Design of a NIR-Concentrator System Integrated in a Greenhouse

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Abstract

In warm periods the excess of incoming solar energy into a greenhouse is more than required for the growth of the crop. Particular the near infrared radiation (NIR) part of the incoming radiation is not necessarily. In a previous research project a new type of greenhouse with an integrated concentrated photovoltaic system with thermal energy output (CPVT-system) was developed. The system is based on a circular covering geometry and an integrated filter for reflecting the NIR of the greenhouse and exploiting this radiation in a solar energy system. In this feasibility study the CPVT-system is further optimized in order to avoid the asymmetric greenhouse construction with bended glass, the large construction for solar tracking and the high investments. Hereto all parts of the solar concentrating system will be inside a standard Venlo type greenhouse. NIR-reflective lamellae serve as NIR-reflector and the CPVT-module is mounted to or integrated into the ridge or gutter. With the spectral selective lamellae, which reflect a part of the NIR radiation, the heat load inside the greenhouse can be reduced and the reflected NIR radiation is focused onto the CPVT-module. The optimization process is based on a maximal total annual electricity production and is done with a ray tracing model and actual radiation data. Two types of lamellae are compared: flat lamellae and trough shaped lamellae which focus the radiation individually. Compared to flat lamellae, trough shaped lamellae have the advantage of reducing the number of lamellae in combination with a high concentration ratio. This will lower the costs for the drive of the lamellae. The reflected NIR radiation can be focused with a geometric concentration factor of 100x. The lamellae will not only reflect 49% of the NIR radiation but also reflect a part of the whole solar spectrum. This contribution will result in an effective concentration factor of 46x. The high geometric concentration factor will limit the shadowing effect by the PV-cells with only 1%. Further optimalisations in the energy yield were performed on determination of the optimal focal length of the trough shaped lamellae. The maximal annual electrical output was found for lamellae with individual optimized focal lengths. In that case the annual output for Dutch climate conditions can be over 29 kWh/m².

INTRODUCTION

Especially during summer the amount of incoming solar energy into a greenhouse is more than required for crop growth greenhouses. Particular the near infrared radiation (NIR) part of the incoming radiation is not necessarily. This excess of solar energy can be converted with spectral filtering of the Photosynthetic active radiation (PAR) and NIR, a concentration technique to avoid large PAR interception and a suitable concentrated photovoltaic thermal (CPVT)-module. This CPVT-module exploits the concentrated NIR-radiation and convert this into useful electrical and thermal energy. This concept was demonstrated in a prototype greenhouse (Sonneveld et al., 2010a, b; Swinkels, 2007). In the first concept a circular geometry of the greenhouse covering was integrated into the greenhouse construction. For the solar tracking the photovoltaic module (PV-module) was moved into the focal point by linear actuators. This type of greenhouse is in principle suitable for all crops, while the Fresnel greenhouse (Tripanagnostopoulos et al., 2005) is especially suitable for pot plant (typical shadow plants). During research in 2008 and 2009 (Sonneveld et al., 2010a, b) some bottlenecks of this concept were found. The most important bottlenecks were: high costs of the system due to the asymmetric greenhouse construction with the bended glass, large construction of the tracking system, no optimal collimation for all angles of incident and power losses due to shadow bands on the PV-module. Some changes in the concept were made to avoid these bottlenecks. In the proposed concept the PV-module is integrated in the ridge or gutter of the greenhouse and rotating lamellae situated inside the greenhouse and coated with a NIR-filter will reflect the NIR radiation onto the PV-module. The first results of this new concept were recently presented (Sonneveld et al., 2010c). Recently the positions of the lamellae were changed, which will improve performance. In this paper the results of the optimization process of the optics for the new concept are presented. The optimizations are based on a maximal total annual electrical output and were done with a ray tracing model and actual radiation data. In Figure 1 the working principle of the new concept is shown.

MATERIALS AND METHODS

Greenhouse Design

The new concept is based on a standard Venlo type greenhouse. To avoid high costs for the tracking mechanism, the mechanism is based on rotating lamellae inside the greenhouse just above the trellis girder (Fig. 1). Compared with the system proposed in 2010 (Sonneveld, 2010), with the rotating lamellae mounted just under the south side of the asymmetric greenhouse covering two advances were found: 1) The greenhouse is changed from asymmetric to a standard symmetric Venlo type greenhouse which will lowering the investment costs, and 2) the annual electric output is increased from 25 to 29 kWh per m² greenhouse per year. The greenhouse has a span width of 4 m and two or three roofs on a trellis girder. Because of the required distance between the module and the rotating lamellae the trellis girder in mounted 1.5 m below the gutter.

Annual Electric Yield

The geometric concentration efficiency of the system is defined as the total radiation on the PV-module as a fraction of the total incoming direct NIR per greenhouse area unit. The momentary concentration efficiency is related to the solar position at a specific time. The resulting electrical power produced by the PV-cells depends on the momentary direct NIR radiation. This is assumed to be 50% of the direct global radiation. For calculating the annual electrical output (kWh per m² greenhouse per year) all occurring direct NIR radiations and corresponding concentration efficiencies are taken into account. With ray tracing simulations the concentration efficiency of the system is calculated for every occurring solar position and stored in a table first. In this way the hourly radiation multiplied by the corresponding concentration efficiency and the PV efficiency results in the momentary electrical power output which can be integrated into an annual yield. This is performed with and without taking the shading effects into account (kWh gross and net, see Table 2). The results in this paper are based on averaged hourly data of direct radiation, measured in Wageningen, The Netherlands during 2007, 2008 and 2009 (Sonneveld et al. 2010b). Besides NIR, the lamellae will also reflect a significant part of the ultraviolet and visible radiation (UV-VIS). However, dependent on the type of PV-cells, this contribute significantly to the total electrical output, this is left out of consideration in this paper.

Optimization Approach

Target for optimization is a maximum annual electrical output of the system. For the determination of the collecting efficiency of the CPVT-module and the optimal position of the lamellae the ray tracing simulation software Raypro was used (Swinkels, 1999) taking into account a large number of parameters (material properties, greenhouse dimensions) were taken into account. Because of mechanical restrictions, plant conditions and costs the number of parameters were restricted because of high computational time and costs. of the optimized parameters were: a) Number and width of the lamellae, b) Lamella type (flat, trough), c) Influence of tolerances, d) Roof slope.

Furthermore the following assumptions were made: The absorbance of PV-cells is 100% and incidence dependent efficiency is not taken into account. Ridge, gutter & glazing bars are 100% absorbent. Lamellae do not overlap each other & are able to rotate 360°.

RESULTS AND DISCUSSION

Concentration System

Every span has a concentration system, including rotating lamellae just above the trellis girder and an CPVT-module integrated into the ridge. The span width is 4000mm and the CPVT-module has an effective width of 40 mm. This will result in a effective geometric concentration factor of C_{geo}= 4000/40 = 100x. Because C_{spec} = 46% (Sonneveld et al. 2010a) only a part of the entire solar spectrum is reflected to the module and the effective concentration factor is reduced to: $C_{eff}= C_{spec}\times C_{geo} = 0.46\times100 = 46$x. Due to imperfections in the lamellae and solar tracking a somewhat lowered concentration factor is expected in practice. Flat lamellae will not focus the incoming radiation individually. Therefore the width of the PV-module must be at least equal to the lamella width. Using only a few lamellae will result in a high lamellae width and as a consequence a high module width which will block the incoming radiation partially. In Figure 3 the average annual concentration efficiency in relation to the lamellae count is presented. The figure shows an asymptotic increase in efficiency with an increasing module width. Using circular trough shaped lamellae each lamellae will focus the reflected light which limits the module width and thus the area of (expensive) PV cells. Using a trough shape the focus will not be affected by incidences in length direction other than normal. Compared to a parabolic trough a circular trough has a major advantage: at off-normal angles of incidence in width direction the focus will stay intact to some extend (Swinkels et al., 2007). Disadvantage of both circular an parabolic trough however is a decreasing focal length at off-normal incidence.

Shading

Shading of the PV-module can result in a strong decrease of power output of the PV-module (Sonneveld et al., 2010b). Shading is caused by the light-blocking effect of glazing bars and the absence of lamellae surface just under the glazing bars (necessary space for assembly and rotation of the lamella). The influence of the glazing bars is dual: the incoming as well as the reflected radiation will be blocked. In Figure 2 an example of shading on the PV-module is shown. The extent of power loss depends on the width of a single PV-cell. If the shadow covers the complete cell the electrical power will drop dramatically and with this the power of the whole PV-module as the cells are serially connected. Therefore, a module with small cells will be much more vulnerable for shading than a model with larger cells.

Lamellae with Generic Focal Length

The focal length of the lamellae is a parameter to optimize and as every lamella is located at a specific distance to the PV-module the optimal focal length should be determined for each individual lamella. However, a generic focal length is more convenient for manufacturing and reduces the cost of the system. In Figure 4 the yearly average concentration efficiency in relation to the generic focal length is shown for two different sizes of the CPVT-module (Fig. 4) An optimal generic focal length of about 2.6 m is found. Compared to flat lamellae the performance slightly improves while the number of lamellae and the PV-cell area is significant reduced with a factor 2. This will increase the overall concentration factor with the same value.

Lamellae with Individual Focal Length

Despite the increase mold costs in case of individual lamellae focus lengths this will increase the effectiveness of the concentrator system resulting in a increase energy yield. The optimal focal distance of each individual lamella was calculated (Fig. 5). From this figure a much lower efficiency of the lamellae at the right side of the lamellae position can be noticed due to unfavorable angles of incident for the incoming radiation. In Tables 1 and 2 an overview of the optimal focal lengths and radii of the different lamellae are shown for lamellae widths of 500 and 800 mm. In Table 3 the efficiency of the system with generic and individual optimized focal distance are presented for both lamellae widths. From this table the optimal yield is noticed for the individual optimized focal distance of the lamellae with a width of 500 mm. The concentration efficiency is also determined for the four seasons and given in Figure 6. For the annual electricity yield the influence of the roof slope is determined for four different sizes of the PV-Cells. In the line “bruto” the effect of shadow stripes is not taken into account.

CONCLUSIONS

This feasibility study has provided a greenhouse design combining reduced heat load with generation of electricity and thermal energy. The concept investigated is a greenhouse with symmetric cover (22° roof slope), a span width of 4 m and 60×40 mm glazing bars every 1.225 m and a high transparent glass covering material. With the spectral reflective lamellae, which reflect a part of the NIR radiation, the heat load inside the greenhouse can be reduced and the reflected NIR radiation can be focused to the CPVT-module. The optimization process is based on a maximal total annual electricity production and is performed with a ray tracing model and actual radiation data. Two types of lamellae are compared: flat and circular trough shaped lamellae. Compared to flat lamellae, circular trough shaped lamellae have the advantage of reducing the number of lamellae in combination width a high concentration factor. This will lower the costs for solar tracking by the lamellae. The reflected NIR radiation can be focused with a geometric concentration ratio of 100x. The lamellae will not only reflect 49% of the NIR radiation but also a considerable part of the whole solar spectrum. This total contribution will result in an effective concentration ration of 46x. The high geometric concentration ratio will limit the shadowing effect by the PV-cells with only 1%. Further optimalizations in the energy yield were performed on the optimal focal distance of the lamellae. The maximal annual electrical output was found for lamellae with individual optimized focal lengths. In that case the annual output for Dutch climate conditions can be over 29 kWh/m^2.

ACKNOWLEDGEMENTS

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Tables

Table 1. Optimal focal distance for each individual 5×800 mm lamellae.

Lamella	Focal distance [m]	Curvature
1	3.50	7.00
2	2.75	5.50
3	2.50	5.00
4	2.50	5.00
5	3.00	6.00

Table 2. Optimal focal distance for each individual 8×500 mm lamellae.

Lamella	Focal distance [m]	Curvature
1	3.75	7.50
2	3.25	6.50
3	2.75	5.50
4	2.50	5.00
5	2.50	5.00
6	2.50	5.00
7	2.75	5.50
8	3.00	6.00

Table 3. Comparison of the efficiencies and yearly yields.

Variant	Optimal focal distance	Efficiency [%]	Yield [kWh]
5 x 800 mm lamellae			
	generic	52.3	20.3
	individual	71.0	27.5
8 x 500 mm lamellae			
	generic	63.6	24.7
	individual	75.4	29.2

Figures

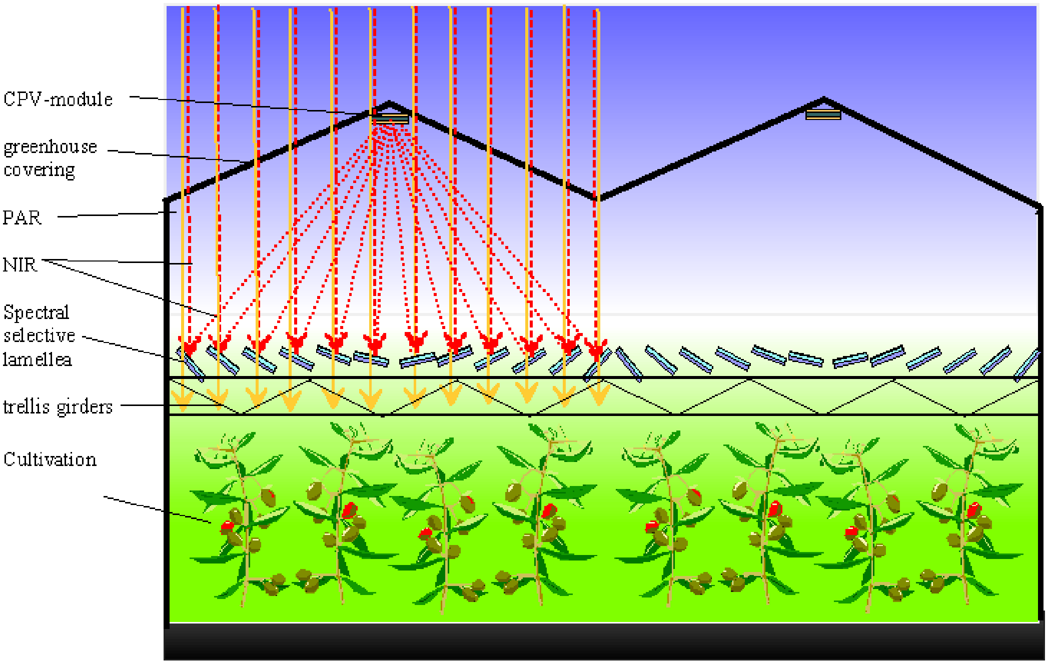

Fig. 1. A. Working principle of the NIR-concentrator System: the lamellae performed as a Fresnel mirror and reflect the direct solar Near Infrared Radiation (NIR) onto the PV-module (——►) indicate visual light, (——►) indicate NIR radiation.

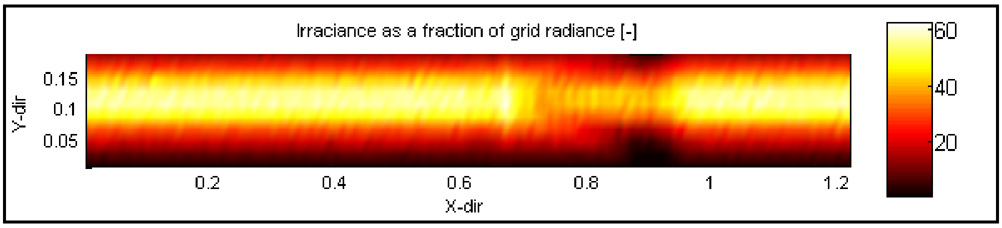

Fig. 2. Example of the light distribution on the PV-module. Shading on PV-cells causes significant loss of power output.

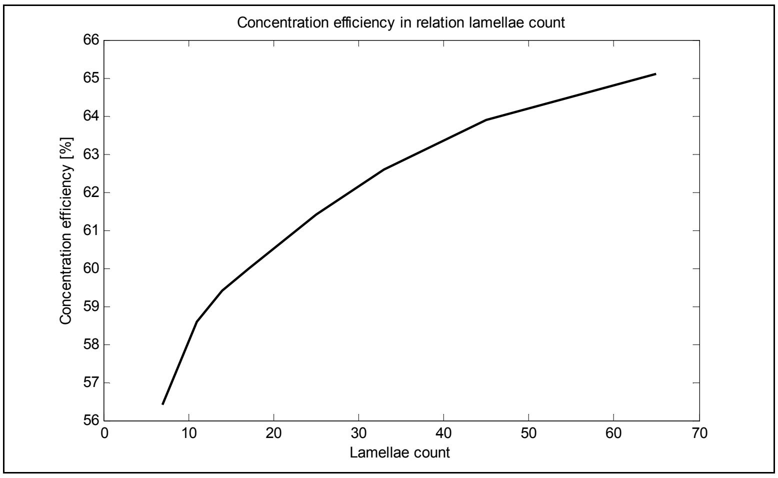

Fig. 3. Average annual concentration efficiency in relation to the lamellae.

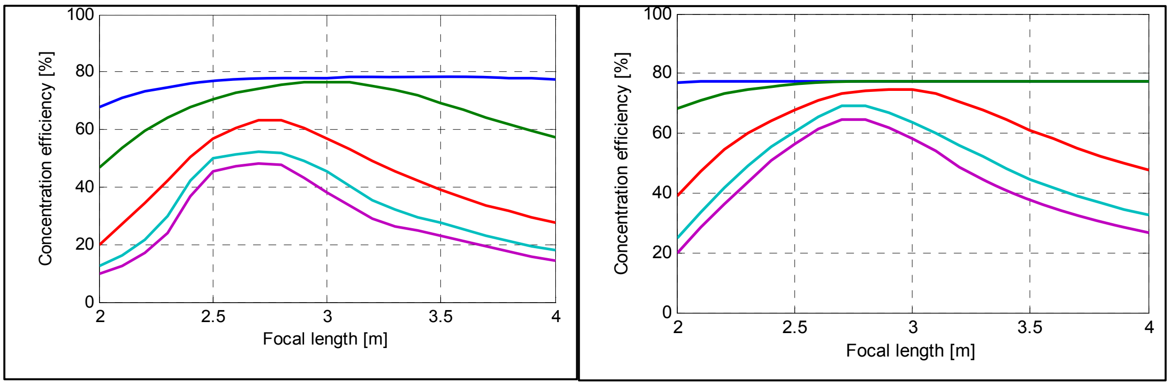

Fig. 4. Concentration efficiency as a function of the lamella width and the generic focal length of the lamellae (—lamella 1, —lamella 2, —lamella 3, —lamella 4, —lamella 5). Left: Module width 40 mm, right: Module width 80 mm.

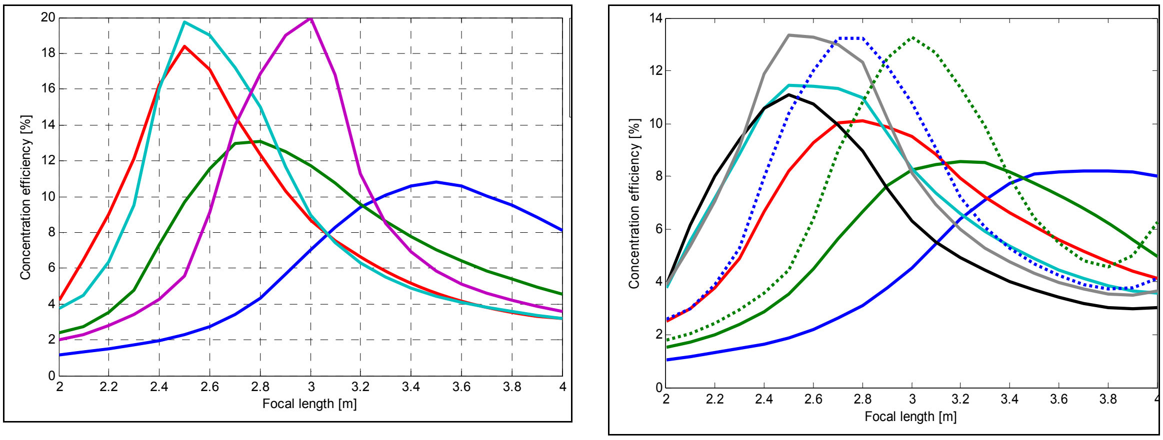

Fig. 5. Left: Concentration efficiency for the 5 lamellae of 800 mm. wide in relation to individual focal length. The blades are numbered from south to north (—lamella 1, —lamella 2, —lamella 3, —lamella 4, —lamella 5). Right: Concentration efficiency for the 8 lamellae of 500 mm wide in relation to individual focal length. The blades are numbered from south to north (—lamella 1, —lamella 2, —lamella 3, —lamella 4, —lamella 5, —lamella 6……lamella 7, ……lamella 8).

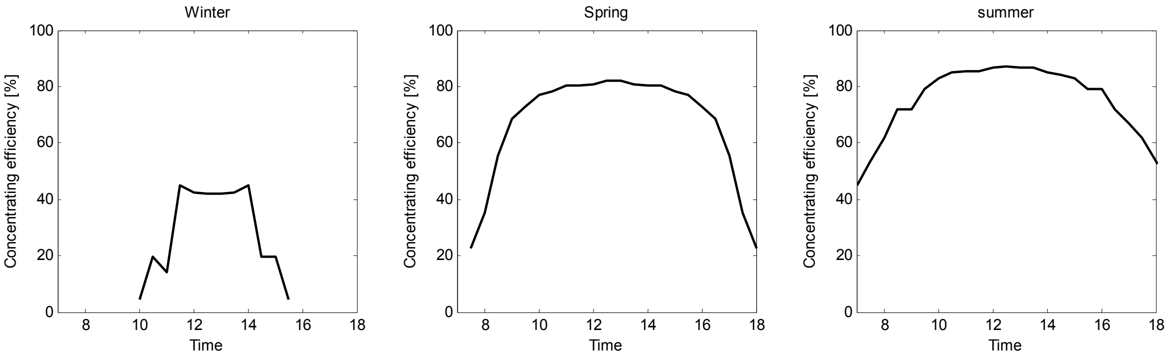

Fig. 6. Concentration efficiency of a system with 8 lamellae of 500 mm for a clear day in winter, spring and summer.