The Solar Greenhouse: State of the Art in Energy Saving and Sustainable Energy Supply

G. Bot [1], N. van de Braak[1], H. Challa (✝)[1], S. Hemming[1], Th. Rieswijk[2], G. v. Straten[1] and I. Verlodt[3]
[1]Wageningen University & Research Centre, Dept. of Agrotechnology and Food Sciences, PO Box 43, 6700 AA Wageningen, The Netherlands
[2] Priva Hortimation B.V., Zijlweg 3, 2678 LC De Lier, The Netherlands
[3] Hyplast N.V., St. Lenaartseweg 26, B-2320 Hoogstraten, Belgium

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Abstract

The objective of the solar greenhouse project was the development of a Dutch greenhouse system for high value crop production without the use of fossil fuels. The project was completed and the results are reported here. The main approach was to first design a greenhouse system requiring much less energy, next to balance the availability of natural energy with the system's energy demand, and finally to design control algorithms for dynamic system control. This paper discusses the first two design steps. Increasing the insulation value of the greenhouse cover was the first step towards a reduction in energy demand. The challenge was in maintaining a high light transmission at the same time. A first generation of suitable materials was developed. The realizable energy saving is almost 40 %. The next reduction in fossil fuel requirement was accomplished by capturing solar energy from the greenhouse during the summer months, storing it in an underground aquifer at modest temperatures, and finally using the stored energy during the winter months by using heat pumps. Then the total realizable energy saving is more then 60%. For sustainable energy supply per ha greenhouse at this low energy demand 32 ha biomass is needed, or 600 kW nominal wind power or 1.2 ha PV assuming storage via the public grid.

INTRODUCTION

In 2003, the value of Dutch greenhouse crop production was over 4.8 billion Euro (1 Euro ≈ 1.20 US$) from an area of approximately 10,500 ha. Including trade and related infrastructure, the contribution to the national economy is approximately double that amount. The cool summers and mild winters of the maritime north-western European climate allows for year-round greenhouse production. The resulting average yearly production rates per m^2 are approximately 100 kg for cucumber, 60 kg for tomato, and 300 stems of roses. During the last decade, the industry has transformed from production driven to consumer driven. This had an impact on the types of crops grown, marketing, and also on the types of production systems. The focus has been on sustainability and production licenses. Important aspects of sustainability include the application of plant protection chemicals and the use of water and nutrients. During the last decade, the amounts of plant protection chemicals applied have drastically declined due to the use of biological control, strict application regulations, and the reduction of soil sterilisation due to substrate growing for almost all crops (Ekkes et al., 2001). Through the widespread implementation of closed irrigation systems, emission of nutrients to the outside environment is drastically reduced too. Further improvements are to be expected from ion selective nutrient dosing, a practice that improves the relationship between solution composition and crop demands (Gieling, 2001).

Greenhouse energy consumption is the largest component of the system's environmental impact, and this is true for countries with comparable climates. Goals for reductions in energy consumption and a larger contribution from sustainable energy sources were agreed to after voluntary discussions between the greenhouse industry and the Dutch government (Bot, 2001). Most research on energy saving strategies is funded by the Ministry of Agriculture, Nature and Food Quality and by the Product Board for Horticulture, and is aimed at improving existing greenhouse systems and quick implementation of novel approaches enabling growers to meet the target 2010 goals. It is expected that implementation of the new energy consumption goals will commence slowly and continue after the year 2010. These days, optimised greenhouse systems include improved thermal screening, improved climate control (temperature, humidity and CO_2 enrichment), improved use of supplemental lighting, and developing cultivation methods aimed at low energy consumption. A practical constraint is that energy costs are only 15 to 20% of total production costs and growers view energy consumption as a tool to reduce their production risks. Moreover, with the new system for assessment of energy costs in the European Union, energy costs are no longer linearly proportional to energy consumption. Energy costs will consist of two components: the first component is called transport capacity. A grower has to secure a so-called transport capacity and this capacity is linked to the peak demand during cold periods. During periods of high peak demand, the transport capacity has to be high and so will be the cost. The second component is the commodity prize for a m^3 of natural gas, which is fixed. Therefore, when trying to save energy, it is extremely important to lower peak demand (and thus the required transport capacity), and to have a more constant energy demand. This will result in the lowest total cost per unit of energy. Lowering peak demand is possible by using control algorithms that allow for integration of climate parameters, by using thermal screens during periods of peak demand, and by using alternative fuels (e.g., bio-fuels) during periods of peak demand. Energy saving strategies during other periods only saves on the commodity cost of fuel, which is relatively low. So, in the Netherlands, the original political demand for an industry-wide reduction in energy consumption is not fully in line with the political chosen energy price structure.

In 2003, a long-term the goal was set by the Dutch Growers Association LTO to operate newly build greenhouses without the use of fossil fuels by the year 2020. With the solar greenhouse project, started in 1998, the concept of a greenhouse production system without the use of fossil fuels was investigated. This paper presents the results of this project.

ENERGY DEMAND AND ENERGY AVAILABILITY

In the Netherlands, the yearly solar irradiation sum equals approximately 3.5 GJ m^{-2} (Giga = 10^9), which is equivalent to the combustion value of 100 m^3 of natural gas (= 100 NGE). Using 80% as an average greenhouse light transmission, 80 NGE will enter the greenhouse, qualifying it as a solar collector. However, energy demand is high during colder periods with low solar radiation (at night and during the winter). During the summer period experiencing high irradiation levels, most of the entering solar radiation has to be removed by ventilation (as sensible and latent heat). As part of the solar greenhouse project, the first goal was to decrease energy demand substantially, and the second to harvest and store summer solar radiation at a rate that balanced winter energy demand. To decrease energy demand, greenhouse covering materials were developed that combined improved insulation with high light transmittance. This development is reported separately at GREENSYS2004 (Waaijenberg et al., 2005). In addition, integrating climate control strategies were developed to reduce energy demand. Using this approach, the crop buffers energy in the short term. Such a rather complex control system has to be evaluated minute by minute in order to accomplish optimum energy management. This development is reported separately at GREENSYS2004 (Van Ooteghem et al., 2005). For short-term peak shaving, the crop can be regarded as a virtual energy buffer to which integrating control algorithms can be applied (Körner, 2003).

CAPTURING SOLAR ENERGY

During the summer, energy can be captured from the warm greenhouse air with an air to water heat exchanger. For efficient heat exchange, the initial water temperature has to be as low as possible. At summer greenhouse temperatures of about 25°C, groundwater can be heated to approximately 20°C. Thus, the energy is stored in groundwater at a modest temperature. Per 10 NGE storage capacity per m^2 of floor area a volume of 8.3 m^3 water per m^2 of floor area is needed for a water inlet-outlet temperature difference of 10K (or 10 °C). Such storage capacity can only be realised with an underground aquifer (a porous water containing layer in the sub-soil between 20-100 m below soil surface and bounded by horizontal and impermeable clay layers). The most common practice is to drill two wells at sufficient horizontal distance, one for the cold and another for the warm part of the aquifer. This is illustrated in Figure 1. The warm side of the aquifer will extend during the summer, while the cold part will shrink. During the winter, this situation is reversed. An alternative approach of using phase shift materials would require approximately 1000 kg per m^2 of floor area at this very low energy demand, which is economically unfeasible. To store the earlier mentioned 10 NGE, the required aquifer depth is approximately 20-25 m. Thus, such a system can be implemented in large parts of the Netherlands that have horizontal porous layers with negligible ground water flow.

GREENHOUSE HEATING

As explained, solar energy captured during the summer can be stored in water contained in underground aquifers at approximately 20°C. This temperature is too low to heat the greenhouse during winter even if this greenhouse is well insulated resulting in a low energy demand. The energy can be captured from the aquifer water using a heat pump. Then the water will be cooled and can be stored in the cold part of the aquifer. As a result, the cold section of the aquifer is extending and the warm part is contracting. The captured heat is released by the heat pump at a higher temperature of approximately 40°C. Thus the heat pump COP (coefficient of performance, ratio of released energy per unit of time and work input) will be at an acceptable level of around 4. In the Netherlands, and for a well-insulated greenhouse, such a system can cover the base energy demand. During cold periods some extra heating by a boiler is needed.

The capture of solar energy and the use of the heating system are connected via the constraint that, on a yearly basis, the input and output of energy has to balance. So a determination has to be made when to stop the capture of energy knowing that the energy demand during the winter is (much) smaller than the maximum amount of energy that can be captured. Linked to the challenges of capturing and using energy are the sizes of the heat exchangers (heat pipes) and the capacity of the heat pump. This is illustrated in Figure 2. This figure shows year-round energy consumption by the heat pump-boiler combination for greenhouses with various degrees of insulating covers and heat exchange capacities of 1, 1.5 and 2 two-inch pipes per span. In the reference situation, no solar energy is captured. In evaluating Figure 2, keep in mind that the energy listed as 'from the boiler' can also be delivered as reject heat from a gas motor driving the heat pump. With increasing numbers of pipes per span, the heat pump is able to cover more of the heat demand. This way, the various sizes and capacities are optimised resulting in a minimum energy demand for the solar greenhouse system.

GREENHOUSE INSULATION

With an increase in the amount of greenhouse insulation, the energy demand decreases if heat exchanger/aquifer sizes and heat pump/boiler capacities are optimised. The challenge with cover insulation is the light transmittance of the material. Increased insulation can be obtained by low emission coatings or multi-layer covers as is illustrated by the k-value for various combinations as shown in Table 1. However, up until now increasing the insulating value was connected to reduced light transmission and thus to production loss. To reduce the energy demand of the solar greenhouse, research was conducted with the goal of improving the cover insulation value while maintaining high light transmission, and special attention was given to plastic foils. The focus was on PVDF. In addition, PE was studied with the goal of improving multi-layer applications with alternating refraction indices. This approach was promising but did only result in the theoretical concept for such materials. Another promising material available is ETFE, but its cost is still an obstacle. These films can be applied in double or triple layers with light transmissions comparable to single layer conventional covers. In parallel projects, the research focused on other materials like rigid plastics or glass. Results are reported at GREENSYS2004 by Sonneveld et al. (2005).

Year-round energy demand of greenhouses with increasing insulation was calculated by the greenhouse simulation model Kaspro (De Zwart, 1996) for the energy demanding crop sweet pepper. This model is extended and validated continuously and is considered as a reliable virtual greenhouse model, especially for greenhouse climate calculations and year-round energy analyses. The results are shown in Table 2. Due to latent and sensible heat losses and radiative effects, the decrease in energy consumption with increasing insulation is not proportional to the decrease in k-value (Table 1). The energy consumption was calculated for the classical case of heat supplied by a boiler and for the situation where solar energy is harvested during the summer, stored in an underground aquifer, and energy supplied by the aquifer through a heat pump in addition to boiler supplied heat for the peak demand (Fig. 1). The effects of increasing insulation can be observed separately from any application of sustainable energy. When a triple-layered cover is used (a double cover with thermal screen), energy demand can be reduced to approximately 40 % of the reference situation represented by a single cover and a boiler for heat supply. If the reference case is represented by a single cover with a thermal screen (as is a common situations for many crops grown in Dutch greenhouses), then 50 % energy saving is possible under current conditions. With future improvements in greenhouse covers, a reduction to approximately 25% will be possible.

ENERGY SUPPLY

A greenhouse with a low energy demand can be realized by using an insulating cover, adaptive climate control, integrating control algorithms, and optimal energy management. In rough terms, half of the reduction in energy demand can be realised through the insulating properties of the cover material and half can be realised by the capture of solar energy in an underground aquifer for use during cold periods when using a heat pump. The energy required to operate the heat pump and from time-to-time the boiler, can be supplied by fossil energy but the goal is to provide it from sustainable energy. Various options were investigated and order of magnitudes could be estimated.

Using electric energy to operate the heat pump (see Fig. 3) allows for the use of photovoltaics or wind power. However, in such cases energy demand and supply will not always match, requiring the use of the public grid as a backup system. For an energy demand of 20 NGE per m^2, possible for the best available system at this moment (a double-layer covered greenhouse with thermal screen), approximately 100 kWh of driving energy is needed per m^2. In that case, per ha of greenhouse a PV system covering an area of about 1 ha is needed (using current efficiencies), or a wind powered generator at a nominal power capacity of about 600 kW. Using materials with improved insulation values, these energy requirements can be further reduced in the future.

Another option is the conversion of energy fixed in biomass, using the energy content in a gas motor to drive the heat pump and also use the reject heat (see Fig. 4). With a low photosynthetic efficiency of less than 1 %, large areas are needed to fix sufficient amounts of solar energy. For the best possible system available today with 20 NGE energy demand, about 33 ha of biomass per ha greenhouse will be needed assuming no energy losses during energy conversion from biomass to useful energy. Gasification and combustion are the best options for this application, but sophisticated equipment is needed to prevent environmental problems. If bio-oil should be used then about 130 ha oil crop is needed to cover the energy demand. The biomass option is feasible in extensive agricultural production systems that will likely not be located near greenhouse production areas.

ACKNOWLEDGEMENTS

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Tables

Table 1. k-values for greenhouse covers with increasing insulation. The k-value represents the sensible heat loss for a well-defined temperature difference over the greenhouse cover and measured in a dry laboratory situation.

Description of cover	*dry k-value ($W\ m^{-2}\ K^{-1}$)*	*relative k (%)*
Single cover	5.7	100
Single with thermal screen		
Double cover	3.0	52
Double with thermal screen		
Double with low TIR* emission coefficient ε	1.6	28
Triple	2.3	40
Triple, with low ε	1.0	18

*TIR: thermal infra-red

Table 2. Yearly energy consumption of greenhouses outfitted with various covers and using a boiler for heat supply or underground energy storage and heat pump for a sweet pepper crop (NGE: Natural Gas Equivalence or energy equivalent to the combustion value of 1 m^3 of natural gas).

Description of cover	*energy consumption with boiler*		*with aquifer and heat pump*	
	NGE	*%*	*NGE*	*%*
Single cover	53	100	nr*	nr
Single with thermal screen	40	75	29	55
Double cover	40	75	26	49
Triple/double with thermal screen	33	62	20	38
Double low ε (nya**)	28	53	16	30
Triple, low ε (nya)	26	49	12	23

* nr = not relevant

** nya = not yet available

Figures

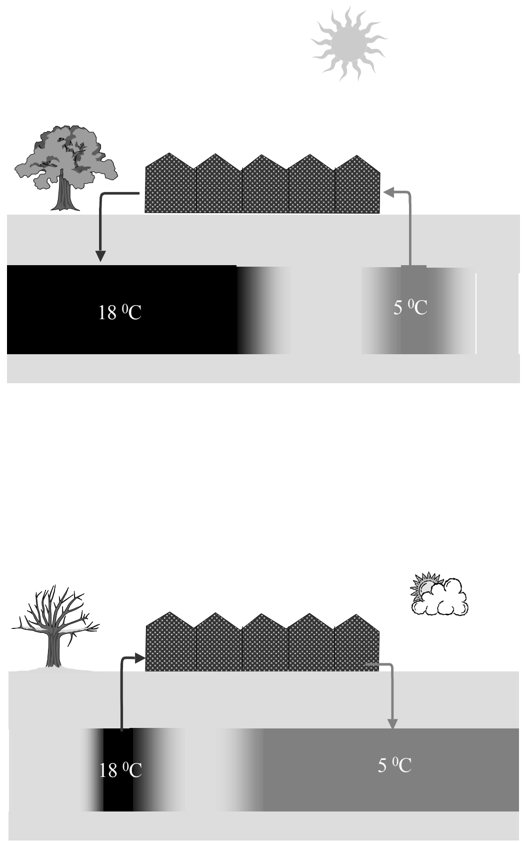


Fig. 1. Sketch of the aquifer:
after summer (left picture), the warm part is filled and the cold part is empty;
after winter (right picture), the warm part is empty and the cold part is filled.

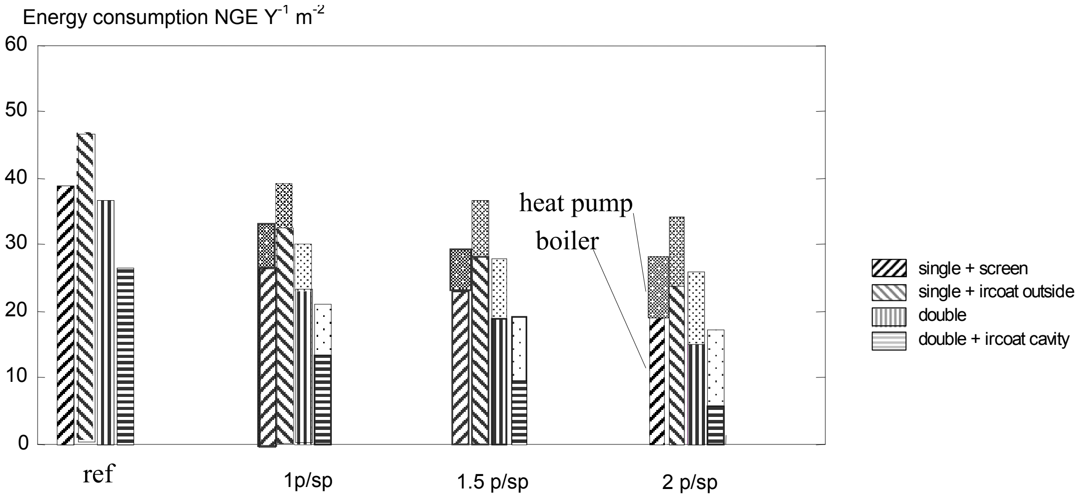
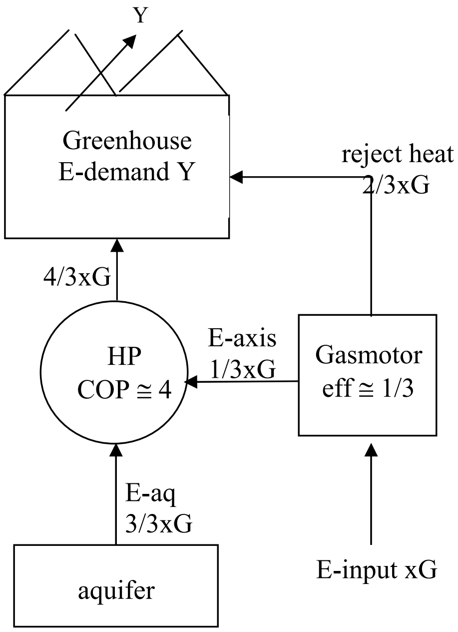


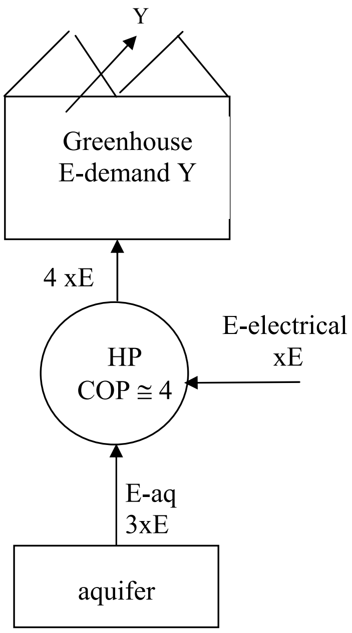
Fig. 2. Year round energy consumption of a tomato crop for various capacities of cooling, heating and heat pump. Four situations are given: the reference situation (heating by a boiler), and heating by a heat pump-boiler combination with aquifer heat storage for three heating capacities given by p/sp: the number of pipes per span. For these four situations the resulting yearly energy consumption of four covers with different insulation values are given. The energy consumption for the boiler and for the heat pump are given separately (upper and lower part of the bar). It can be observed that the heat pump can cover more of the heat demand with increasing heating capacity and increasing insulation.



Order of magnitude Energy-input xG for a gasmotor driven Heat Pump to satisfy the energy demand Y of the greenhouse:

Y = 4/3 xG + 2/3 xG = 2xG
So E-input xG = ½ E-demand Y
From aquifer also ½ E-demand Y

Fig. 3. Energy input xG for a gas motor driven heat pump with reject heat to satisfy the energy demand Y of a greenhouse.



Order of magnitude Energy-input x for an electrical driven Heat Pump to satisfy the energy demand Y of the greenhouse:

Y = 4xE
So E-input xE = 1/4 E-demand Y = ½ xG
From aquifer 3/4 of E-demand Y

Fig. 4. Energy input xE for an electrical driven heat pump to satisfy the energy demand Y of a greenhouse.