Use of Supplementary Lighting Top Screens and Effects on Greenhouse Climate and Return on Investment

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Abstract

Discomfort caused by light pollution from greenhouses that apply supplementary lighting is an issue in Dutch society nowadays. At this moment Dutch legislation requires an opaque screen that reduces light transmission of the greenhouse wall by 95%. In 2008 also the light transmission of the greenhouse roof must be reduced equally and supplementary light will be limited to 15,000lx(180µmol/m^2/s), unless light emission is totally prevented. The objective of this research was to calculate the economic consequences of installing reflecting, light emission reducing or blocking screens by considering crop yield and costs. A mathematical correction equation was developed to approach the light gain for the crop as a result of internal reflection. Greenhouse climate and tomato crop growth were simulated for a reference greenhouse with supplementary lighting and without an emission blocking screen and for a low-light-emission greenhouse with a blocking screen. The supplementary lighting level was set at 180µmol/m^2/s. Results show that the greenhouse climate below the screen remained manageable, but that the desired DIF of 2°C was affected. The light gain was on average about 3% and resulted in production increase. A small net yearly profit resulted based on direct and indirect effects of the screen. In conclusion, the simulation suggested that stopping light emission at the source with help of reflective opaque screens is economically feasible if screen operation is included in planning the lighting scheme.

INTRODUCTION

In 2005 17% of the total greenhouse area in Dutch greenhouse horticulture applied supplementary lighting with an area increase of 1.9% every year. Until some years ago these greenhouses were generally equipped with sidewall screens only. This results in high light emission caused by light reflection from the white greenhouse floor cover and the crop. 13-15% of Dutch population (Langers et al., 2005) and 89% of people living near greenhouses with supplementary lighting (Kool and Spanbroek, 2004) have problems with high night time light levels. Little over 1,700ha of a total area of about 10,000ha of greenhouses use supplementary lighting for, on average, 3000h a year and 80% of the lighting hours are applied during darkness. Since 2002 legislation sets limits to relative and absolute light emissions from greenhouses with supplementary lighting and in 2008 light emission must be at an acceptable level for all stakeholders. Lamps may not be visible from outside at 10m distance from the greenhouse and light emission may not exceed a light level over 5% of total radiant flux anywhere around the greenhouse. The maximum light level in the greenhouse will be limited to 15,000lx/m^2, and this level may only be exceeded if opaque screens or combinations of screens reduce the light flux outside the greenhouse by 100%.

According to growers a 100% opaque top screen has a negative effect on the greenhouse climate (Van Rijssel and Oostingh, 2004). Tomato growers indicated fruit set problems in tomato as a result of higher temperature and humidity below a closed screen. Also crop morphology was affected resulting in a thin less vital crop and an economic

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loss of up to 5 €/m^2 was indicated, despite the expected additional supplementary light yield of 0.5-5%. Based on experiments Van Rijssel et al. (1995) indicated that assimilation lights under a closed white screen show a light gain of 4-5% at crop level and 2-3% natural light loss in opened position like any screen type. The closed screen showed only little effect on greenhouse humidity compared to an open screen. Several studies already identified a problem with a higher greenhouse temperature (Vrieze, 2004). Apparently, growers are caught in a dilemma. On one hand society demands a strong reduction of light emission from greenhouse production sites. On the other hand growers need supplementary lighting to produce high quality products in enough quantity to satisfy the demand of their customers, especially in the low light season. So, the negative influence of blocking screens on product quality or quantity are to be avoided and technical and economical feasibility of solutions is required to reach synergy for stakeholders involved.

This research aimed to calculate the economic consequences for growers of installing reflective, light emission reducing or blocking top screens by considering greenhouse climate effects, crop yield effects and screen costs in a case study on tomato. The calculations needed to consider light reflection between the opaque screen above the crop, the crop itself and the white film soil cover. Even though growers may choose lighting regimes based on market motives, in this study lighting strategy was to work at the economic break-even point where marginal crop yield equals marginal costs of supplementary lighting on a daily basis. The hypothesis to prove true or false was that application of a reflective top screen in a 4 ha tomato greenhouse with a screening factor of at least 95% is economically feasible and meets grower requirements with respect to greenhouse climate.

MATERIALS AND METHODS

Case Study

In a case study using model simulation a reference greenhouse and a low-light-emission greenhouse were compared. Both greenhouses were of Venlo-type with a floor area of 4 ha (L·W=200m·200m) and column length 5m. Span width was 4m and bay width 5m and total cladding surface was 47,303m^2. A fixed light transmission factor of 0.76 was used for both greenhouses. The greenhouses had natural ventilation with 1 window per bay (dimensions 1.07m·3.0m). At night when the screens were closed a maximum ventilation rate of 1h^{-1} was used in the low-light-emission greenhouse. The crop grown was round tomato. Crop properties and parameters for growth simulation were derived from Van Woerden (2006), Bakker et al. (1995). Target temperature in the greenhouse was 20°C with DIF=2°C. Relative humidity should not exceed 85%.

Both greenhouses had a supplementary lighting level of 15,000lx (180μmol/m^2/s for high pressure sodium lamps of type Philips SON-T Greenpower). This is indicated as an absolute upper limit for greenhouses without a complete light block and it shows strongest climate effects. The reference greenhouse has an energy saving screen at sidewall and roof (Svensson SLS10UltraPlus) with light transmission coefficient 0.8 and energy saving of 43%. The low-light-emission greenhouse was equipped with a supplementary lighting screen only (Svensson XLS-SL95Revolux) which was also used as energy saving screen with light transmission coefficient <0.05 and energy saving of 30%. From September 1 to May 1 the reference greenhouse had a curfew on supplementary lighting between 8 and 12PM because of legislation. In the reference greenhouse with a transparent energy saving screen, the screen was closed during the dark period and in the light period until outside radiation was 30W/m^2. In the low-light-emission greenhouse with an opaque screen, the screen was closed until 5W/m^2 outside radiation. For both greenhouses screens were closed at outdoor temperatures under -1°C. For generation of heat, power and CO_2, two co-generators (CHP) with power grid connection and one central boiler were used. In case electricity demand existed and no heat demand the heat was buffered in a 100 m^3/ha buffer or in case buffer capacity failed power from the grid was used. As CO_2 sources the heating equipment and industrial CO_2 were used. With available equipment and given grid capacities (electricity 4.5MW, natural gas 2100m^3/h) the solution with lowest variable costs was selected at each discrete time step.

Simulation Procedure

The model used for the simulation study was GTa-tools (Van 't Ooster, 2007), a modular set of calculation procedures on crop growth, greenhouse climate and on equipment performance. An inside light reflection procedure was added in the light control module that consisted of two correction factors. The light emitted from the lamps is partly absorbed by the crop, partly transmitted to the floor and partly reflected from the crop to the screen. The soil and also the screen in their turn reflect part of the light back to the crop. These reflection processes were modelled for infinite reflections as geometric series. The result is given in eqn (1) and (2) as a correction factor on the original light flux. A separation was made between light directed downwards to the crop ($Cf_{r,t}$) and light directed upwards to the crop ($Cf_{r,b}$) with p indicating the relative capability of the crop to assimilate with light directed upwards:

$$Cf_{r,t} = \frac{1}{1-(r_s.r_{c,t}.(1-e^{-k.LAI})+r_s.r_f.(e^{-k.LAI})^2)} \tag{1}$$

$$Cf_{r,b} = \frac{(1-r_{c,b}).r_f.e^{-k.lAI}/(1-r_{c,t})}{1-(r_{c,b}.(1-e^{-k.LAI}).r_f+r_s.(r_{c,t}.(1-e^{-k.LAI})+r_f.(e^{-k.LAI})^2))} \tag{2}$$

$$\phi_{L,\,with\,screen} = (1-r_{c,t}).(1-e^{-k.LAI}).\phi_{L,\,lighting}.(Cf_{r,t}+p.Cf_{r,b}) \tag{3}$$

Eqn 3 describes the light absorption by a crop in a greenhouse with closed reflective screens. The standard crop absorption function (Bakker et al., 1995) is multiplied with the weighed sum of reflection correction factors. With the PAR flux from supplementary lighting $\phi_{L,\,lighting}$ (MJ/m^2/h), leaf area index (LAI), the extinction coefficient of the crop (k) and the reflection coefficients of crop ($r_{c,t}, r_{c,b}$), soil cover (r_f), and screen (r_s) the light available for the crop can be calculated $\phi_{L,\,with\,screen}$ (MJ/m^2/h). Both greenhouses have a white floor cover with r_f=0.4, other parameters values used were $r_{c,t}=0.1$, $r_{c,b}=0.05$, p=0.5, r_s=0.07 in the reference greenhouse and r_s=0.8 in the low-light-emission greenhouse.

Break-Even Analysis

The model components GTa-Light Control and GTa-Crop Growth were used to find the operational break-even point for different lighting regimes with (6, 8, 10, 12, 16 and 20h/d) at an average supplementary light flux of 180µmol/m^2/s. The marginal crop yield compared to no supplementary lighting was determined (€/m^2/d) at different natural radiation sums (MJ/m^2/d). Also the variable costs (€/m^2/d) of the lighting regimes were determined from the electricity demand of the system and commodity costs of power when generated with combined heat and power. The cross section of these lines indicates the operational break-even point where marginal crop yield equals marginal costs of supplementary lighting. If the natural daylight sum exceeded this break-even point the lamps were switched off.

With one lamp per 5.9m^2, an average crop price of 0.75€/kg and a natural gas price of 0.30€/m^3, the functions for marginal yield and marginal cost are: $dY=0.01082\cdot(GR_2-GR_1)$ and $dC=0.00373\cdot t$, with GR_1 and GR_2 being respectively the dry matter production at natural light level and at the light level resulting from natural light and supplementary lighting. The number of lighting hours planned in the lighting regime is indicated with t. In the case study a lighting regime with 8 hours a day was chosen.

Economic Assessment

A rough economic evaluation was used to get an indication of the economic feasibility of supplementary lighting screens. Variations of costs and prices in time were neglected. This means for instance that an average yield price was used for tomato.

1. Screen Costs. The screen costs were mainly fixed costs for the sidewall screen and the top screen and consisted of costs for the screen installation and the screen fabric. The costs for the reference greenhouse and the low-light-emission greenhouse were respectively 1.5€/m^2 and 1.76€/m^2.

2. CHP Costs. The variable costs of the co-generator was split up into costs for generation of heat and electricity. Heat costs were determined by the net heat demand of the greenhouse which was the heat demand of the greenhouse minus the heat production by the lighting installation. Electricity costs were restricted to the amount used in the greenhouse for supplementary lighting and the remaining electricity was delivered to the public grid to generate a net economic profit. The case was simulated at a gas price level of 0.30€/m^3.

3. CO_2 Enrichment. CO_2 enrichment was calculated according to the economical principal of marginal crop yield equalling marginal CO_2 costs. The cost of CO_2 produced by heating equipment was set to 0.025€/kg, which where mainly transport costs, and for industrial CO_2 to 0.11€/kg. The installation costs were equal for both greenhouses and thus omitted.

RESULTS

Radiation and Crop Growth

1. Radiation. Figure 1 indicates the break-even point for lighting regimes with 6 to 20h/d. For 8h of supplementary lighting a day, a PAR gain of 1.04MJ/m^2/d was realised in the reference greenhouse and 1.12MJ/m^2/d in the low-light-emission greenhouse at an LAI of 2.5. The resulting break-even points were at a natural radiation integral of 5.1MJ/m^2/d in the reference greenhouse and 6MJ/m^2/d in the low-light-emission greenhouse. When these break-even points were applied to the whole growing period, supplementary lighting is used for 1,032h/y in the reference greenhouse and for 1,128h/y in the low-light-emission greenhouse mainly between September 1st and May 1st. The contribution of supplementary lighting to radiation sums is indicated in Table 1. The effective PAR increase at 20°C, 350ppm CO_2 in the low-light-emission greenhouse as a result of eqn 3, break-even point and crop development was 2% on the yearly PAR sum and 1.8% on the PAR light absorbed by the crop. In the low-light-emission greenhouse LAI increased faster than in the reference greenhouse which resulted in more light absorption when the crop was young, but less reflection of light. With chosen screening strategies in the low-light-emission greenhouse screens were closed for 4452h/y and 226h/y during the light period. In the reference greenhouse for 5156h/y and 930h/y respectively.

2. Crop Growth. At the simulated climate conditions the reference greenhouse produced 73.4kg/m^2 of fresh tomatoes and the low-light-emission greenhouse 76.0kg/m^2, with a difference in dry matter production of 180g/m^2 and in fresh tomato production of 3.4% where PAR increase is 1.9%. This is close to the 1%-rule (Marcelis et al., 2004).

Temperature and Humidity

1. Temperature. Figure 2 indicates that indoor temperature shows a gradually increasing band above night target temperature at outdoor temperatures ranging 5-17°C when the screen was operated as planned. Above this range, night target temperature could not be realised without cooling. This affected DIF. Supplementary lighting effects are indicated separately. Departure from the target starts at lower temperature. In the low-light-emission greenhouse this effect was strongest since the screen remains closed to prevent light emission. During supplemental lighting target temperature 18°C was exceeded for 321h and 844Dh ($\Delta T = 1.37°C\ sd = 1.71°C$). In Figure 2 the first peak relates to young crop with low transpiration and the second to mature crop. In the reference greenhouse the screen (partly) opened in case of a positive heat balance and some light emission was accepted. This greenhouse exceeds target for 55h and 111Dh ($\Delta T = 0.42°C\ sd = 0.74°C$).

At daytime in both greenhouses the screens opened at unacceptable temperature rise. If the lighting regime was extended into the summer greenhouse temperature tended to rise above 25°C at outdoor temperature above 17°C and also average temperature rise increased strongly. The simulations indicated that temperature in the greenhouse was maintained at acceptable level with the lighting regime applied, but DIF was negatively affected by supplementary lighting at this level.

2. Humidity. Relative humidity in both greenhouses exceeded the target of 85%. In the reference greenhouse relative humidity was above target for 1548h in total and 41h during supplementary lighting and in the low-light-emission greenhouse for 2972h in total and 849h during supplementary lighting.

Energy and Economics

1. Energy and CO_2. Table 2 indicates for the low-light-emission greenhouse a difference with the reference of +10.3m^3/m^2 in yearly usage of natural gas, of -0.8kg/m^2 CO_2 use for enrichment and +22.6kg/m^2 total CO_2 production. The gas usage and CO_2 production was mainly higher because of electricity generated. For the reference greenhouse 37m^3/m^2 g.e. was used for electricity production and for the low-light-emission greenhouse 43m^3/m^2. The use of industrial CO_2 could not be avoided as a result of timeliness problems in CO_2 production, despite of the high CO_2 production by the heating system and despite of the use of a heat buffer tank.

2. Economics. Table 3 gives the differences between the two greenhouses with at the cost side focus on the screen costs, energy and carbon dioxide and at the profit side focus on crop yield and power delivery to the grid. Total costs were 5.72€/m^2 higher for the low-light-emission greenhouse as a result of higher screen costs, a higher energy use and higher CO_2-costs. The crop yielded in total 2.6kg/m^2 (+3.5%) more tomatoes with an estimated economic value of 1.95€/m^2. Also power delivery to the grid differed with 63kWh/m^2. Based on a commodity price of 0.08€/kWh in peek hours and 0.04€/kWh otherwise, the economic value is 4.24€/m^2. This resulted in an increased profit of 0.47€/m^2 and a return on investment of 3-4 years for existing and less then one year for newly built greenhouses.

DISCUSSION

Light regimes with supplementary lighting for longer than 8h a day also need evaluation of the daytime. Closing of the screen to prevent light emission is unnecessary at daytime but screen control should find a balance between light gain and optimal climate conditions. This part is not considered here since it is not relevant in relation to reduction of light emission. Light regimes exceeding the break-even points or with lighting periods less than 8h/d result in use of supplementary lighting in summer nights as well. These regimes need separate evaluation since unacceptable temperature rise is simulated at outdoor night temperatures above 17°C but not reported. This is in agreement with growers experiences. Key solution may be a screen that allows ventilation rates up to 7h^{-1} and blocks light. In the evaluation cost prices were estimated high to follow trends and product price and revenues were estimated relatively low to check if return on investment was acceptable even under more adverse economic conditions.

CONCLUDING REMARKS/CONCLUSIONS

The correction factors $Cf_{r,t}$ and $Cf_{r,b}$ introduced in the light yield calculation seem to give good results on the estimated increase in crop yield, though experimental proof is required. Simulations indicated that the use of supplementary lighting screens is economically feasible at moderate lighting regimes as a result of more crop yield and better options for electricity delivery to the grid. This is a strong indication that the hypothesis stated earlier is true. The greenhouse climate is acceptable but the required DIF of 2°C was often not realised. The crop model used did not indicate production decrease for given lighting regimes, however development of a screen that blocks light and allows ventilation rates of up to 7h^{-1} is highly recommended.

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Tables

Table 1. Radiation sum in reference greenhouse with and without supplementary lighting, and in the low-light-emission greenhouse when reflections and break-even points are applied. Crop production is indicated for standard climate conditions.

$MJ.m^{-2}.y^{-1}$	No supplementary lighting	Reference greenhouse	Low light emission greenhouse
Radiation in greenhouse	2672	2793 (+4.5%)	2814 (+5.3%)
PAR available	1256	1387 (+10.4%)	1413 (+12.5%)
PAR absorbed	867	978	997
Tomato production ($kg.m^{-2}$) ($T=20°C$, $CO_2=350ppm$)	53.3	62.1 (+16.5%)	63.2 (+18.6%)

Table 2. Yearly use of resources for heating, supplementary lighting and CO_2 enrichment.

Resource	Reference greenhouse	Low-light-emission greenhouse
Natural gas use (m^3.m^{-2})	97.7	108.0
Energy use heating (MJ.m^{-2})	2133	2133
Electricity production CHP (MJ.m^{-2})	915	1180
Electricity use suppl. lighting (MJ.m^{-2})	406 (1032h)	443 (1128h)
Net electr. delivery to grid (MJ.m^{-2})	509	737
CO_2-production (kg.m^{-2})	187.7	210.3
CO_2-supply equipment (kg.m^{-2})	41.1 (75%)	36.1 (67%)
Industrial CO_2 (kg.m^{-2})	13.9 (25%)	18.1 (33%)

Table 3. Yearly costs and yield €.m^{-2} for screening, heating, electricity and carbon dioxide.

€.m^{-2}	Reference greenhouse	Low-light-emission gh	d-Revenues d-Costs
Crop yield	55.05	57.00	+1.95
Heating	29.47	31.17	+1.70
Electricity production (incl. lighting)	9.63	11.84	+2.22
Electricity from grid	10.19	11.40	+1.21
Sold electricity delivery to grid	10.56	14.80	+4.24
CO_2-supply equipment	1.03	0.90	-0.13
Industrial CO_2	1.53	1.99	+0.46
Screening	1.50	1.76	+0.26
Total increase revenues	65.61	71.80	+6.19
Total increase costs	51.85	57.31	+5.72

Figures

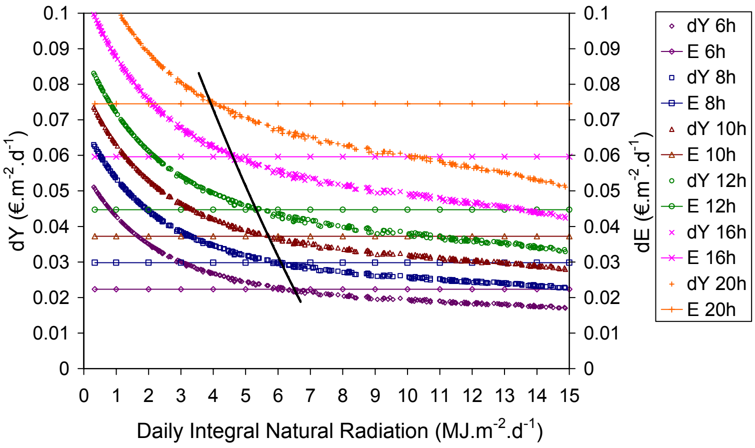

Fig. 1. Break-even points of supplementary lighting in the low-light-emission greenhouse. Horizontal E-lines indicate daily electricity costs for lighting regimes with 6, 8, 10, 12, 16 and 20h.d^{-1}. dY-curves indicate marginal crop yields induced by supplementary lighting. Calculations with: T_{grh}=20°C, [CO_2]=350ppm, LAI=2.5, P_{crop}=0.75€.kg^{-1}, P_{gas}= 0.30€.m^{-3}.

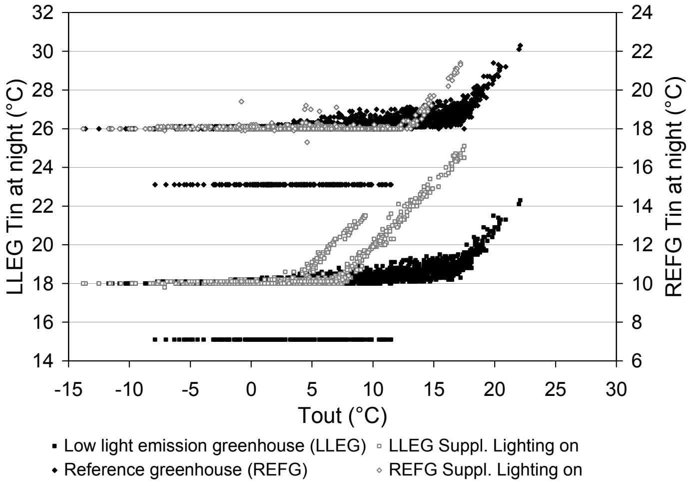

Fig. 2. Simulated relation between outdoor temperature and greenhouse air temperature at night with active screening. Coinciding points with supplementary lighting are indicated separately. Maximum ventilation rate in the low light emission greenhouse is $1h^{-1}$. The reference greenhouse is vented when heat surplus occurs or humidity rises above 85%. During supplementary lighting ventilation is $>1h^{-1}$ for 584h. Highest ventilation rate is $5.1h^{-1}$ for heat removal and $6.8h^{-1}$ for moisture removal. (15°C line= period with no crop).