Innovative Technologies for an Efficient Use of Energy

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Abstract

Efficient use of energy in greenhouses has been subject of research and development for decades. The final energy efficiency, e.g. the amount of energy used per unit of product, is determined by improvements in energy conversion, reductions in energy use for environmental control and the efficiency of crop production. The new European targets on reduction of CO_2 emission have resulted in a renewed interest in innovative technologies to improve energy efficiency in greenhouses designed for North- as well as South European regions. In this paper an overview of the recent developments is presented from both the Northwest European as well as the Mediterranean perspective. The developments range from new modified covering materials, innovative and energy conservative climate control equipment and plant response based control systems, to integrated energy efficient greenhouse designs.

INTRODUCTION

After the first "energy crisis" in the early 1980ies, where the limited supply of energy caused the first significant increase in energy prices, the energy use of greenhouses has again become a major research issue. The need for (energy) cost reduction becomes of higher importance when energy forms a substantial fraction of the total production costs. For Italy, it has been calculated that energy use for conditioning is already about 20-30% of the total production costs (De Pascale and Maggio, 2004), while in France it is 12-14% on average (Boulard, 2001) and 22% for vegetables, which is comparable to the northern regions (van der Knijff et al., 2004). The absolute use, however, differs between the specific locations: e.g. for Finland the total energy consumption, has been estimated at 1900 MJm^{-2} per year (Olofsson et al., 2006), for The Netherlands 1500 MJ m^{-2} (van der Knijff et al., 2004) and for southern France 500-1600 MJ m^{-2} (Vesine et al., 2007).

With the recently more pronounced interest in global warming and climate change, the use of fossil fuel is on the political agenda again (see Al Gore's recent movie: An inconvenient truth). The international Kyoto protocol resulted in a new worldwide goal and many governments have set maximum CO_2 emission levels for different industries, e.g. for The Netherlands: -30% CO_2 emission in 2020 compared to 1990. The greenhouse industry is thereby again confronted with economical, political and social pressure to reduce the energy use and improve the energy efficiency.

There are mainly two ways to increase the energy efficiency:

- reduction of the energy input into the greenhouse system
- increase the production per unit energy.

The first strategy can be divided in two different parts: 1) efficient conversion technology to maximize the conversion of the energy source into a usable form (e.g. heat, cold, light) and 2): the reduction of the energy loss to the environment. The increase of the production per unit of energy, can be achieved in many ways, especially under sub optimal growing conditions. In fact, all cultivation measures which increase the production like improved irrigation, better nutrition, pest and disease control, a better utilization of the available greenhouse area etc, in the end also improve the energy efficiency.

Focussing solely on energy efficiency without any focus on the absolute energy use may have unexpected (and undesired from an environmental point of view) effects. In Mediterranean areas, heating is now also used to obtain early production and a constant quantitative-qualitative yield (Baudoin, 1999), leading on one hand to a higher energy efficiency but at the same time also to a higher absolute energy use (Boulard, 2001; Vésine et al., 2007). Also an improved environmental control (e.g. more CO_2 supply, additional lighting), intensified production schemes, (e.g. Boulard, 2001) and use of cooling systems to expand the growing period into months with high temperatures, all cause an increase in energy consumption (De Pascale and Maggio, 2004). The same holds for the Northern regions with respect to the use of artificial light up to very high levels (e.g. over 200 Wm^{-2}) in Finland (Olofsson et al., 2006) and over 100 Wm^{-2} in Netherlands.

In countries like Italy, France, UK and the Netherlands, the total energy consumption and related CO_2 emission, shows little fluctuations despite all kinds of improvements on energy efficient greenhouses [e.g. in The Netherlands the CO_2 emission in 2004 was 6.44 million tons, compared to 6.76 in 1990 (van der Knijff et al., 2004)]. The energy efficiency has however gradually improved, primarily due to the increase in production.

The major challenge is to find ways which meet both needs: improved energy efficiency combined with an absolute reduction of the overall energy consumption and related CO_2 emission of the greenhouse industry. The development of energy conservative and –efficient systems is an optimization process and the overall result of a step by step improvement and adaptation of the production system to meet the requirements for the given constraints and local conditions. However, in general the objectives stated by De Pascale and Maggio (2004) for Mediterranean areas also hold for the Northern regions. During fall/winter the objective is to maximize the radiation quantity (either from natural light or artificial light) and minimize the energy loss; during the spring/summer the objective is to reduce high temperatures. For this purpose, even in Finland, greenhouse cooling has been introduced (Särkkä et al., 2006). This fits in the attempts to control the crop production process (almost) year round to optimize the production level and consequently the energy efficiency.

Since the technology and developments related to energy efficiency in greenhouse horticulture are numerous, this paper only concentrates on several aspects of energy efficient greenhouse designs with underlying components as covering materials, energy conservative climate control equipment and plant response based control systems.

STUDY

Maximize and Modify Radiation

The first step in creating energy efficient greenhouses is to maximize the use from the incoming natural radiation by its positive impact on the production and the reduction of the additional heating power. For a tomato crop, grown under Dutch conditions, a 10% higher greenhouse transmission was predicted to give an 8% improvement in efficiency (Elings et al., 2005). Further improvement of the greenhouse as an energy efficient solar collector is obtained by improving the light transmission of its structure and minimizing reflection losses through the modification of the roof slope. In Southern Europe, considerable enhancement of light transmission has been reached by increasing the roof slope from nearly zero, typical from areas with low rainfall, to values close to 30º which has had a direct effect on crop response in the winter time (Soriano et al., 2004).

Modifications for Northern latitudes have led to integrated construction parts, minimized dimensions of gutters, the use of wide (>1.7 m) glass panels and white coated frames resulting in constructions with a limited light interception (Janssen and 't Hart, 2006). Within the limitations of current materials technology and international construction norms, further improvement of the construction transmission is expected to be only marginally (2%), e.g. by using trellis type columns. Any significant increase of the light transmission therefore now depends primarily on innovations of the cover materials.

We can divide the covering materials roughly into three groups: glass, film and hard plastic sheets, each with its own characteristics with respect to light transmission for different wavelengths, insulating value but also sustainability and price. For energy efficiency and optimal use of solar radiation, the transmission for visible light (or Photosynthetic Active radiation) and Infra red radiation are to be considered (Hemming et al., 2004a). For the winter period, one should aim at materials which combine a high transmission for visible light with a low for IR radiation and a high insulation value. These materials enable a maximum amount of solar (or "green") energy to enter the greenhouse (to be used for crop production and temperature increase), while the IR radiation loss from the greenhouse is being restricted. Many film materials are sub-optimal for energy efficient greenhouses since their IR transmission is high except for the recently introduced ETFE membrane (Hemming, 2005; Waaijenberg et al., 2005).

To further improve the light transmission of the materials, several anti reflex coatings have been developed and introduced in commercial products during the last decades to prevent light reflection, which enables light transmission to be increased by 5-6% (Hemming et al, 2006a). Coatings can also reduce the light reduction by condensation, which is especially important with plastic materials. Recent innovations in this field are modifying the surface structures with e.g. micro V, which may first be implemented on solar panels but which is also a promising technology for greenhouse covers (Sonneveld and Swinkels, 2005a).

Although overall light transmission is of major importance, recent studies show that diffuse light is able to penetrate deeper into a plant canopy in comparison to direct light. Covering materials which diffuse the incoming light, at equal overall transmission and insulation values, improve crop production and energy efficiency (Pollet et al., 2000; Jongschaap et al., 2006; Hemming et al, 2006b). For conditions with high solar radiations, the use of Fresnel lenses is considered to separate the direct from the diffuse radiation and using the surplus of direct radiation into electricity (Souliotis et al., 2006).

However, the positive effect of all innovative technologies to improve greenhouse light transmission can only have its potential effect if the cover is regularly cleaned since the transmission of the cover may significantly be reduced by dust.

Minimize Energy Loss by Screens and Insulating Materials

The major processes of energy loss in natural ventilated greenhouses are: 1) convection and radiation from the greenhouse cover and 2): thermal and latent heat transfer through ventilation. Improved insulation and reduced ventilation are therefore the first steps to create energy conservative greenhouses.

A thermal screen adds an additional barrier between the greenhouse environment and its surrounding and it reduces both the convection and ventilation loss. When movable, it has less impact on the light transmission compared to fixed screens or double covering materials. In The Netherlands, 79% of the greenhouse area is equipped with thermal screens and in France 33% of heated greenhouses (Van der Knijff et al., 2004; Vésine et al., 2007). Theoretically, screens may reduce the energy use by more than 35-40%, depending on the material, if being used almost permanently (Bakker and van Holsteijn, 1995). In practice, movable screens are closed only a part of the entire period depending on the criteria for opening and closing (Dieleman and Kempkes, 2006). Due to the restrictions for closing, generally enforced by criteria related to humidity and light, in commercial practice the energy effects are restricted to 20%. The overall effect on the energy efficiency is even slightly lower due to the light reduction caused by the construction and the screen material. The screen materials itself have been subject of innovations by finding compromises between insulation value and vapour transmission, either through woven materials or the use of materials with a specific vapour resistance.

In the field of screen construction a wide range of systems have been investigated, but today the movable sliding system is most widespread throughout Europe and developments aim at reducing the light interception by the construction and the screen material (e.g. Van Staalduinen, 2007). Other innovations in the field of thermal screens are related to its operational control by which energetic effects are balanced against the production. Dieleman and Kempkes (2006) showed that with tomato, and additional energy saving of up to 4% can be obtained without production effects, when delaying the screen opening to radiation levels above 50-150 Wm^{-2}.

Increasing the insulation value of the greenhouse, cover has a major impact on the energy consumption of the greenhouse but a major disadvantage of most fixed insulating covers is the reduction in light transmission and increased humidity. Development of materials which combine high insulation values with high light transmission is one of the most challenging issues. Under practical conditions, the potential energy saving of double and triple covering materials is almost never achieved, since the grower tries to compensate for the negative effects by increasing the dehumidification of the the greenhouse environment (e.g. Sonneveld and Swinkels, 2005b).

The Lexan® ZigZag™ greenhouse covering material is an example of a material which combines a high light transmittance (80% for diffuse light) with an insulation value of 3.4 $Wm^{-2}K^{-1}$ (Swinkels et al., 2001). The momentary energy saving might be 45% and year round 20-25% when compared to single glass (Sonneveld and Swinkels, 2005b), but practical application is still limited due to additional costs for the greenhouse construction and the overall economic benefit. Promising alternatives for the future are double side coated Anti Reflex glass (Hemming et al., 2006a), combinations of micro V treated glass (Sonneveld and Swinkels, 2005a) or triple layer systems (Bot et al., 2005). An extensive simulation study showed that double Anti Reflex glass combines a high diffuse light transmission (82-86%) with an energy reduction of 26%, leading to a gain in energy efficiency of 40%. At current price levels the estimated pay back time is about 7 years (Hemming et al., 2006a).

Minimize Energy Loss through Ventilation and Latent Heat

On a year round basis, the energy transfer from the greenhouse to the environment by natural ventilation accounts for a major fraction. Many attempts to reduce the energy input for greenhouses therefore have concentrated on the ventilation process and its effects on the heat- and mass transfer (e.g. Molina-Aiz et al., 2005; Valera et al., 2005; Baeza et al., 2006; Baeza, 2007; Sase, 2006) and the use of this knowledge in energy efficient operational control (Körner and Challa, 2003a). During periods with relatively low radiation and moderate ambient temperatures, natural or forced ventilation is generally used to prevent (too) high humidity and this is related to a significant (5 to 20%) fraction of the energy consumption (Campen et al., 2003).

There are several different ways to reduce the “humidity control related” energy consumption e.g. using higher humidity set points (Elings et al., 2005); reducing the transpiration level of the crop, or dehumidification with heat recovery (Campen and Bot, 2002; Rousse et al., 2000).

Increasing the humidity setpoint saves energy: a 5% higher RH was predicted to reduce the average the energy use by 5 to 6% (Elings et al., 2005). Although high humidity levels are generally associated with increased risk of fungal diseases and reduced quality (e.g. botrytis, Blossom End Rot), increasing humidity may also be positive for crop production and quality, under moderate as well as under more sub tropical conditions (e.g. Bakker, 1991; Katsoulas et al., 2006; Montero, 2006). Increasing the humidity level therefore should be considered an effective way of increasing the energy efficiency. Also the first practical experiments in closed greenhouses showed that growers gradually shifted their setpoints to higher temperature and humidity levels during the (summer) daytime, which may partly explain the positive production and energy efficiency effect observed (Raaphorst, 2005).

Reduction of the transpiration also has positive effects on energy efficiency since lower transpiring crops bring less water into the air and therefore require less energy for humidity control under low irradiation conditions. Crop transpiration might even be reduced by 10-30%, during winter and early spring conditions without affecting fruit production (Esmeijer, 1998). Different techniques might be used. If applied only in winter, antitranspirants in combination with higher CO_2 levels did not significantly affect photosynthesis and growth. Simulation studies show energy savings of 5-10% for tomato and sweet pepper, and 2-5% for cucumber, (Dieleman et al., 2006). Controlled reduction of the leaf area for crops with a high leaf area index like pepper may reduce energy use without impact on production (Dueck and Marcelis, 2005). Systematic reduction of the lower leaves to maintain LAI’s between 6 and 3, resulted in a 10% reduction in transpiration and 5% energy conservation. While in tomatoes halving the leaf area by removing old leaves was shown to reduce transpiration by 30% without having a detrimental effect on crop yields (Adams et al., 2002).

Reducing the ventilation rate to minimize the energy loss or even using completely closed greenhouses without natural ventilation (Opdam et al, 2005) require technical solutions to prevent high temperatures and humidity levels. Energy efficient dehumidification systems for both moderate and semi-arid regions are based on cooling and dehumidification systems with heat pumps combined with innovative heat exchangers and heat recovery (e.g. Campen and Bot, 2001; Yildiz and Stombaugh, 2006; Buchholz et al., 2005). The application in commercial practice is until now limited since economic benefits in terms of crop production and energy saving still do not meet the additional costs.

Energy Efficient Cooling

In most European regions and especially at Southern latitudes, there is a large surplus of solar energy on a year basis, but cooling is not only used in these areas. In 2006 the first Symposium on Greenhouse Cooling in Almeria included presentations from the equatorial to even artic regions. With the trend toward more completely controllable conditions in greenhouses and with the expansion of year round production, reduction of energy loss seems to become of equal importance in the energy efficient design of greenhouses compared to cooling.

Natural ventilation is of course the first method of greenhouse cooling. Especially for Southern Latitudes numerical methods (CFD) are being used to study the greenhouse geometry for the enhancement of natural ventilation and design of more efficient natural ventilation systems. Some of the recent findings on this area have been shown by Baeza (2007). Windward ventilation is more efficient than leeside ventilation, therefore new greenhouse constructions have bigger-size openings facing the prevailing winds. In existing designs, outside air may enter and leave the greenhouse without mixing with the internal air and the use of deflectors to conduct the entering air through the crop area is strongly recommended. The greenhouse slope has a significant effect on ventilation rate, therefore traditional horizontal roof greenhouses are being replaced with symmetrical or asymmetrical greenhouses with near 30º roof slope. Above 30º of slope, no further increase in ventilation has been detected from CFD simulations. Windward ventilation has the drawback of creating a temperature and humidity gradient from the windward side to the lee side. Then, new southern greenhouses are expected to have limited width, ideally less than 50 m. Lee ventilation can be suitable for large-size greenhouses, but lee ventilation in southern greenhouses require further studies to be operative. Some suggestions on this area are currently being developed (Montero et al., in press).

Hamer et al. (2006) compared different cooling systems to maintain the same greenhouse temperature as with natural ventilation for North West European conditions while de Zwart (2005) designed different cooling systems with a capacity to keep the greenhouse completely closed, even at maximum radiation levels. Return on investment is poor except for the direct and indirect evaporative cooling (Hamer et al., 2006; de Zwart, 2005). Anton et al. (2006) compared different cooling and mechanical ventilation systems for Spanish conditions. Mechanical ventilation required a yearly energy consumption of 9.3 kWh m^{-2} and it was concluded that the direct evaporative cooling by fogging shows both economically and environmentally favourable results compared to forced cooling. This is most likely the result of the positive effect of the lower temperature and higher humidity since increasing humidity in the lower ranges, generally shows positive effects on growth and production, at least with major fruit vegetables (e.g. Bakker, 1991; Montero, 2006; Kastoulas et al., 2006). These results indicate that direct evaporative cooling by misting and pad and fan cooling still give the best economic results and increase the energy efficiency primarily through the impact on production.

Reduction of the solar energy flux into the greenhouse during periods with an excessive radiation level is a common way of passive cooling. Mobile shading systems mounted inside or outside have a number of advantages, such as the improvement of temperature and humidity, quality (e.g. reduction of Blossom End Rot in tomato crops) and a clear increase in water use efficiency. Especially for southern regions movable and external shading are very interesting cooling systems to improve the energy efficiency (Lorenzo et al., 2006).

Specific materials which absorb or reflect different wave lengths or contain interference or photo or thermochromic pigments may be used to bring down the heat load (Hoffmann and Waaijenberg, 2002) but mostly these materials also reduce the PAR level. Materials reflecting part of the sun's energy not necessary for plant growth (the near-infrared radiation, NIR) show promising results (e.g. Runkle et al., 2002; Garcia-Alonso et al., 2006; Hemming et al., 2006c) and may be applied either as greenhouse cover or as screen material. The use of this NIR energy and its conversion into electric power to run a pad and fan cooling system is an example of combined passive and active cooling to be used in the future (Sonneveld et al., 2006).

Energy Efficient Operational Control

Efficient greenhouse environmental control has large potential to improve the energy efficient greenhouse production and the continuously increasing knowledge on physiological processes and crop growth – environment interactions gradually opens new possibilities.

One way of substantially reducing energy use is to lower production temperatures. However, this approach generally slows development and for some crops reduces quality. In the longer term it might be possible to breed for low temperature tolerant cultivars (van der Ploeg, 2007), but currently temperature integration (TI) is probably a better option for most crops. In 1981 Cockshull et al. demonstrated that the effect of temperature on the timing of developmental events such as flowering can be attributed to mean diurnal temperature rather than distinct day/night effects. In contrast, Hurd and Graves (1984) showed that tomato yields and earliness were also dependent on temperature integral, rather than diurnal variation. However, there are limits to this approach. When plants are grown at both sub- and supra-optimal temperatures problems can arise. This is because supra-optimal temperatures cannot be used to compensate for a period of low temperature. Langton and Horridge (2006) showed that alternating between sub- (14°C) and supra-optimal temperatures (24°C) delayed flowering in chrysanthemum when compared with plants grown at a constant 19°C (average temperature).

The first use of TI was to improve energy savings by manipulating set-points based on wind speed (Bailey, 1985; Hurd and Graves, 1984). Heat losses increase linearly as wind speed increases, therefore, energy can be saved by reducing the heating set-points when it is windy and compensating for this at other times. Bailey (1985) predicted savings of 5-10%, although Tantau (1998) suggested that modulation of set-points based on wind speed would result in an energy saving of just 4% realistic for an ornamental crop grown with a thermal screen.

A more commonly exploited TI strategy is to use higher than normal vent temperatures to maximise the heating due to solar gain and to compensate by running lower temperatures at night or on dull days. Energy savings will depend on the crop and the temperature fluctuations that are allowed, but annual savings of up to 16% are possible (Langton and Hamer, 2003). Comparable savings of 5-15% were found with simulations and experiments without affecting plant growth and production (e.g. Körner and Challa, 2003b; Dueck and Marcelis, 2005; Elings et al., 2005). In completely closed greenhouses this method is used to reduce the cooling power during daytime. Originally, in these systems during the summer, relatively low day temperatures were aimed at (Opdam et al., 2005). Later on the tendency was towards higher day temperatures and lower night temperatures to restricts the necessary maximum cooling capacity during daytime. Combined with normal ventilation during the night time (when CO_2 is not needed), this reduces the required capacity and total amount of cold water from the aquifer, making the system more economically feasible.

To maximise energy savings, the approach of using higher vent set-points can be combined with the use of lower than normal day heating set-points and higher temperatures under thermal screens at night. The aim is to exploit fully solar gain and then, when additional heat is required, to add this preferentially at night when heat losses are reduced due to the thermal screen. Energy savings of up to 30% have been predicted (Langton and Hamer, 2003). In a simulation for cut chrysanthemums Körner (2003) suggested that TI could reduce the weekly energy consumption by up to 60% and they predicted annual savings of 8, 15 and 18% with fluctuations around the standard regime (band widths) of 2, 4 and 6°C, respectively, on a 24h basis. Rijsdijk and Vogelezang (2000) have demonstrated an 18% energy saving in pot plants, rose and sweet pepper with a band width of 8°C. However, when setting band widths a balance is needed between maximising energy savings, while minimising any detrimental effects of crop yields or quality, particularly when low-day/high-night strategies are used.

Energy efficient thermal screen control involves balancing the production and quality effects related to humidity and light against the energy saving. In this field Dieleman and Kempkes (2006) showed that on top of the energy saving by closing the screen at night, 4% additional energy saving can be obtained without production losses, by delaying the opening of the screen until radiation levels outside of 50-150 Wm^{-2}. The basics for energy efficient (humidity) screen and natural ventilation control were evaluated by van de Braak et al. (1998), who showed that it is more energy efficient to control the screen prior to the ventilation windows when aiming at a given humidity setpoint. Humidity control strategies also have a big impact on the savings that can be made as a result of temperature integration. Reduced ventilation and heating result in increased relative humidity when the temperature drops, and aggressive humidity control can negate the savings that can be made as a result of TI. Higher RH set-points and dynamic humidity control can significantly reduce energy use (Körner, 2003).

To gain maximum profit of environmental control in the field of energy efficiency, the control should no longer aim at environmental factors or actuators like heating, ventilation and CO_2 supply, but on energy efficient crop production and quality control. This requires (model based) control systems in which the impact of control actions on both crop production and energy consumption is taken into account. This approach has been followed for decades since in the early 1980ies Challa and van de Vooren (1980) first described an optimization routine between energy consumption and earliness of cucumber crop production. Next steps were the use of relatively simple models on crop photosynthesis and transpiration, followed by more sophisticated physical models (e.g. Stanghellini, 1987; Van Henten, 1994), and photosynthesis models (Körner and van Ooteghem, 2003). Parts of these models (especially the parts considering heat and mass transfer and gross photosynthesis) are used in commercial environmental control systems, however the primary use is still in design studies. Instead of being used for on-line operational control the models are used to evaluate new environmental control strategies such as the receding horizon optimal control system as part of an integral system design and described by Van Ooteghem et al. (2005). Also the optimization routine for temperature and CO_2 as developed by Dieleman et al., (2006) was designed using a "model based virtual greenhouse". The experimental test with this routine showed a slight but significant increase in energy efficiency. Another example of a step to successful energy efficient operational control is the model based humidity control (Körner, and Challa, 2003a) which improved the humidity routine to avoid fungal diseases like grey mold (e.g. Körner and Holst, 2005).

So far existing models are seldom used in on-line control of greenhouses because this requires a completely different approach by the end-user compared to current practice and also because most existing models are not suitable for rigorous optimal control, as they are seldom formulated in state-space form (van Straten, 2006). Reducing a complex model to a few or even a single state model has been successful (Jones et al., 1999; Seginer and Ioslovich, 1998) and according to Van Straten et al. (2006) this approach is valuable to improve the use of models for energy efficient greenhouse control.

Although the introduction of innovative environmental control technologies will add to energy efficiency, large improvements compared to the current situation can already be made by simply improving the hardware design like heating and ventilation systems (e.g. Campen, 2004), improving both accuracy and frequency control of the sensor network (Bontsema et al., 2005) and more regularly checking of the set points. Innovative developments in this field are e.g. automatic fault diagnosis systems, on line DSS for energy conservative settings and on-line comparison of control settings through the internet (Buwalda et al., in press).

Integral Design of Energy Efficient Greenhouse Systems

Although development and implementation of individual energy saving components can result in energy savings, the only way to reach the ambitious targets of -30% CO_2 emissions is by integrating energy conservative greenhouse systems including covering material, heating and ventilation/dehumidification, control algorithms and energy conversion systems. For the design and operational use of energy efficient greenhouse systems several decision support systems have been developed such as SERRISTE in France (Tchamitchian et al., 2006) to support either designers or growers with reliable and quick assessment of energy conservation measures in greenhouse cultivation. The rapid changes in technology and energy costs require a dynamic approach like the interactive decision support system developed by Swinkels (2006). In this DDS, one can select a wide range of components (e.g. greenhouse dimensions, heating systems, covering materials, lighting, conversion- and storage systems) together with energy prices and settings for operational control. The output shows the energetic and economic effects of both the strategic and the operational choices. A more general and wider applicable design method for energy conservative greenhouses, based on methodological design procedures was suggested by van Henten et al. (2006). It aims at conceptual designs of protected cultivation systems for various regions throughout the world. This design tool is coined 'the adaptive greenhouse' because all protected cultivation systems from low-tech to high-tech are considered to be based on the same generic components, such as construction, cover material, equipment etc., but the particular choice of cultivation system is, so to say, adapted to the local conditions in the region.

1. Examples North West Europe. The solar greenhouse concept as developed by Bot et al. (2005) is a perfect example of an integral energy efficient design where all components, including the energy conversion technologies and optimal control are incorporated. The objective of the solar greenhouse project was the development of a greenhouse system for high value crop production without the use of fossil fuels. The concept is a system that during the summer collects as much heat as possible to balance the minimized energy requirement during the winter (Waaijenberg et al., 2005). Such a system could be, combined with control algorithms for a dynamic control (Van Ooteghem et al., 2005), resulting in a total realizable energy saving of over 60%. This enables a sustainable energy supply per ha greenhouse of only 600 kW eg. through wind power or Photo Voltaic Panels.

With completely closed greenhouses (e.g. Opdam, 2005) the next step in the integral design is to extract the total heat surplus during the summer and reuse this during the winter for heating the greenhouse itself and e.g. neighbouring greenhouses or buildings. To achieve this, the performance of the greenhouse as a solar collector has to be maximized by 1): further reduction of the heat loss and 2): maximizing the heat collection by very efficient heat exchangers (Bakker et al., 2006). Simulations showed that with this system theoretically a year round heat production might be expected of about 800 MJ, comparable to the equivalence of 25 m^3 natural gas (de Zwart and Campen, 2005). The first trials in a commercial scale greenhouse, however, show that this heat production will be hard to achieve since the output is restricted by the growers temperature band widths to minimise detrimental effects on his crop (de Zwart en van Noort, 2007). Another disadvantage of these systems is the low level of energy delivered by the system (water at 40°C).

In an attempt to combine greenhouse production with electricity production in stead of warm water production, Sonneveld et al. (2006 and 2007) described a system with a parabolic NIR reflecting greenhouse cover. This cover reflects and focuses the NIR radiation on a specific PV cell or solar collector to generate either electricity or steam. So far the results however, show that the electric power which might be generated, is not enough for the necessary heat pump capacity to keep the greenhouse completely closed. On the other hand, the reduced heat load in the greenhouse, by the NIR reflecting cover, significantly reduces the required cooling power, which in combination with the limited electricity generated, overall still might have significant impact on the energy efficiency. Due to the current price level of energy, the still limited increase in crop production and the complex and costly installations, however, up till now (for the Dutch circumstances), all systems and concepts of completely closed greenhouses, have shown not to be economic competitive. At this moment (at the current price levels for electricity and gas), the greenhouse concept of a traditional normally ventilated greenhouse, with heating and CO_2 supply from a Combined Heat and Power (CHP), and selling the generated "green" electricity to the national grid, turns out to be the best economic option. Although it doesn't directly save energy at the greenhouse level it reduces the CO_2 emission at national level by reducing the CO_2 emission of the central power plants. However, in other NW European countries the situation can vary. E.g. in the UK, CHP installations have not been installed for years as the economic of CHP currently do not stack up there. Furthermore the geology in different areas might limit the potential for long term heat storage and the closed greenhouse. Therefore various alternatives to reduce the use of fossil fuel such as waste heat, biomass, anaerobic digestion systems and geothermal sources are being introduced.

2. Examples South Europe. Also for Southern latitudes some interesting research projects aim to design innovative and energy efficient greenhouses that incorporate high levels of technology and that intend to adapt the concept of closed or semi-closed greenhouse for these regions. In the Watergy project, a completely closed greenhouse was developed aiming at complete recirculation of water based on an innovative heat exchanger (Buchholz et al., 2005). The actual prototype showed promising results, but like for the Northern Latitudes, the economic feasibility of complete closed greenhouses still is the major bottle neck.

The prevailing "Southern approach" for developing future greenhouse systems is therefore still based on the development of passive greenhouses, for those areas where heating may be convenient but is not essentially needed. This approach normally leads to attain lower production levels, but also achieved at lower investment and running costs and therefore economically feasible. A sustainable greenhouse production without pesticide is also of primary importance and one must try conciliating using new technologies such as CFD studies, the generalisation of insect proof nets with a fair climate control, particularly in summer conditions (Boulard and Fatnassi, 2006; Fatnassi et al., 2006). Since in this situation, the energy input for climate conditioning is very limited, reduction of other processes responsible for CO_2 emission in the operation of passive greenhouses are taken into account using Life Cycle Analysis.

LCA is applied to the whole production process to identify which parts of the process are more energy consuming and a comprehensive analysis of the environmental impact of tomato production in Southern European unheated greenhouses has been done by Antón (2004). This study considered all the energy and material inputs in the process of tomato production, and the waste or outputs produced through out the process as well. Anton's study showed that the greenhouse structure and auxiliary equipments (irrigation pipes, plastics for mulching, crop supporting members, etc) accounted for 51% of the total gas emissions. Within the structure itself, the foundations and perimeter walls made of concrete were responsible for most of the emissions. Therefore efforts are being made to redesign the foundation system and to use recyclable concrete to reduce the energy use. Fertilizer production and use was another factor with strong influence on the energy consumption of tomato production (about 36 % of emissions). Tests are currently being conducted to significantly reduce the fertilization programmes, since it has been demonstrated that at present nitrogen application is usually higher than needed. Results suggest that N concentration in the nutrient solution can be reduced to 7 mM, implying a 70 % reduction in nitrate leaching as compared to the 'control', without reducing fruit yield or physical quality (Muñoz et al, 2007).

CONCLUSIONS

For both North West and Southern European conditions, attempts to design more energy efficient greenhouses have involved optimization of the greenhouse as a solar collector, improved production by a better control of the growth environment, and expanding the growth season. For NW Europe there is increased interest in more airtight greenhouses with cooling, heat recovery and optimized environmental control, while for Southern European conditions there is greater focus on using efficient natural ventilation, cooling and reducing the solar energy flux into the greenhouse during the summer. For passive greenhouses in Southern regions, that use no fossil fuel at all, the focus is on reducing the energy inputs for the greenhouse structure, irrigation, auxiliary equipments and inputs like fertilizers. Apart from the reduction of energy use, throughout Europe the interest in various alternatives for fossil fuel such as waste heat, biomass, anaerobic digestion systems and geothermal sources increases again.

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