# Energy Screens in Tomato: Determining the Optimal Opening Strategy

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**Abstract**

In general, the use of energy screens is a good means to reduce the energy consumption and to lower peaks in energy use in greenhouse horticulture. In tomato, experience with screens is limited since the use of screens is not so widespread as in other fruit vegetable crops. In this study effects of different screen opening strategies on greenhouse climate, energy consumption and crop production were quantified by means of an experiment and model calculations. In the experiment, two treatments were compared, i.e. opening the energy screen (SLS 10 Ultra plus) at 5 or at 50 W m$^{-2}$ outside global radiation. Plant dry weights and tomato production did not differ between the treatments. Due to the larger number of screening hours, energy consumption in the 50 W m$^{-2}$ treatment was 3.5% lower during the experiment than when screens were opened at 5 W m$^{-2}$.

With a greenhouse climate model and a crop growth model, effects of different screen opening criteria on greenhouse climate, energy consumption and crop growth were simulated. Application of a screen during the night reduced the energy consumption by 16% without affecting crop production. When screens were opened at higher levels of outside global radiation (up to 150 W m$^{-2}$), energy consumption decreased by 1.6 m$^3$ gas m$^{-2}$ year$^{-1}$ and crop production by 0.3 kg m$^{-2}$ year$^{-1}$. Financial considerations between energy saving and production loss were discussed. Screen opening based on a combination of global radiation and outside air temperature reduced the energy use, but increased the number of hours with high humidities. Screen opening based on the temperature difference below and above the screen performed comparable to the temperature and light strategy. Opening the screen caused a temporarily decrease in greenhouse air temperature. Increasing the number of opening steps before the screen was opened completely, decreased this temperature drop.

This study provides growers with information to determine their screening strategy. However, screen use could be further optimized by offering growers a decision support tool that, given outside weather conditions and prices of gas and tomatoes, gives daily advice on the optimal moment of screen opening.

## INTRODUCTION

In view of the 1997 Kyoto protocol, Dutch horticulture and government have agreed to improve the energy efficiency by 65% in 2010 compared to 1980. The energy efficiency, i.e. the amount of energy used per unit of produce, can be improved by reducing the amount of energy required or by increasing the production. An established means to reduce the energy consumption is the use of energy screens. In greenhouse vegetable crops such as cucumber and sweet pepper the use of an energy screen is generally accepted, whereas in tomato cultivation growers still hesitate to use a screen due to the dreaded risks, such as *Botrytis*. Due to the liberalisation of the Dutch energy market in 2002, growers do not pay a fixed price per m$^3$ natural gas anymore, but the price is greatly determined by the maximum supply capacity of the gas contract. Therefore, since 2002 it is especially important to reduce peaks in energy use, which can be realized by an efficient screen opening strategy. In other countries, however, this is not an issue. Also in the 1980s, when energy prices were high, effects of screen opening strategies in tomato were investigated (Mercier et al., 1984; Bailey, 1988). However,

cropping systems have changed considerably since then. In this paper a study is described in which the effects of different screen opening strategies on greenhouse climate, energy consumption and tomato crop production were quantified by means of an experiment and model calculations.

## MATERIALS AND METHODS

### Experiment

Grafted tomato plants cultivar 'Durinta' were planted in 4 greenhouse compartments of 144 $m^2$ each in Wageningen (The Netherlands) on 12 January 2004. Transmission of diffuse light of the Venlo greenhouse was 65%. Plants were placed on hanging gutters on rock wool slabs (Expert, Grodan, The Netherlands) at a planting density of 2.5 plants $m^{-2}$ (1 stem/plant). Trusses were pruned to 6 fruits per truss. Lower leaves were picked up to about the ripening truss. The plants in the outer rows and the outer 2 plants of each row were considered to be guard plants and were not used for the experiment. The energy screens, SLS 10 Ultra plus (Ludvig Svensson; transmission direct light 88%, diffuse light 81%), were opened according to the following 2 treatments: "standard screening", screens open at 5 W $m^{-2}$ outside global radiation and "prolonged screening", screens open at 50 W $m^{-2}$ global radiation. Two greenhouse compartments were used per treatment.

Temperature set points were 18/16.5°C (Day/Night, D/N) first week after planting, then 17/14.5°C (D/N) during the following 4 weeks. Thereafter, temperature set points were gradually increased to 19/17°C. Pure $CO_2$ was supplied to a concentration of 600 ppm when the ventilation windows were closed or opened less than 5% and to 400 ppm when the ventilation windows were opened further. Climate data were registered every 5 minutes. Energy consumption in the compartments was calculated by means of the difference between air temperature and pipe temperature.

Every 4 weeks, 6 plants per compartment were harvested destructively. Length, leaf area and weights of leaves, stems and fruits were determined. To maintain shoot density, plants were replaced or shoots shoved together. From April trusses with red fruits were harvested weekly. The number and fresh weights of the fruits per plant were determined. The experiment finished on 4 May 2004.

### Simulation

Simulations were performed by a greenhouse climate model (De Zwart, 1996) and a crop growth model (Marcelis et al., 2000). Model calculations were based on a tomato crop planted on 12 December and cleared out on 20 November in a modern Venlo-type greenhouse of 4 ha with 2 heating circuits. The boiler had a power of 150 W $m^{-2}$, which equals the use of approximately 171 $m^3$ gas $ha^{-1}$ $h^{-1}$. For $CO_2$ supply, there was a heat storage tank of 100 $m^3$ $ha^{-1}$. Heating set points were 19/19°C (D/N) (12-22 December), 19/18°C (until 15 January), 18.5/17.5°C (until 1 April), 18/17°C (until 1 May), 18/16°C (until 15 November) and 16/16°C (until 20 November). The zone between set point heating and set point ventilation where no action was taken by the climate controller is 3°C in December and gradually decreased to 0.5°C in April. Model calculations considered a movable SLS 10 Ultra plus screen, used between 15 October and 1 May. Screens were closed at outside temperatures below 12°C (12 Dec-15 Jan), 10°C (15 Jan-1 Apr) or 8°C (1 Apr-20 Nov). Screens opened in steps of 0.5% each 2 min up to 5% opening and were then opened completely. Set points for relative humidity (RH) are 85% during the day and 88% during the night. When RH under a closed screen exceeded the set point, a screen gap of maximum 3% can be drawn. When this was insufficient, additionally vents were opened to maximum 5% and 30 min later, if necessary, the screens were opened completely to lower the RH. When the greenhouse air temperature under the closed screen exceeded the set point heating by more than 1.5°C, the screen was opened for 2% (temperature gap). Calculations were based on an outside weather data set (Breuer and Van de Braak, 1989). For the economic evaluations, the gas price was assumed to be 0.18 € $m^{-3}$ gas and the price for tomatoes 0.90 € $kg^{-1}$.

Effects of a number of scenarios on greenhouse climate, energy consumption and crop production were calculated:
1. Screen opening determined by outside global radiation.
2. Screen opening determined by a combination of outside global radiation and outside air temperature.
3. Screen opening determined by temperature difference below minus above the energy screen (ΔT-screen).
4. Rate of screen opening dependent of temperature difference below minus above the energy screen (ΔT-screen).

## RESULTS

### Experiment

Over the experimental period from 12 January to 3 May the total amount of radiation measured was 0.34% lower in the compartments with the prolonged screening treatment (open at 50 W $m^{-2}$) compared to the standard screening treatment (open at 5 W $m^{-2}$). Around screen opening, the pattern of greenhouse temperatures clearly differed between the treatments (Fig. 1A). Between 7:00 and 9:00 am, temperatures in the standard screening treatment were lower than when the screens were opened later. In the standard treatment, temperatures dropped approximately 0.5°C, whereas in the prolonged screening treatment no temperature drop occurred. The minimum pipe temperature of 35°C caused the difference in set point and realized temperature. In the prolonged screening treatment, screens were closed for 1545 hours whereas the standard screening treatment realized 1380 screening hours. Consequently, the heat demand differed between the treatments (Fig. 1B). This resulted in 3.5% lower energy use in the period 15 Mar-3 May for the prolonged screening treatment compared to the standard treatment.

The cumulative dry weights of the plants did not differ significantly between the screening treatments (Fig. 2). Stem and leaf dry weights tended to be slightly, but not significantly, higher for the prolonged screening treatment. Fruit weights were not affected by the screening treatments (data not shown).

### Simulation

**1. Reference.** Simulation of a standard tomato crop without a screen yielded an energy consumption of 47.0 $m^3$ gas $m^{-2}$ year$^{-1}$. When an energy screen was applied that opened at 5 W $m^{-2}$ outside radiation, energy consumption was reduced by 16% to 39.4 $m^3$ gas $m^{-2}$ year$^{-1}$, without affecting the production of the tomato crop, which remained at a level of almost 62 kg $m^{-2}$ year$^{-1}$. The maximum daily energy consumption of 3579 $m^3$ ha$^{-1}$ day$^{-1}$ without a screen was reduced by 33% to 2382 $m^3$ ha$^{-1}$ day$^{-1}$ when a screen was used that opened at 5 W $m^{-2}$ (Fig. 3). Also the number of hours with the maximum hourly energy consumption was reduced when an energy screen is used (data not shown).

**2. Screen Opening Dependent of Outside Global Radiation.** As the screen opens at a higher level of outside radiation, the number of screening hours increased considerably, and the energy consumption decreased concomitantly (Table 1). When the number of screening hours increased, the number of hours with a RH that exceeded the set point increased, due to reduced condensation against the cover. However, RH never exceeded 95%, due to the use of screen gaps and vents. Due to light loss of the screen, fruit production decreased at increasing numbers of screening hours (Table 1). When savings in energy costs were compared with the yield loss of tomatoes, the optimum level of outside global radiation to open the screen was found to be about 50 W $m^{-2}$ (Table 1). Financial results of screen closure at intensities of up to 150 W $m^{-2}$ were also positive. When screens were opened at higher levels of global radiation, the number of hours with maximal gas consumption decreased considerably. When an arbitrarily chosen limit of 120 $m^3$ ha$^{-1}$ h$^{-1}$ was considered, this was exceeded for 163 hours when screens were opened at 150 W $m^{-2}$ and for 309 hours when the screens were opened at 1 W $m^{-2}$.

**3. Screen Opening Dependent of Outside Global Radiation and Outside Temperature.** Effects of 5 screen opening strategies (Table 2) on energy consumption and production were calculated. The number of screening hours increased from 1748 hours for case E to 2033 hours for case B (Table 3). This increase reduced the energy consumption, but the number of hours with high humidities increased (Table 3). Production of scenario E is comparable to screen opening at 1 W m$^{-2}$ radiation (Table 1), however, 0.4 m$^3$ gas m$^{-2}$ year$^{-1}$ is saved. In all other cases, the production is up to 0.2 kg m$^{-2}$ year$^{-1}$ lower.

**4. Screen Opening Dependent of Temperature Difference Below minus Above the Screen ($\Delta$T).** This strategy assumes that heating the compartment above the screen by the sun to approximately the temperature under the screen reduces the temperature drop when opening the screen. Therefore energy consumption should be reduced since no drop needs to be compensated by additional heating. In this scenario, screens were opened at temperature differences of 4, 6, 8, 10 and 12°C. At lower $\Delta$Ts, results were not due to the screen opening criterion, since vents had to be opened because of temperature levels exceeding set point values. When the $\Delta$T was lower, the number of hours the screen was closed increased, reducing both the energy consumption (1.3 m$^3$ m$^{-2}$ year$^{-1}$) and the production (0.3 kg m$^{-2}$ year$^{-1}$). On average, this screen opening strategy had a slightly higher energy consumption than opening the screen on a combination of temperature and radiation at a comparable number of screening hours (data not shown). The number of hours with high humidities however, were lower in this strategy than in the strategies mentioned before.

**5. Rate of Screen Opening Dependent of Temperature Difference Below minus Above the Energy Screen ($\Delta$T-Screen).** Opening the screen according to one of the above mentioned criteria in general led to a drop of the greenhouse air temperature of 0.8-1.3°C. An improved way of screen opening might decrease this drop. The standard way of opening (steps of 0.5% with an interval of 2 min up to 5% opening, then open completely) was compared to intervals of 4 and 6 min and percentages at which the screen opened completely between 0.5 and 7.5% opening. Results showed that the temperature dropped less when the screen opened at once from a more open state (7.5% opening). Length of the interval (2-6 min) hardly affected the temperature drop (data not shown). However, effects of the variations in rate of screen opening on energy consumption and production were minor.

**DISCUSSION**

In this project the effect of screen use for tomato crops was investigated and the optimal strategy to open the energy screen was quantitatively determined. Until recently, the share of tomato growers that used movable screens was limited, in contrast to for example sweet pepper growers. Besides fear of fungal diseases, this is due to the light loss of the parked screens (3-4%). Because of the recent increases in gas prices, tomato growers are increasingly interested in the use of energy screens. Our results show that opening the screen at 50 W m$^{-2}$ outside global radiation compared to 5 W m$^{-2}$ saved 3.5% energy (Fig. 1B) without affecting crop growth and production. Comparable results were obtained by Mercier et al. (1988), who compared screen opening at 1 or 30 W m$^{-2}$. In spite of the considerable number of screening hours realised during the experiment, light loss was very limited (0.34%). This was due to the fact that even in the prolonged screening treatment, screens were closed only at low outside radiation and transmitted 81-88% of the light.

Model calculations showed that application of a screen can reduce the year-round energy consumption by 16%. Instantaneous energy savings can be 35-40% (Bakker and Van Holsteijn, 1995). Besides the reduction in the absolute amount of gas used, the maximum hourly consumption also greatly determines the price growers pay for their energy. Application of a screen proved to reduce the number of hours with an hourly use over 130 m$^3$ gas ha$^{-1}$ h$^{-1}$ considerably with approximately 400 hours per year. Therefore, the use of a screen enables growers to conclude a gas contract with a lower supply capacity at a minor risk of insufficient capacity to realize the set point temperatures.

In this study, effects of three screen opening criteria on energy consumption and production were compared. The first and most simple one is to open the screen based on the outside global radiation. Opening the screen at higher light intensities reduced both energy consumption and production. The optimal light intensity to open the screen is determined by the financial consideration of the loss of production value and the saving of energy costs and greatly depends on the gas and tomato prices. In this consideration, effects of a reduction in peak capacity on the gas price or the lowering of gas transport costs were not considered. However, this can have a major effect on the gas price paid by the grower. Also Bailey (1988) calculated positive financial results if screen opening is based on irradiance compared with time control. If the night temperatures were increased, in combination with decreased day temperatures, a further energy saving could be realized with the screen. The second screen opening criterion considered in our study was a combination of outside radiation and outside temperature. Although a series of cases were constructed that seemed quite distinct, calculations showed that energy consumption and production levels of most cases differed only slightly. Differences between the cases appeared to be mainly at the extremes of temperature and radiation which do not occur frequently. Mostly, radiation and temperature levels are moderate, which caused the small differences between the cases. Opening the screens on a combination of outside radiation and outside temperature resulted in a reduced energy consumption at equal production levels and therefore proved to be more successful. The third strategy simulated was based on the temperature difference between the compartments below and above the screen. This strategy was found to perform slightly less than the previous one. The drawback of this strategy is that it requires the measurement of temperatures above the screen, which is not standard in Dutch commercial greenhouses.

To calculate the effects of screen opening strategies on energy consumption and crop production, settings were used that were fixed for the entire growing season. As a matter of course, this does not agree with commercial practice. Growers consider weekly or even daily their screen settings, based on outside weather conditions and the crop appearance. If considered well, growers will therefore perform better than when maintaining year-round identical settings as in the simulations. The results obtained in this study can support them in these considerations. Screen use could be further optimized by offering growers a decision support tool that, given outside weather conditions and prices of gas and tomatoes, gives daily advice on the optimal moment of screen opening.

## Literature Cited

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**Tables**

Table 1. Effects of screen opening criterion on the number of screening hours, RH, energy consumption, production and financial evaluation of energy costs (0.18 € m$^{-3}$ gas) and production loss (0.90 € kg$^{-1}$; reference is opening at 1 W m$^{-2}$).

| Screen open criterion (W m$^{-2}$) | Screens closed (hours) | RH > set point (hours) | Gas consumption (m$^3$ m$^{-2}$ year$^{-1}$) | Production (kg m$^{-2}$ year$^{-1}$) | Energy costs-production loss (€ ha$^{-1}$) |
|---|---|---|---|---|---|
| 1 | 1673 | 156 | 39.6 | 61.86 | - |
| 2 | 1680 | 170 | 39.6 | 61.86 | - |
| 5 | 1718 | 168 | 39.4 | 61.86 | 360 |
| 10 | 1759 | 176 | 39.2 | 61.85 | 630 |
| 25 | 1853 | 175 | 38.8 | 61.80 | 900 |
| 50 | 1924 | 190 | 38.4 | 61.75 | 1170 |
| 100 | 2014 | 203 | 38.1 | 61.64 | 720 |
| 150 | 2049 | 214 | 38.0 | 61.57 | 270 |

Table 2. Combinations of outside temperatures and levels of outside global radiation at which the energy screens will be opened in the simulation study.

| Outside temperature (°C) | Case | | | | |
|---|---|---|---|---|---|
| | A[1] | B | C | D | E |
| | Global radiation (W m$^{-2}$) | | | | |
| -15 | 900 | 280 | 140 | 280 | 100 |
| -10 | 627 | 240 | 120 | 240 | 100 |
| -5 | 354 | 200 | 100 | 175 | 100 |
| 0 | 150 | 160 | 80 | 120 | 20 |
| 5 | 65 | 120 | 60 | 75 | 5 |
| 10 | 18 | 80 | 40 | 40 | 5 |
| 15 | 1 | 40 | 20 | 15 | 5 |

[1] Case A: Screen is opened when there is a small temperature difference between inside and outside the greenhouse. Case B: based on a k-value model (heat exchange coefficient), the global radiation of the sun to compensate the heat loss of the greenhouse is calculated (k-value is 8, air temperature is 20°C). Case C: as case B with a k-value of 4. Case D: combination of cases B and C. Case E: comparable to commercial Dutch practice.

Table 3. Effects of screen opening criterion on the number of screening hours per year, RH, energy consumption and production.

| Screen open criterion (W m$^{-2}$) | Screens closed (hours) | RH > set point (hours) | Gas consumption (m$^3$ m$^{-2}$ year$^{-1}$) | Production (kg m$^{-2}$ year$^{-1}$) |
|---|---|---|---|---|
| A | 1963 | 192 | 38.2 | 61.69 |
| B | 2033 | 208 | 38.0 | 61.61 |
| C | 1938 | 187 | 38.3 | 61.72 |
| D | 1978 | 194 | 38.2 | 61.67 |
| E | 1748 | 173 | 39.2 | 61.85 |

**Figures**



Fig. 1. Realised greenhouse air temperatures (A) and average energy use during the day (B) for the treatments standard (open at 5 W m$^{-2}$) and prolonged screening (open at 50 W m$^{-2}$) and set point heating during 24 h averaged over the period 15 March – 3 May.

cumulated dry weights (g)



time after planting (weeks)

Fig. 2. Course of the cumulated shoot dry weight (including picked leaves and harvested fruits) for the treatments standard (open at 5 W $m^{-2}$) and prolonged (open at 50 W $m^{-2}$) screening. Symbols indicate average values (n=12) with $se_{mean}$.



Fig. 3. Frequency distribution curves of the daily consumption of gas without and with an energy screen (open at 5 W $m^{-2}$ outside global radiation).

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