# **Overall Energy Analysis of (Semi) Closed Greenhouses**

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## Abstract

Natural ventilation to discharge excess heat and vapour from the greenhouse environment has serious drawbacks. Pests and diseases find their way through the openings; carbon dioxide fertilisation becomes inefficient and the inescapable coupling of heat and vapour release results often in sub-optimal conditions for either temperature or humidity. The present trend, therefore, is to reduce ventilation as much as possible, also in Mediterranean conditions. This relies obviously on improved means for diminishing the heat load and proper use of cooling equipment. Especially the latter can combine the benefits of cooling the greenhouse air with serious energy conservation. However, opposite to the clear benefits there are also serious investments associated with active cooling of greenhouse. Therefore, there is a growing demand for some computational tool that enables quantitive comparisons between the vast number of alternatives with respect to the different components of (semi) closed greenhouse systems. The benefits in terms of improved production (quality, ornamental value and quantity) are quite difficult to quantify, due to the complexity of the biological processes involved. On the energy side of the balance, however, since the physics of greenhouses, climate controllers and horticultural hardware can be described very well, it is quite possible to develop such a tool for predicting the energy consumption of a (semi) closed greenhouse for a wide range of horticultural and outside climate conditions. This paper gives an outline of such a tool and discusses some results. Just as an illustration, a number of quantitative effects are shown of changing the fraction of closed greenhouse surface in a 1 hectare enterprise that consists of closed and non-closed compartments. This analysis is made for both a Dutch climate situation and a Mediterranean weather data set.

## **INTRODUCTION**

Dutch horticulture aims to decrease the fossil energy input to horticulture. One of the promising means to do so is to transform the greenhouse in a so called "Energy producing greenhouse". There are some innovative ideas of achieving this goal by adding PhotoVoltaic elements in the construction (Sonneveld, 2006), but most of the concepts that contribute to this goal are based on extracting heat from the greenhouse air or the cover (Opdam et al., 2004; Bot et al., 2004; Campen et al., 2001). The amount of surplus heat ready to harvest is large. Even in the northern latitudes, in non shadow screened greenhouses, at least 1500 MJ/(m<sup>2</sup> yr) of surplus heat is carried off by opened windows during sunny days. Additionally, around 500 MJ/(m<sup>2</sup> yr) is ventilated away on dull days, when greenhouse air is exchanged with outside air for dehumidification purposes.

Due to the botanic 'comfort zones', the heat extraction, particularly when serving a dehumidification demand, takes place at a low air temperature level. In addition, because the costs associated with realizing low cooling water temperatures are high, the typical temperature differences between air and the cold heat extracting surface are limited to some 5 to 15°C. This means that, when aiming at serious heat extraction capacities of around 300 W/m<sup>2</sup>, the heat exchanging surface must be large and/or provided by a high heat exchange coefficient. It is obvious that the heat exchanging surface and the heat exchange coefficient are more or less interchangeable. Therefore, each design will need a survey to determine the optimal configuration. This optimum will not only be dependent on static parameters, determining the fixed costs of the one or the other heat exchanging device, but will also depend on energy prices since forced convection by ventilators is a powerful means of enhancing the heat exchange coefficient. Another article presented on GREENSYS 2007 (de Zwart, 2007) focuses in detail on all aspects having to do with characterizing heat exchangers.

However, even after a selection procedure has found the heat exchanger that promises to provide the cheapest way of gathering heat out from surpluses of thermal heat (a greenhouse being too hot) or from surpluses of latent heat (too high a humidity), there is another, much more complicated optimization to perform. This second optimization has to balance all costs of cooling the greenhouse with the benefits. The costs come from the capital costs associated with the investments and from electricity for making cold water and driving pumps and ventilators. From these components, the determination of the costs of making cold water is the most complicated because, when heating a greenhouse with a heat pump in winter, a certain amount of cold water is produced as 'waste product'. This means that, providing that the driving power for the heat pump is addressed as heating costs, at least part of the cooling water can be get for free. With respect to the benefits of cooling, the present work only rates the advantage of an elevated  $CO_2$ -concentration on photosynthesis.

This paper presents a brief outline of the optimisation instrument called the Synergy-Compass and the simulation tool that it uses. Then, as an illustration, this tool is used to show the effect of closing a certain fraction of a greenhouse area on energy consumption, canopy production and variable costs and benefits in Dutch and in Mediterranean weather conditions.

### **BRIEF DESCRIPTION OF THE SYNERGY-COMPASS**

In Figure 2, the main input sheet of the Synergy-Compass is presented. On this sheet, amongst some administrative settings, three prominent sets of input data can be found, namely the greenhouse climate requirements, the building characteristics and the description of the devices that serve the climate control. These data comprise the main input for a simple but quite complete simulation model describing the greenhouse climate and heating and cooling demand on an hourly base. Besides, the simulation model describes the main energy conversion processes in the boiler house in order to translate a heating and cooling demand to primary energy sources like natural gas and electricity.

The base of the simulation model is to compute an hourly stationary energy balance that satisfies the user defined temperature set point as a function of outside weather conditions and the actual heat loss coefficient (the u-value). This u-value depends on user defined thermal screen characteristics and control (see Fig. 2), but also on ventilation. Ventilation is partly uncontrollable (leakage), and partly controlled in order to carry off moisture from the greenhouse, having a user defined maximal humidity. On sunny days, however, the ventilation is predominantly a controlled air exchange rate in order to prevent too high a greenhouse temperature.

Solar radiation absorbed by the canopy is split into a sensible heat flux and an evaporation rate (representing a latent heat flux). It is assumed that 40% of the absorbed radiation is turned into vapour but there is always a minimum evaporation rate of 5 Watt times the LAI. The remainder of the absorbed radiation is transformed to sensible latent heat, which means that during the night the canopy absorbs some 15 W sensible heat per  $m^2$  greenhouse area.

By defining temperature excess driven ventilation as a last resort action, the insertion of a certain active cooling capacity will show the effects of greenhouse cooling on a diminished ventilation rate and the related increment of  $CO_2$ -concentration (if  $CO_2$ -dosing is provided). The benefits of an increased  $CO_2$ -concentration are computed in terms of an increased carbon fixation, computed by a standard photosynthesis algorithm (Gijzen, 1992).

Besides as a means to enhance production, the hourly applied cooling rate serves as an amount of gathered heat that can be stored in a diurnal and/or seasonal storage facility. When storing in a seasonal storage facility, a user defined temperature loss across a heat exchanger that separates aquifer water from heating system water is taken into account. The main consequence of such a temperature loss is a decrement of the charge and discharge rates of the aquifer (in terms of thermal power) and an increase of pumping costs.

The cooling capacity of any cooling device depends strongly on the conditions of operation. Not only because of the need to define the maximal capacity, but also in order to determine the characteristics of cooling in terms of electricity consumption and return water temperature, a separate input sheet was developed. This sheet can be accessed with the button "Properties Cooling units" (see Fig. 2). The reasoning and results of this tool are discussed in a related article presented on GREENSYS 2007 (de Zwart, 2007).

When the greenhouse doesn't need to be cooled, but needs to be heated, the simulation model satisfies this heat demand by emptying the high temperature storage tank, applying the CHP, the boiler or the heat pump (each, except for the boiler, limited by its user defined maximal capacity). Most of the time, the high temperature storage tank is the first device to extract heat from (if not emptied yet). Then, preferably the heat pump is switched on, in combination with the CHP that serves the electricity demand of the heat pump. The boiler is treated as a last resort device. However, when there is a demand of flue gas  $CO_2$  (which only can be provided by the boiler and CHP-unit), or a demand of electricity that can be sold at a high price to the public grid, using the CHP and boiler (in that order) will prevail over the other heat sources. Obviously the optimization tool assumes that the flue gases of the CHP-unit can be used as  $CO_2$ -fertilizer.

Having enabled to compute the hourly status of the boiler house and greenhouse climate, a year round simulation can be made that computes the use of consumables like natural gas, electricity, liquid  $CO_2$  but also computes the carbon fixation by photosynthesis and the production of electricity for the public grid. This simulation can be performed for an ordinary reference situation, typically without a heat pump and cooling units, and for a new situation, comprising a fully or partially conditioned greenhouse. A partially conditioned greenhouse can mean that there is only a base cooling capacity that must be accompanied with conventional ventilation, but it can also mean that only a small fraction of a new greenhouse is equipped with cooling units. In this second situation the boiler house serves cooling for only a part of the greenhouse but provides heating for the full greenhouse site. The main input datasheet even enables to define differently set greenhouse climate conditions and different constructions for the one and the other part, by means of an extra column if the conditioned fraction is not 100%.

In general, the application of highly conditioned greenhouses increases the fixed costs for capital, but also increase the income from an elevated production level and a decrease of costs for energy input. All parameters needed for this economic evaluation can be entered by a special worksheet (see button "Economic input data" in Fig. 2). Then, by comparing the effects of a new, conditioned greenhouse on cost and benefits in comparison with a relevant reference gives the user the quantitative information with which a (semi) closed greenhouse configuration can be optimized.

#### EXEMPLARY RESULTS AND DISCUSSION

When looking at the number of parameters in the main input sheet, without even having seen the additional sheets behind the 'parameter buttons', it is clear that it is quite impossible to define such thing as THE optimum. Apart from the fact that such an optimum would always be a strong function of varying economic parameters, the present models that describe the development of canopies are not yet suitable for automated optimizations. Therefore, currently only parts of the optimization demand can be served by an arithmetical assistant like the Synergy-Compass. This tool can provide a large number of quantified consequences of possible adaptations or innovations on greenhouses which will help a humane optimization procedure, trying to separate good ideas from less good ideas.

In this paper, just as an illustration, the Synergie-Compass is used to find out which fraction of a new built greenhouse can be equipped as an (almost) closed greenhouse. When too large a fraction is closed, the amount of cooling water will become such large that the heat pump will have to be used as a cooling machine, annihilating the major fraction of the summertime heat excesses. There can be improvements of production expected, but the electricity costs will grow substantially as well. When too small a fraction is chosen, the heat pump in winter, when serving as an energy friendly heating device, will lack low thermal heat in the seasonal storage facility (typically an aquifer).

Figure 1 shows a schematic representation of the major energy flows when the settings shown in Figure 2 are used for mean Dutch weather conditions. It can be seen that, from the total heating demand of 1065 MJ, less then half is supplied by the heat pump. The second heat source for the greenhouse is the reject heat of the combined heat and power unit. The figure shows that the CHP runs predominantly to sell electricity to the public grid. Not visible in Figure 1, but provided in other output sheets of the Synergy-Compass, it is computed that almost all excess electricity is sold during the high value day time hours, mostly coinciding with hours where the CO<sub>2</sub> of the exhaust gases can be used for CO<sub>2</sub> dosing. During night, the CHP only serves the on-site electricity demand. The boiler plays quite an important role as well, mainly as an additional CO<sub>2</sub> source because the CHP-unit provides only 70 kg of CO<sub>2</sub> per hour. Finally, in Fig. 1 can be seen that there is a small excess of low thermal heat.

The energy flows, shown in Figure 1, represent a certain financial value. The Synergy-Compass computes this value by making a distinction of the costs and revenues of electricity buying and selling in dependence of the on-peak and off-peak status. Also it uses different prices for gas to be combusted in the CHP-unit and in the boiler. This enables a detailed analysis of the impact of closed greenhouses on the exploitation of CHP for the public grid, which is very relevant in the current Dutch situation. However, in this paper, for the sake of simplicity the value of electricity is rated at  $\in 0.05$  per kWh (irrespective selling or buying) and all gas is rated at  $\in 0.20$  per m<sup>3</sup>. With these prices, from Figure 1 can be read that the total gas costs are 29 m<sup>3</sup> \*0.20 =  $\in$  5.8. There seems to be an income from sold electricity of 48 kWh\* $0.05 = \notin 2.40$ . However, since Fig. 1 shows that there is a surplus of low thermal heat, some electricity must be used to annihilate that amount of energy. When it is assumed that the annihilation of this excess heat takes place with a COP of 4, the excess of 85 MJ requires 85 MJ / 4 /3.6 MJ/kWh = 5.9 kWh of electricity. This means that the final amount of electricity to be sold is only 42 kWh. Thus the overall net energy costs will be 5.80 - 42 kWh\*0.05 = € 3.70. If a computation would have been made with a smaller closed fraction there wouldn't be a surplus of low thermal heat, but then there would be a shortage. If this is the case, the heat pump would have to produce less heat, and the boiler would have to produce more heat.

The financial effect of the energy saving by means of the heat pump can be computed by comparing the energy costs in the new situation with the costs in the reference situation, described by the data in the last columns of each block of input-data in Figure 2. This computation is performed by the Synergy-Compass as well, resulting in a total gas consumption of 46 m<sup>3</sup> gas, and a net selling of 101 kWh of electricity. This means that in the reference situation the net energy costs are 46 m<sup>3</sup> \*0.20 – 101 kWh\*0.05 = € 4.15. Thus, the net savings on energy costs when furbishing 40% of the greenhouse as a closed greenhouse are € 0.45 per m<sup>2</sup> per year.

Apart from the energetic implications the effect of greenhouse cooling on a diminished ventilation rate will help to achieve elevated  $CO_2$ -levels in the closed fraction. In Figure 3 it is shown that in summer this increment can reach levels of almost 25%. However, in colder months, the impact is much less of course, so on a yearly base the overall increment of production is computed to be only 12%. Moreover, this 12% increment is achieved on only 40% of the greenhouse, so the increment of production on the enterpris is only 4.8%. Finally, of course, not the increment in weight, but the

increment in market value counts. Therefore, the Synergy-Compass computes the produce income effects by multiplying the monthly extra photosynthesis with a month-specific mean price. For the case in consideration, and using the current Dutch prices of tomatoes through the year, it appears that the income effect is 4%, so a bit less than the weight effect. In terms of money, 4% is about  $\in 2.00$ 

In Table 1 the results of an exercise as described above is performed for a greenhouse with a 10%, 20%, 30% and 40% closed fraction for Dutch and Mediterranean weather conditions (obtained from Nimes, France). The table shows in the first line that, for Dutch conditions a small closed fraction leads to higher gas-consumptions because the heatpump cannot be used as much as liked. There is simply not enough low thermal heat in the aquifer. In the Mediterranean situation, the amount of electricity to be sold drops rapidly with increasing closed fractions because there is a fast growing amount of electricity needed to annihilate the low thermal heat surpluses. In Mediterranean conditions these heat excesses already emerge with a closed fraction of 20%

Obviously, Table 1 shows that, when looking at variable costs only, for Dutch conditions an optimal closed fraction lies near 40%, whereas in Mediterranean conditions a closed fraction of 20% looks best.

## **CONCLUDING REMARKS**

The number of variables in greenhouse horticulture and especially the lack of a reliable and appropriate growth and development model for greenhouse canopies prohibit to define THE optimal set of greenhouse exploitation parameters. Nevertheless, when a large number of parameters is given a fixed value, trusting that ones horticultural craftsmanship prevents the selection of too unfavourable settings, the Synergy-Compass presents interesting results. It can quantify the trade off between pro's and con's of the most important design variables around (semi) closed greenhouses and the climate controlling devices that achieve the greenhouse cooling. When using the Synergy-Compass it will be obvious that optima will be very much dependent on location and economic parameters.

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## <u>Tables</u>

Table 1. An exemplary table of the effect of the fraction closed of a partially closed greenhouse on variable costs associated with net energy consumption and production for two outside weather conditions. The gasprice is € 0.20 per m<sup>3</sup> and the electricity price € 0.05 per kWh. The annual turnover of the canopy produce is set to € 50 per m<sup>2</sup>. All horticultural and greenhouse building parameters are defined in Figure 2.

	Dutch weather				Mediterranean weather (Nimes)			
	(Refer.: 46 m <sup>3</sup> , 101 kWh sold)				(Refer.: 40 m <sup>3</sup> , 96 kWh sold)			
Fraction closed	10%	20%	30%	40%	10%	20%	30%	40%
gas consumption [m <sup>3</sup> ]	34.7	33.7	30.0	29.0	30.1	28.0	28.0	28.0
sold electricity [kWh]	55.0	52.0	50.0	42.0	60.0	28.8	33.0	17.0
Energy saving [€]	-0.57	0.01	0.65	0.45	0.17	0.04	-0.75	-1.55
production [€]	0.50	1.00	1.50	2.45	1.00	2.00	2.50	3.50
total benefit [€]	-0.07	1.01	2.15	2.45	1.17	2.04	1.75	1.95

## **Figures**



Fig. 1. Screen dump of the energy flows resulting from the settings as described in Fig 2, when using the Dutch weather data.



Fig. 2. A screendump of the major input screen of the SynergieCompass. In this example can be seen that all settings concerning the climate and building characteristics are equal, except, of course, for the closed greenhouse specific boilerhouse parameters.



Fig. 3. Increment of carbon fixation in the closed fraction, relative to the non-closed fraction as computed by the Synergy-Compass for Dutch weather conditions with the horiticultural settings as shown in Figure 2.