Model Application for Energy Efficient Greenhouses in The Netherlands: Greenhouse Design, Operational Control and Decision Support Systems

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Abstract

The development of energy conservative greenhouse systems is the overall result of improvement of greenhouse construction, cladding materials and insulating techniques, innovative climate control equipment and implementation of physical and physiological knowledge in the operational climate control systems. The development of these systems represents an optimisation problem and the use of both physical as well as physiological information and models has shown to be a most powerful tool in dealing with this. In this paper some recent examples of relevant application of models in the design, operational control and evaluation of energy conservative greenhouse systems are presented, based on recent results and research in The Netherlands.

INTRODUCTION

The greenhouse cover causes a change in the climate conditions with a significant impact on growth, production and quality of the greenhouse crop. This forces the grower into an active role with respect to climate conditioning. Originally, when control was still by hand, the main issue was to avoid climate extremes: over-heating, especially due to strong radiation, and low temperature damage by night and during cold spells. Later, with the introduction of heating and automatic ventilation, the focus shifted towards the question of optimal set-points for crop growth (Bakker, 1995). Nowadays greenhouse system design and climate control are important issues in protected cultivation, because they enable the grower to control the production process, more or less independently of the outside weather conditions. The optimal greenhouse production system design and control have become important strategic and operational management issues to optimise the economic output of the horticultural industry. A major factor in this optimization are the energy costs m^{-2}. Over the last decades they have steadily increased and although the price levels may show some fluctuations, the energy costs are becoming an increasing fraction in the total production costs. Apart from that, the environmental impact of the use of fossil fuel is a major issue on the political agenda resulting in the international Kyoto protocol and large groups of the social community consider the greenhouse industry as an “energy spilling” agricultural business. The greenhouse industry is thereby confronted with economical, political and social pressure to reduce the energy use. The other side of this medal is however that this situation has led over the last 30 years to a continuous stream of technical innovations to reduce the energy consumption of greenhouse production systems, either by developing energy conservative greenhouses, efficient energy conversion and supply systems and improving the energy efficiency.

These days, the normal commercially used 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. The development of these energy conservative systems is the overall result of a step by step improvement greenhouse construction, cladding materials and insulating techniques, innovative climate control equipment and implementation of physical and physiological knowledge in the operational climate control systems.

In the most recent attempt to further stimulate these innovations, the Dutch horticultural industry has set the target of the introduction of “fossil fuel free” greenhouses in 2020. To reach this ambitious goal, a research and development

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programme has been started under the name: “Kas als energiebron” (Greenhouse as energy source). Since decades it has been recognized that greenhouses are large solar collectors which collect almost 80% of all incoming solar radiation (e.g. Garzoli and Shell, 1984). For North West European conditions the yearly solar irradiation sum equals approximately 3.5 GJ m^{-2}, 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. The average energy use (in the form of fossil fuel) under the same conditions, is about 40-50 m^3 natural gas per m^2 (Bot et al., 2005). Since the incoming solar radiation represents about twice the energy used in the greenhouse itself, this theoretically creates the possibility to use the greenhouse as a combined crop and heat producing system. The basic principle is a completely closed greenhouse from which the heat surplus during the summer is extracted by a cooling system, stored in a long term storage medium, and reused during the winter period for heating the greenhouse itself and neighbouring greenhouses or buildings (Bakker et al., 2006).

The design and operational use of energy conservative and completely controllable greenhouse systems fits in the long term trend from passive, via hand to automatic control of individual environmental factors to control crop-production and quality, independently of the ambient conditions. Also the scale of control shows a clear trend: from control of the greenhouse macroclimate to control on a microclimate level. The optimal greenhouse design and climate control represents an optimisation problem and the use of both physical as well as physiological information and models has shown to be a most powerful tool in dealing with this problem. Around the world many research groups develop and use models for greenhouse design and operational control of which a wide range was presented during the ISHS International Conference on Sustainable Greenhouse Systems in Leuven (2004). This paper has not the intention of presenting a complete world wide overview but focuses on a range of examples of relevant application of physical models in the design and (operational) control of energy conservative greenhouse systems in The Netherlands.

MODEL BASED DESIGN OF COMPONENTS FOR ENERGY EFFICIENT GREENHOUSES

Covering Materials

For an effective development of new energy saving greenhouse components they should be evaluated as part of the entire system (including the greenhouse environmental conditions aimed at under practical conditions). Within Wageningen UR the integral design tool Kaspro (de Zwart, 1996) has been developed based on the model set up by Bot (1983). The dynamic model describes the entire energy, vapour and CO_2 balance of the greenhouse and includes also the energy conversion systems and a set of control modules comparable to those available in commercial systems. Over the last 10 years the model has been expanded with experimentally validated modules for thermal screens, heat exchangers, a cooling tower, heat pump, co-generator and short- and long-term heat storage (aquifer). The model also includes a crop photosynthesis module which enables the use for integrated design and component evaluation.

In the attempt to create energy conservative greenhouses improved insulation combined with high light transmission is one of the most challenging issues. The major disadvantage of most insulating covers and thermal screens is the drawback in light transmission and the increased humidity, which may both have negative effects on crop production and quality. Under practical conditions the potential energy saving of the covering materials and screens is therefore almost never achieved (e.g. since the grower tries to compensate these negative effects by modifying his greenhouse environment by increasing dehumidification) e.g. Sonneveld and Swinkels (2005).

The recently developed Lexan® ZigZag™ greenhouse covering material (Sonneveld and Swinkels, 2005) is an example in which the cover as a greenhouse component was developed and evaluated as a part of an entire greenhouse system. The optimal Zigzag geometry of the material was designed using a ray tracing computer program. To allocate the insulation value for the different sheet geometries computational fluid dynamics (CFD) calculations were performed according to the European Standard. Finally the overall greenhouse environmental conditions and energy consumption was simulated using the expanded Kaspro model. An inclination of 48° is ideal, for a sheet with a grid length of 50 mm and a thickness of 25 mm this combines a light transmittance of 90.8% for direct and 80% for diffuse light with an insulation value (U-value) of 3.4 W m^{-2} K^{-1}. Although the momentary energy saving might be 45%, a year round energy saving of 20-25% compared to single glass is expected under practical conditions (Sonneveld and Swinkels, 2005). Measurements in the first large scale commercial greenhouse with the ZigZag™ cover are now being carried out to confirm these values.

Heating and Ventilation Systems

Another major component of energy conservative greenhouses is a well designed heating system to create a proper horizontal temperature distribution and a sufficient ventilation system. Before the new climate control concepts will gain the additional profit aimed at, even within the basic economic limitations, a number of practical problems (limitations) has to be dealt with, one of them being uneven temperature distribution (Bakker, 1995). Today the optimal design of heating or ventilation systems can be realized using the simulation tool Computational Fluid Dynamics (CFD) to determine flow field and temperature distributions in and around geometries (Mistriotis et al., 1997). It is now a wide spread and frequently used tool for optimal design of ventilation systems in greenhouses (e.g. Campen and Bot, 2003; Campen, 2005; Molina-Aiz et al., 2005; Valera et al., 2005; Baeza et al., 2005). In the CFD program, a system is modelled by discretising space and time (finite volume method) and by solving the conservation equations for the discretised parts for the relevant quantities considered, the flow field for heat and mass can be determined.

The improvement of the technical installations has been subject of study for decades since large temperature (and humidity) differences arise from either malfunctioning of technical installations (Bakker and Van Holsteijn, 1989) or the fact that from the design itself uneven distributions will arise, leading to production and quality loss and reduced energy efficiency. Above that, the varying heat loss from the greenhouse with variation in wind direction needs to be compensated to obtain even temperatures in the greenhouse. Recently Campen (2004) used the tool to optimize the pipe heating system for traditional Venlo type greenhouses. Dividing the greenhouse heating system in several sections and independently controllable side wall heating shows a large potential in improving the temperature distribution and an increase of the energy efficiency by 1 to 7% (Fig. 1).

Cooling and De-humidifying

For large regions in the world however, heating is less a problem in the energy efficient design of greenhouses compared to cooling and dehumidification. With the trend to more “closed greenhouses” aiming at completely controllable conditions also in the more moderate climates, energy efficient cooling/dehumidification systems are subject of model and experimental studies. Hammer et al. (2006) used integrated physical and physiological models to compare different cooling systems aiming at the same greenhouse temperature as obtained with natural ventilation while de Zwart (2006), compared different cooling systems with a capacity to keep the greenhouse completely closed, even at maximum radiation levels. Return on investment of the evaluated cooling systems is poor except for the direct and indirect evaporative cooling (Hammer et al., 2006; de Zwart et al., 2004; de Zwart, 2005). Using a water layer in a rainwater basin under the greenhouse floor as a direct evaporative cooling system turned out to be less efficient and cost effective compared to convectional methods (Campen, 2006).

INTEGRAL DESIGN OF ENERGY EFFICIENT GREENHOUSE SYSTEMS

The use of models as powerful design tools is best shown in projects aiming at integral design of energy efficient greenhouse production systems. With the availability of combined models, the possibilities for designing an overall optimized greenhouse system including covering material, heating and ventilation/dehumidification, control algorithms and energy conversion systems are within sight. The solar greenhouse concept as developed by Bot et al. (2005) is a perfect example of model based integral energy efficient design since also the energy conversion technologies and optimal control are incorporated. 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 basic design steps were first designing a system requiring much less energy (Waaijenberg et al., 2005; Fig. 3), next to balance the availability of natural energy with the system's energy demand, and finally to design control algorithms for dynamic system 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 600 kW nominal wind power or 1.2 ha PV assuming storage via the public grid. In this solar greenhouse, during the summer as much heat is collected and stored to balance the energy requirement during the winter.

With the 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 period for heating the greenhouse itself and neighbouring greenhouses or buildings. The function of the greenhouse as a solar collector is thereby maximized by further reduction of the heat loss from the greenhouse and maximizing the heat collection by much more efficient heat exchangers (Fig. 4; Bakker et al., 2006). Currently in the Netherlands projects are set up with heat delivery from greenhouses to normal houses in so-called "energy grids". Recently PRI developed a model based decision support system to design the energy infrastructure for greenhouse related "energy grids" (Swinkels et al., 2005; Fig. 5).

MODEL BASED ENERGY EFFICIENT OPERATIONAL CONTROL

The development of energy efficient greenhouse environmental control has been directly related to the developments of new hardware and increasing physiological knowledge. E.g. it has been known for decades that crops react primarily to the average temperature rather than to the exact 24 h temperature course (e.g. De Koning, 1988). Using the capability of compensating lower temperatures by higher temperatures has a significant potential for energy saving which becomes greater with an increasing integration capacity of the crop (determined by the bandwidth of the deviation from the average temperature as well as the period during which this deviation occurs). Simulations and experiments with temperature integration show that 5-15% energy conservation can be realised without affecting plant growth and production (e.g. Hurd and Graves, 1984; Bailey and Seginer, 1989; Körner and Challa, 2003; Dueck et al., 2004; Elings et al., 2005). Today almost all commercial greenhouse control systems are equipped with the temperature integration feature; however, the practical use of these possibilities so far has been limited resulting from the relatively low economic benefits (Elings et al., 2005). Two factors are now creating a renewed interest in the temperature integration capacity of crops: the increasing energy costs and the implementation of closed greenhouses. In the latter, originally during the summer, relatively low temperatures were aimed at (Opdam et al., 2005). However, more recently in the practical experiment (Themato) the tendency is towards higher day temperatures and lower night temperatures. This restricts the necessary maximum cooling capacity during daytime and, combined with normal ventilation during the night time (when CO_2 is not needed), reduces the required total amount of cold water from the aquifer.

In the field of thermal screen control a clear example of a model based control algorithm development was shown by van de Braak et al. (1998). Based on an extensive simulation study the basics for energy efficient (humidity) slid and natural ventilation control were evaluated. The results showed that it is more energy efficient to control the screen prior to the ventilation windows. The knowledge has now been implemented in commercial greenhouse controllers. Further fine tuning of the removal of vapour from screened greenhouses to the ambient environment using controllable micro fans is now subject of a research project at PRI.

In the attempt to move from control of environmental factors towards crop process-control and finally crop production and quality control, relatively simple models on crop photosynthesis and transpiration have been used in computer algorithms from the early 1980s (e.g. de Graaf, 1988; Bakker, 1985). The more sophisticated physical models (e.g. Bot, 1983; Stanghellini, 1987; Van Henten, 1994; De Zwart, 1996) photosynthesis models (Körner et al., 2002; Körner and van Ooteghem, 2003; Heuvelink, 1996) are primarily used in design studies to create a “virtual greenhouse” which is used to evaluate new developed environmental control strategies. E.g. the receding horizon optimal control system as part of an integral system design and described by Van Ooteghem et al. (2005) is completely developed using a “virtual greenhouse” based on the models mentioned above. Also the optimization routine for temperature and CO_2 as developed by Dieleman et al. (2005) was designed using a “virtual greenhouse”. The experimental test with this routine showed a slight but significant increase in energy efficiency. Other example of steps to successful energy efficient model based control is the humidity control (Körner and Challa, 2003) which recently improved the humidity routine to avoid fungal diseases like grey mold (e.g. Körner and Holst, 2005; Fig. 2).

The optimal use of models in on-line control of greenhouses however requires modification into a form that makes them easy to use in these advanced applications. The existing models that describe the evolution in time of a tomato or cucumber crop (e.g. Marcelis et al., 1998) are developed for research purposes and are not suitable for rigorous optimal control, as they are seldom if ever formulated in state-space form. Reducing a complex model to a few or even a single state model has been relatively successful (Jones et al., 1999; Seginer and Ioslovich, 1998) and recently Van Straten et al. (2006) demonstrated that the state space approach made it possible to implement a receding horizon scheme in a consistent and relatively fast way (for nutrient control). According to Van Straten et al. (2006) this technique is valuable to improve both modelling and the use of models, also for energy efficient greenhouse control. It is also the modelling paradigm for the development of so-called software sensors: model based measurements of greenhouse processes like photosynthesis. As first steps in the development of soft-sensors (Bontsema et al., 2005) have applied this technique for the on-line measurement of the ventilation rate which is now expanded to the overall crop photosynthesis and transpiration in naturally ventilated greenhouses. This self tuning approach has much more potential for wide spread application than current techniques based on a physical model of the ventilation rate since the parameters largely differ for different greenhouse designs (e.g. de Jong, 1990).

EVALUATION OF ENERGY SAVING MEASURES AND DECISION SUPPORT SYSTEMS

The third application of models in the design and operational use of energy efficient greenhouse systems is for the evaluation of energy saving technology and in the form of decision support systems. Reliable and quick assessment of energy conservation measures in greenhouse cultivation supports growers in their operations. E.g. Elings et al. (2005) carried out a comprehensive model study to evaluate the effects of a wide range of energy saving technology producing an overview which quantifies the consequences for total energy consumption, amount and quality of production, and farm economy. The rapid changes in technology and energy costs however require a more dynamic approach. In this field an interactive decision support system usable for selecting decisions as well was developed by Swinkels (2006). In this DDS the grower 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 his operational control. The output shows the energetic and economic effects of both the strategic and the operational choices. The first version of the model was made available as free software on the internet in 2004.

CONCLUSION

The development of energy efficient and sustainable greenhouse systems has been enhanced significantly by the application of physical and physiological simulation models, however for the further optimization of the operational control, the current models should be formulated in state-space form to maximize their application in on-line control of energy efficient and completely controlled greenhouses.

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Figures

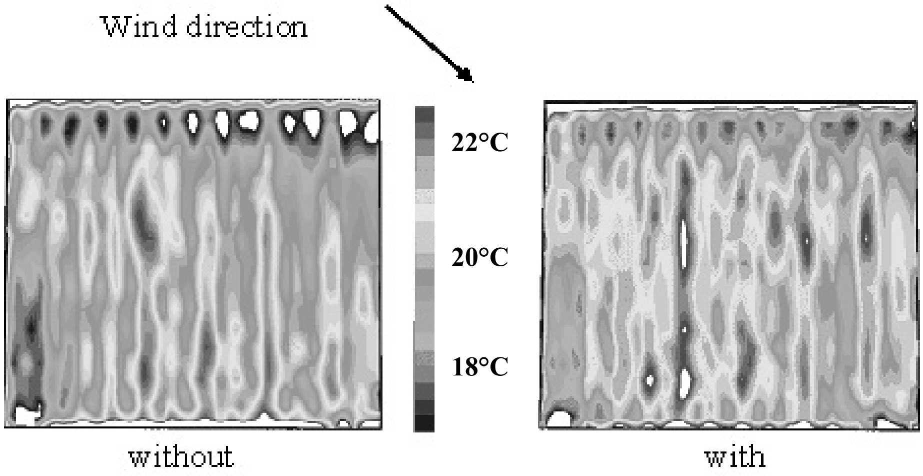

Fig. 1. CFD as design tool for optimal lay-out of heating systems: temperature distribution without (left) and with (right) independently controllable side wall heating. From Campen, 2004.

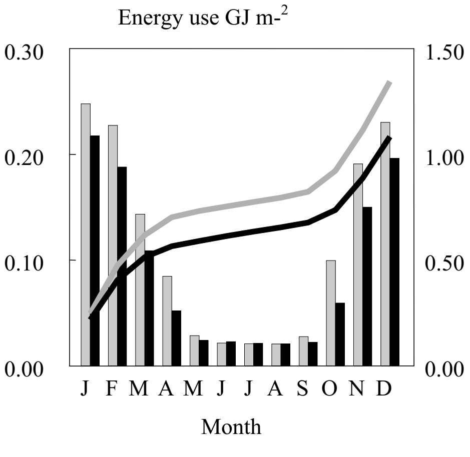

Fig. 2. Model based environmental control: Simulated greenhouse energy use with a fixed relative humidity set point of 80% (grey) and the Botrytis based dynamic humidity regime (black). Lines are cumulative and bars are monthly values. From Körner and Holst, 2005.

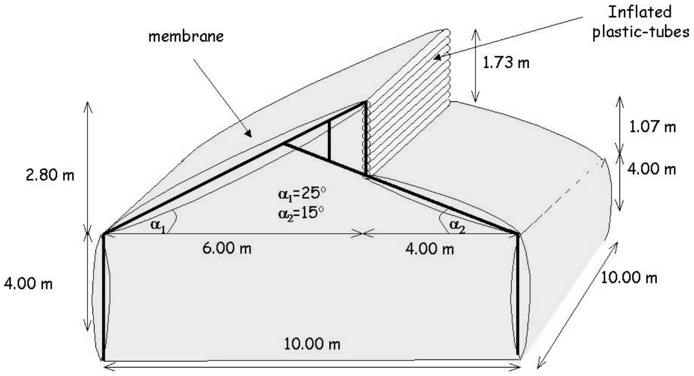

Fig. 3a. Example of model based integral design of an energy conservative greenhouse: Inflated cladding and a new principle of opening and closing the natural ventilation system. From Waaijenberg et al., 2005.

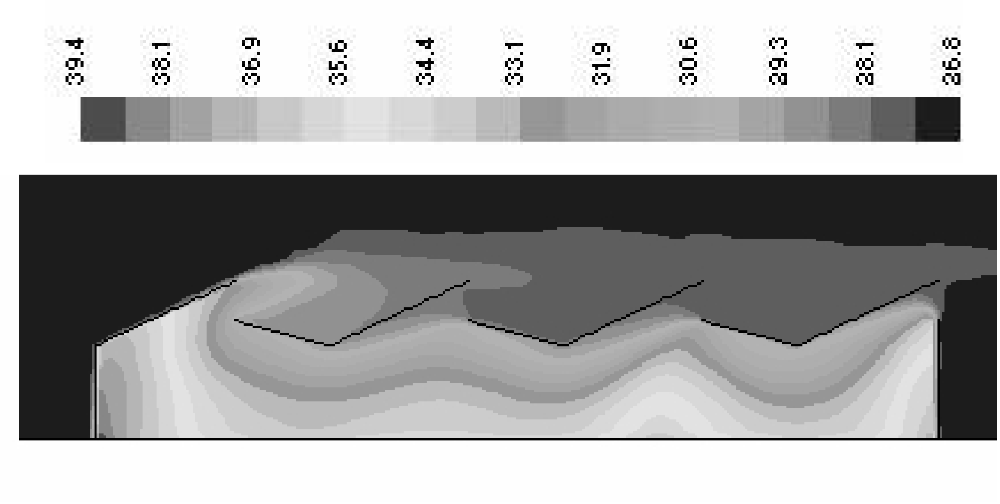

Fig. 3b. Example of model based integral design of an energy conservative greenhouse: Temperature distribution in the solar greenhouse as simulated with CFD. From Bot et al., 2005.

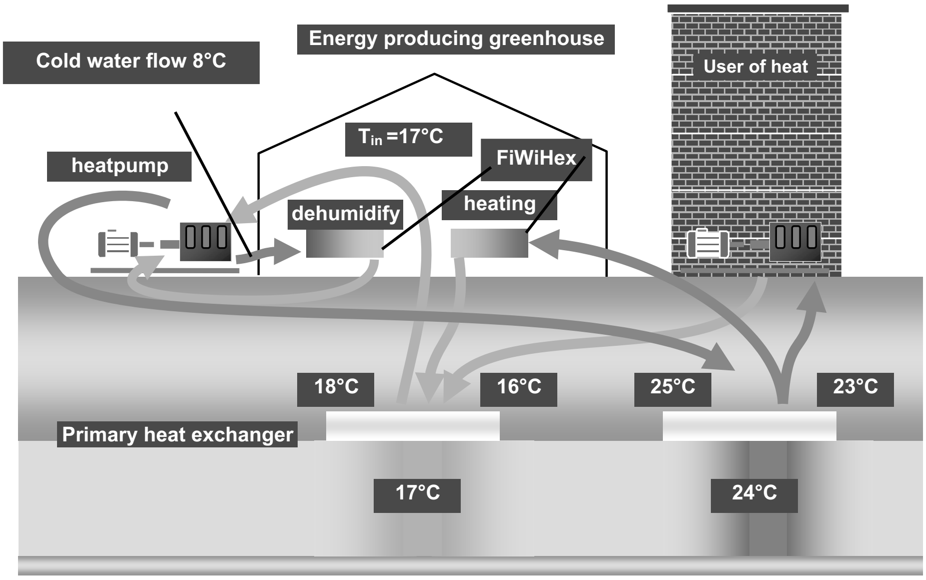

Fig. 4. Schematic lay out of the major components, heat fluxes and temperature levels of the “energy producing” greenhouse. From Bakker et al., 2006.

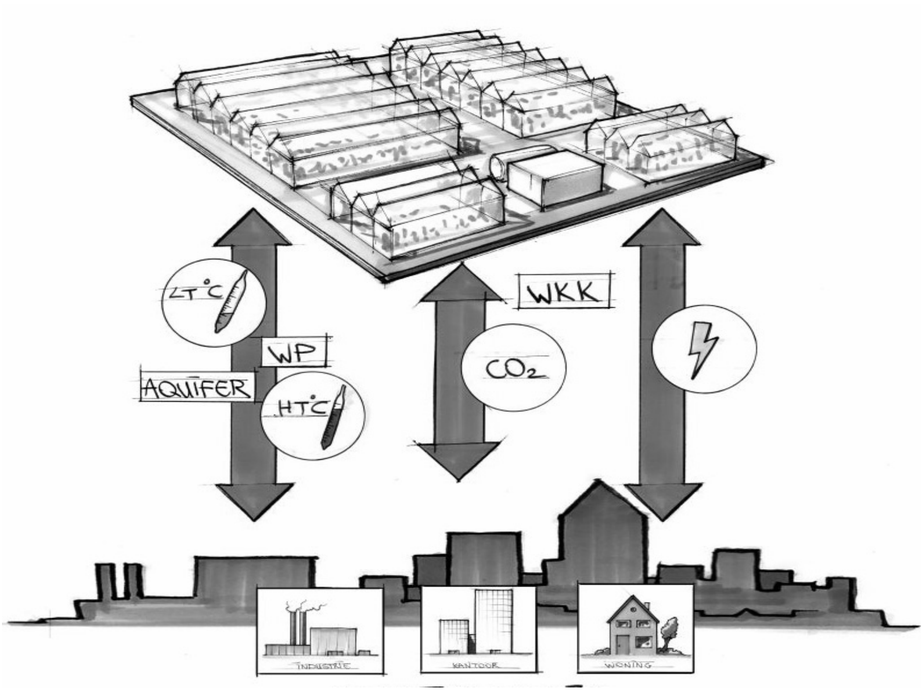

Fig. 5. Schematic representation of the basic components of the model based decision support system to design the energy infrastructure for greenhouses combined with other energy consumers in “energy grids” (Swinkels et al., 2005).