The Solar Greenhouse; Technology for Low Energy Consumption

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Abstract

In conventional greenhouse crop production the high level of inputs conflicts with consumer demands for safe products and with restrictions to environmental emissions. In Northwest Europe the main problem is to reduce absolute energy consumption. If today's available technology is applied energy saving will be too low to meet the standards in future. Therefore new technology has to be developed on aspects ranging from improving the greenhouse insulation and light transmittance to climate conditioning and control and energy management. In all aspects the production system is converted from a production-driven to a consumer-oriented activity. Information technology has to link the various units in the chain from consumer to seed.

INTRODUCTION

In greenhouses light levels are reduced but climate conditioning improves growing conditions in such a way that it results in much higher yields with better quality compared to outdoor production. This justifies the extra costs for investment and operation. In general a development can be observed from sheltering to active conditioning. This can be illustrated by the situation in The Netherlands where a production area of about 10.000 ha of active conditioned, computer controlled glasshouses developed from sheltered cultivation (Jacobs, 1995). For other production regions this can be observed too in a different stage of development (Zhang, 1999). The maritime Northwest European climate in the Netherlands proved to be very suitable for greenhouse production while cool summers and mild winters allowed year round production and exploitation of the high investments. Normal yields for climate conditioned greenhouses in this area are high as is illustrated by a yearly production per m2 of about 100 kg for cucumber to 60 kg for tomato or 300 rose stems. In a market with high demand for greenhouse products, production could be increased in the past without problems. However high inputs are needed for the intensive way of production. Water and nutrients, plant protection chemicals, substrates or soil substitutes, handling material and fossil energy are the main inputs, which has lead to environmental problems. Moreover, consumers considered greenhouse products to be unnatural and therefore not tasty and loaded with chemicals. In the early nineties these factors have initiated a crisis in greenhouse industry. By facing the problems and reformation of the industry from production-driven to consumer oriented, the crisis could be overcome and nowadays Dutch greenhouse industry is flourishing again. At the market side the system was redesigned with a changed role of auctions and wholesalers. This redesign process is on going in interaction with information technology developments. Annual turnover is at a level of about 8 billion US dollars and there is a strong position in global trade. Contribution to national economy is considerable. On 0.5 % of the agricultural area about 25 % of the agricultural production value is realized. These positive developments can serve as an example for other regions and therefore will be explained in more detail.

An important drive for improvements was a set of voluntary agreements between greenhouse industry and the government. It was agreed to strongly reduce the consumption of chemicals for both soil disinfection and plant protection and to reduce significantly the emission of nutrients. Rockwool substrate is successful in making annual soil disinfecting superfluous. Biological control of pests is implemented at large-scale for plant protection. Closed watering systems were developed to prevent emission of nutrients and developments of these systems are still in progress (Gieling et aI., 1997). Systems were set up to recollect and recycle substrate and handling materials. A severe bottleneck for improvement is in energy saving.

In the early nineties Dutch greenhouse industry and government agreed that in 2000 greenhouse energy consumption per unit produce (specific energy consumption or SEC) has to be decreased by 50 % compared to that in the reference year 1980. To do so greenhouse systems were improved and productivity was increased. However, intensifying the productivity included higher levels of CO_2 dosing in the greenhouse by natural gas combustion, therefore increasing energy consumption. Though SEC decreased, the absolute energy consumption per unit area (AEC) increased, conflicting with the CO2 reduction goal. The main contributions to absolute energy saving nowadays are made by the application of thermal screens, by improved construction and detailing of the existing greenhouse types, by the application of co-generation and short term energy storage and by energy oriented climate control methods. However potentials for energy savings are limited for the conventional greenhouse. In 1998 SEC was at the level of 59%. A recent agreement is to reduce it further to 35% by 2010. So about 25 out of 59 % has to be achieved in a ten-year period, indicating a reduction of about 40 % from now on. There is general consensus that this cannot be achieved by increasing productivity but that AEC has to be decreased significantly. Rebuilding greenhouses to most modern types with today's technology can result in a saving of about 15 % (Bakker, 1999) which is far away from the earlier mentioned 40%. Therefore new technology has to be developed aimed at designing and operating energy-friendly greenhouse production systems with a fast penetration into practice, contributing to the goals on reduction of CO_2 emission.

The situation in The Netherlands is more or less illustrative for other North European greenhouse production areas with a maritime climate. In more southern regions with hot summers year-round operation is a problem. Summer cooling demands high energy input due to the high heat loads in an environment at high temperature. In this presentation we will focus on sustainable greenhouse production systems for a maritime climate.

DEVELOPMENTS

Overall View

In conventional, single glass greenhouses the energy inputs and losses are given schematically in figure 1.

Solar radiation is the main input for the photosynthesis process in plant production. However almost all solar energy entering the greenhouse is absorbed as thermal energy by the greenhouse system. Part is converted into crop transpiration or soil evaporation, so to latent heat, and part is contributing to the sensible heat balance of the total greenhouse system. Latent heat is lost by condensation to the cold greenhouse cover and by ventilation. Sensible heat is lost through the cover and by ventilation. In periods with surplus of solar energy ventilation will remove this surplus. Heating is applied in periods when losses are higher than solar energy input. For Dutch climate conditions it can be estimated that solar energy contributes about 50 % of the total yearly heat demand of a single glass greenhouse; input from fossil energy has to contribute the other 50 % (Bot, 1994). In fact a greenhouse system is a combination of a solar collector and a biotechnological reactor in which CO_2, water and nutrients are converted into a marketable product.

To decrease the fossil energy consumption significantly first of all the energy demand has to be low by insulating the greenhouse properly. In well-insulated greenhouses climatisation has to be redesigned with emphasis on humidity control. For further decrease of fossil fuel consumption the coverage of the low energy demand by sustainable energy has to be maximized. Interaction with crop sciences to formulate the demands and constraints is essential. The various aspects will be presented in the next sections.

Greenhouse Cover

The solar collector exploits solar energy input to create favourable conditions for plant production. From a technical point of view the heat loss of the solar collector has to be decreased by improved insulation, decreasing the demand for extra heat input. At the same time the solar radiation input, driving crop productivity, must not be decreased in such a way that energy saving is counterbalanced by production loss. Moreover, such a decrease results in lower energy input. So in energy saving strategies light transmission of the greenhouse cover is a bottleneck. From the rule of thumb that one percent light loss implies one percent production loss and from the fact that energy costs are about 15 % of total costs it can be deduced that in energy saving strategies each percent of light loss has to be compensated by 6-7 % energy saving. When fuel prices increase this ratio will be lower, facilitating energy saving measures. For special crops like ornamentals, light level is of less importance. From today's strategies thermal screens have energy savings just compensating production loss due to light loss while they can be opened at day with low light loss (3-5%) and closed at night with high energy savings (30-40%) (Bakker and Van Holsteijn, 1995). Cover insulation by double layering decreases light transmission by 10-15% and energy savings of 25-40 % are too low for compensation (Waaijenberg, 1995). So cover materials have to be improved or new materials have to be developed which enable the combination of high insulation with high light transmission. This combination is pretty specific for greenhouse industry though it is also an important item in solar collector design. However then allowable cost per unit area is higher. In domestic and utility buildings optical and thermal criteria are different. There the emphasis is more on preventing high thermal losses in winter and high thermal loads in summer without the need for high light transmission. So developments in material and construction technology focused on the combination of high insulation and high light transmission at low cost have to be initiated by greenhouse industry. In The Netherlands initiatives have been taken and promising developments are started. They range from alternative cover geometry's (Stoffers, 1997) to coating technology and new plastic materials with a long lifetime like fluorpolymere, polyurethane and aerogels (Sonneveld, 1999). In the design of new or improved materials physical modeling of the optical material properties is applied (Macleod, 1996). It can be expected that greenhouse covers can be produced in due time with the desired properties as a base for the design of low energy demand greenhouse systems. The new or improved materials have to be integrated in the greenhouse construction.

Greenhouse Climate

In greenhouses with improved insulation climate will be modified. The inner cover temperature will be increased compared to that of the badly insulated single cover greenhouse so condensation will be at higher greenhouse air humidity, then problems can be expected with crop quality (Vonk Noordegraaf and Welles, 1995) and with diseases (Hand, 1988). In practice, growers prevent high humidity by simultaneous ventilation and heating. So with conventional climate conditioning improved insulation would lead to increased ventilation. In the conventional way this will increase sensible heat losses and then heat demand will only differ 15-25 % of the badly insulated greenhouse (De Zwart, 1996). To really benefit from improved insulation energy friendly humidity conditioning has to be designed. Operation with forced air circulation introduces high fan electricity consumption. Applying natural circulation is therefore attractive. Moreover dehumidification should be distributed uniformly through the greenhouse in order to prevent high humidity and temperature gradients.

Some methods for active dehumidification can be considered. One is applying hygroscopic materials in a cycle of absorbing water vapour and reconditioning the material (e.g. Pritchard and Currie, 1993). Another principle is condensation on cooled surfaces. Also ventilation with heat recovery is possible. In the hygroscopic method latent heat is immediately released at the absorbing surface and transferred to the greenhouse air while heat and mass transfer coefficients are coupled and have to be high. So it can only be applied in heat demand periods. For reconditioning the hygroscopic material sustainable energy can be used if available. The application of hygroscopic materials may cause serious environmental problems due to leakage or accidents. Another disadvantage is that the method is not suited for uniform distribution in the greenhouse but demands forced air circulation units. The condensation method has the disadvantage that also sensible heat is absorbed at the cool surface. In a greenhouse the amount of absorbed sensible and latent heat will be about equal. With a heat pump to cool the surface about twice the latent heat has to be pumped which implies doubling the driving energy for the heat pump. An advantage is that cold surfaces can be uniformly distributed through the greenhouse similar to the hot water pipes of the heating system. Moreover the temperature difference between cold surface and greenhouse air can induce natural convection air circulation. Therefore the cool surface method seems the most practical applicable for greenhouse dehumidification but it has to be developed for proper implementation (Campen and Bot, 1999). The alternative may be ventilation combined with heat recovery. The final solution needs further research.

Another important aspect in climate conditioning is in the spatial distribution. It is known that in nowadays greenhouses large temperature gradients exist, with local temperature differences up to about 5 K (Bloemhard et al., 1998). These differences vary over different locations in the greenhouse due to varying outside weather conditions and actions like opening or closing of thermal screens. The large differences not only cause non-uniform production and quality but also problems with pests and diseases. Hot spots are sensitive for pests and at cold spots relative humidity is high with the risk of fungi. So in climate conditioning temperature and relative humidity are set at a safe level. If climate distribution can be conditioned more accurately, energy can be saved and risk of pests and diseases is decreased enabling pest and disease control in a more sustainable way, e.g. biologically. Extending climate conditioning to conditioning of the spatial distribution is a new subject in our research.

Energy Supply

In conventional greenhouses, boilers supply heating. Combined heat and power generation (CHP) has penetrated on a wide scale. At first rose growers (area about 1000 ha) applying artificial lighting generated their electricity and used their waste heat. Nowadays electricity is generated also for the public grid and the waste heat is sold to the growers. CHP is a suitable instrument to increase the energy efficiency and it is chosen as an important instrument for the energy supply in new greenhouse regions. At the same time CO_2 has to be supplied for the enrichment of the greenhouse air otherwise the growers will burn natural gas for this purpose. By lowering the heat demand of improved greenhouses the solar collector efficiency of the greenhouse is improved so sustainable energy contributes more to the energy supply. Another way of climatisation will also change the energy and CO_2 supply.

In a novel greenhouse system with low energy demand and adapted climate conditioning the challenge is in a high degree of supply of this low energy demand by sustainable energy with solar energy as most suited. The daily and seasonal patterns of energy demand and available solar energy do not fit so energy storage has to be applied. Short-term energy storage on a daily base is normal operation in greenhouse industry to fit the pattern of the heat demand to that of the CH P or CO_2 production linked energy production (De Zwart, 1996). Seasonal storage is not yet normal practice. To investigate the applicability of energy storage dynamic year-round simulation is a powerful tool.

The combination with dehumidification and heat pump application complicates the system. Situations with heat surplus are distinguished from periods with heat demand. During heat surplus the long-term heat storage system has to be charged with heat withdrawn from the greenhouse. In periods with heat demand, heat has to be subtracted from the long-term energy storage and supplied to the greenhouse. For long-term storage aquifers are suited. The availability of aquifers under all greenhouse areas in The Netherlands opens the possibility to do so. In recent years experience on application of aquifers for energy storage in utility buildings like offices and hospitals is positive (Buitenhuis, 1997). This technology can be adapted in the design of aquifer application for greenhouse industry. While energy at different temperature levels has to be transported the combination with heat pumps is obvious. Aquifers can be operated best at temperature levels that are symmetric to the natural aquifer temperature_ being at local yearly average outside air temperature. With this temperature at about 10 DC, low temperature may be at 2-5 DC and the other temperature at the medium level of 15-18 DC. The low temperature is well suited for dehumidification. The systems outline responding to the requirements during the heat demand period is given in figure 2.

Energy is withdrawn by the heat pump from the medium temperature side of the aquifer to heat the greenhouse. The cooled water is partly used for dehumidification, so latent heat recovery, and partly returned to the low temperature side of the aquifer. The heat pump has to be driven electrically or by a gas motor at a constant rate to cover the base line of the heat demand. In both cases waste energy is available at 50-60 DC, so at relatively high temperature. Dependent on the heat demand this waste energy can be stored on a short time base to heat the greenhouse above the heat demand base line. In heat surplus periods the aquifer has to be recharged. Then the low temperature water can be heated to the medium temperature in the greenhouse as indicated in figure 3.

In this way ventilation can be delayed and CO_2 dosing can be continued till the moment the cooling capacity has exceeded. The first goal is to operate the total system as energy friendly as possible, so year-round with minimal heat demand and minimal capacities of the heat storage and heat pump. The constraint is that the aquifer charging and discharging has to be balanced on a year-round base. In the second step an optimization of costs and yield can be performed. In the design of the total system to the optimal dimensions dynamic simulation is crucial. In a first survey the energy saving potential of the proposed system with well- insulated cover is about 75 %, so very promising (Saye et al., 1999). With improved insulation even higher energy savings are possible.

Climate Control

So far the focus has been on the design of a sustainable greenhouse system including climate conditioning. This can only be operated as a production system if it can be controlled from minute to minute to respond to the varying outside weather conditions. In conventional control the grower decides on the control set points for temperature, humidity and carbon dioxide, so he acts as an operator. In general this did not change after introduction of computer control (Udink ten Gate, 1983). Due to the many interactions in the system sets of decision rules are implemented to solve conflicts resulting in complex control operation. The grower has to decide not only on the set points or the rules to adapt the set points but also on control parameters or control settings. By implementing knowledge on the greenhouse and crop behavior via models operation can be simplified and performance can be improved enabling the grower to act as a manager (Van Straten and Challa, 1995).

The goal for the grower is not controlling set points but maximization of the profit Le. the difference between yield and costs. This can be implemented in optimal dynamical control (Seginer et al., 1994, Van Henten, 1994, Chalabi et al., 1996). Models to calculate the operational costs and the yield have to be implemented. The operational costs for climate control are the energy costs that can be derived from the dynamical interaction of the greenhouse and the varying ambient conditions. A simulation model can calculate this. To improve the accuracy, on line parameter estimation and self-learning algorithms can be applied. The yield has to be derived from crop performance. This is a combination of crop productivity and crop development. Crop productivity can be coupled to photosynthesis that can be modeled. Measuring crop performance in the "speaking plant" approach as already introduced by Udink ten Gate et al. (1978) can support this. Sensors to do so have been developed for research purposes (Hashimoto, 1993). Recently crop temperature sensors have been introduced in practice to be integrated in the climate control loops and a fluorescence sensor for crop photosynthesis status is available. Models for crop development are not yet available. A problem is the difference in time scale of operational costs and yield. There still the grower is the ultimate sensing system. Recently Van Straten (1999) reviewed optimal operation and control methods for greenhouses. In low energy consuming greenhouses optimal control has to be extended to spatial distributed climate control and to energy management. Another aspect of control is in the water and nutrient supply. There the conventional pH and EC based control will be supplemented by ionselective dosing since ion-selective sensors will be available for practice in the near future (Gieling et al., 1997).

For the interaction between crop and temperature the integrated temperature is more important than the momentary temperature level (Hurd and Graves, 1985, De Koning, 1990). In this way heating can be postponed on a time base of about one to two days until solar energy is available or until the greenhouse can be better insulated by e.g. closing a thermal screen. This can reduce operational costs at the same yield. Of course lower and upper temperature limits have to be considered. In this way control is not really optimal but a practical, relatively simple control method can be derived with the crop applied as a virtual energy buffer

Modelling

For design, analysis and control of the greenhouse system it is of utmost importance that static and dynamic system performance is known. Modelling is a tool to implement this knowledge. Dynamic system behavior can be represented by a set of non-linear first order differential equations based on the energy and mass balances over homogeneous parts of the system (lumped parameters), and this set can be solved numerically (e.g. Bot, 1983). The dynamic boundary conditions (outside weather conditions) have to be given as data sets. In this way the time dependency of the state and flow variables of the system is calculated. It demands careful quantification of the various energy and mass transfer processes in the greenhouse. Special attention has to be paid to light transmission of the cover (Bot, 1983; Critten, 1993), ventilation (Bot, 1983, De Jong, 1990, Boulard et al., 1996) crop transpiration (Stanghellini, 1987), energy supply and energy storage (De Zwart, 1996) and thermal screens (Bakker and Van Holsteijn, 1995, Miguel et aI., 1998). Dynamic modelling is a proven tool in greenhouse analysis (De Zwart and Bot, 1997). The development is in the description of new processes and their implementation. For novel system designs new system parts like an aquifer, a dehumidifier or a heat pump have to be included in the modelling but there is no fundamental lack of knowledge to do so. In greenhouse control the models can be reduced to the core of describing the dynamics of the control variables (Van Straten, 1999) and they can range from black box to mechanistic models. To improve accuracy and reliability they can be self-tuning on-line.

Modelling of the spatial distribution of greenhouse climate for design and analysis is less conventional. The spatial distribution can be represented by a set of partial differential equations including velocity (vector) and pressure as state variables. Computational fluid dynamics (CFD) is a tool to solve this set numerically in a discrete spatial grid (e.g. Patankar, 1980). However application to modelling of greenhouse climate distribution is not yet standard but it is possible through the availability of commercial software (Mistriotis et al. 1997a,b, Boulard et al., 1999). Problems to be solved are quantification of the interaction between the flow pattern and the crop geometry, representation and calculation of evaporation, modelling of thermal and solar radiation, modelling of ventilation and choosing the proper sub-model for the effect of turbulence. The grid size is a compromise between accuracy and calculation time. Also the convergence of the calculations may call for some trial and error and the use of tools to speed it up. The calculations are for characteristic steady state situations. Software is running on modern powerful PC's. The application is in design and in analysis. Though in principle the calculations can be dynamic this is far away due to the long calculation time for each time step. So in control application is far away. Then combination of mechanistic and black box modelling with on line parameter estimation as used in the principle of imperfect mixing may be applicable (Berckmans et al., 1993). Though quite successful in livestock building spatial distributed climate control (Vranken, 1999) the principle is not yet applied in spatial distributed greenhouse climate control.

Information Technology

A general aspect is in the transformation from a production-driven to a consumer-driven activity. In this transformation consumer demands have to be translated to production aspects. Then production data on factors like quality and reliability have to be visible. Production is not an isolated process anymore but is part of a chain "from seed to mouth". The information and data transfer through the chain in both directions is a challenge for new technology (Schieffer, 1999). In the production process itself both the optimal management and the logistics demand new information technology (Annevelink, 1999). Recently Udink ten Cate and Dijkhuizen (1999) edited an overview on information and communication applications in agriculture.

Other Aspects

Of course there are a number of other interesting technological developments like robotization and automation in picking, trimming and sorting including image processing. However their main focus is not on sustainability but on reduction of labor costs, improvement of labor conditions or increasing production efficiency. Therefore these developments are not included in this paper. However information can be generated that can be included in the chain operations as mentioned in section 2.7.

CONCLUSIONS

Development of sustainable greenhouse systems demands a range of activities in various disciplines. In the greenhouse system itself the development of is in materials and construction, in climate conditioning and climate control and in application of sustainable energy including energy storage. Modelling and information technology is integrated in these developments. Close cooperation with plant sciences is needed enabling the focus on optimal plant production. In this optimal production the constraints are given by the consumer demands. A proper implementation of these aspects in the chain "from seed to mouth" and vice-versa also demands new information technology.

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Figures

Figures

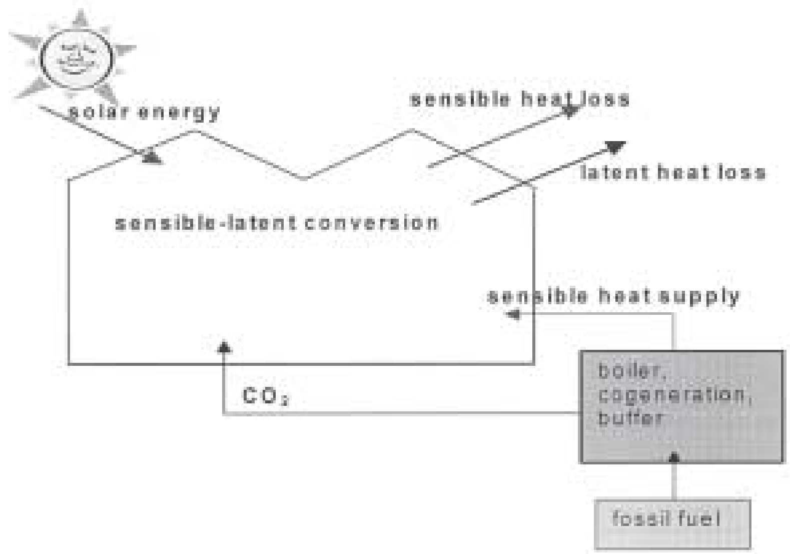

Fig.1. Energy scheme of a conventional greenhouse

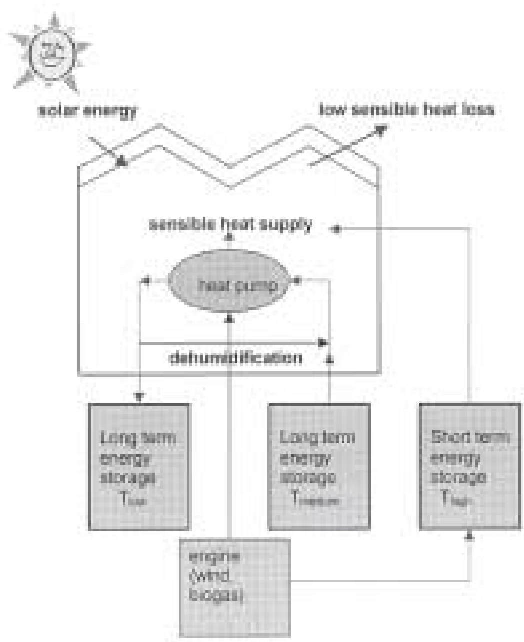

Fig. 2. Energy supply during heat demand periods

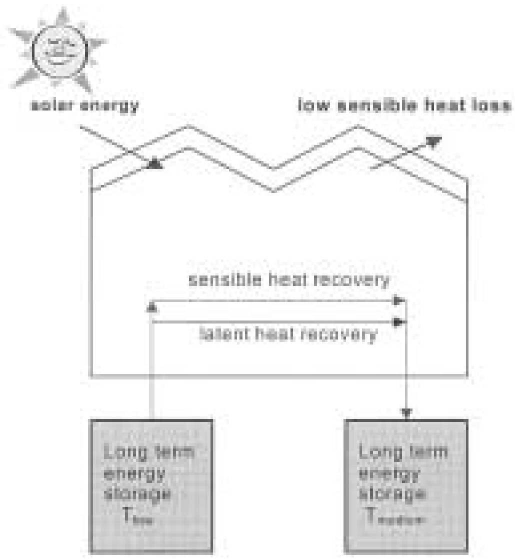

Fig. 3. Harvesting energy during heat surplus periods