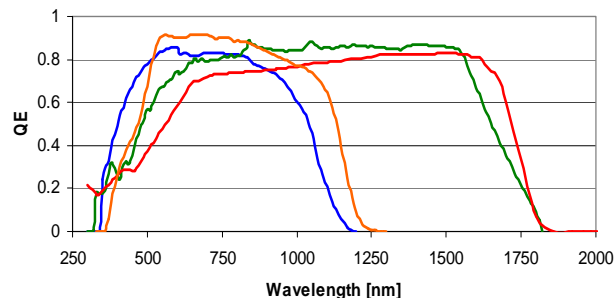


Fig. 8 Quantum efficiencies of Ge-cells (—), GaSb cells (—), Si-cells (—) and CIS-cells (—).

In Fig. 8 the quantum efficiencies of Ge, GaSb, CIS and Si cells are depicted. The quantum efficiencies of the Ge and Si (multi crystalline) cells were measured by IMEC in Leuven. For GaSb cells the quantum efficiencies were given by Schlegl et al. [9], and data for CIS cells was obtained from Powalla and Kniese [10]. From this data  $I_{sc}$  was calculated.

The results for the NIR region are summarized in table 2 together with the band gap, typical values for  $V_{oc}$  the fill factor, and the resulting efficiency. Despite of the lower band gap and resulting higher current density of the TPV cells with Ge and GaSb, the power density and efficiency obtained with a silicon cell are higher due to the higher  $V_{oc}$  of the latter. Combined with the lower costs and better availability of these cells further development will be done with Si-cells.

Table 2 Overview of the properties of (T)PV cells, the currents (calculated from QE) and efficiencies obtained for radiation with a wavelength larger than 750 nm.

system	Band-Gap [eV]	$V_{oc}$ [V]	$I_{sc}$ [A/m <sup>2</sup> ]	Fill-factor	Power Dens. [W/m <sup>2</sup> ]	Eff. [%]
Ge	0.67	0.27	306	0.70	57.8	12.0
GaSb	0.74	0.37	173	0.71	45.8	9.5
CIS	1.05	0.51	172	0.72	63	13.1
Si	1.11	0.65	146	0.80	75.9	15.7
Si+Ge	-	-	-	0.80	99.9	20.7

An interesting option could be a combination of the Si and Ge cells, which would result in a total efficiency of 20,7 %. However from a practical point of view this combination is more complicated.

As a reference, in table 3 the performance of the PV cells is given for the total solar spectrum. Of course  $I_{sc}$  increases, however also the total irradiation increases and only Si efficiency increases

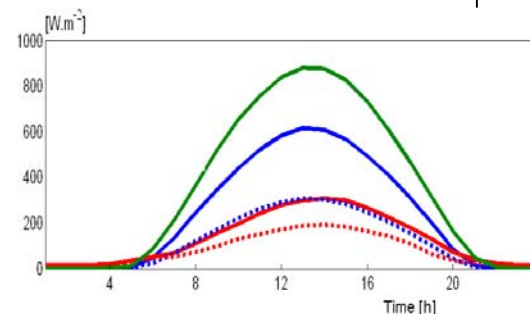


Fig. 9 Calculated results of the global radiation on a clear day June 25 the Netherlands (De Bilt), the heat load inside the greenhouse and the corresponding cooling effect by transpiration of tomato crops with the computer simulation program KASPRO [10]. (—)Global radiation, (—) heat load inside, (—) transpiration, (---) heat load inside with NIR film and (---) transpiration with NIR film.

Table 3 Overview of the properties of (T)PV cells and the currents (calculated from QE) and efficiencies obtained for AM 1.5 Solar radiation.

system	Band-Gap [eV]	$V_{oc}$ [V]	$I_{sc}$ [A/m <sup>2</sup> ]	Fill-factor	Power Dens. [W/m <sup>2</sup> ]	Eff. [%]
Ge	0.67	0.27	447	0.70	84.6	8.3
GaSb	0.74	0.37	243	0.71	64.4	6.4
CIS	1.05	0.51	351	0.72	129	12.7
Si	1.11	0.65	318	0.80	165	16.3

### 2.4 Climate conditions in the greenhouse system

A computer simulation of the thermal balances of a greenhouse [11] was used to predict the implications for the climate inside a greenhouse. When NIR radiation is reflected by the special selective covering material, a reduced heat load remains, which will result in a better climate in the case of high global radiation. This reduced

heat load will also affect the transpiration of the crops according to the model of Stanghellini [1]. The effect of the heat load is presented in Fig. 9. From this figure a reduction of the heat load of roughly a factor two can be concluded. This reduced heat load also reduces water consumption, it makes the greenhouse easier to cool with ventilation or pad and fan and improves growth conditions in the greenhouse [6].

All subjects mentioned before are integrated in a newly designed greenhouse with an integrated NIR-reflective cover, circle geometry and PV cells in the focus point. The proof of principle will be tested in a prototype greenhouse with an area of 100 m<sup>2</sup>.

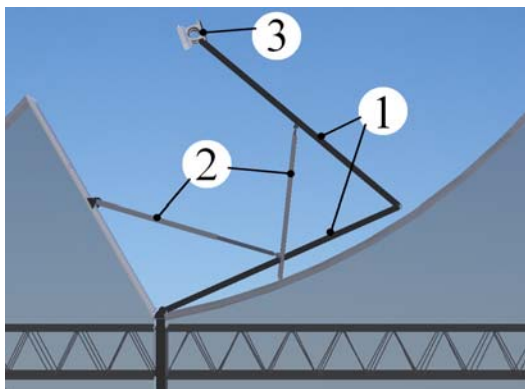


Fig. 10 Side view of the framework (1) with two linear actuators (2) and the PV cells (3).

### 2.5 Integration in the greenhouse system

The system of a selective reflector, circular curved glass cladding, a control unit for the position of the PV module and the Silicon cell module are integrated in a greenhouse. In Fig. 10 a side view is shown with the framework to control the position of the PV cells with two linear actuators. With the two electric actuators the PV cells are held in the focal point of the reflected NIR-radiation by the curved glass of the greenhouse. For stability reasons the two actuators form both a triangle with the framework.

The main structure of the (prototype) greenhouse will be comparable to a traditional greenhouse: beams, trellis girders, stability bracings will be made of standard steel and aluminum profiles. A model of the greenhouse is presented in Fig. 11. The span of the trellis girders is 9.60 m with two roofs of 4.80 m. The mutual distance of the trellis girders is 4.80 m. The curved glass sheets are force fitted water tight on the prebended glazing bars, aluminum gutters and cam profile. Here the covering structure is made asymmetrical. The stiff curved glass rods have a slope of 30° with the horizontal and are oriented to the south direction. In the north direction the glass rods have a slope of 60° with the horizontal. The ventilation windows are mounded in the part of the roof oriented in the north direction. The walls of the greenhouse will be covered mainly with standard double-web PC-sheets.

### 3 SUMMARY

With a newly developed spectral selective NIR-reflecting film the heat load inside the greenhouse can be reduced with nearly a factor two. The reflected NIR radiation can

be focused with a circular trough reflector with a concentration factor of 40. This requires adjustment of

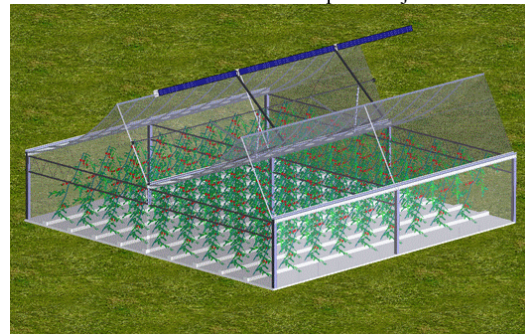


Fig. 11 Model of the greenhouse with an integrated concentrating PV system.

the collector to the solar elevation. For the collector Silicon, Germanium, CIS or GaSb cells can be applied. The maximal efficiency of 15,7% energy conversion from the solar radiation with wavelength larger than 750 nm is achieved with Si cells. The application of a combined Si PV and a Ge-cells TPV will result in a elevated efficiency of 20.7%. The PV cells are mounted in a framework and controlled in position with two linear actuators. The system is integrated in a greenhouse with a covering of curved glass. The produced energy can be used for energy supply and/or extra cooling with a pad and fan system and/or a desalination system.

### 4. ACKNOWLEDGEMENTS

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