Energy Saving: from Engineering to Crop Management

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Abstract

In greenhouse horticulture, energy costs form an increasingly larger part of the total production costs. Energy is primarily used for temperature control, reduction of air humidity, increase of light intensity and CO_2 supply. Use of fossil energy can be reduced by limiting the energy demand of the system and decreasing energy losses, by intelligent climate control, by increasing the energy efficiency of the crop and by replacing fossil energy sources by sustainable ones. Energy requirement of the greenhouse can be lowered up to 20-30% by using greenhouse covers with higher insulating values and the use of energy screens. A prerequisite is that these materials should not involve considerable light loss, since this would result in a loss of production. In energy efficient greenhouse concepts, durable energy sources should be included. In (semi-)closed greenhouses, the excess of solar energy in summer is collected and stored in aquifers to be reused in winter to heat the greenhouse. Ventilation windows are closed, with specific benefits to the crop: high CO_2 levels can be maintained, and temperature and humidity can be controlled to the needs of the crop. Development of new greenhouse concepts is ongoing. Current examples are greenhouse systems which convert natural energy sources such as solar energy into high-value energy such as electricity. Given a certain technical infrastructure of the greenhouse, energy consumption can be further reduced by energy efficient climate control and crop management. Essential elements are to allow fluctuating temperatures, lower crop transpiration, allow higher humidities, make efficient use of light and create fluent transitions in set points. Consequences for plant growth are related to rate of development, photosynthesis, assimilate distribution, transpiration and the occurrence of diseases or disorders. Since processes involved are complex, knowledge exchange between researchers and growers is essential to realize the goals set to reduce the energy consumption.

INTRODUCTION

In current greenhouse horticulture, next to high production levels, quality and timeliness of production are important. This can be reached by optimal control of greenhouse climate for which energy is of major importance. The need for (energy) cost reduction has become higher, since with increasing prices of natural gas in the last decade, energy forms a substantial fraction of the total production costs. The liberalisation of the energy market for growers since 2002 has increased the growers' awareness of the energy consumption of their cropping systems. This free market implies that growers do not pay a fixed price per unit of natural gas anymore, but that prices are greatly determined by the maximum supply capacity of the gas contract. Therefore, it is important to reduce peaks in energy use. In view of the Kyoto protocol several governments have set goals for energy use and CO_2 emission. In the Netherlands, the horticultural sector and government have agreed to improve the energy efficiency (production per unit of energy) by 65% in 2010 compared to 1980 and to increase the contribution of sustainable energy to 4%. Over the period 1980-2005, energy efficiency in the Dutch greenhouse industry has more than doubled. However, total energy use per

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square meter of greenhouse has hardly changed (Van der Velden and Smit, 2007). Efficiency improvement resulted from a more than doubling in yield per m^2 caused by amongst others improved greenhouse transmission, cultivars and cultivation techniques (Heuvelink et al., 2008). Recently, due to the international Kyoto protocol, maximum CO_2 emission levels were set by many governments. To reduce CO_2 emission from greenhouses, the use of fossil fuels needs to be reduced.

Energy in the greenhouse is primarily used for temperature control, reduction of air humidity, increase of light intensity and to a lesser extent for CO_2 supply. The use of fossil energy can be reduced by limiting the energy demand of the system and decreasing energy losses (higher insulation), by intelligent control of (micro)climate, by increasing the energy efficiency of the crop and by replacing fossil energy sources by sustainable ones. In this paper, recent developments concerning reduction of energy consumption in greenhouse production systems will be presented, as well as the consequences for crop management.

ENERGY DEMAND OF THE SYSTEM

Energy requirement of the greenhouse can be lowered by reducing energy losses. Energy losses occur through the ventilation as sensible and latent heat, but also through the greenhouse covering by convection and radiation. Using greenhouse covers with higher insulating values and the use of energy screens highly limits the amount of energy losses. Increased insulation can be obtained by low emission coatings combined with anti-reflection coatings. Hemming et al. (2009) showed in their research that it is possible to produce double glasses with anti-reflection coatings having a higher light transmission than traditional single greenhouse glass (83-85% for hemispherical light, compared to 82-83% for traditional single glass) and a k-value of 3.6 W m^{-2} K^{-1} (compared to 7.6 W m^{-2} K^{-1} of a traditional single glass). It is possible to produce other double glasses using a combination of anti-reflection and modern low-emission coatings, reaching an even lower k-value of ≈2.4 W m^{-2} K^{-1}. Calculations of year-round greenhouse climate (temperature, humidity, CO_2), energy consumption and tomato production (dry matter) with a validated dynamic climate model showed that energy saving of 25-33% were possible with the new double materials compared to a greenhouse with single glass and energy screen, without production losses in the case of double anti-reflection glass. Earlier studies by Bot et al. (2005) showed that when a triple-layered cover is used (double cover with thermal screen), energy saving can be up to 50% compared to a reference situation of a single cover with a thermal screen (Bot et al., 2005). The question is whether those high energy savings are still realistic since in nowadays systems energy consumption is already very low due to new climate control strategies. 25-30% energy saving due to increased insulation values of the systems seems to be possible.

A prerequisite is that new insulating materials should not involve considerable light loss, since this would result in a loss of production. Marcelis et al. (2006) evaluated the role of thumb “1% additional light results in 1% additional production”. Their literature study and analysis of data on climate and yield revealed that for vegetables and flowers 1% additional light resulted in 0.8-1% more production. The effects of increasing the transmission of the cover from 70 to 80% on tomato were simulated by Elings et al. (2005). Due to the increased light interception by the crop, fruit production increased by 6% and the energy required to heat the greenhouse decreased by 2% due to increased amount of solar heat in the greenhouse. Hemming et al. (2009) showed that with the newly developed double materials loss of light is not to be expected. If additional CO_2 is applied and attention is paid to humidity control, production will not decrease, in spite of considerable energy savings.

Thermal screens add an additional barrier between the greenhouse environment and its surroundings. When movable, it has less impact on the light transmission compared to fixed screens. If they are used almost permanently, screens can reduce the energy use by more than 35%, depending on the material (Bakker and Van Holsteijn, 1995). In practice, movable screens are closed only part of the cropping season depending on the criteria for opening and closing. Due to restrictions for closing, generally enforced by criteria related to humidity and light, in commercial practice reduction in energy use by thermal screens is restricted to 20% (Bakker et al., 2008). Efficient screening strategies can save energy while maintaining crop production level. Optimal control of screen use, by balancing the energetic effects against production effects was shown to yield an additional energy saving up to 4% without production effects when delaying the screen opening to radiation levels above 50-150 W m^{-2} (Dieleman and Kempkes, 2006). Also Bailey (1988) calculated positive financial results if screen opening is based on irradiance. If night temperatures were increased, in combination with decreased day temperatures, a further energy saving could be realised with the screen.

GREENHOUSE CONCEPTS

In energy efficient greenhouse concepts, durable energy sources such as solar energy, wind energy or geothermal energy should be included. A number of recently developed concepts are the solar greenhouse (Bot, 2003; Bot et al., 2005); closed greenhouse (Opdam et al., 2005), energy producing greenhouse (Bakker et al., 2006), Sunergy greenhouse (de Zwart, 2011) and the electricity producing greenhouse (Sonneveld et al., 2006). In closed greenhouses, the excess of solar energy in summer is collected and stored in aquifers to be reused in winter to heat the greenhouse. This concept results in a reduction in primary energy use of 33%, based on 1/3 of the area with closed greenhouse and 2/3 with traditional greenhouse with ventilation windows (Opdam et al., 2005). Besides aquifers for seasonal energy storage, the technical concept consists of a heat pump, daytime storage, heat exchangers and air treatment units which either bring the cold air directly into the (top of the) greenhouse or do so via air distribution ducts below the gutters (De Zwart et al., 2011). In this concept, ventilation windows are closed. Thereby, CO_2 levels, temperature and humidity can be controlled to the needs of the crop (De Gelder et al., 2005). To reduce investment costs, in practice growers tend to choose for a semi-closed system (Marcelis et al., 2011). Cooling capacity of this system is lower than that of a closed greenhouse. Therefore, when the active cooling capacity is insufficient to keep the temperature below the maximum, ventilation windows will be opened (Heuvelink et al., 2008). CO_2 emission in (semi-)closed greenhouses is considerably lower than in open greenhouses. In a recent experiment, in which tomatoes were grown with a CO_2 supply capacity of 230 kg ha^{-1} h^{-1} up to a maximum concentration of 1000 ppm, in the open greenhouse 54.7 kg CO_2 m^{-2} was supplied whereas in the closed greenhouse this was 14.4 kg CO_2 m^{-2} (Qian et al., 2011).

Specific characteristics of climate in (semi-)closed greenhouses with cooling ducts under the gutters are: high CO_2 concentrations, vertical temperature gradients, high humidities, combined conditions of high light intensity and high CO_2 concentration, and increased rates of air movement (Qian et al., 2011), Elings et al. (2007) investigated whether increased air flow rates cause photosynthetic adaptation in full grown tomato plants. Air circulation did not change the photosynthesis light-response curves. Yield increase was therefore attributable only to the instantaneous effects of elevated CO_2 concentrations (Elings et al., 2007; Heuvelink et al., 2008). Körner et al. (2009) showed that at high irradiance, the optimum temperature for crop photosynthesis increased with CO_2 concentration. This shift in optimum temperature was with 1.9°C much lower than that reported for leaves (Cannell and Thornley, 1998), due to the fact that the leaves deeper in the canopy are not at saturating light levels (Körner et al., 2009).

The higher humidities cause a reduction in transpiration, and thereby increased temperatures of the top of the canopy. In systems where cooling ducts are below the gutters, temperature differences of 5°C between roots and top of the plant can occur (Qian et al., 2011). This affected the time necessary for fruits to mature. At lower temperatures, fruits need more time to ripen (Verkerk, 1955). Tomato fruits were found to be more sensitive to temperature in their later stages of maturation (De Koning, 1994; Adams et al., 2001) at which they are at lower temperatures in (semi-)closed greenhouses.

Development of new greenhouse concepts is ongoing. Current examples are greenhouse systems which convert natural energy sources such as solar energy into high-value energy such as electricity. Sonneveld et al. (2006, 2007) designed a system with a parabolic NIR reflecting greenhouse cover. This cover reflects and focuses the NIR radiation on a specific PV (photo voltaic) cell to generate electricity (electricity producing greenhouse).

ENERGY EFFICIENT CLIMATE CONTROL

Although numerous high-tech developments take place, the majority of the growers still have a standard equipped greenhouse. Given their technical infrastructure of the greenhouse, they should reach a reduction in energy consumption by adaptations in their greenhouse climate or cropping system. Essential elements of an energy efficient climate control are to allow fluctuating temperatures within certain bandwidths, allow higher humidities and create fluent transitions in set points (Dieleman et al., 2006). In this chapter, an overview of the perspectives of these adaptations is presented, classified by the climate factors primarily involved.

Temperature

Greenhouse climate is commonly controlled by rather rigid set points for heating and ventilation. Energy consumption strongly increases with increasing set points for heating temperature. Reducing the average 24-h temperature in tomato was calculated to reduce the energy consumption of a year-round grown tomato crop by 16% (Elings et al., 2005). However, the lower temperatures affected leaf area development and light interception negatively, which resulted in 3% decrease in production. When temperature integration is applied, temperatures are allowed to fluctuate within predefined bandwidths with a fixed period in which temperature deviations should be compensated. Several studies have shown that most horticultural crops tolerate these fluctuations, as long as the average temperature over 24 hours (Bakker and Van Uffelen, 1988) or several days (Hurd and Graves, 1984; De Koning, 1990) is kept constant. This may result in energy savings of 3% at a bandwidth of 2°C (Elings et al., 2005) to 13% at a bandwidth of 10°C (Buwalda et al., 1999).

Since 2002, especially peaks in energy use are expensive. When pipe temperatures are maximized to prevent peaks, usually temperatures in the greenhouse around sunrise will be low. A temporarily low temperature (DROP) reduces plant length (Sysoeva et al., 1999). In many crops, this effect is largest when the DROP is applied in the first part of the day (Myster and Moe, 1995; Grimstad, 1993). However, many of these results were obtained with young plants. A DROP of 2.5°C during 1 hour after sunrise in a fruit bearing tomato crop did not affect stem length, plant development or fruit production (Dieleman et al., 2005b). This implies that energy saving can be obtained by allowing the temperature in the greenhouse to lower when temperatures outside are low, without negative effects for the crop.

Humidity

In general, humidity in the greenhouse is high due to crop transpiration. The transpiration of a crop depends on solar radiation, air temperature and humidity of the greenhouse air (Stanghellini, 1987). The most important reason for humidity control is the risk of fungal diseases and physiological disorders (Grange and Hand, 1987). Heating and ventilation are used to dehumidify, both at the cost of considerable amounts of energy (10-25% of the total use of energy). The energy use involved in dehumidification can be reduced by increasing the humidity set points, reducing crop transpiration or dehumidification with heat recovery. Increasing the set point for relative humidity from 85 to 90% in tomato was calculated to reduce the energy consumption by 4% (Elings et al., 2005). If transpiration can be reduced, humidity will be lowered without heating or ventilation, thereby saving energy. Li et al. (2001) showed that transpiration in tomato can be reduced by 35% without affecting fruit production. One of these measures may be the removal of leaves of crops with high LAIs (Dueck et al., 2006). Simulations showed that reducing the LAI from 6 to 3 in a sweet pepper crop in August resulted in a 10% reduction in transpiration and 5% energy conservation without affecting light interception and production. In tomato, halving the leaf area by removing old leaves was shown to reduce transpiration by 30% without having a detrimental effect on crop yield (Adams et al., 2002).

In better insulated greenhouses, or when energy screens are used, the benefits of the better insulation are reduced when dehumidification via ventilation is applied. Since condensation on the cover is lower for these greenhouses, additional dehumidification becomes more important (Campen et al., 2003). For these conditions, a system was designed to dehumidify air in a greenhouse when a thermal screen is used (Campen et al., 2009). In this system, outside air is exchanged at low level with greenhouse air. The ventilation with cool dry outside air is mechanically controlled using a ventilator mounted in the greenhouse sidewall and an air distribution system with ducts below the growing gutters. The dry air is blown in the greenhouse near the floor, thereby forcing humid air to pass through the thermal screen. The excess air in the greenhouse flows out through leaks in the cover. It resulted in a homogeneous climate under the screen with temperature differences less than 1°C. This system enables growers to keep their energy screens closed for longer periods without increasing the risks of high humidity, thereby saving energy (Campen et al., 2009).

Light

Energy-efficiency of the greenhouse can be increased by making optimal use of the incoming global radiation energy from the sun. Global radiation that enters the greenhouse can be divided in ultraviolet radiation (UV, 300-400 nm), photosynthetically active radiation (PAR, 400-700 nm) and near infrared radiation (NIR, up to 2500 nm). NIR is partly reflected by the crop (45% in the case of roses as shown by Kempkes et al., 2008), but it is absorbed by installations and construction elements of the greenhouse and increases air and crop temperature. This heating effect is desirable during cold periods, but in warm periods the temperature in the greenhouse can increase above levels optimal for crop growth and production. Under Dutch climate conditions, permanent NIR filtering in the cover would increase energy consumption depending on crop and outside climate (Hemming et al., 2005a, 2006). Therefore, movable NIR reflecting screens would be more suitable under these conditions to reduce the energy load (or need for cooling) during warm periods. In an experiment with a young rose crop, Kempkes et al. (2008) showed that plant transpiration under a NIR reflecting screen was lower at the same levels of global radiation, compared to a standard energy screen. Plant development and production, however, was not affected. The lower humidity caused by reduced crop transpiration offers a potential application for decreasing costs of energy caused by humidity management in temperate regions (Kempkes et al., 2008). NIR-filtering screens reduced the greenhouse air temperature and crop temperature (Runkle et al., 2002). This was shown to reduce crop height depending on the species. They conclude that the NIR-reflecting screen provides an alternative to metalized shading fabrics since it transmits more PAR per unit solar energy.

Another possibility to increase the energy-efficiency of greenhouses are new covering materials improving the light-use efficiency of crops. In greenhouses with a glass cover, light is not evenly distributed. Fruit vegetables like cucumber, tomato and sweet pepper have a high LAI and intercept a large quantity of light with the upper leaves, whereas the middle and lower leaves receive much less light and contribute very little to photosynthesis, growth and production (Dueck et al., 2006). When light is made diffuse, it will penetrate deeper in the canopy in comparison with direct light. Light and temperature distribution in the crop will thereby be more even. Recently, covering materials are produced that can make light diffuse without a significant reduction in light transmission (Hemming et al., 2005b, 2008b). On sunny days, light interception in a cucumber crop under diffuse greenhouse cover was higher than under direct light, especially by the intermediate leaf layers (Hemming et al., 2008a). No difference in light interception between the diffuse and direct light treatments was observed on cloudy days, as it can be expected. Photosynthesis rates of intermediate leaf layers under diffuse light were higher at normal light conditions (500 µmol PAR m^{-2} s^{-1}) (Hemming et al., 2008a). Yield of cucumber under diffuse light was 8-10% higher than under direct light. Diffuse light also positively affected the growth of pot chrysanthemum and other pot plants. Although diffusing covering materials did not affect energy use of the greenhouse, the increase in production resulted in a higher energy efficiency.

CO_2

A small part of the energy used in greenhouse horticulture is used for CO_2 supply. When the gas consumption for heating is reduced due to energy conserving measures, the amount of CO_2 available from flue gases associated with heating also decreases. To make more efficient use of temperature and CO_2, an optimised climate control system was developed in which temperature and CO_2 were deployed such that energy use was minimised while maintaining crop production (Dieleman et al., 2005a). The optimization of CO_2 supply was based on an algorithm that weighed the positive effect of CO_2 on production in relation to light intensity and temperature (Aaslyng et al., 1999; Körner et al., 2009) against the CO_2 loss by ventilation. This resulted in a simulated 2.5% higher production at a reduction of 6% in energy use due to an optimisation of temperature while mimimising the heat demand, based on the principle of temperature integration (Dieleman et al., 2005a).

KNOWLEDGE TRANSFER

In Dutch greenhouse horticulture, especially vegetable growers are organised in groups of approximately 10 growers which generally grow the same crop in the same area. They meet weekly, visit each others' greenhouses and discuss matters related to production. This has greatly improved knowledge transfer within greenhouse horticulture. Recently, growers' groups started using internet technologies to obtain and exchange information. Via internet, models were applied to show growers, nearly real-time, the consequences of management practices in their local situation (Buwalda et al., 2008).

Furthermore, on specific topics like assimilation lighting, energy consumption or (semi-)closed greenhouses, groups have developed, in which the growers are guided by either extension workers or researchers. Examples are groups of tomato and cucumber growers that had set aims to increase the number of screening hours and thereby reducing their energy consumption. Weekly their climate data were analysed, and the analysis was sent to them by mail. Bimonthly meetings were held with growers and researchers to discuss the climates realised and the effects on the crop. Where relevant, growers' questions were answered (Ruijs et al., 2006). Around the topic closed greenhouses, a community of practice was developed, in which the growers shared experiences with and posed questions to researchers (Hoes et al., 2008). Cooperation and active exchange of knowledge proved to be necessary to help all participants of the platform to increase understanding, apply the information and realise their goals.

CONCLUSION

Recently, covering materials were developed that can reduce energy consumption in greenhouses by 25-30%. New greenhouse concepts were developed, which collect solar energy, thereby becoming net energy producers. In practice, the majority of the growers will have to reduce the energy consumption by an energy efficient climate control and adaptations in the cropping system. Knowledge exchange between researchers and growers is essential to reach the goals set for the reduction in energy consumption.

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