PV SYSTEM INTERGRATED IN A SOLAR GREENHOUSE WITH NIR SELECTIVE COATING

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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). The properties of different materials, Ge, GaSb, CIS and Si cells were investigated to find the optimal cell for this application. All parts are integrated in a greenhouse structure with a size of about 100m^2.

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 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 30). The (T)PV 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 floor area of about 100 m^2.

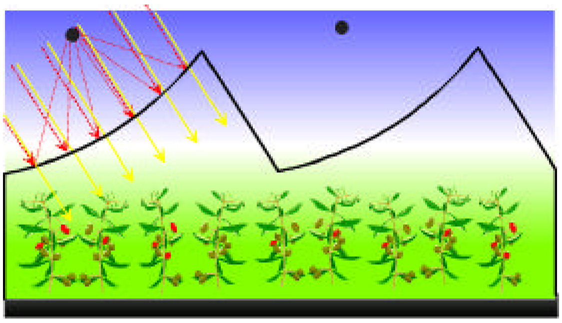

Fig. 1 Greenhouse with spectral selective cylindrical mirror and a collector in the focal point (- - ?) indicate visual light, (- - ?) indicate NIR radiation

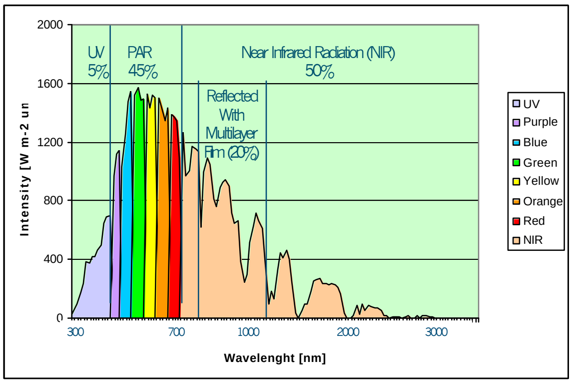

Fig. 2 The AM 1.5 Solar radiation. Radiation between 800 – 1200 nm is reflected by the multilayer film.

2 METHODS AND RESULTS

2.1 Separation of visible and thermal radiation

The spectrum of AM 1.5 solar radiation is depicted in Fig. 2. This spectrum consist at about 45% of the visible (Photo Active Radiation or PAR wavelength 400-750 nm), about 50% thermal radiation (NIR wavelength 750-2500nm) and about 5% UV radiation. 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 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, which will function very well for horticultural applications. Implications for the climate conditions in greenhouses with a NIR reflecting film are given by Hemming et al. [5] and Sonneveld et al. [6].

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. 3 and 4 show the different parabolic or circular trough reflector variants. An advantage of the parabolic trough reflector of Fig. 3 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.

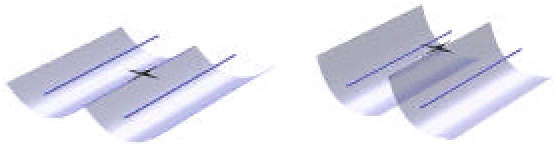

Fig. 3 Parabolic reflectors rotate in the East-West direction

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 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 positions and shapes of the focal point at an angle of incident of the solar radiation of 30, 45, 60 and 90^o are seen in Fig. 5. At low and high angles of incident the focal point is less sharp. 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^o and 20^o. At a higher angle of incidence the concentration factor drops to about 40 with a reasonable yield of the concentration system.

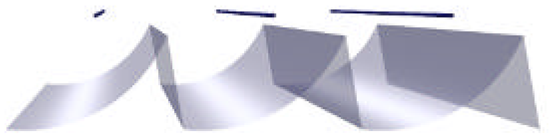

Fig. 4 Cylindrical reflectors oriented in the North-South direction

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. 3 and 4.

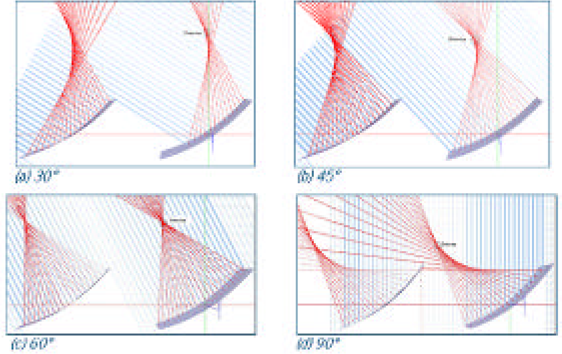

Fig. 5 Positions and shapes of the focal points at an angle of incident of the solar radiation of 30, 45, 60 and 90^o.

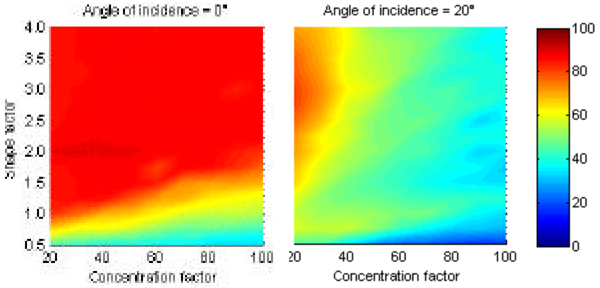

Fig. 6 Yield of a cylindrical trough concentrator as a function of the concentration and shape factor for a angle of incidence of 0^o and 20^o. The shape factor is defined as: radius of the cylinder divided by the chord distance

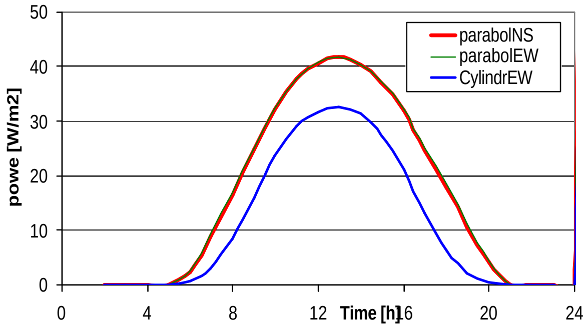

Fig. 7 Calculated results of the electrical power output on a clear day June 25 the Netherlands (De Bilt) of the Silicon PV cell in the focus point of : (- -) Parabolic trough reflector with North-South orientation, (- -) Parabolic trough reflector with East-West orientation and (- -) Cylindrical trough 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 m² 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/m²]	Daily Energy Yield* [MJ/m²]	[KWh/m²]
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).

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 excessive heat. The effective concentration factor for the incident radiation 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 cut current of the solar cells with a factor C_{Isc} which 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 value of C_{Isc}=0.38. However this radiation has to pass two time the glass covering with a typical glass transmittance of t_1 =0.90% so the total transmittance t_1 can be calculated with:

$$t_t = \frac{t_1^2}{1-r_1^2} \qquad (3.1)$$

The typical Fresnel reflectivity of glass r_1 is 0.08, then the total transmittance t_1 is 81,5%. Therefore C_{Isc} will reduce to C_{Isc}=0.31. The effective radiation concentration factor $C_{eff} = C_{opt} \cdot C_{Isc}$ will then be 9.3. However the curved glass and film will also reflect part of the visible radiation. From Figure 3 the reflectivity of the film r_2 can be determined at about 0.15 because this is only the visual spectrum this will reduce to 0.093. The total reflectivity r_t of the combination glass and film is calculated according to:

$$r_t = r_1 + \frac{t_1^2 \cdot r_2}{1 - r_1 \cdot r_2} \qquad (3.2)$$

Then the total reflectivity r_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.

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.

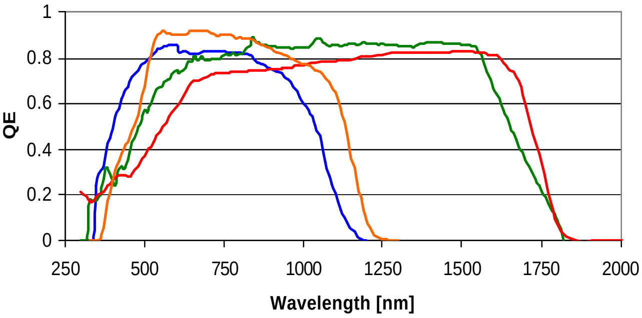

Fig. 8 Quantum efficiencies of Ge-cells (- -),GaSb cells (- -), Si-cells (- -) and CIS-cells (- -) .

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^2]	Fill-factor	Power Dens. [W/m^2]	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

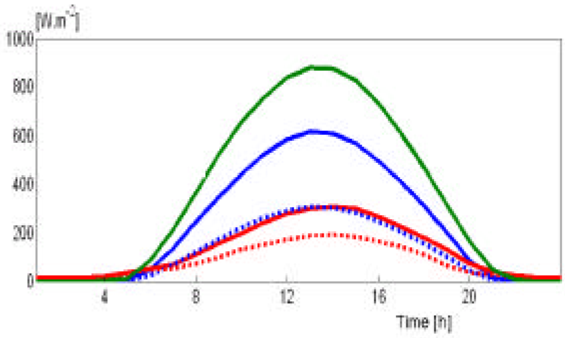

Fig. 9 Calculated results of the global radiation on a clear day June 25 the Netherlands (De Bilt), the heat load inside the greenhouse and the corresponding cooling effect by transpiration of tomato crops with the computer simulation program KASPRO [10]. (- -)Global radiation, (- -) heat load inside, (- -) 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^2]	Fill-factor	Power Dens. [W/m^2]	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.

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. Two linear electric actuators position the PV cells 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 and stability bracings are made of standard steel and aluminum profiles. The actual prototype 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 circular bended glazing bars, aluminum gutters and cam profile. Here the covering structure is made asymmetrical. The stiff 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 part of the roof oriented in the north direction. The walls of the greenhouse will be covered mainly with standard double-web PC-sheets.

Fig. 10 Side view of the framework with two linear actuators and the PV cells.

Fig. 11 Greenhouse at real size

2.6 Measurement of the yield of the system

The maximum yield was measured with a small module with two PV cells in series. By using this small module the effect of partial shading was avoided. With the data of the first measurements, the Fill factor was calculated on 0.7. The results on the measurements on September 26,

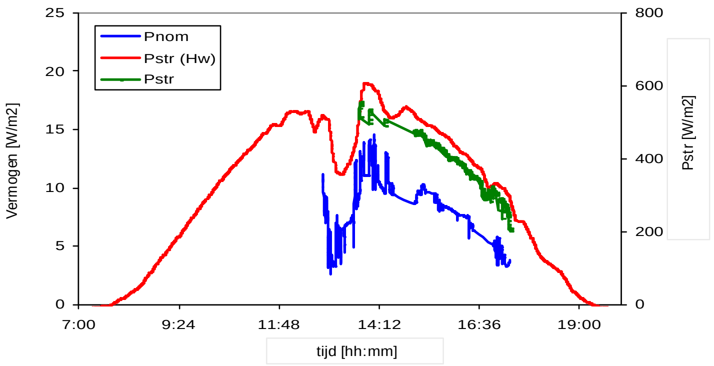

Figure 12 Output (Pnom) and incident radiation (Prad) by location and the Haarweg (Hw) Wageningen measured on Sept. 26. 2008

2008 is depicted in Fig. 12. During this day also the thermal yield was determined on 150 W/m^2 at a incident radiation of 600 W/m^2. From this data the yearly yields are calculated with typical Dutch climate data as given in Fig. 13. The yearly total electric yield is determined on 16 kW/m^2 and the thermal yield on 107 kW/m^2. In graphical form the result is given in Fig. 14.

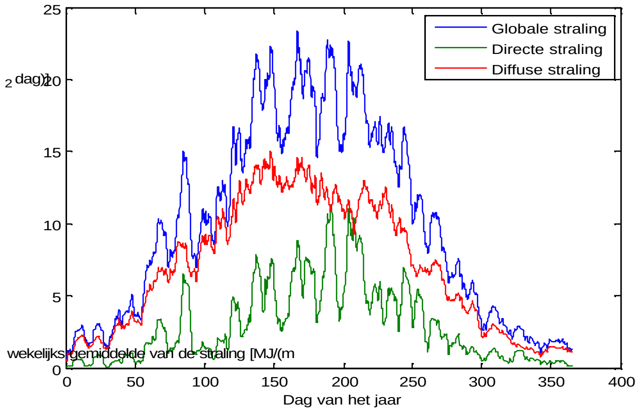

Figure 13 Daily radiation sums (global, direct and difuuse part) for a year measured in De Bilt.

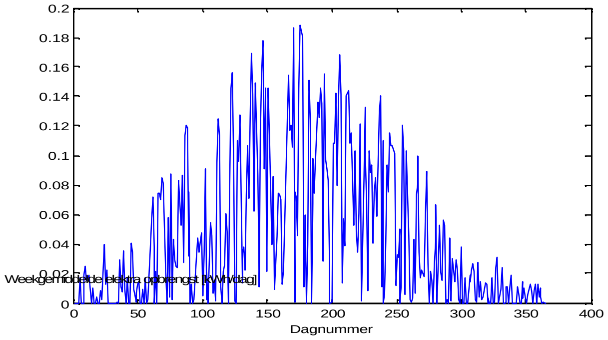

Figure 14 Week average of the electrical power in kW/m^2 per day output as a function of the day number.

3 SUMMARY

With a newly developed spectral selective NIR-reflecting film the heat load inside the greenhouse can be reduced nearly 40% and in future with 70%. The reflected NIR radiation can be focused with a circular trough reflector with a concentration factor of 30. This requires adjustment of 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 then 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 concept is feasible with existing materials and components and a peak power of approximately 21 W/m^2 electrical and thermal peak power of 150 W/m^2 is expected with an illumination of 900 W/m^2.The produced energy is determined on 16 kW/m^2 and the thermal yield on 107 kW/m^2 and 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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5. REFERENCES

[1] C. Stanghelini., 1987. Transpiration of Greenhouse Crops. PhD- Thesis Wageningen University, 150p

[2] V. Jirka,, K.. Kuceravý, M. Malý, F. Pech, J. Pokorný, 1999, Energy flow in a greenhouse equipped with glass raster lenses, Renewable Energy, 16, pp 660-664

[3] Y. Tripanagnostopoulos, M.Souliotis, J.K Tonui., A. Kavga, 2004. Irradiation aspects for energy balances in greenhouses. Greensys2004 Int. conf.; Acta Hort. 691, pp733-740.

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

[5] S. Hemming , F. Kempkes, N. van der Braak, T. Dueck and N. Marissen, 2005. Filtering natural light at the greenhouse covering – Better greenhouse climate and higher production by filtering out NIR? Presented on ISHS Light symposium June 2005, Lillehammer; Acta Hort. 711, 105-110

[6] Sonneveld, P. J, G.L.A.M. Swinkels, F. Kempkes, J. van Campen and G.P.A. Bot , Greenhouse with an integrated NIR filter and a solar cooling system, Paper no. 06-99, Greenhouse Cooling Conference Almeria, Spain, 24 - 27 April 2006

[7] Th. Bartzanas, Kittas C., Heat and Mass Transfer in a Large Evaporative Cooled Greenhouse Equipped with a Progressive Shading, Greensys 2004, Acta Hort. 691, October 2005, pp 625-631.

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

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

[10] M. Powalla and R. Kniese. ZSW Foundation Stuttgart. Private communication

[11] H.F. Zwart, de, 1996, Analyzing energy-saving options in greenhouse cultivation using a simulation model, PhD- Thesis Wagengen University, IMAG

rapport 96-5, 236p