# The Energy Balance and Energy-Saving Measures in Greenhouse Tomato Cultivation

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**Abstract**

**Reliable and quick assessment of energy conservation measures in greenhouse cultivation supports growers in their operations. Such an overview should quantify the consequences of changes in energy flows for total energy consumption, amount and quality of production, and farm economy.**

**Using tomato as an example crop, comprehensive energy balances were developed for a reference situation in The Netherlands. Solar radiation, primary and secondary heating circuits and $CO_2$ from the flue gasses of the heating system were quantified as energy sources. Energy use for air and leaf temperature increase, crop photosynthesis, crop transpiration, as well as energy losses through the roof, walls and ground surface were quantified. Subsequently, the effects of 11 energy conservation measures were computed. Consequences for gas consumption and production were simulated with a greenhouse and a crop growth model, respectively, consequences for quality were assessed on the basis of expert knowledge, and economic consequences were simulated with a cost-benefit model.**

**For tomato, most energy was saved by increased insulation of the greenhouse cover (23% saving) and lowered temperature set point (16%), followed by increased set point for air relative humidity, screen gap control in steps, and temperature integration (all about 5%). Fresh tomato production fell in most cases, except in case of increased light transmission by the greenhouse cover. Energy use efficiency was defined as the amount of energy required to produce a certain quantity of fresh harvestable product. Energy-conservation aims to decrease the energy use efficiency. Greatest gains were reached through insulation (-20%), lowered temperature set point (-12%) and improved light transmission (-8%). Improved light transmission resulted in the strongest increase of the balance of yield and costs (€2.6, or 10%), followed by increase of RH set point, crop-based RH control, crop-based use of the energy screen, increased size of the thermal storage tank and reduction of crop transpiration (all less than €0.5).**

**Although energy conservation reduces fuel costs, its implementation depends on the effects on production an overall economic profitability of the farm. Improved roof insulation, reduced temperature set point, screen gap control in steps, increase of the RH set point, temperature integration, and crop-based RH control are first candidates for (further) implementation. Other measures require prior technological advancements or fine-tuning.**

## INTRODUCTION

Given the high costs of energy and obligations imposed on national governments by the Kyoto protocol (UNFCCC, 1997), energy conservation in horticulture has become increasingly important. Reliable and quick assessment of measures to conserve energy supports growers in their operations, and policy makers in directing research funds. Energy conservation assessments require an overview of the most important energy flows and their consequences. Changes in energy flows may have consequences for the greenhouse climate and therefore for photosynthesis, transpiration, growth and production, for the quality of the produce, and for farm economic performance.

This paper describes the consequences of a number of conservation measures in terms of energy consumption, crop production, product quality and farm economics. Tomato was chosen as example crop.

## MATERIALS AND METHODS

### Reference Situation

A representative tomato production system of a modern grower in The Netherlands was described in terms of greenhouse construction, climate control, cultivation methods and farm economic performance. Reference greenhouse characteristics were: surface 40,500 $m^2$; gutter height 4 m; bay width 4.8 m; span width 4.5 m; single glass; window ventilation; a natural gas fired boiler; a heat storage tank of 120 $m^3$ $ha^{-1}$; and primary and secondary heating pipes per bay, 5 ∅ 51 mm and 2.5 ∅ 28 mm tubes, respectively. Climate control made use of set points for air temperature (day/night values of 19/19, 19/16.5, and 18/17 $^oC$ up to January 10th, March 31st and final harvest, respectively; no temperature integration), ventilation (max 85% relative air humidity, RH), and $CO_2$ (1000 ppm, only achieved if ventilation and $CO_2$ loss to the outside environment is limited). $CO_2$ was applied as boiler exhaust gasses from sun rise to one hour before sun set, at a rate of 1980 kg $ha^{-1}$ $h^{-1}$.

A transparant energy screen (SLS 10 ultra plus) was closed from planting to February 15th at outside air temperature below 7 $^oC$, and until May 1st at outside air temperature below 5 $^oC$. It was opened during daytime if solar radiation exceeds 1 W $m^{-2}$. The screen was not used from May 1st to September 15th. If RH was above 0.5% of the set point of 85%, the screen was opened for 4%, and was opened fully if RH continued to be too high for more than one hour.

A high-wire grown tomato type was assumed. Dates of planting and last harvest were December 10th and November 20th, respectively. Plant density was 2.5 plants $m^{-2}$, and one extra shoot was realised on one out of 6 plants on March 22nd and April 8th, resulting in a final shoot density of 3.33 $m^{-2}$. Water and nutrient supply were assumed to be sufficient.

Economic performance was determined on the basis of specific quantitative data of greenhouse horticulture (van Woerden, 2001).

### Energy-conservation Measures

Eleven energy-conservation measures were studied by means of simulations:

M1. Reduction of the day and night temperature set points by 2 $^oC$.

M2. Temperature integration for 24 h with a 4$^oC$ bandwidth. Ventilation and heating set points were increased and decreased, respectively, by 2 $^oC$ and regulated to maintain the average greenhouse temperature.

M3. Temperature integration for 72 h. This measure is comparable to case M2, differing only in the period over which air temperatures can be compensated.

M4. Increase of the relative air humidity (RH) set point from 85% to 90% by reducing the ventilation.

M5. Air humidity control on the basis of a minimum difference of 1.5 $^oC$ between dew point temperature of the greenhouse air, and crop temperature. This crop-based control ensured prevention of condensation on the leaf, which reduced disease development.

M6. Screen gap control in steps. Screens were opened in steps of 0.3% (with an interval of 6 min) up to a maximum of 4% if RH exceeds its set point. The screen was never fully opened. This control was expected to result in more hours of screen closure and less heat loss.

M7. Increase of the heat buffer capacity and the $CO_2$ dosage capacity by 50%. For tomato, this implied a heat buffer capacity of 180 $m^3$ $ha^{-1}$. This control was expected to result in higher $CO_2$ concentrations, therefore increased production and energy use efficiency.

M8. A 10% reduction of crop transpiration by assuming an increased stomatal conductance.

M9. A greenhouse roof with a 10% higher insulation capacity, but maintaining 70% transmission of global radiation (including the absence of condensation).

M10. A greenhouse roof with 10% higher transmission (80% instead of 70%) for global radiation at the same degree of insulation, through application of a glass coating that reflects less radiation.

M11. Cooling through a flooded roof with cold water, at un-affected transmission for global radiation. The greenhouse was ventilated only if this type of cooling was insufficient. This control was expected to result in higher $CO_2$ concentrations, therefore increased production and energy use efficiency.

### Consequences of Energy Conservation

Annual energy flows at the greenhouse level and total energy consumption were computed for the reference situation and all energy-conservation measures with the KASPRO greenhouse climate model (de Zwart, 1996), describing the amount of energy entering the greenhouse (from solar radiation, primary and secondary heating circuits and the $CO_2$ heating system), the amount of energy used to maintain air temperature, and energy losses through the roof, walls and ground surface.

Annual energy flows at the crop level were computed with the INTKAM crop model (Marcelis et al., 2000), using climate information provided by the KASPRO model. The amount of energy intercepted by the crop, and the distribution of this energy over net photosynthesis, change in leaf temperature, and transpiration were described.

Consequences for production were also determined with the INTKAM model, while the consequences for product quality were assessed on the basis of literature, existing experiments or expert knowledge (van den Berg et al., 2001; Kaarsemaker et al, 2002; Kaarsemaker and van Rijssel, 2003).

Economic performance was determined with a partial cost-benefit model, which contained the most relevant components related to energy consumption and farm result: production and financial yield, and costs of energy consumption, labour, sales and investments (except M11, as investments were difficult to assess). The model excluded annual costs such as depreciation, maintenance and interest (more than €20 $m^{-2}$ $year^{-1}$). The farm result was calculated as the difference of yield and total costs.

## RESULTS AND DISCUSSION

### Reference Situation

The reference tomato crop was characterised by a growing season of 11 months and a relatively high energy consumption of 45 $m^3$ gas $year^{-1}$ (Table 1). Greenhouse simulations showed that on an annual basis, 4319 MJ $m^{-2}$ energy entered the greenhouse, of which 65% originated from solar radiation (Fig. 1). Primary and secondary heating circuits and $CO_2$-application accounted for 31, 3 and 1%, respectively. Obviously, most fossil fuel was used in the winter months, when much heat is lost to the outside environment. Air temperature increase costed 2604 MJ $m^{-2}$ $year^{-1}$, while crop transpiration required 1558 MJ $m^{-2}$ $year^{-1}$. On an annual basis, 4 MJ $m^{-2}$ nett was lost to the air from the leaves (the direction of the energy flow was alternating). Most energy left the greenhouse through the roof, *viz*. 4050 MJ $m^{-2}$ $year^{-1}$ (94%; 43% as radiation and convection, and 51% as sensible and latent heat loss through ventilation), while energy loss through walls and ground accounted for 2 and 4%, respectively. Crop simulations showed that only 72 MJ $m^{-2}$ $year^{-1}$ (2%) of the energy was fixed as carbohydrates through crop photosynthesis. Simulated fresh production was 60 kg $m^{-2}$ $year^{-1}$ (Table 1), with production peaks in the $2^{nd}$ and $3^{rd}$ quarter. At an average price of €0.92 $kg^{-1}$ this resulted in €54.43 $m^{-2}$ proceeds. The costs of gas amounted to €10.1, and the financial balance resulted in €25.5.

**Energy-conservation Measures**

All comparisons were made with respect to the reference situation.

**1. Energy.** Substantial amounts of energy could be saved by improved roof insulation (M9, 23%) and reduced temperature set point (M1, 16%). An increase in the RH set point (M4), screen gap control (M6) and temperature integration (M2, M3) reduced the use of energy by approximately 5%. An increased size of the thermal storage tank to enable greater $CO_2$ flows (M7) resulted only in the early morning of spring and autumn in greater $CO_2$ flows, and had on an annual basis a marginal effect on energy use. Because window opening in winter was minimal, the $CO_2$ concentration of 1000 ppm was realised with standard $CO_2$ application from flue gasses. In summer, windows were often open, causing a demand for increased $CO_2$ dosage. However, in view of energy conservation, it was assumed that no excess heat was destroyed by releasing it to the environment. The storage tank was too warm for a large part of the day to permit heating, hence no $CO_2$ could be generated. In spring and autumn, early-morning low temperatures demanded heating so that $CO_2$, a by-product of the heating process, was applied only then. Therefore, the expected increase in air $CO_2$ concentration was only marginally realised, while temperature and RH remained the same. The main effect with regards to energy use was a shift of the gas consumption from night to day, following the cooling of the buffer. Roof cooling (M11) increased energy use because periods with temperature below the heating set point lengthened, requiring heating, and because RH increased slightly, requiring ventilation followed by heating.

**2. Climate, Production and Quality.** A reduced temperature set point (M1) lowered air temperature, especially in winter and spring when radiation was low. As a consequence, leaf area development and absorbed radiation early in the season were lower. However, as leaf removal and consequently, leaf area reduction commenced later in the season, more radiation was intercepted during the bright summer months. In all, cumulative dry matter production increased by 0.8%. Lower air temperature also led to a reduced truss formation rate, contributing to a 3.3% reduction in fresh weight (Table 1). Quality was expected to decline, as lower temperatures increase the probability of cuticle cracking and *Botrytis*.

Temperature integration over 24 h (M2) and 72 h (M3) both caused a reduction in night-time temperatures and a smaller reduction in day-time temperatures. Average daily temperatures showed a shift from 19 to 18 $^{o}C$, while $CO_2$-concentrations showed a not-systematic change, causing a 1% reduction in annual production. Also quarterly productions showed similar (small) reductions. Simulated productions corresponded with the general claim that temperature integration does not affect production, although well-documented data on temperature integration are scarce. In one example on rose (Dieleman et al., 2004), temperature integration over 2 days was proven to be possible, and with a smaller band with also for longer periods.

An increase in the RH set point (M4) can only be effective if the RH increases above the reference threshold. This occurred to some extent, altering the sharp peak frequency at 85% to a plateau between 82.5 and 92.5%. Ventilation was reduced only at night, increasing $CO_2$ concentrations, while daytime $CO_2$ concentrations, which are relevant for photosynthesis, remained the same. Production was maintained, but the probability of *Botrytis* increased by 5%.

Crop-based RH control (M5) resulted on the whole in a slight RH reduction, which hardly affected crop production or quality.

Screen gap control in gaps (M6) led to a slight increase in screen closure during daytime. However, neither the greenhouse climate nor the cumulative amounts of absorbed radiation and production changed significantly. The probability of cuticle cracking and *Botrytis* increased slightly.

Increasing the size of the heat storage tank (M7) did not result in the expected increase of $CO_2$ concentration (see above) and production. It could be argued that summer settings should be different, causing $CO_2$ application earlier during daytime, which might indeed lead to increased production.

Reducing crop transpiration (M8) led to a slight reduction of RH, and as increased stomatal closure negatively affects $CO_2$ exchange and therefore photosynthesis, production was slightly reduced as well.

Improved roof insulation (M9) reduced the demand for heating and as less flue gas were available, $CO_2$ concentration was reduced, negatively influencing production.

Increased light transmission (M10) raised the levels of absorbed radiation by the crop, improving production (+6%).

Cooling (M11) resulted during the summer period in less ventilation and a slightly higher air $CO_2$ concentration. On a yearly basis, however, this did not lead to significant changes in production.

In summary, production increased only in case of increased transmission (M10), *viz*. by 6.3 %, and remained constant in case of increasing the size of the heat storage tank (M7). Production decreased less than 1% in case of temperature integration (M2, M3), increased RH set point (M4), crop-based RH control (M5), screen gap control in steps (M6), reduced crop transpiration (M8) and roof cooling (M11). It decreased by approximately 3% in case of reduced temperature set point (M1) and better insulation (M9). Quality was also expected to decrease though M1 and M9. None of the measures leads to increased quality.

**3. Energy Use Efficiency.** Energy use efficiency is defined here as the amount of energy (excluding solar radiation) required to produce a kg fresh harvestable product (MJ $kg^{-1}$). A reduction implies that less energy is required for the production of the same amount of tomato fruits, which is the aim of energy-conservation. Energy use efficiency improved for all energy conservation measures, except in case of roof cooling (Table 1). The latter was caused by increased energy requirements. Greatest gains in energy use efficiency were reached through insulation (M9, -20%), lowered temperature set point (M1, -12%) and improved light transmission (M10, -8%). Temperature integration (M2, M3), increase in RH set point (M4), crop-based RH control (M5), screen gap control in steps (M6) and reduction of crop transpiration (M8) lowered energy use efficiency by 3-6%, while increasing the heat buffer (M7) lowered energy use efficiency only by less than 1%.

## Farm Economics

Energy conservation reduces fuel costs. Improved light transmission (M10) increased the cost balance by €2.6 (10%, reference €25.5). An increase in the RH set point (M4), crop-based RH control (M5), screen gap control in steps (M6), increase of the heat buffer (M7) and reduction of crop transpiration (M8) also improved the balance, by less than €0.5. Temperature integration (M2, M3), insulation (M9) and roof cooling (M11) had a negative effect on the balance by less than €1, while lowered temperature set point decreased the balance by €3.0. Crop-based RH control (M5), reduction of crop transpiration (M8) and roof cooling (M11) did not result in economic consequences related to product quality. If the possible effects on produce quality are accounted for, and for which wide cultivar variation exists, balances in all cases may reduce.

## Prospects of Energy Conservation

Energy conservation methods are attractive if they do not negatively affect production in practice and improve the grower's income. If these two criteria are met, farmers are likely to invest in their implementation, and government policy of energy conservation can be supported. Much will depend on future price developments and technological advancements.

Simulations indicated that improved roof insulation (M9) saved most energy (23%), and although realised at the cost of 2.9% production, energy use efficiency improved with 20%. A reduced temperature set point (M1) was second best, saving 16% energy, reducing annual production by 3.3% and increasing energy use efficiency by 12%. In both cases, production loss can be prevented by the application of extra $CO_2$. Additional simulations indicated that a 50 ppm increase of the $CO_2$ concentration brings production to that of the reference situation. This suggests possibilities to remove the negative economic effects, which are simulated at reductions of €1 $m^{-2}$ and €3 $m^{-2}$, respectively. With modifications from the studied versions, the two energy conservation measures that save most gas should be applicable in practice.

Screen gap control in steps (M6) and increase of the RH set point (M4) saved 6% energy per year, hardly affecting production and improving energy use efficiency by 5-6%. As economic benefits increased, and as the measures can be implemented without additional investments, these methods appear worth further exploration. With regards to increase of the RH set point, it is known that highly productive greenhouse systems maintain a relatively high levels of $CO_2$ concentration by limiting ventilation and allowing relatively high levels of RH.

Temperature integration for 24 h (M2) and 72 h (M3) on an annual basis saved 4% gas, while barely affecting production and economic benefits. These figures were confirmed in a recent analysis of two farms (Ruijs et al., 2005). Energy use efficiency improved by 4%. Our simulations suggest that there was no additional benefit to extending the period of temperature integration in tomato cultivation. From an energy-conservation perspective, temperature integration appears an attractive measure, which indeed is already being implemented by approximately 1/3 of the Dutch growers.

The greatest economic benefit was realised by increasing the light transmission of the greenhouse roof (M10), which was primarily caused by a 6% higher production accompanied by a 2% decrease in energy requirement. Such greenhouse roofs are not available as yet, and therefore, technological advancements that improve greenhouse transmission are attractive also from an energy-conservation perspective.

Crop-based RH control (M5) also resulted in substantial economic benefits (€0.5), while reducing energy requirements by 3% without affecting production. This control is based on knowledge of crop temperature. Sensors or well-validated models can be added to the system.

Increasing the heat storage tank (M7) was expected to increase air $CO_2$ concentration, but did not lead to great climatic changes. However, further optimisation of the control may realise the desired $CO_2$ concentration, leading to increased production at un-changed energy use, and therefore to improved energy use efficiency.

Reduction of crop transpiration (M8) reduced energy consumption by 2%, at the cost of 0.6% production, with an economically neutral result. Innovative methods that reduce crop transpiration are worth exploring.

Cooling (M11) was expected to reduce ventilation and increase air $CO_2$ concentration, but did not lead to significant changes in climate, production, or economic benefit, and therefore appears a less likely candidate for further exploration. Fine-tuning of the control may bring about the expected changes.

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**Tables**

Table 1. Consequences of energy conserving measures for a tomato crop, for gas consumption, production, product quality and energy use efficiency (EEU), relative to the reference situation. The reference situation is given in absolute terms, except for product quality, which is given in relative terms. All variables are given per energy conservation measure, in terms of relative changes. Gas consumption is given per year and per quarter (Q). Production, product quality and EEU are given per year. Negative values imply a lower value than in case of the reference situation.

| Measure | Period | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Year | Q 1 | Q 2 | Q 3 | Q 4 | Year | Year | Year |
| | Gas consumption ($m^3$ $m^{-2}$ $period^{-1}$) | | | | | Prod. (kg fresh $m^{-2}$) | Qual. (%) | EEU (MJ $kg^{-1}$) |
| Reference | 45.3 | 18.5 | 9.4 | 6.4 | 11.0 | 58.9 | 100 | 25.7 |
| | Change[1] (%) | | | | | | | |
| M1. Temp. set point | -16 | -19 | -15 | -3 | -16 | -3 | -5 | -12 |
| M2. TI 24 h | -4 | -2 | -10 | -6 | -3 | -1 | 0 | -4 |
| M3. TI 72 h | -4 | -2 | -10 | -6 | -3 | -1 | 0 | -4 |
| M4. RH set point | -6 | -7 | -8 | -1 | -4 | 0 | -5 | -6 |
| M5. RH – crop based | -3 | -6 | -7 | 0 | -2 | 0 | 0 | -5 |
| M6. Screen gap | -6 | -9 | -7 | -1 | -2 | 0 | -1 | -5 |
| M7. Heat buffer | 1 | 0 | +1 | +1 | +1 | 0 | 0 | -1 |
| M8. Transpiration | -2 | -3 | -3 | -1 | -2 | -1 | 0 | -2 |
| M9. Insulation | -23 | -24 | -22 | -14 | -27 | -3 | 0 | -20 |
| M10. Light transm. | -2 | -2 | -3 | -1 | -2 | 6 | 0 | -8 |
| M11. Roof cooling | 3 | +2 | +4 | +3 | +2 | 0 | 0 | 3 |

## Figures

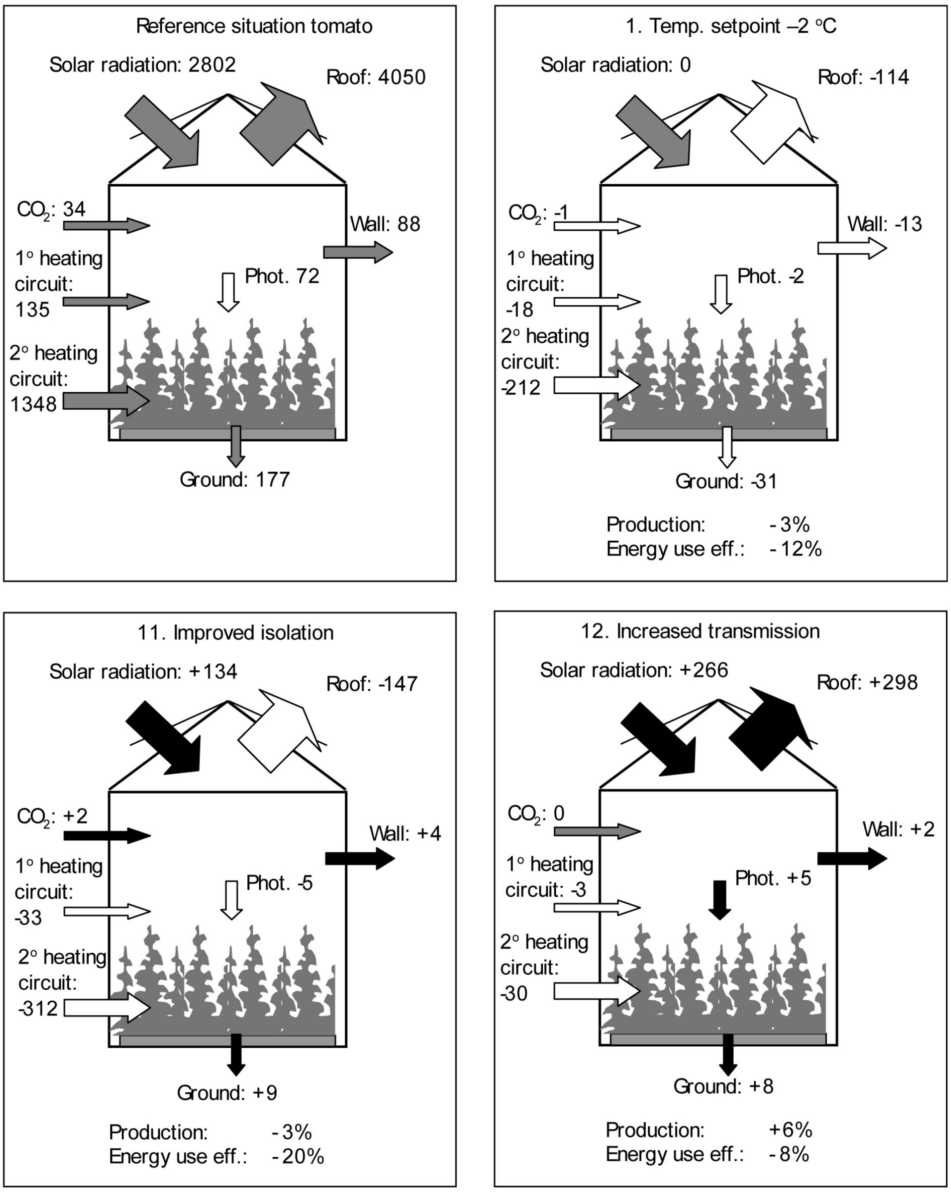


Fig. 1. Energy flows (MJ $m^{-2}$ $year^{-1}$) for the reference situation of tomato (upper left), and changes in energy flows relative to the reference situation for three energy conservation measures. The colours black, grey and white stand for an increase, decrease, and no change, respectively. Relative changes in production and energy use efficiency are indicated. 32 MJ $m^{-2}$ $year^{-1}$ corresponds with 1 $m^3$ natural gas.