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Plant Production in Solar Collector Greenhouses - Influence on Yield, Energy Use Efficiency and Reduction in CO_2 Emissions

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Abstract

A semi-closed solar collector greenhouse was tested to evaluate the yield and the energy saving potential compared with a commercial greenhouse. As such, new algorithm for ventilation, carbon dioxide (CO_2) enrichment, as well as for cooling and heating purposes initiated by a heat pump, cooling fins under the roof and a low temperature storage tank were developed. This cooling system showed that the collector greenhouse can be kept longer in the closed operation mode than a commercial one resulting in high levels of CO_2 concentrations, relative humidity and temperatures. Based on these conditions, the photosynthesis and associated CO_2 fixations within the plant population were promoted during the experiment, resulting in a yield increase by 32%. These results were realized, although the mean light interception by energy screens and finned tube heat exchangers was increased by 11% compared to the reference greenhouse. The energy use efficiency was improved by 103% when the collector greenhouse was considered as energy production facility. In this context, the energy saving per kilogram produced tomatoes in the collector greenhouse is equivalent to the combustion of high amounts of different fossil fuels, where the reduced CO_2 emissions ranged between 2.32 kg and 4.18 kg CO_2 per kg produced tomatoes. The generated total heat was composed of approximately one-third of the latent heat and over two-thirds of the sensible heat, where a maximum collector efficiency factor of 0.7 was achieved.

Keywords: energy use efficiency, CO_2 emission, tomato, fossil fuel, solar energy, climate change, energy saving

1. Introduction

Originally, producers transferred field grown tomatoes to greenhouses in order to improve yield, to reduce phytosanitary problems and to extend the harvest season. However, this substantial progress is overshadowed by the increase in fossil fuel prices, where the demand for energy used in greenhouses is significant high (Ozkan, Fert, & Karadeniz, 2007; Rout et al., 2008). The energy consumption in Dutch greenhouses, for instance, accounts for 79% of the energy used in the agricultural sector and 7% of the total energy use in the Netherlands (Lansink & Bezlepkin, 2003). These dimensions show that the growth of greenhouse horticulture production contributes to a large proportion of carbon dioxide (CO_2) emissions, which are jointly responsible for the predicted mean global temperature increase (WBGU, 2008). Based on these facts, scientists invested much effort into the development of approaches for using renewable energies, in order to reduce the consumption of fossil fuels for greenhouse heating. Esen and Yuksel (2013), for instance, found that various renewable energy sources such as biogas, ground and solar energy can be efficiently used to heat a greenhouse during winter conditions in eastern Turkey. They demonstrated that a combination of flat-plate water cooled solar collectors, a biogas production plant and a ground source heat pump with horizontal slinky-type ground heat exchanger can be used as a stand-alone greenhouse heating system. Near-surface and deep geothermal-energy are also important alternative sources of energy for greenhouse heating, where the utilization of deep geothermal energy is not so prevalent in Germany (Lund, Freeston, & Boyd, 2005; Sanner, Karytsas, Mendrinos, & Rybach, 2003). Another source of energy is the solar energy, which can be collected in heated closed-greenhouses using cold water from soil layers (De Gelder, Dieleman, Bot, & Marcelis, 2012). After absorbing the excess heat in the greenhouse, the heat energy is stored in the aquifer, which can be reused in winter by means of a heat-pump (Bot, 2001). In this context, the solar radiation sum impinging on the earth´s surface in Berlin (52°28´02´´N, 13°17´56´´E) was

3992.4 MJ m^{-2} measured in 2011. This heat quantity per square meter is approximately equivalent to that produced by the combustion of 99.8 m³ methane, 159.8 kg coal, 99.8 kg vegetable oils, 199.6 kg wood pellets or 87.9 kg heating oil (Demirbas, 2004; Fassinou, Sako, Fofana, Koua, & Toure, 2010; iwo, 2012; Telmo & Lousada, 2011; Ulbig & Hoburg, 2002). Assuming that the light transmission of a conventional glass-covered greenhouse is 85% (Dannehl, 2010), it can act as a solar collector, whereby large amounts of energy can be collected and stored in summer, which would be available for heating during cooler periods. Therefore, the objectives of this study were to improve the CO_2 fixation within the crop, the total yield, the energy use efficiency (EUE) and an associated reduction in CO_2 emissions using a semi-closed greenhouse, which was controlled by new algorithm for cooling and heating purposes initiated by a heat pump, as well as for ventilation and CO_2-enrichment.

2. Materials and Method

2.1 Experimental Set-Up and Calculation of the Energy Distribution, as well as Climate Parameters

During an annual production in 2011, energy cycles and their effects on tomato plants in a conventional controlled four-span Venlo-type greenhouse (reference GH) (ground area = 307 m^2, floor level heating < 17 °C, ventilation opening > 24 °C, closed energy screen < 3 W m^{-2}) were compared with those prevailing in a semi-closed glasshouse with new algorithm for cooling, heating, ventilation and CO_2-enrichment. Both greenhouses were arranged on a north-south axis. The semi-closed greenhouse with a ground area of 307 m² acted as solar collector, where 16 finned tube heat exchangers (4 per roof bar) were installed under the roof region (Figure 1). These were used for cooling processes, whereby sensible heat caused by transmitted solar energy and latent heat produced by plant transpiration were collected simultaneously. The total length of one finned tube was 21.4 m, which was separated into 125 galvanised fins per meter of tube. The outer diameter of the core tube was 48.3 mm and that of the fin was 100 mm. The thickness of one fin was 0.8 mm. These dimensions lead to a total cooling surface of 684 m² resulting in a ratio of 2.23 in consideration of the total cooling surface and the ground area of the greenhouse. As coolant solution it was used water containing 31% glycol (v/v), which was pumped into the finned tubes with a minimum flow temperature of 7 °C. For this cooling process and for heating processes, a system consisting of a reversible heat pump with 40 kW electrical power, 120 kW heating power and 100 kW cooling power, as well as one warm water tank (1 m^3) and one cold water tank (1 m^3) was connected to this pipe system. In this context, a maximum cooling capacity of 390 W m^{-2} can be achieved. While the ventilation was opened in the reference GH to lower the inside temperature, the cooling process in the solar collector greenhouse (collector GH) was started at a temperature of 22 °C followed by the ventilating at 29 °C to avoid plant damage. During cooling processes, large amounts of energy were collected simultaneously. The generated heat was determined using magnetic inductive heat meters with a measuring inaccuracy of 0.02 K and stored in a rain-water tank (300 m³), which is commonly used in practice for rain water storage. The tank was additionally equipped with polystyrene insulation panels to suppress heat losses. This type of energy harvesting was associated with the dehumidification of greenhouses, which was realized by the removal of water vapour by means of condensation on the cooled finned tubes. The resulting excess condensate water was removed using aluminium gutters, which were fixed below the cooling pipes (Figure 1). This water was measured automatically with a precisely operating volumetric dosing system to calculate the latent energy (1 L is equal to 2.49 MJ) and to derive the sensible energy from the total energy that was removed from the greenhouse. The collected energy dimension of this system was shown as an example for one week and expressed as the daily amount of energy per square meter ground area of the greenhouse (MJ m^{-2}).

The stored thermal energy above 30 °C was used directly for heating in the collector GH, whereas lower water temperatures in the rain-water tank between 7 °C and 30 °C were increased to the required level by a heat pump. At temperatures below 7 °C in the rain-water tank, a floor-level heating was used for the heat output in cooler periods. Otherwise, the heat supply in the collector GH was realized via heat exchanger, i.e., using tubular film blowers fixed under the channels (set = 16 °C) and a vegetation heating system (set = 17 °C). Additionally, the reference GH was fitted with a daily energy screen, whereas the collector GH was equipped beside a daily energy screen with highly aluminized energy screens in the roof and side wall regions to avoid energy losses. To improve the conditions of plant production, the carbon dioxide fumigation was applied in both greenhouses up to a level of 800 ppm for 12 hours, starting at 6 AM. In this context, the CO_2 supply was interrupted when the ventilation was opened above 10%. To obtain the desired environmental conditions in both greenhouses, all the aforementioned set points for climatic conditions were controlled by different sensors arranged in the middle of the growing tomato plants and under the roof. To provide accurate values of the experimental conditions, the measurement uncertainties of the relative humidity sensors, temperature sensors and CO_2 sensors were maintained as low as possible, i.e. high precision sensors were used. In this context, the measurement uncertainties caused by the sensors were ± 3%, 0.02 K and ± 3%, respectively. Furthermore, the sensors were calibrated at regular intervals to ensure scientifically proven results. The measurements were forwarded to a central control computer and recorded every 30 seconds, where the software program for controlling the operating mode of the greenhouses was developed at the Humboldt-Universität zu Berlin.

In order to show how the different climate control strategies affect the microclimatic conditions, the mean values of microclimatic data were separately logged for each greenhouse and subsequently used to calculate the daily average of CO_2 concentration, relative humidity (RH) and temperature. The results were expressed as ppm d^{-1}, % d^{-1} and °C d^{-1}, respectively.

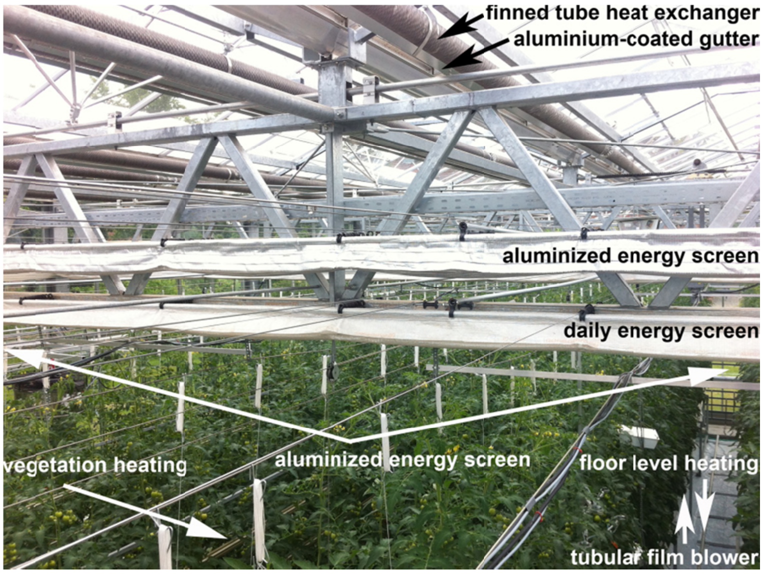

Figure 1. Equipment for cooling and heating of the solar collector greenhouse

2.2 Yield Determination and Calculation of the Fixed CO_2 Within the Tomato Crop and Light Distribution

A net-acreage of 200 m² per greenhouse was used to cultivate 400 tomato plants (cv. Pannovy), respectively. These were grown on the high channel in rock-wool slabs and irrigated *via* drip irrigation, which was controlled using light summation and by the recirculation of drain water after each irrigation cycle (set = 30%). This study was conducted between February and October 2011. During this time, the harvested tomatoes of each plant (n = 400) were weighed weekly to compare the total yield (kg m^{-2}) potential and the total number of marketable fruit in terms of both previously described climate regimes. To determine fruit quality, parts of the harvested fruit were additionally categorized into different weight classes named as A-fruit (> 70 g), B-fruit (50-70 g), C-fruit (< 50 g) and blossom-end rot fruit (BER). As such, 100 tomato plants (n = 100) of each greenhouse were evaluated weekly to calculate the number of fruit of the respective weight class. At the end of the production cycle, the number of fruit of the individual quality characteristic was extrapolated to the total number of fruit, which were harvested during the whole cultivation period. The results were expressed as number of fruit per square metre.

Preliminary experiments showed that the photosynthesis can be measured with high accuracy using the Berlin Plant Response Monitoring System (BERMONIS). Under the same measurement conditions, the highest variation of photosynthesis regarding two different devices of the same type was not higher than 1.9% (Schmidt et al., 2013). In the present study, ten leaf cuvettes per greenhouse were fixed at different heights in the canopy to measure the photosynthesis every 30 seconds as CO_2-gas exchange ($GECO_2$) using the leaf cuvette based gas exchange system BERMONIS. As such, the volumetric flow rate of the air (Q), the CO_2 level difference between ambient air and the air in the chamber ($DiffCO_2$), the atmospheric pressure (p), the chamber area (ChA), the air temperature (T_{AIR}) and a constant (29.93), derived from the molar mass and the specific gas constant of CO_2, were used to calculate $GECO_2$ (Equation 1). The amount of the $GECO_2$ was generated daily excluding all dissimilation processes. To evaluate the fixed CO_2 within the tomato crop, the daily quantity of the $GECO_2$, the leaf area index for the respective greenhouse and the molar mass of CO_2 were included in the calculations. The results were plotted cumulatively, where the measurements of the $GECO_2$ started one week before the first harvest of tomatoes began. The fixed CO_2 was expressed as gram CO_2 per square meter of the cultivated net-acreage (g CO_2 m^{-2}). The $GECO_2$ was specified as follows:

$$\mathrm{GECO_2} = \frac{\mathrm{Q} \times \mathrm{DiffCO_2} \times \mathrm{p}}{29.93 \times \mathrm{ChA} \times \mathrm{T}_{AIR}} \tag{1}$$

To determine the light conditions in the passively cooled greenhouse, the spatial light difference ratio between the reference GH and the collector GH was calculated. As such, 84 measuring points were located at a height of 4.60 meters for a uniform measuring distribution. The incoming light in both greenhouses was measured with PAR-sensors at the same measuring points and at the same time on a sunny day in October 2011. Subsequently, the spatial light difference ratio in the collector GH was derived, where zero is defined as 100% of the incoming light in the reference GH. The results were expressed as percentage (%).

2.3 Calculation of the Energy Use Efficiency and Reduced Fuel Consumption

The energy use efficiency is defined as the amount of energy required to produce one kg of marketable fruit and was expressed as MJ kg^{-1}. The calculations were performed cumulatively, where the respective tomato yield and the energy consumption of each greenhouse were used. In this context, variables such as the energy consumed (EC) for the circulation pumps (CP) and for heat pump processes (HP), the primary energy factor for electrical energy (PFEE) and the collector GH as heat producing system were considered to calculate the EUE for the collector GH (Equation 2). The latter means that the excess energy (EE) stored in the rain water tank was subtracted from the actual energy consumption in the collector GH, because the available energy could theoretically be used elsewhere. Regarding the reference GH, the EUE was calculated in consideration of the consumption of district heat (DH), the primary energy factor for district heat (PFDH) and excluding energy generation (Equation 3). The EUE was calculated as follows:

$$\mathrm{EUE}_{collector\ GH} = \frac{(\mathrm{EC}_{DH} \times \mathrm{PFDH}) + (\mathrm{EC}_{CP+HP} \times \mathrm{PFEE}) - (\mathrm{EE})_0}{\mathrm{Total\ yield}} \tag{2}$$

$$\mathrm{EUE}_{reference\ GH} = \frac{(\mathrm{EC}_{DH} \times \mathrm{PFDH})_0}{\mathrm{Total\ yield}} \tag{3}$$

The EUE was plotted weekly from the first to the last harvest date. In this context, the energy consumption from planting to the first harvest date was added in equal amounts to each calculation of the EUE. An improved EUE exists when less energy is required for the same amount of tomato fruit.

To evaluate the possible reduction of the fuel consumption per kilogram produced tomatoes using a collector GH, the difference of the energy use efficiency between the collector and reference greenhouse was calculated at the end of the experiment. This result and the heating value of a variety of fuels were set in relation, in order to calculate the equivalent amount of the corresponding fuel and CO_2 emissions produced by their combustion. The heating values of natural gas, coal, vegetable oils, heating oil and wood pellets, as well as their properties regarding CO_2 release were used as reported by Ulbig and Hoburg (2002), Demirbas (2004), Fassinou et al. (2010), iwo (2012), Telmo and Lousada (2011) and using a special software program named GEMIS version 4.8 (GEMIS, 2010), respectively. Depending on the heating material, the saved fuel was either expressed as cubic metre or kilogram per kilogram tomatoes, whereas the reduced CO_2 emission was displayed as kilogram CO_2 per kilogram tomatoes.

2.4 Statistical Analysis

The effect of the CO_2 fixation within the crop on the yield increase was evaluated with SPSS, package version 19.0. In this context, the linear correlation between these variables was calculated *via* linear regression analysis to obtain the coefficient of determination (R^2) and to test whether the slope (m) in $y = mx + b$ differs significantly ($p < 0.05$) from zero. Comparisons regarding fruit yield and the number of fruit were calculated using t-tests ($p < 0.05$). Asterisks or different small letters indicate significant differences. The mean variability is pointed out by the standard deviation (±). All other calculations regarding CO_2 fixation, energy distribution and EUE were calculated with EXCEL, package version 2010.

3. Results and discussion

3.1 Generation of Energy Using a Solar Collector Greenhouse and Changes in Climate Conditions

During the warm period, the energy caused by the transmitted solar radiation and water vapour was captured using a cooling fin system under the roof, which was connected to a reversible heat pump and a low temperature storage tank. The graphs in Figure 2 present the behaviour of the removed energy depending on the transmitted solar radiation for seven days during the summer period in 2011. On the fifth day of the recorded data, a maximum daily amount of energy (11.5 MJ m^{-2}) was removed from the collector greenhouse, where a maximum cooling capacity of 368 W m^{-2} was measured. The calculations showed that a maximum collector efficiency factor of 0.7 was achieved on this day, when the removed total energy was considered in relation to the transmitted solar energy. Comparable results regarding cooling capacity and collector efficiency were reported by Grisey, Grasselly, Rosso, D´ Amaral, and Melamedoff (2011), who have used 9 FiWiHEx® heat exchanger. This type of cooling is referred to as active cooling, which requires high amounts of energy for ventilators, pumps and the cooling machine. In the present study, however, a passive cooling system only equipped with cooling pipes and a reversible heat pump was used. Therefore, the construction of the collector GH can be applied to reduce the energy costs compared with the FiWiHEx® system mentioned before. According to Eisenmann, Vajen, and Ackermann (2004), as well as Kumar and Prasad (2000), the collector efficiency factor of a thermal solar collector ranged between 0.7 and 0.9. Despite these higher values, the effectiveness of the installed system in the solar collector greenhouse is comparable to a thermal solar collector due to the fact that higher plate temperatures result in more heat losses, which lead to a lower value of the collector efficiency factor (approximately 0.5) of such systems. Based on an annual production of tomatoes, this value corresponds to the mean value obtained in the collector GH. In general, the captured total energy increased with increasing solar radiation (R^2 = 0.87) (Figure 2). This result was caused by low ventilation, a high ambient temperature and higher levels of relative humidity. In relation to the total energy removal, the mean daily quantity of sensible heat energy and latent energy was 71% and 29%, respectively. However, it was shown that the rate of latent energy can be increased to 44% when a dehumidification system combined with a cucumber crop is used (Campen & Bot, 2002; Campen, Bot, & de Zwart, 2003). Viewed over the year, a total amount of energy of 50% of the impinging solar radiation sum was collected with the solar collector greenhouse, although the emergency ventilation was frequently activated to avoid plant damage. In this context, it should be pointed out that a high energy removal in the closed operation mode is accompanied by high levels of temperature and relative humidity as shown in Figure 3. Based on the semi-closed operation mode in the collector GH, a mean RH of approximately 92% was maintained during the production cycle, whereas the RH in the conventionally controlled greenhouse varied widely from 64% to 92% (Figure 3). Due to the later opening of the ventilation in the collector GH, a higher mean temperature and mean CO_2 concentration were reached compared to the reference GH. A maximum difference in the daily mean temperature (2 K) and CO_2 concentration (233 ppm) was measured in spring. However, the calculated levels of RH, temperature and CO_2 did not differ significantly during the autumn period, which was caused by cooler outside conditions and the associated ventilation set-point in the reference GH. These characteristics may influence the plant vigour, e.g., the occurrence of *Botrytis* (Heuvelink, Bakker, Marcelis, & Raaphorst, 2008) and can complicate the working conditions for the employees, especially in summer time. Therefore, the challenge to producers is to learn how to work using the new system, including the use of precise measuring technologies, to control dew points and plant physiological processes.

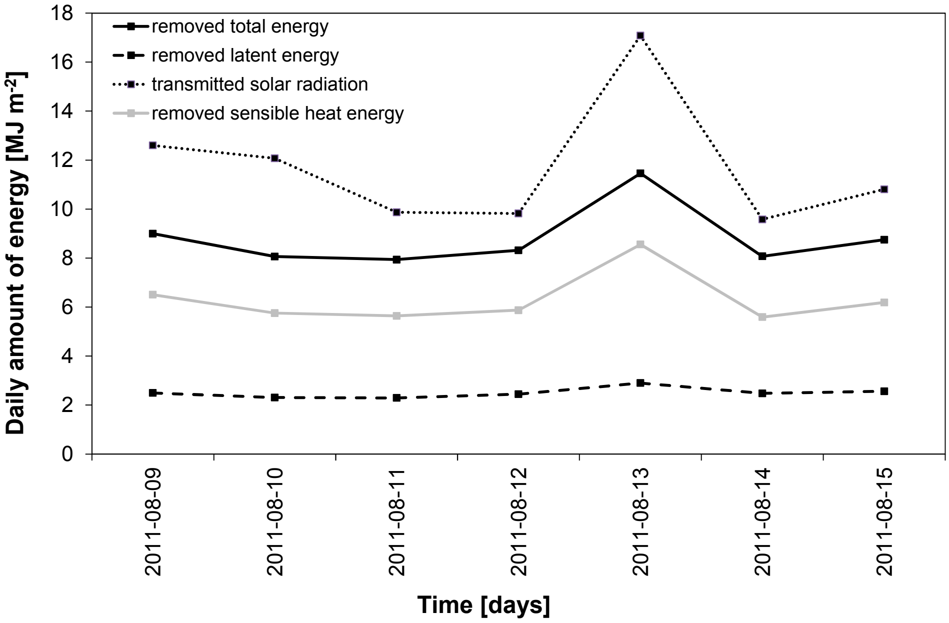

Figure 2. Collected energy dimensions depending on transmitted solar radiation

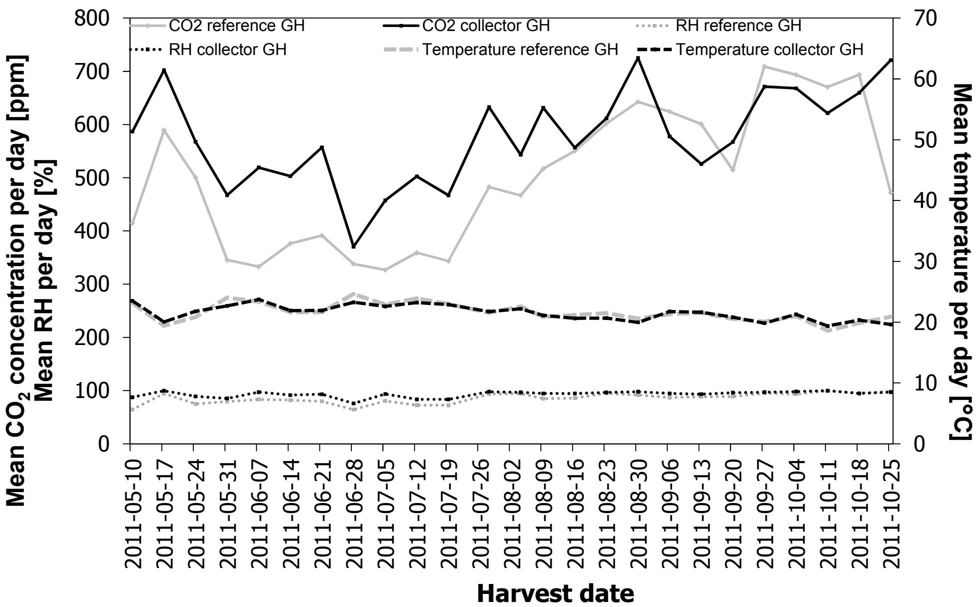

Figure 3. Effects of different cliamte control stratgies on relative humidity, temperature and CO_2 concentration during harvest period

3.2 Effects of Prevailing Climate Conditions in a Solar Collector Greenhouse on Fruit Yield and CO_2 Fixation

In comparison with the conventional climate control strategy, it was found that changing climate conditions - caused by the collector GH - were responsible for a significantly increase in quantity of tomatoes (Figure 4). A maximum yield increase by 32% was achieved at the end of the experiments. This extra yield was attained, even though the mean light intensity in the collector GH was reduced by 11%. This result was computed from the spatial light difference ratio as shown in Figure 5. The low values of these calculations were mainly induced due to the cooling fins and energy screens installed in the roof region of the collector GH, where it meight be possible that probably 3% of the light was intercepted by the cooling fins as shown by Campen and Bot (2002). Light sinks especially occurred under the energy screens as detected at the measuring point one, four, seven, ten and twelve. Marcelis, Broekhuijsen, Meinen, Nijs, and Raaphorst (2006) reported that 1% less radiation results in 0.6% to 1.1% less production of tomatoes. These results were not confirmed in the present study as previously described. Rather, it might be possible that compensations for the light deficiency can be obtained by the optimisation of other climatic parameters, such as temperature, relative humidity and CO_2 concentration, particularly in spring and summer. Based on the ventilation behaviour and associated changing climate conditions, it was demonstrated that the calculated CO_2 fixation within the crop was increased by 77% compared to that observed in the reference GH (Figure 4). When a collector GH was used, 60% of the enriched technical CO_2 was fixed within the crop, whereas this amount was reduced to approximately 35% by the influence of the reference situation. In this context, it is common in commercial practice that the CO_2 enrichment remains switched on in greenhouses, although the ventilation is opened. Compared to this case, the operation mode of a semi-closed greenhouse leads to a reduction in CO_2 emissions and costs of the technical CO_2, because it can be kept longer closed. Furthermore, a significant correlation and a significantly increased slope compared with zero was found between the cumulative CO_2 fixation and the total yield ($R^2 = 0.89$; $m = 3.55$, $p = 0.000$). Regarding photosynthetic activity, the results do not agree with those of other scientists. Besford, Ludwig, and Withers (1990), for instance, found that plants did not maintain a photosynthetic gain with longer-term CO_2 enrichment at 1000 ppm. However, plants in this investigation were solely exposed to different CO_2 concentrations, while the temperature and the relative humidity remained unchanged. Therefore, the evidence in the current study indicated that a combination of higher levels of temperatures, relative humidity and CO_2 concentration in a semi-closed GH promoted photosynthesis, which resulted in an increased CO_2 fixation and an associated increase in total yield. This total yield was characterized by high quality fruit consisting of a significantly increased number of marketable fruit (24%) when compared with the reference plants. This means in detail that the number of A-fruit was increased and that of B-fruit was decreased by 45% and 8%, respectively (Figure 6). Furthermore, the occurrence of BER-fruit was affected by the collector GH, because the number of these fruit was reduced by up to 83% in relation to that of BER-fruit formed under conventional conditions. It is assumed that the lower levels of RH in the reference GH led to high transpiration losses followed by a calcium deficiency in plant cells during the summer period. In this case, the BER-fruit can spread throughout the crop as shown by De Kreij (1996).

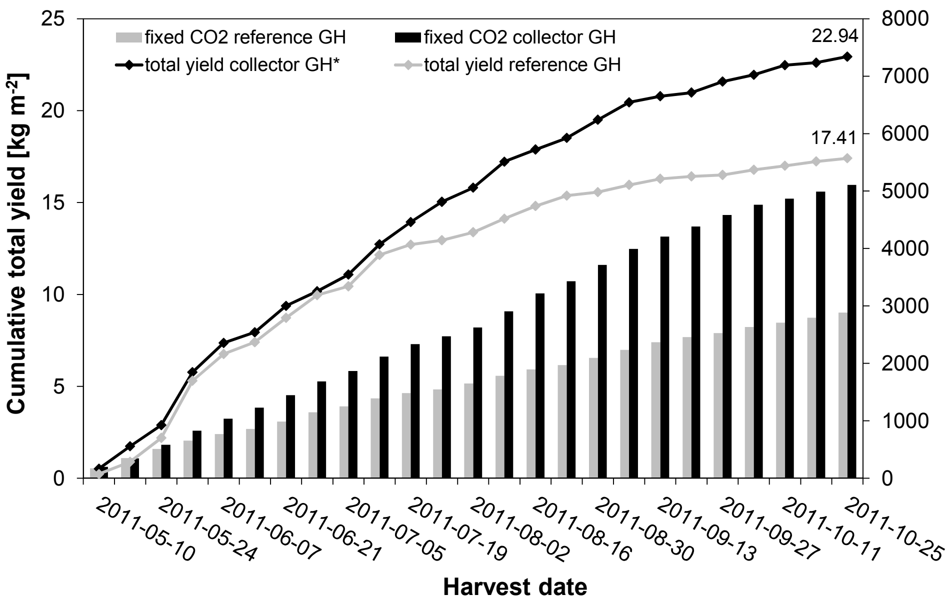

Figure 4. Effects of different climate control strategies on the cumulative total yield (n = 400) and carbon dioxide fixation within the crop. The total was tested using t-tests, where asterisks indicate significant differences in total yield at the end of the experiment ($p < 0.05$)

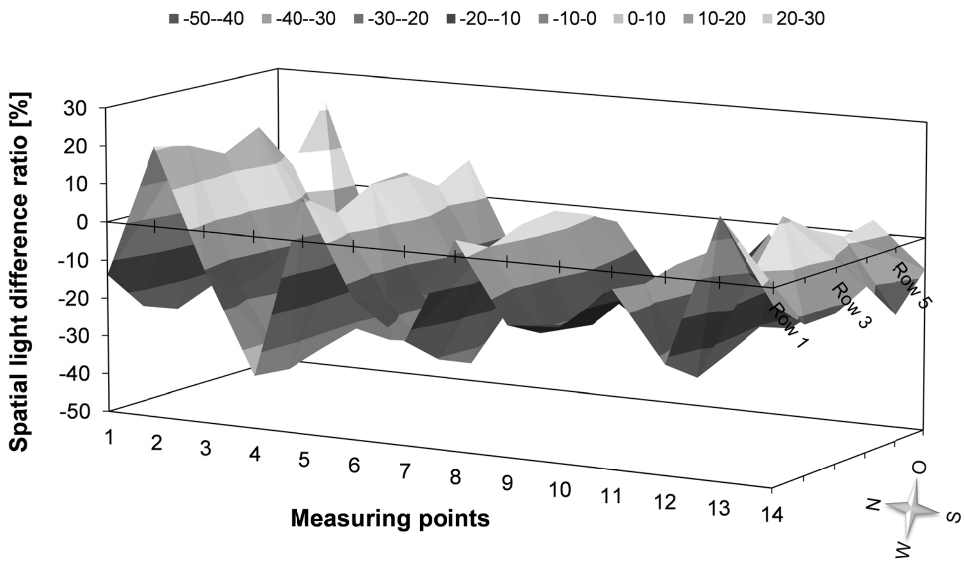

Figure 5. The spatial light difference ratio in the collector greenhouse versus reference greenhouse (n = 84). Zero is defined as 100% of the incoming light in the reference greenhouse

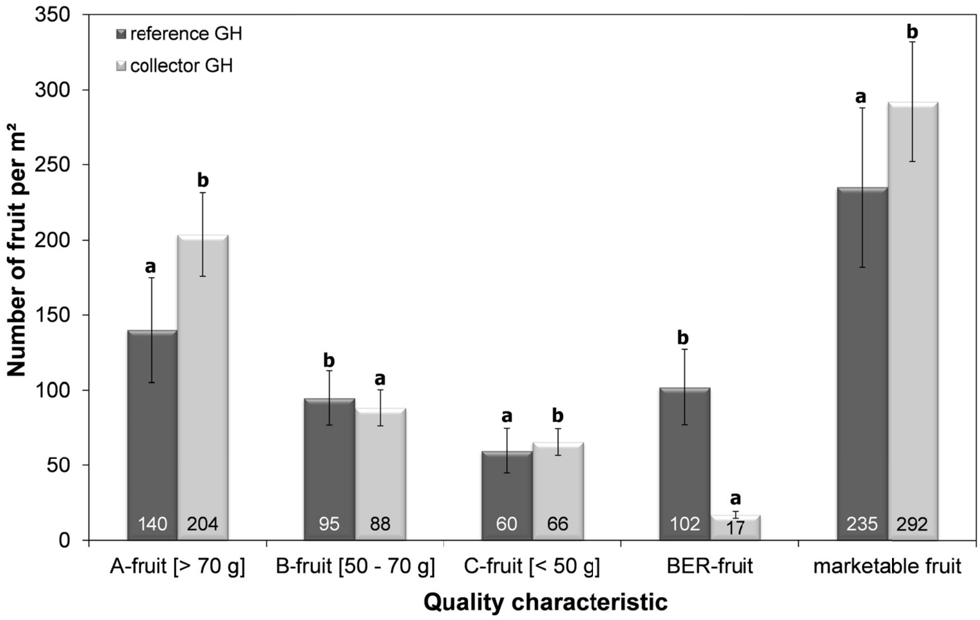

Figure 6. The effects of different climate control strategies on fruit quality (n = 400). The number of fruit was tested using t-tests, where small letters indicate significant differences in number of fruit at the end of the experiment ($p < 0.05$)

3.3 Influence of a Solar Collector Greenhouse on the Energy Use Efficiency and Reduced Fuel Consumption

The EUE is a useful tool to estimate the total energy use for greenhouse production. In the present study, the EUE for both greenhouses was approximately 40 MJ kg^{-1} produced tomatoes, when the excess energy stored in the rain water tank was not considered to calculate the EUE for the collector GH (data not shown). In contrast, the results elucidated that the EUE in the collector GH can be improved by 103% compared to the reference GH as consequence of the reuse of the stored energy. Based on the dimension of the cooling system in the collector

GH and using the equation to calculate the EUE (Equation 2), an energy input of -1.41 MJ had to be applied in the collector GH, in order to produce one kilogram tomatoes (Figure 7). Therefore, an energy gain was achieved in the solar collector greenhouse at the end of the experiment (Figure 7). Comparable values were determined in Spain and in the tropics of Columbia as well (Elings et al., 2005; Medina, Cooman, Parrado, & Schrevens, 2006). With respect to these countries, an EUE level of 1.97 MJ kg^{-1} and 1.11 MJ kg^{-1} was estimated, respectively, where this low energy input for crop production was a result of unheated greenhouses. However, the energy use efficiency in the collector GH was improved by means of the additional yield, collected solar energy throughout the year and strongly aluminized energy screens. Due to the energy screens, the energy demand decreased with increasing insulation up to 33% (data not shown). Similar results were reported by Tantau (1998) and Bot et al. (2005) using thermal screens. Furthermore, the deteriorating energy use efficiency in the collector GH was assessed as a disadvantage, which was observed over the harvest period (Figure 7). This result was a consequence of the energy consumption for cooling processes in summer, whereas this procedure contributed to the fact that large amounts of energy were stored in the rain water tank. Especially in summer, there was an energy excess, which can be used primarily to cover the basic load for heating in other greenhouses or to provide subareas in greenhouses with luxury heat. The stored energy can also be delivered to sanitary facilities in the immediate vicinity or to postharvest processes, e.g., for drying of tomatoes. In this context, the collected heat can be directly applied via heat exchangers to fruit, because a low drying air temperature protects the quality of nutritional components in tomatoes (Hossain, Amer, & Gottschalk, 2008). Moreover, the water containing in the low temperature storage tank had drinking water quality concerning microbiology criteria, although this was circulated in cooling and heating processes for a year. Neither Escherichia coli (≤ 0 most probable number 100 ml^{-1}) nor coliform bacteria (≤ 0 most probable number 100 ml^{-1}) were detected in this water. Therefore, it can be reused for watering without concern.

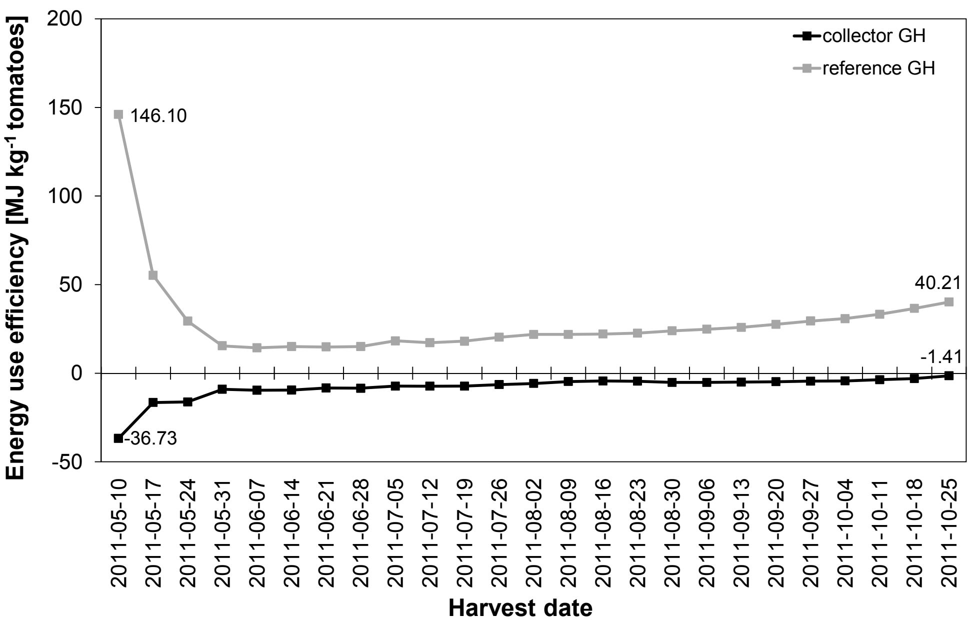

Figure 7. The weekly cumulative energy use efficiency depending on different operation modes of greenhouses

Finally, the energy saving per kilogram produced tomatoes in the collector GH is equivalent to the combustion of 1.04 m^3 natural gas, 1.67 kg coal, 1.04 kg vegetable oil, 0.92 kg heating oil or 2.08 kg wood pellets when compared with the conventional tomato production (Figure 8). Hence, this technology can be utilized to reduce a substantial volume of CO_2 emissions, whereby it is possible to produce tomato plants in a sustainable way. The equivalent reduced CO_2 emission ranged between 2.32 kg and 4.18 kg CO_2 per kg produced tomatoes, where these data depend on the fuel used (Figure 8).

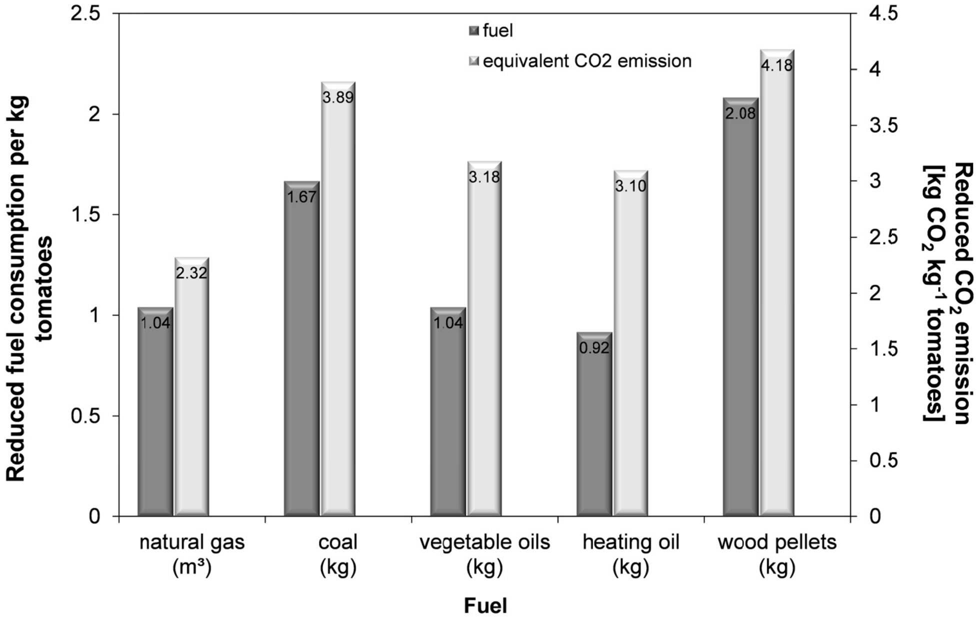

Figure 8. Several examples of a possible reduction of the fuel consumption per kilogram produced tomatoes in the collector greenhouse and fuel-related CO_2 emissions released by their combustion

4. Conclusion

Due to the results, it was concluded that a semi-closed solar collector greenhouse can be recommended as agronomic approach to produce a high quantity of marketable tomatoes and additional energy, whereby the environment can be relieved. On an annual basis, a considerable amount of energy of the incoming solar radiation was captured using the cooling fin system. This energy can be reused for heating in cooler periods or provided for the heat export to other purchasers. Furthermore, the mean light interception of 11% caused by energy screens and cooling fins in the collector GH did not influence the yield adversely. The opposite was observed. It is obviously possible that a reduced ventilation opening and associated higher levels of temperatures, relative humidity and CO_2 concentrations can compensate the light reduction over the year, leading to higher CO_2 fixation and more yields. Nevertheless, a lower light interception by mounting parts (e.g., energy screens) should be sought in future projects, whereby possibly higher yield differences between both climate control strategies could be achieved. In this context, a combination of a solar collector and a conventional greenhouse area in a ratio of one to three is conceivable. As such, the excess energy may be provided for the conventional greenhouse production while the light reduction caused by cooling fins and additional energy screens is limited to the closed greenhouse area.

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References

Besford, R. T., Ludwig, L. J., & Withers, A. C. (1990). The greenhouse effect: acclimation of tomato plants growing in high CO_2, photosynthesis and ribulose-1, 5-bisphosphate carboxylase protein *Journal of Experimental Botany, 41*(229), 925-931. http://dx.doi.org/Doi 10.1093/Jxb/41.8.925

Bot, G. P. A. (2001). Developments in indoor sustainable plant production with emphasis on energy saving. *Computers and Electronics in Agriculture, 30*(1-3), 151-165. http://dx.doi.org/10.1016/s0168-1699(00)00162-9

Bot, G. P. A., Van de Braak, N., Challa, H., Hemming, S., Rieswijk, T., Von Straten, G., & Verlodt, I. (2005). The solar greenhouse: State of the art in energy saving and sustainable energy supply. *Acta Horticulturae,* *691*, 501-508.

Campen, J. B., & Bot, G. P. A. (2002). Dehumidification in greenhouses by condensation on finned pipes. *Biosystems Engineering, 82*(2), 177-185. http://dx.doi.org/10.1006/beng.2002.0058

Campen, J. B., Bot, G. P. A., & de Zwart, H. F. (2003). Dehumidification of greenhouses at northern latitudes. *Biosystems Engineering, 86*(4), 487-493. http://dx.doi.org/10.1016/j.biosystemseng.2003.08.008

Dannehl, D. (2010). *Gewächshaus-Eindeckmaterialien. Die Bedeutung der Lichtquantität und Lichtqualität in Tropenhäusern*. Saarbrücken: VDM Verlag Dr. Müller.

De Gelder, A., Dieleman, J. A., Bot, G. P. A., & Marcelis, L. F. M. (2012). An overview of climate and crop yield in closed greenhouses. *Journal of Horticultural Science & Biotechnology, 87*(3), 193-202.

De Kreij, C. (1996). Interactive effects of air humidity, calcium and phosphate on blossom-end rot, leaf deformation, production and nutrient contents of tomato. *Journal of Plant Nutrition, 19*(2), 361-377.

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science, 30*(2), 219-230. http://dx.doi.org/10.1016/j.pecs.2003.10.004

Eisenmann, W., Vajen, K., & Ackermann, H. (2004). On the correlations between collector efficiency factor and material content of parallel flow flat-plate solar collectors. *Solar Energy, 76*(4), 381-387. http://dx.doi.org/10.1016/j.solener.2003.10.005

Elings, A., Kempkes, F. L. K., Kaarsemaker, R. C., Ruijs, M. N. A., Van de Braak, N. J., & Dueck, T. A. (2005). The energy balance and energy-saving measures in greenhouse tomato cultivation. *Acta Horticulturae, 691*(691), 67-74.

Esen, M., & Yuksel, T. (2013). Experimental evaluation of using various renewable energy sources for heating a greenhouse. *Energy and Buildings, 65*, 340-351. http://dx.doi.org/10.1016/j.enbuild.2013.06.018

Fassinou, W. F., Sako, A., Fofana, A., Koua, K. B., & Toure, S. (2010). Fatty acids composition as a means to estimate the high heating value (HHV) of vegetable oils and biodiesel fuels. *Energy, 35*(12), 4949-4954. http://dx.doi.org/DOI 10.1016/j.energy.2010.08.030

GEMIS. (2010). Global Emissions Model for Integrated Systems, 2013. Retrieved from http://www.iinas.org/gemis-download-de.html

Grisey, A., Grasselly, D., Rosso, L., D´ Amaral, F., & Melamedoff, S. (2011). Using heat exchanger to cool and heat a closed tomato greenhouse: application in the south of France. *Acta Horticulturae, 893*, 405-411.

Heuvelink, E., Bakker, M., Marcelis, L. F. M., & Raaphorst, M. (2008). Climate and yield in a closed greenhouse. *Acta Horticulturae, 801*, 1083-1092.

Hossain, M. A., Amer, B. M. A., & Gottschalk, K. (2008). Hybrid Solar Dryer for Quality Dried Tomato. *Drying Technology, 26*(12), 1591-1601. http://dx.doi.org/10.1080/07373930802467466

Iwo. (2012). Das Plus an Informationen zum Produkt Heizöl EL (pp. 4-43). Hamburg: Institut für Wärme und Oeltechnik.

Kumar, A., & Prasad, B. N. (2000). Investigation of twisted tape inserted solar water heaters - heat transfer, friction factor and thermal performance results. *Renewable Energy, 19*(3), 379-398. http://dx.doi.org/10.1016/S0960-1481(99)00061-0

Lansink, A. O., & Bezlepkin, I. (2003). The effect of heating technologies on CO2 and energy efficiency of Dutch greenhouse firms. *Journal of Environmental Management, 68*(1), 73-82. http://dx.doi.org/10.1016/S0301-4797(02)00233-5

Lund, J. W., Freeston, D. H., & Boyd, T. L. (2005). Direct application of geothermal energy: 2005 Worldwide review. *Geothermics, 34*(6), 691-727. http://dx.doi.org/10.1016/j.geothermics.2005.09.003

Marcelis, L. F. M., Broekhuijsen, A. G. M., Meinen, E., Nijs, E. M. F. M., & Raaphorst, M. G. M. (2006). Quantification of the growtdh response to light quantity of greenhouse grown crops. *Acta Horticulturae, 711*, 97-103.

Medina, A., Cooman, A., Parrado, C. A., & Schrevens, E. (2006). Evaluation of energy use and some environmental impacts for greenhouse tomato production in the high altitude tropics. *Acta Horticulturae, 718*, 415-422.

Ozkan, B., Fert, C., & Karadeniz, C. F. (2007). Energy and cost analysis for greenhouse and open-field grape production. *Energy, 32*(8), 1500-1504. http://dx.doi.org/10.1016/j.energy.2006.09.010

Rout, U. K., Akimoto, K., Sano, F., Oda, J., Homma, T., & Tomoda, T. (2008). Impact assessment of the increase in fossil fuel prices on the global energy system, with and without CO2 concentration stabilization. *Energy Policy, 36*(9), 3477-3484. http://dx.doi.org/10.1016/j.enpol.2008.05.030

Sanner, B., Karytsas, C., Mendrinos, D., & Rybach, L. (2003). Current status of ground source heat pumps and underground thermal energy storage in Europe. *Geothermics, 32*(4-6), 579-588. http://dx.doi.org/10.1016/s0375-6505(03)00060-9

Schmidt, U., Schuch, I., Dannehl, D., Rocksch, T., Salazar Moreno, R., Rojano Aguilar, A., & Lopez, I. (2013). Long time plant response measurements for yield prediction, water use and climate control optimization using gas exchange measurements in semi closed and ventilated greenhouses. *Acta Horticulturae*, submitted.

Tantau, H. J. (1998). Energy saving potential of greenhouse climate control. *Mathematics and Computers in Simulation, 48*(1), 93-101. http://dx.doi.org/10.1016/S0378-4754(98)00145-1

Telmo, C., & Lousada, J. (2011). The explained variation by lignin and extractive contents on higher heating value of wood. *Biomass & Bioenergy, 35*(5), 1663-1667. http://dx.doi.org/10.1016/j.biombioe.2010.12.038

Ulbig, P., & Hoburg, D. (2002). Determination of the calorific value of natural gas by different methods. *Thermochimica Acta, 382*(1-2), 27-35. http://dx.doi.org/10.1016/S0040-6031(01)00732-8

WBGU. (2008). *Welt im Wandel. Sicherheitsrisiko Klimawandel*: Springer-Verlag, Berlin Heidelberg.