Design of a Solar Greenhouse with Energy Delivery by the Conversion of Near Infrared Radiation - Part 1 Optics and PV-cells

P.J. Sonneveld, G.L.A.M. Swinkels and G.P.A. Bot
Wageningen UR Greenhouse Horticulture
Wageningen
The Netherlands

Keywords: ray tracing, greenhouse, concentrators, energy options, PV system, solar cell efficiencies

Abstract

In this paper the design and development of a new type of greenhouse with an integrated filter for reflecting near infrared radiation (NIR) and a solar energy delivery system is described. Especially the optical parts as the spectral selective film, the properties of the circular reflector and the efficiencies of photo voltaic cells are studied. As a first measure, the spectral selective cover material, which prevents the entrance of NIR radiation, is investigated. It has to block up to 35% of the solar energy outside the greenhouse, which will reduce the needed cooling capacity. The second measure is the integration with a solar energy system. When the NIR reflecting coating is designed as a 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 optimal geometry of the reflector was designed with respect to the collecting efficiency. The PV cells mounted in the focal point require cooling due to the high heat load of the concentrated radiation (geometric concentration factor of 30). The properties of different PV materials were investigated to find the optimal cell for this application. Cooled greenhouses are an important issue to cope with the combination of high global radiation and high outdoor temperatures. All parts are integrated in a 100m^2 prototype greenhouse which will be applied for the proof of principle.

INTRODUCTION

The combination of a greenhouse with photovoltaic cells is interesting due to the excess energy during summer. This is complicated by the need for high light levels and thus high light transmittance for crop production. While photosynthetic active radiation (PAR) is only about 45% of the solar spectrum the heat load can be reduced substantially by separating PAR. The other part, the near infrared radiation (NIR) is then available for PV conversion. Another problem is the large PV area needed. A very suitable solution for this is the use of concentrated radiation with concentration factor C. In that case only a factor 1/C is required as area of the photo voltaic cells. At sufficient concentration factors the required area for the cells is only a few percent of the total greenhouse surface area. Other advantages are the reduction of costs due to this reduced PV-cells area and the increasing efficiencies of the cells at concentrated radiation. Examples of the use of solar concentrators (Fresnel lenses) in combination with greenhouses were presented by Jirka et al., (1999) and Tripanagnostopoulos et al., (2004). Fraas et al., (2001) presented an illumination system with glass fibres. Referring to problems in greenhouse industry, 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 southern countries with higher global radiation and higher outdoor temperatures during summer, cooling of greenhouses is even more important (Stanghellini, 1987).

In the present paper a novel approach is presented separating PAR from NIR, focussing NIR on PV cells and thereby directly converting NIR to electricity. In Fig. 1 this is translated in a schematic greenhouse design. These principles will be integrated in a 100 m^2 test prototype greenhouse.

Proc. IS on Prot. Cult. Mild Winter Climate
Eds.: Y. Tüzel et al.
Acta Hort. 807, ISHS 2009

MATERIALS AND METHODS

Separation of Visible and Thermal Radiation

The spectral intensities of the AM 1.5 Solar spectrum is presented in Fig. 2. The main areas of the spectrum are UV (about 5% wavelength 300-400nm), PAR (wavelength 400-700nm) or visible spectrum (about 45%) and NIR (wavelength 750-2500nm). For the separation of the PAR part of the spectrum and the thermal radiation (NIR) standard and new materials were investigated with respect to PAR transmittance and NIR reflectance. Two materials were selected with useful material properties: one metallic multilayer and one dielectric multilayer based on plastic film. These films are very durable; the life time is about ten years. The spectral selective reflection and transmission are depicted in Fig.3. The dielectric multilayer film shows a very good transmission in the PAR region (low absorption) 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. Implications for the climate conditions in greenhouses with a NIR reflecting film are given by Hemming et al., (2005) and Sonneveld et al., (2007).

Maximal Concentration Factor and Yield of Concentration System

With a ray tracing computer program (Raypro) the optimal geometry and yield of the reflector was designed. Circular design was chosen because this will result in a much simpler construction (Sonneveld et al., 2007) compared with a parabolic design. With the circular trough geometry (Fig. 4) the position of the focal point (line) depends on the elevation angle of the sun. The focal point moves in dependency of the solar position along a prescribed curve with defined power density in the focal point. The movement of the focal point as function of solar elevation is visible in figures 4 a to f. In Fig. 5 the yield of this concentrator is given at an angle of incidence of 0^o and 20^o. At a higher angle of incidence the (optical and geometric) concentration factor drops to about 30 with reasonable yield of the concentration system. Due to the maximal achievable optical concentration factor of 30, the required PV area is a lot smaller compared to a normal silicon PV system. This will result in an area of the PV cells of about 3.3% of the total greenhouse area. Therefore the light loses are acceptable for horticulture. The solar cells have to be cooled with air or water to remove the access of heat. This method was described in detail by Zondag et al., (2006). The effective concentration factor C_{eff} will be lower than the optical concentration factor C_{opt}=30 because only part of the solar spectrum is reflected to the PV cells. This will result in a limited short shut current of the solar cells. This factor is called C_{Isc} and is calculated from the AM1.5 solar spectrum, the reflective properties of the NIR-reflective film and the properties of the silicon solar cell.

This calculation resulted in a C_{Isc} value of 0.38. However this radiation has to pass two times the glass covering with a typical glass transmittance τ_1 of 0.90% so the total

transmittance τ_t can be calculated with: $\tau_t = \dfrac{\tau_1^2}{1-\rho_1^2}$

The typical Fresnel reflectivity of glass ρ_1 is 0.08, then the total transmittance τ_t is 81.5%. Therefore C_{Isc} will reduce to 0.31. The effective radiation concentration factor $C_{eff} = C_{opt} \cdot C_{Isc}$ will then be then 9.3. However the curved glass and film will also reflect part of the visible radiation. From Figure 3 the reflectivity of the film ρ_2 can be determined at about 0.15 because this is only the visual spectrum this will reduce to 0.093. The total reflectivity ρ_t of the combination glass and film is calculated according to:

$\rho_t = \rho_1 + \frac{\tau_1^2 \cdot \rho_2}{1 - \rho_1 \cdot \rho_2}$, Then the total reflectivity ρ_t is: 0.156. This part will result in an effective concentration factor of 4.6. The total effective concentration factor for the incident radiation will be the sum of both factors being 13.9. This will still result in the need for cooling the PV cells.

RESULTS AND DISCUSSION

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. In Fig. 6 the quantum efficiencies of these 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., (2005), and data for CIS cells was obtained from Powalla and Kniese, (2006). From this data I_{sc} was calculated.

The results for the NIR region are summarized in table 1 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 and the elevated intensities in the wavelength area of 800-1200nm compared with that of the wavelengths larger than 1200 nm. Combined with the lower costs and better availability of the Silicon cells further development will be with Si-cells. 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 and is beyond direct application.

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 an experimental prototype greenhouse. In figure 7a the realised greenhouse construction is shown and in figure 7b a side view of the framework to control the position of the PV cells. With the two linear actuators the PV cells are held in the focal point of the reflected NIR-radiation. For stability reasons the two actuators are a triangle together 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 aluminium profiles. 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 glass sheets are easy to fit water tight on the prebended glazing bars, aluminium gutters and cam profile. The covering structure is asymmetrical. The curved glass rods have a slope of 30^o with the horizontal and are oriented to the south direction. In the north direction the glass rods have a slope of 60^o with the horizontal. The ventilation windows are mounded in the north oriented roof. The walls of the greenhouse will be covered mainly with standard double-web PC-sheets.

CONCLUSIONS

With a newly developed spectral selective NIR-reflecting film the heat load inside the greenhouse can be reduced and the reflected NIR radiation can be focused with a circular trough reflector with optical concentration factor of 30. Due to this concentration factor the shadowing effect by the PV cell is limited to only 3.3%. Because only the NIR part of the spectrum is reflected by the NIR film and also a part of the visual spectrum is reflected by glass and the NIR-film, the total effective concentration factor equals 13.9. For the collector Silicon cells reveal the maximal efficiency of 15.7% energy conversion from the solar radiation with wavelength larger than 750 nm. This was because of the high open voltage of silicon cells and the more intense solar radiation in the wavelength area between 800-1200 nm. In the greenhouse design the PV cells are mounted in a framework and controlled in position with two linear actuators. The system is integrated in an experimental 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.

ACKNOWLEDGEMENTS

This research is funded by the Dutch organization SenterNovem (EOS), the Ministry of Agri-culture, Nature and Food quality (LNV) and Dutch Product Board for the Horticulture (PT).

Literature Cited

Fraas, L.M., Daniels, W.E. and Muhs, J. 2001. Infrared photovoltaics for combined solar lighting and electricity for buildings, Proceedings of the 17th European PV Solar Energy Conference, Munich Germany, October 2001.

Hemming, S., Kempkes, F., van der Braak, N., Dueck, T. and Marissen, N. 2005. Filtering natural light at the greenhouse covering – Better greenhouse climate and higher production by filtering out NIR? Acta Hort. 711:411-416.

Jirka, V., Kučeravý, K., Malý, M., Pech, F. and Pokorný, J. 1999. Energy flow in a greenhouse equipped with glass raster lenses, Renewable Energy, 16:660-664.

Powalla M. and Kniese, R. 2006. ZSW Foundation Stuttgart. Private communication

Schlegl, T., Dimroth, A., Ohm, A. and Bett, W. 2005. TPV Modules based on GaSb Structures, 20th European photovoltaic solar energy conference and exhibition, CCIB Barcelona Spain, 6-10 June

Sonneveld, P.J, Swinkels, G.L.A.M., Holterman, H. and Bot, G. 2007. Solar Energy Delivering Greenhouse with an Integrated NIR filter, Greensys 2007, October 4-6, Naples, Italy (in press).

Stanghellini C., 1987. Transpiration of Greenhouse Crops. PhD- Thesis Wageningen University.

Tripanagnostopoulos, Y., Souliotis, M., Tonui, J.K. and Kavga, A. 2004. Irradiation aspects for energy balances in greenhouses. Greensys2004 Int. conf.; Acta Hort. 691:733-740.

Zondag, H.A., de Vries, D.W., van Velden, W.G.J, van Zolingen, R.J.C. and van Steenbergen, A.A. 2002. The thermal and electrical yield of a PV-Thermal collector. Solar Energy 72:113-128.

Zwart, H.F. de, 1996. Analyzing energy-saving options in greenhouse cultivation using simulation model, PhD- Thesis Wageningen University, IMAG rapport 96-5.

Tables

Table 1. 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]	VOC [V]	ISC [A/m2]	Fill-factor	Power Density [W/m2]	Efficiency [%]
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

Figures

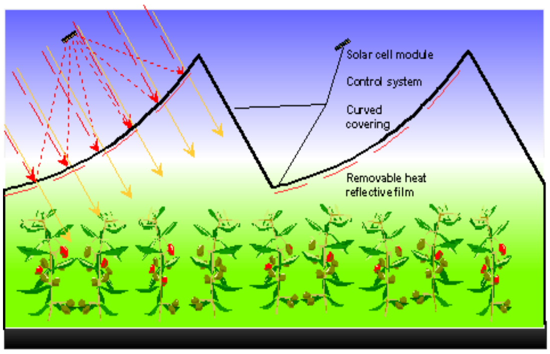


Fig. 1. Greenhouse with spectral selective cylindrical mirror and a collector in the focal point (——►) indicate visual light, (-----►) indicate NIR radiation and (········) indicate NIR reflecting film.

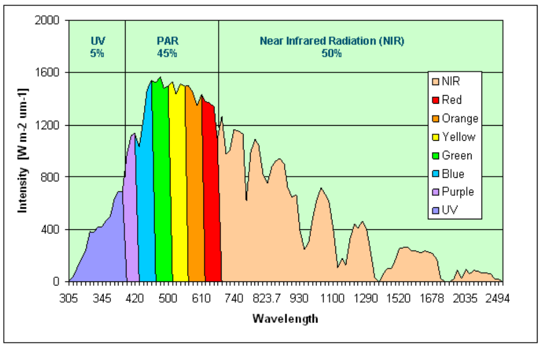


Fig. 2. AM1.5 Solar radiation with the contribution of UV, PAR and NIR radiation.

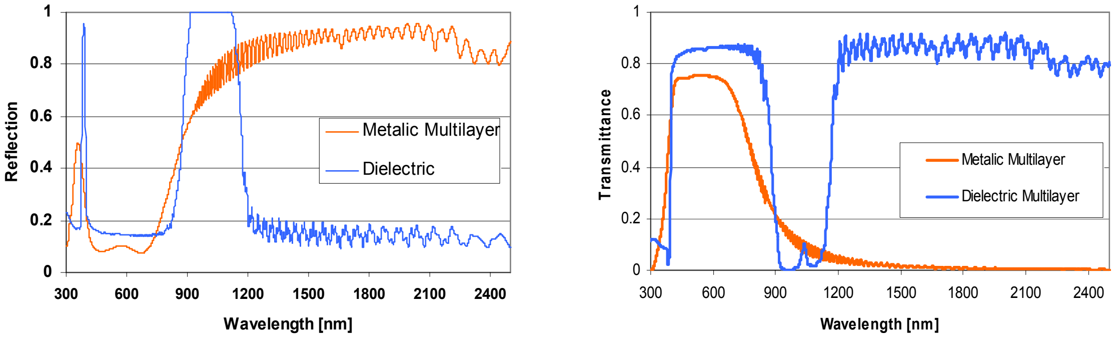
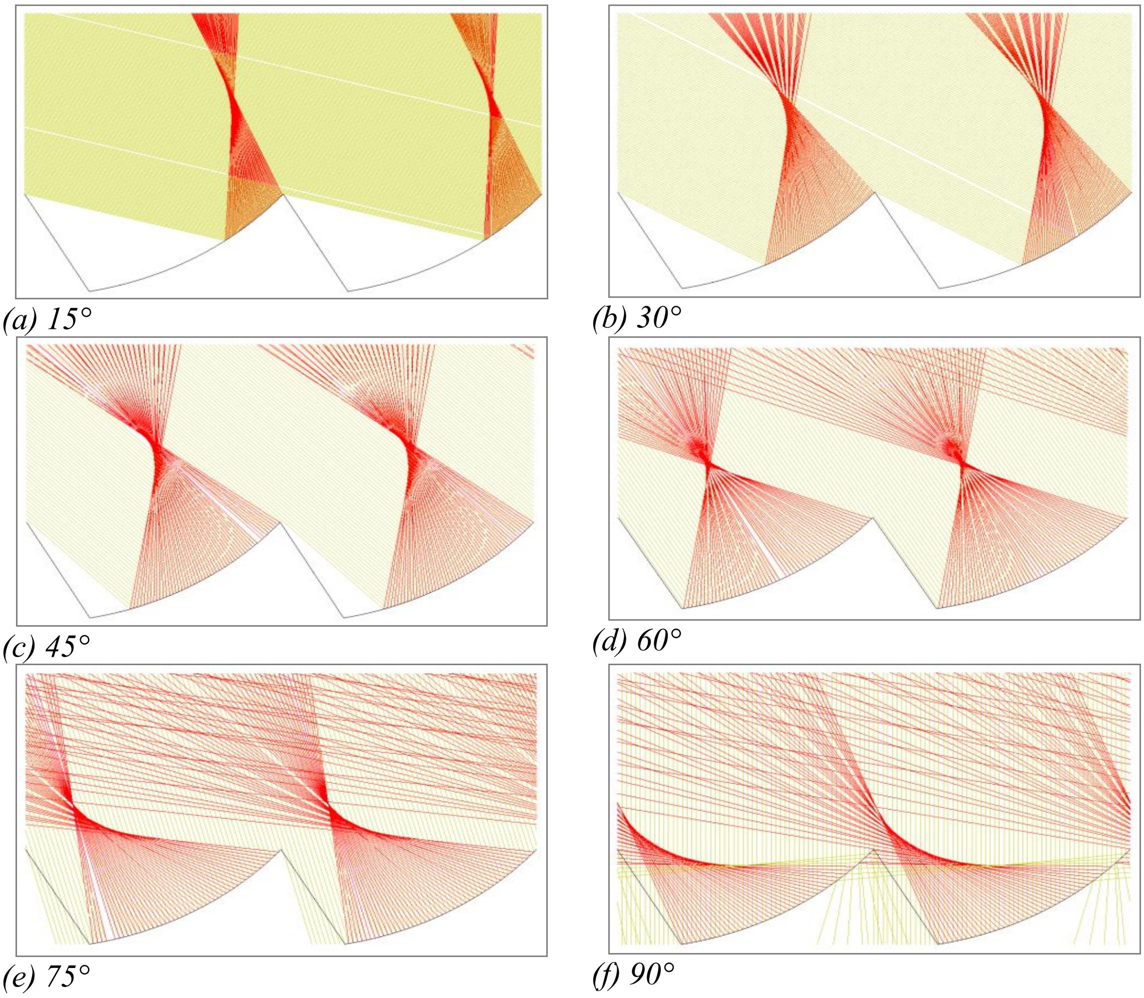


Fig. 3. a. Reflectance of spectral selective reflecting metallic and dielectric multilayer film.

b. Transmittance of spectral selective reflecting metallic and dielectric multilayer film.


(a) 15° *(b) 30°*

(c) 45° *(d) 60°*

(e) 75° *(f) 90°*

Fig. 4. Visualization of the focussing radiation of a cylindrical trough concentrator at projected elevations of 15, 30, 45, 60, 75 and 90^{o} (—) indicates incident solar radiation; (—) indicates reflected NIR-radiation.

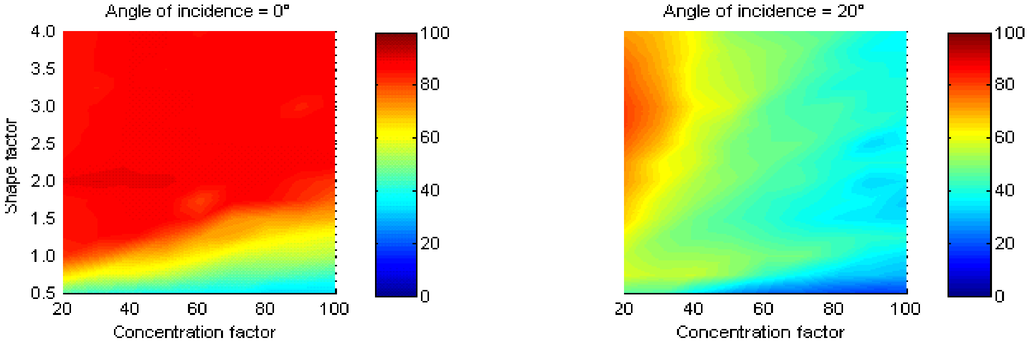


Fig. 5. Yield of a cylindrical trough concentrator as a function of the concentration and shape factor for a angle of incidence of 0^{o} and 20^{o}.

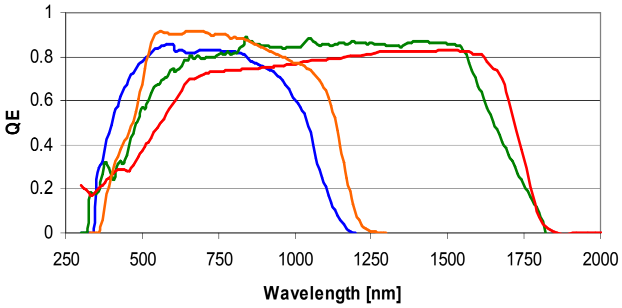
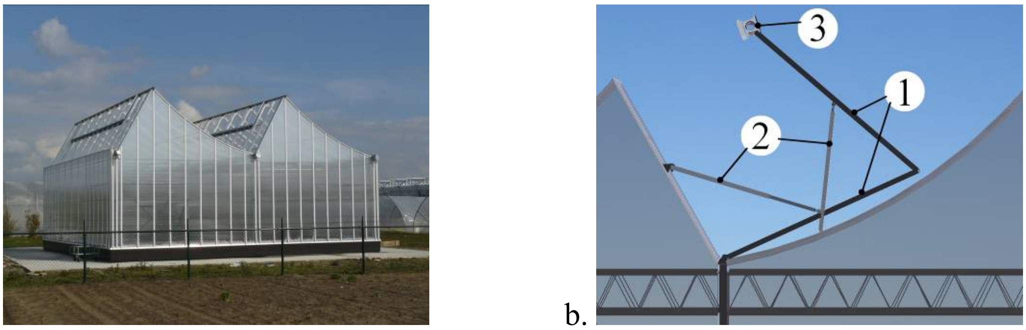


Fig. 6. Quantum efficiencies of Ge-cells (—),GaSb cells (—), Si-cells (—) and CIS-cells (—).



a. b.

Fig. 7. (a) Actual greenhouse construction (b) Side view of the framework (1) with two linear actuators (2) and the PV cells (3).