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Each heating system is optimised in terms of capacity and additional components applied in practice. The conventional boiler system is equipped with short term heat storage of around 100 m3 per hectare of greenhouse, which is optimal in terms of carbon dioxide enrichment and investment costs. The electrical capacity of the cogeneration is most economically around 500 kW per ha of greenhouse with additional heating capacity of a boiler for peak load and back up. By installing an electrical driven heat pump covering the basic load of the heat demand, the fossil fuel consumption by the greenhouse, which is directly related to the CO2 emission, can be reduced by 33%. The heat is extracted from underground heat storage also known as an aquifer. The heat has to be supplied to the aquifer by removing the excess heat directly from the greenhouse in summer. Then ventilation is less and carbon dioxide levels can be maintained at higher level provided carbon dioxide enrichment is available. Economically the application of a heat pump is not the optimal solution due to the high investment costs and the cost of electricity compared to the cost of natural gas. Applying cogeneration the fossil fuel consumption is almost double that of the conventional system, however the electricity produced is delivered to the public grid. This substitutes the fossil fuel consumed by a power plant which releases the reject heat and produced carbon dioxide to the environment. For these reasons cogeneration is most attractive from the environmental and economical point of view.

Evaluation of energy friendly greenhouse energy supply

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Abstract

Alternatives for greenhouse energy supply are investigated based on fossil energy consumption and costs. The evaluation is performed using an extensively calibrated and validated dynamic simulation model of a single layer greenhouse with thermal screen under Dutch weather conditions on year-round base. The hourly climate conditions are set for a tomato crop. Four nowadays applied energy supply systems, being the conventional boiler as reference, the combined heat and power generator (cogeneration), the electrical driven heat pump and the combination of cogeneration and heat pump are analyzed.

Each heating system is optimised in terms of capacity and additional components applied in practice. The conventional boiler system is equipped with short term heat storage of around 100 m^3 per hectare of greenhouse, which is optimal in terms of carbon dioxide enrichment and investment costs. The electrical capacity of the cogeneration is most economically around 500 kW per ha of greenhouse with additional heating capacity of a boiler for peak load and back up. By installing an electrical driven heat pump covering the basic load of the heat demand, the fossil fuel consumption by the greenhouse, which is directly related to the CO_2 emission, can be reduced by 33%. The heat is extracted from underground heat storage also known as an aquifer. The heat has to be supplied to the aquifer by removing the excess heat directly from the greenhouse in summer. Then ventilation is less and carbon dioxide levels can be maintained at higher level provided carbon dioxide enrichment is available. Economically the application of a heat pump is not the optimal solution due to the high investment costs and the cost of electricity compared to the cost of natural gas. Applying cogeneration the fossil fuel consumption is almost double that of the conventional system, however the electricity produced is delivered to the public grid. This substitutes the fossil fuel consumed by a power plant which releases the reject heat and produced carbon dioxide to the environment. For these reasons cogeneration is most attractive from the environmental and economical point of view.

Keywords

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Notation

CHP	cogeneration
COP	coefficient of performance
COP_{pr}	practical coefficient of performance
COP_{th}	theoretical coefficient of performance
HP	heat pump
A	area, m^2
C_p	specific heat, J kg^{-1} K^{-1}
$T_{evaporator}$	Temperature of evaporator, K
$T_{condenser}$	Temperature of condensor, K
P	power, W
S	source term
T	temperature, K
V	volume, m^3
t	time, s
η	efficiency
ρ	density, kgm^{-3}

ΔT temperature difference, K

1. Introduction

Globally there is a strong demand to reduce fossil fuel consumption and thereby decreasing CO_2 emission. This policy also applies to the horticultural industry especially for the greenhouses at Northern latitudes which need much energy for heating. Moreover energy prices are increasing causing energy to become a substantial part of the overall costs. The beginning of 2008, Dutch growers pay 0.25 EURO per cubic meter of natural gas compared to 0.12 EURO in 1995 (Van Woerden, 2005), an increase of more than 100%. This tendency is also a driving force for the horticultural sector to investigate energy saving measures.

The first option in reducing the energy consumption of a greenhouse is reducing the heat losses. Insulating practical greenhouse is a difficult task since it usually affects the light level negatively (Swinkels *et al.*, 2001). Nowadays thermal screens are applied on a large scale, closed during periods when the light levels are low to reduce the energy losses and open during the day. In this way crop production is almost not affected by the screens (Dieleman & Kempkes, 2006). Insulating covers are in development (Campen *et al.*, 2002) but not yet applied on large scale.

A second option is in more energy friendly climate control with the constraint of humidity control. In practice an energy friendly strategy is applied by lowering the temperature in the greenhouse during cold periods and allowing higher temperatures during warmer periods, realising the same average temperature over the day compared to a conventional temperature set-point regime. Numerous studies have been done to investigate the effect on the production of this so called temperature integration regime (Körner, 2003). Of course there is a constraint too on the minimal and maximal greenhouse temperature, so heating remains needed.

A third approach is in changing the energy supply in order to reduce the energy consumption (Bot *et al.*, 2005). This energy saving strategy is evaluated in this paper. Four energy supply systems which are commercially applied nowadays for heating a greenhouse are studied, being the conventional boiler heating system as reference, the combined heat and power generation (cogeneration), the electrical driven heat pump and the natural gas powered heat pump as combination of cogeneration and electrical driven heat pump. The systems are evaluated on fossil energy consumption, the linked carbon dioxide emission, and economic performance.

A similar study was done by (Garcia *et al.*, 1998) to determine the economic feasibility of solar collectors, heat pumps and cogeneration systems for seven European locations. They concluded that heat pump and cogeneration are economical feasible when electricity/ fuel-price ratios are between 2.1 and 3.0 or lower. The electricity/fuel- price ratio is based on electricity and fuel costs producing the same amount of energy.

2. Materials and Methods

2.1. *The applied model*

The energy consumption of a greenhouse depends on the greenhouse thermal properties, the crop determining the desired greenhouse climate conditions, and the ambient climate conditions. To evaluate the energy saving potentials of a particular option the analysis is performed on a year round base.

The heat and mass transfer processes determining the greenhouse climate and the energy consumption can be calculated using physical models (Bot, 1983; De Zwart, 1996). For the present study the extensively calibrated and validated dynamic physical simulation model KASPRO is used (De Zwart, 1996; Elings *et al.*, 2006; van Henten *et al.*, 2006). This model includes the effects of climate control on the heat and mass flows in a greenhouse at given weather data (Dieleman *et al.*, 2005; Henten *et al.*, 2006). Based on the chosen climatic set points, the model regulates the heating system, the CO_2 supply, *etc.* The state variables in the model like air temperature, heating pipe temperature, air vapour concentration, carbon dioxide concentration, *etc.* are recalculated every two minutes based on the heat and mass transfer processes. Crop production is evaluated with a linked sub-model for crop growth (Gijzen, 1992).

The energy supply systems are compared on a 4 ha Venlo greenhouse with average sized single glass cover (LEI, 2007). Following current greenhouse practice thermal screens were used in wintertime. The outside weather conditions are defined in a selective year (Breuer & Van de Braak, 1989) used as a national standard for energy calculations for Dutch greenhouses. This database contains sets of real hourly averaged values of outside weather data like temperature, relative humidity, global radiation, *etc*. The month of the year having an average value equal to the average value of the period between 1990 and 2000 is selected as a month delivering the data in the selective year. For example, the month of January of the year 1991 is selected as the first month of the selective year. In this way the selective year has the dynamics of normal weather. The hourly weather data are linearly interpolated for the two minute time step in the model calculations. The set points for the greenhouse conditions used in this study are common for Dutch growers (Swinkels *et al.*, 2000) and listed in Table 1.

For the cost evaluation the reference price of one cubic metre of natural gas is set to its current (March 2008) price of 0.25 €, for electricity a price of 0.09 €kWh^{-1} is paid. The electricity/fuel price ratio in this case is 3.2 based on equal energy content. Over the years the price of natural gas has increased more than the price of electricity. For this reason two lower electricity/fuel price ratios are used being 2.7 en 2.2. For the electricity delivered to the public grid, it is assumed 70 EURO per MWh is received. All data are presented for one square metre of greenhouse.

2.2. *The energy supply systems*

Four different energy supply systems as schematically depicted in Figure 1, are implemented in the dynamic simulation model to evaluate their effect on yearly energy consumption and their economic feasibility.

2.2.1. Heating boiler

The reference situation is the conventional method to heat Dutch greenhouses by burning natural gas in a boiler in combination with a condenser (Figure 1a). The overall systems efficiency is around 101% based on the combustion value of natural gas of 31.65 MJ per cubic meter excluding the latent heat of water vapour in the exhaust gasses. The flue gasses are commonly used in the greenhouse for carbon dioxide enrichment so therefore this function of the heating system is an essential part of the present evaluation. In normal practice the excess heat produced during daytime for carbon dioxide enrichment is stored in a short term (day/night) heat storage (hot water) tank to heat the greenhouse during the night. This system allows the natural gas to be used more efficiently. Another aspect of short term heat storage is that it allows the capacity of the boiler to be smaller than needed when the boiler has to meet the peak heat losses. During peak heat demand both the boiler and the storage can provide heat. So the short term heat storage reduces investment costs on the boiler being dependent on the maximum capacity of the boiler.

2.2.2. Combined heat and power generation

Combined heat and power generation (cogeneration), consisting of a gas fired combustion motor and a generator, has recently become common practise in Dutch greenhouse horticulture. In this case the natural gas is used to produce both heat (motor reject heat) and electricity (Figure 1b). The heat and carbon dioxide (after cleaning of the exhaust gases) are directly used in the greenhouse and the electricity is either delivered to the public grid or used on site for artificially lighting the greenhouse crop. The cogeneration installation is operating during daytime for carbon dioxide enrichment. Moreover, electricity is valuated higher during daytime, making daytime operation more profitable. By the end of 2007 the total electricity production capacity of cogeneration installations at greenhouse growers in the Netherlands was 2500 MW so comparable to two large electricity plants. The total greenhouse area involved is about 40% of the total greenhouse area. Growth till 3000 MW is expected for the coming years. A disadvantage of cogeneration is that the CO_2 produced is not as pure as produced with a heating boiler so greenhouse ventilation is obliged when cogeneration CO_2 is used. A modern cogeneration installation with a condenser has a thermal efficiency of 48% and an electrical efficiency of 42% (Deutz, 2007), therefore these numbers are used for our calculations. Cogeneration is usually installed in combination with a conventional heating boiler for back-up and peak heat demand. The capacity of cogeneration installed is designed for covering the basic heat load and not to compensate for the peak heat losses during very cold periods since the investment costs of a cogeneration installation is higher than of a conventional boiler as can be seen in Table 2.

2.2.3. Electrical driven heat pump

The heat pump as a heating system is well established for commercial buildings in various countries as an energy saving heat supply system. The principle is depicted in Figure 1c. Heat is subtracted at the evaporator side of the heat pump from a long term heat storage at a temperature level too low for heating and released at the condenser side at a higher temperature level suited to heat the greenhouse.

A practical option for long term heat storage with large capacity is in the static groundwater at a depth between about 20 and 100 m (Bot, Braak et al., 2005). This so called aquifer consists of two wells, one to store the warm water delivered in summer at a temperature of around 18°C and one to store the cold water generated by the heat pump in the winter period at a temperature of 7°C. In the Netherlands aquifers can be used due to the flat geology of the subsoil layers. Without these aquifers an option is to use the subsoil as passive heat storing medium via vertical soil heat exchangers (Bot *et al.*, 2008)

The heat pump is driven by an electromotor. The heat released at the condenser divided by the energy consumed by the electromotor (both per unit of time) is called the coefficient of performance (COP). Since this coefficient is higher than the heat-electricity ratio during electricity generation (in our case 1/0.42 = 2.4) the heat pump is an energy saving device.

The *COP* of a practical heat pump, COP_{pr}, is limited by a theoretical maximum, COP_{th}, which is given by the thermodynamics of a so called Carnot cycle. This is determined by the temperature levels at the evaporator $T_{evaporator}$ and the condenser $T_{condenser}$ (both in K). For a practical installation it is lower by a factor η, the efficiency of the installation *(in %)*. So from basic thermodynamics it can be deducted that:

$$COP_{pr} = \frac{\eta}{100} COP_{th} = \frac{\eta}{100} \left(\frac{T_{condenser}}{T_{condenser} - T_{evaporator}} \right) \qquad (1)$$

The installation efficiency η depends on the installation itself. For the model calculations η is set to 50%, being a realistic figure for a commercial heat pump for heating with thermal capacity higher than 1 MW (carrier, 2004), a realistic capacity for greenhouse application. Naturally COP_{pr} should be as high as possible so the condenser temperature at the heating side should be as close as possible to the evaporator temperature. However the evaporator produces the cold water in the seasonal storage so evaporator temperature is even lower than the cold water temperature of the seasonal storage. At the other hand the condenser temperature should be at a level high enough to heat the greenhouse. To limit condenser temperature the heat transfer of the heating system to the greenhouse air must be high. It is dependent on both the surface area of the heating pipes as well as the heat transfer coefficient. Floor heating at small temperature difference to the air is normal for domestic houses with relatively low heat demand. Since the heat demand of greenhouses is larger the floor temperature will be relatively warm. Moreover due to the large heat capacity of the greenhouse floor, the response to air temperature changes is very slow, so greenhouse air temperature is hard to control by floor heating. The options for greenhouses are to enlarge the surface area of the heating system or to apply forced heat transfer.

Another important consideration is the operation of the seasonal storage. The capacity of the aquifer depends on the temperature difference between the cold and the warm well and the amount of water circulating. The temperature of the water in the warm well depends on the temperature of the water which has passed the greenhouse during warm periods of the year, being about 18°C. The temperature of the cold well is created by the temperature of the water passing the evaporator of the heat pump in winter, being about 7°C. Lowering this temperature will decrease the COP of the heat pump and thereby will increase the electricity consumption but will lower the capacity of the aquifer in terms of the amount of water circulated. This capacity determines the investment costs of the aquifer (Table 2).

Also for this system as with the cogeneration, the capacity of the heat pump installed is designed for the basic load and not to compensate for the heat losses during very cold periods since the also investment costs of a heat pump is higher than of a conventional boiler as can be seen in Table 2.

2.2.4. Gas driven heat pump

The gas motor driven heat pump can be considered as a combination of a cogeneration installation and an electrical driven heat pump. The cogeneration installation produces the electrical power for the heat pump. The heat and carbon dioxide produced by the cogeneration are supplied to the greenhouse. The heat produced by the cogeneration installation during the day has to be stored to be used in the night for heating. The surplus electricity is supplied to the public grid and can be extracted during the heat demand periods to power the heat pump.

3. Results and discussion

3.1.1. Reference situation: boiler system

In practice the heating boiler includes a condenser to exploit the latent heat in the exhaust gases and day-night heat storage to cover the shift between CO_2 demand and heat demand. The larger the day-night heat storage the more CO_2 can be supplied. To determine the optimal day-night heat storage capacity, in Figure 2 carbon dioxide supply is given as function of day-night heat storage capacity as calculated by the model. From the figure it can be concluded that increasing the storage capacity from 0 to 100 $m^3\ ha^{-1}$ has a large effect on the CO_2 supply (125% increase) and therefore on the dry matter production (calculated at 17% increase). Increasing the capacity from 100 to 200 $m^3\ ha^{-1}$ increases the supply with 6% and the production by 1%. For this reason the short term heat storage installed is about 100 m^3/ha. This is in line with practice (De Zwart *et al.*, 1999). Due to heat losses, the natural gas consumption increases by 1.6% at this capacity compared to the non day-night storage situation. It is calculated that 44% of the total carbon dioxide production is supplied to the greenhouse, the other part is produced during cold periods of the year when irradiation is low and therefore the need for carbon dioxide enrichment is minimal.

An extra advantage of day-night heat storage is in limiting the demanded boiler capacity. The maximum heating power needed during the year within a specific time frame is depicted in Figure 3. As can be read from the figure the yearly maximum heating power needed for a one hour period equals 126 Wm^{-2}. Over a period of 12 hours the maximum heating power needed is about 90 Wm^{-2}. So if the maximum boiler capacity covers 90 Wm^{-2} the short term buffer has to compensate for the hours of the year the heat losses per unit time are higher than 90 Wm^{-2}. This power can be supplied by the short term heat storage if:

$$P_{short\ term\ heat\ storage} = \frac{\Delta T \rho C_p V}{At} \qquad (2)$$

Where ΔT is the temperature difference between the outlet and inlet water in K; ρC_p is the volumetric specific heat of water in J m^{-3} K^{-1}; V is the volume of the heat storage in m^3; A is the area of greenhouse in m^2 and t is the time the heat is supplied in s;. This simple equation is valid for the heat storage while spatial temperature distribution is stratified, so ΔT remains constant during the emptying process. A short term buffer of 100 m^3 ha^{-1} can supply 115 Wm^{-2} of heating power for a hectare with a low temperature difference of 10 K for one hour. So this is by far sufficient to supply 35 Wm^{-2} needed extra during peak heat losses.
The energy consumption of the options will be discussed in section 3.2

3.1.2. Combined heat and power generation

The overall costs of cogeneration compared to that of a conventional boiler in terms of invest, maintenance, interest, gas consumption, and the payment for the electricity delivered to the public grid as a function of the electrical cogeneration capacity installed for different electricity selling prices is depicted in Figure 4 resulting from model calculations. The additional heating capacity for peak load is produced by a conventional boiler. For the reference situation with electricity selling price at 70 EURO/MWh, the optimum cogeneration capacity is around 50 Wm^{-2}. The heating boiler then only consumes 5.7 $m^3m^{-2}yr^{-1}$ of natural gas to cover peak demand. Installing this relatively large capacity of cogeneration is economical attractive due to the low costs of natural gas and the high price growers get for delivering electricity to the public grid. The electricity price is higher during daytime (peak load) compared to the base load price used for the present calculations resulting in a slightly larger capacity of cogeneration being profitable as can be seen from Figure 4. However this peak electricity price varies so can not be taken as a base for our calculations. The additional energy consumption due to the obligated extra ventilation due to lower quality exhaust gasses is calculated to be increased by only 0.4%.

3.1.3. Electrical driven heat pump

For realising a high COP, the heat transfer to the greenhouse air must be high. The conventional heating system surface per square meter of greenhouse is around 0.2 m^2. In Figure 5 the calculated yearly electricity consumption of the heat pump is given with increasing heat exchange surface. For the calculations a heat exchange surface twice the conventional surface is used since this is economical and technically feasible. This reduces energy consumption by 18%. The heat transfer can also be increased using forced ventilation, which has some additional advantages over conventional heating since it creates more air movement in the greenhouse. Growers like an ‘active’ climate by which they mean the air circulates through the crop so the microclimate is more homogenous. Another asset of forced ventilation is that the system can also be used in the summer period to extract heat from the greenhouse to regenerate the aquifer. The consumption of electricity for the needed fans is obviously negative in terms of energy costs.
The relative overall costs in terms of investment and operation as function of the maximum electrical power consumption by the heat pump for different electricity/fuel price ratios is depicted in Figure 6. Again the costs are made relative to the reference situation with boiler heating. From the figure it can be concluded that at the current electricity/fuel price ratio of 3.2 the overall costs of a system with a heat pump having a maximum power of 5 Wm^{-2} is similar to the reference system. If this ratio will decrease, a higher heat pump capacity can be installed and the overall costs will decrease compared to the reference system.
On a yearly base it is calculated that 517 MJm^{-2} of heat is extracted from the aquifer for heating with a heat pump with electrical capacity of 5Wm^{-2}. The annual excess heat for Dutch greenhouses is around 2400 MJ. Approximately 2500 hours per year ventilation is needed for heat removal when carbon dioxide enrichment is applied. Regeneration of the aquifer during this period of the year results in an average cooling capacity of 60 Wm^{-2}. The average concentration of carbon dioxide for the period CO2 is supplied to the greenhouse is 642 ppm without cooling and 814 ppm with cooling

and yearly CO2 supply decreases from 31.8 kg to 22.2 kg with a maximum dosing capacity of 100 kg ha^{-1} h^{-1}. Model calculations show increase of dry mass by more than 6%. The capability to extract heat from the greenhouse during warm periods limiting ventilation therefore is an asset of the heat pump as a heating system.

3.1.4. Gas driven heat pump

It was calculated that the heat pump supplies 1074 MJm^{-2} of heat and cogeneration supplies 278 $MJm^{-}2$. The carbon dioxide from the installation supplied to the greenhouse is 7.5 $kgm^{-2}year^{-1}$. So additionally pure CO_2 has to be supplied to obtain comparable production levels. The heat extracted from the aquifer is 825 MJm^{-2}. The cooling capacity during warm periods when carbon dioxide enrichment is applied is 90 Wm^{-2}, which decreases the carbon dioxide enrichment from 28.7 to 18.9 kgm^{-2} and the CO_2 concentration is increased from 687 ppm to 834 ppm. The dry matter production is increased by 9%.

3.2. *Energy consumption*

A first estimation of the energy consumption can be made from the static situation, as depicted in Figure 1. The heat demand of the reference greenhouse can be set at 100 units and from the CHP electric efficiency of 42%, thermal efficiency of 48% and an average heat pump COP of 4 the energy inputs as depicted in Figure 7 can be easily calculated. The CHP substitutes for 208 gas energy units at the power plant, with separate generation of heat and electricity the total gas consumption would be 308 gas units so the energy saving of cogeneration is estimated at 32.5%. The energy saving potentials of the HP options are estimated at 40 and 54% for electric and cogeneration driven HP respectively, so high. However the various options are applied for covering the basic load in combination with a boiler for peak load so the simple calculation estimates a maximal potential saving.

The more accurate way of calculation of the performance year round for the optimal combination with a peak load covering boiler is by the Kaspro dynamic model following the dynamics of the greenhouse dependent on the outside weather and the climate settings. The calculated yearly energy consumption of the system options by the dynamic model is summarized in Table 3 together with the results of the simple static calculations. Again the gas consumption is linked to the fossil energy consumption by the combustion value of 31.65 MJ per cubic meter of natural gas. For the option cogeneration the fossil fuel consumption needed to produce the electricity consumed in the greenhouse is based on the power plant efficiency including transport losses of 42%. This is equal to the efficiency of the modern cogeneration systems nowadays installed at the grower’s site. As mentioned before, for the option cogeneration electricity is delivered to the public net which otherwise had to be generated by a power plant. The cogeneration installation consumes almost twice the gas compared to the conventional boiler system but it substitutes the energy consumption of the power plant producing the same amount of electricity. Therefore the fossil fuel consumption for heating only is about 14% of the fossil energy of the conventional system being the gas consumption of the boiler for peak demand. The heat generated by power plants is not exploited in most cases which is an asset for producing the electricity at a greenhouse since the CO_2 in the flue gas can also be supplied to the greenhouse. The heating system partly powered by an electric driven heat pump consumes 33% less fossil energy than the conventional boiler system. The cogeneration heat pump combination consumes almost 60% less than the conventional system while here the reject heat is used. Due to the low gas consumption pure carbon dioxide has to be supplied in both HP cases to satisfy the CO_2 demand.

The simple static calculations already produce pretty accurate figures for the relative energy consumption (table 3) due to the fact the basic load is covered. The cogeneration in combination with a heat pump performs better than estimated by the simple calculation due to the higher coefficient of performance calculated by the model due to the more favourable evaporator and condenser temperature levels during operation.

3.3. *Economical evaluation*

In the economical evaluation the energy prices are based on the market prices in March 2008. Investment and maintenance costs are given in Table 2. In Table 4 the overall yearly costs of the systems are summarized. Based on the current energy prices using cogeneration for heating is the most economical heating system and for this reason is widely used. Growers can even increase the benefits of the cogeneration by anticipating on the energy prices on the market. A heat pump as a heating system increases the operational costs by approximately 20% compared to the conventional heating system. Still this system is interesting for crops like orchids where CO_2 enrichment is less needed and for a period during the production a low air temperature is needed so cooling is applied. Using cogeneration in combination with a heat pump the operating costs are 10% higher than with a boiler. The heat pump is economically unattractive compared to the conventional boiler due to the high price of electricity compared to natural gas make together with the need to supply additional carbon dioxide. A heat pump will only become an alternative for the conventional boiler and CHP if the ratio between the electricity price and natural gas cost based on equal energy content decreases or if the price of carbon dioxide is reduced.

4. Conclusions

The four different heating systems being the conventional boiler, the cogeneration, the heat pump and the combination of the cogeneration and the heat pump are analyzed in terms of operation, fossil fuel consumption, and economically. The individual components of each system are economically optimised. The fossil fuel consumption by cogeneration is about twice that of the conventional system, but the electricity produced is delivered to the public grid which substitutes the gas consumption by a power plant. The reject heat and carbon dioxide produced by a power plant are not used in most cases, so producing electricity at the grower's site using natural gas is environmentally and economically attractive. The cogeneration is economically more attractive for growers than the conventional boiler given the current prices of electricity and the high CO_2 production. The fossil fuel consumption by the greenhouse which is directly related to the CO_2 emission can be reduced by 33% using a heat pump to cover part of the heating demand and even by more than 50% by using a heat pump in combination with cogeneration. But from an economical point of view the application of a heat pump option is not the optimal solution.

The present study is based on greenhouse conditions for tomato production, for other crops the results and conclusions will be different since the greenhouse climate conditions differ. For example, Orchid cultivation needs a warm and a cold climate period and carbon dioxide enrichment is limited. Then the heat pump could be the optimal heating system.

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Figure captions

Figure 1. Schematic representation of the energy supply systems: (a): the conventional system consisting of a boiler in combination with a condenser; (b) the combined heat and power installation cogeneration; (c) the electric driven heat pump; (d) the gas powered heat pump

Figure 2. The carbon dioxide supply and dry matter production as a function of the short term heat storage capacity

Figure 3. Maximum heating power demand per m2 greenhouse within a specific time frame

Figure 4. The relative overall costs of cogeneration compared to a conventional boiler as function of the electrical cogeneration power capacity installed for different selling prices of electricity

Figure 5. The yearly energy consumption by the heat pump as a function of the heating surface area both per m2 greenhouse area

Figure 6. The relative overall costs to a conventional boiler as a function of the electrical power of the heat pump for different electricity/fuel-price ratios

Figure 7. Simple static calculation of the energy consumption by the energy supply systems at greenhouse heat loss of 100 units, assuming boiler efficiency of 100%, CHP electric and thermal efficiency of 42 and 48% respectively and heat pump COP of 4.

Figure 1

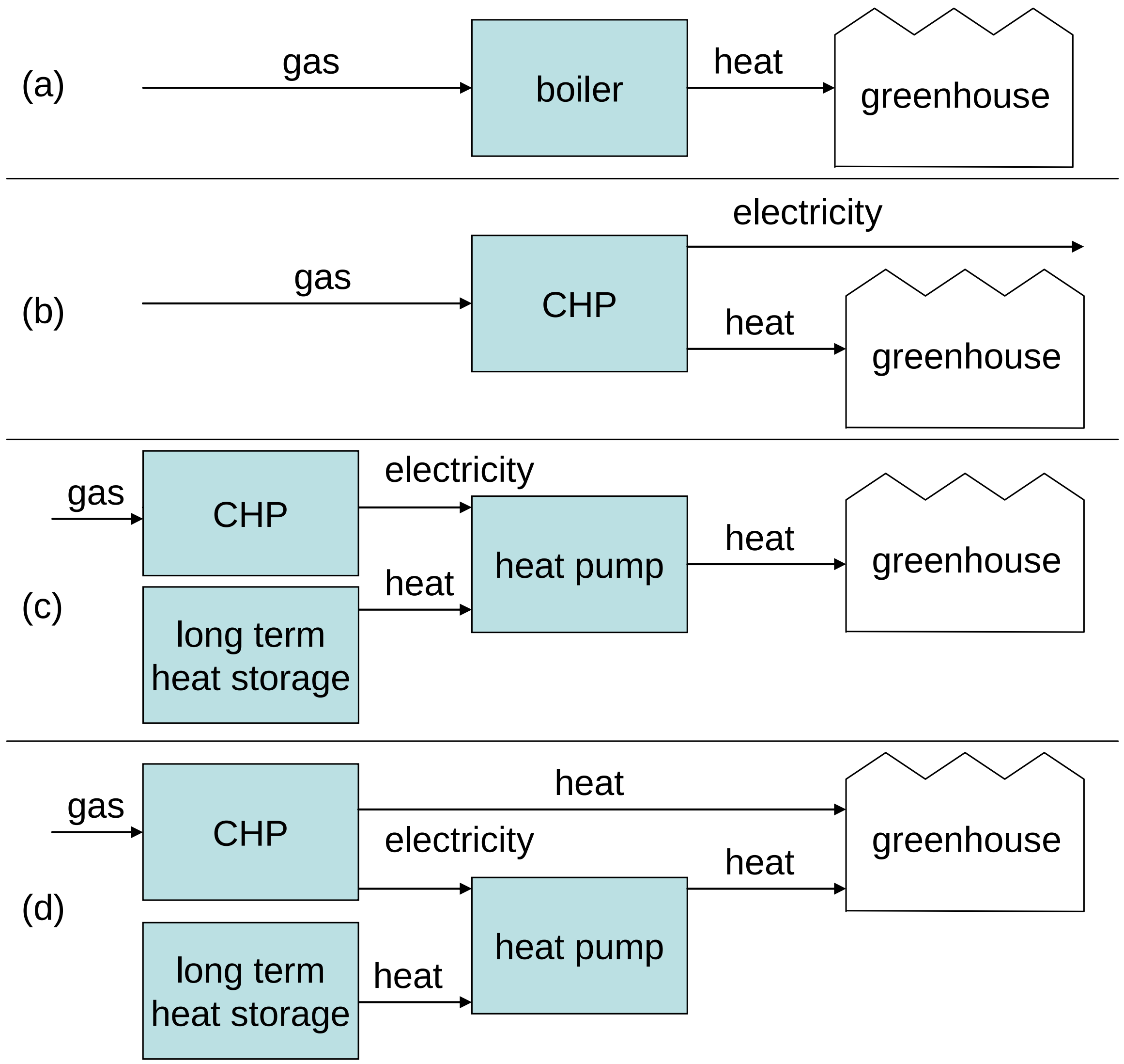

Fig. 1. Schematic representation of the energy supply systems: (a): the conventional system consisting of a boiler in combination with a condenser; (b) the combined heat and power installation cogeneration; (c) the electric driven heat pump; (d) the gas powered heat pump

Figure 2

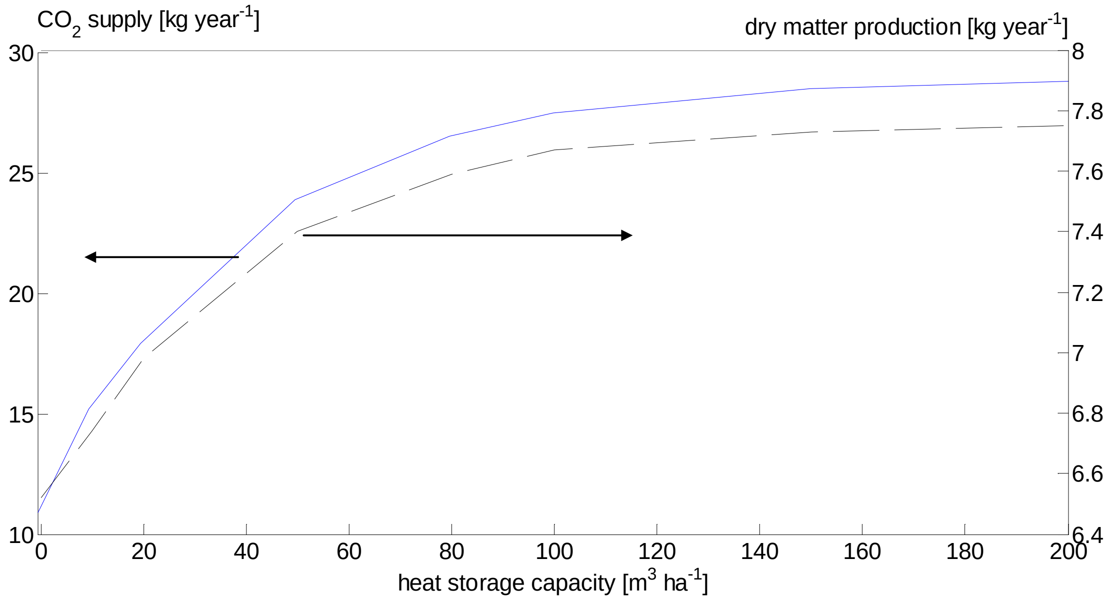

Fig. 2. The carbon dioxide supply and dry matter production as a function of the short term heat storage capacity

Figure 3

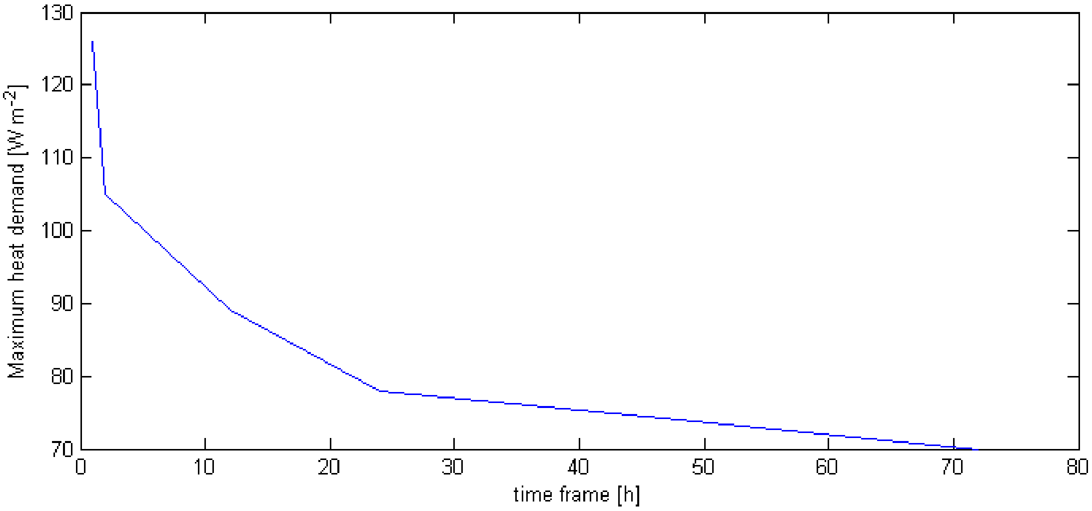

Fig. 3. Maximum heating power demand per m² greenhouse within a specific time frame

Figure 4

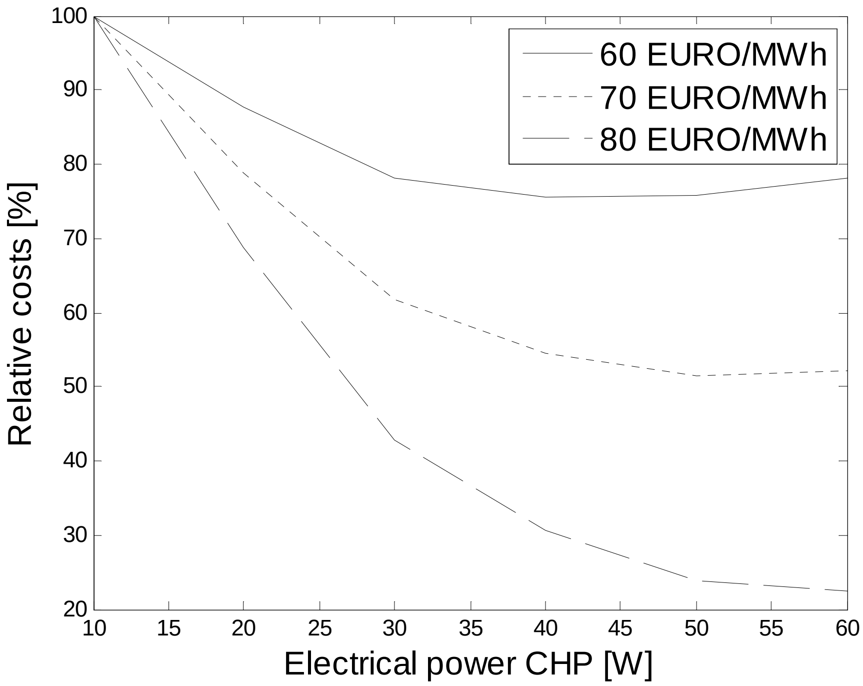

Fig. 4. The relative overall costs of cogeneration compared to a conventional boiler as function of the electrical cogeneration power capacity installed for different selling prices of electricity

Figure 5

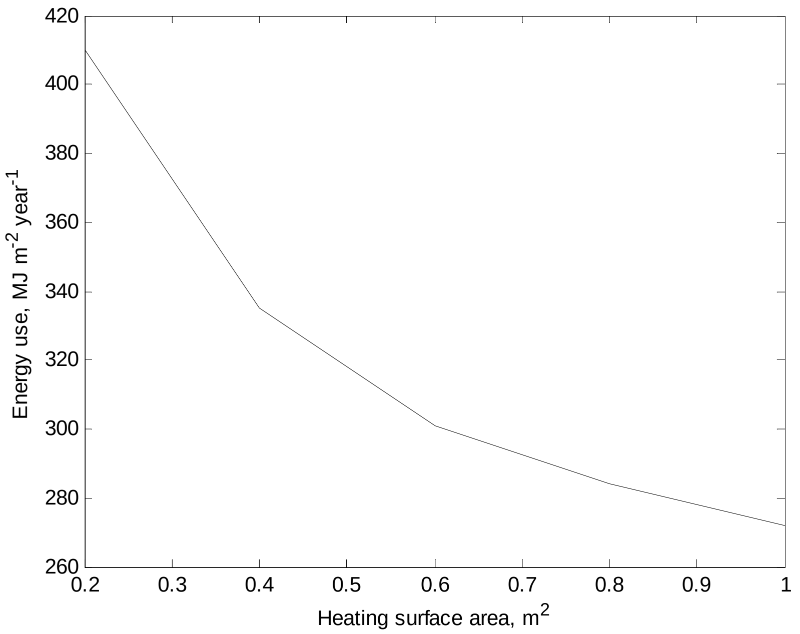

Fig. 5. The yearly energy consumption by the heat pump as a function of the heating surface area both per m² greenhouse area

Figure 6

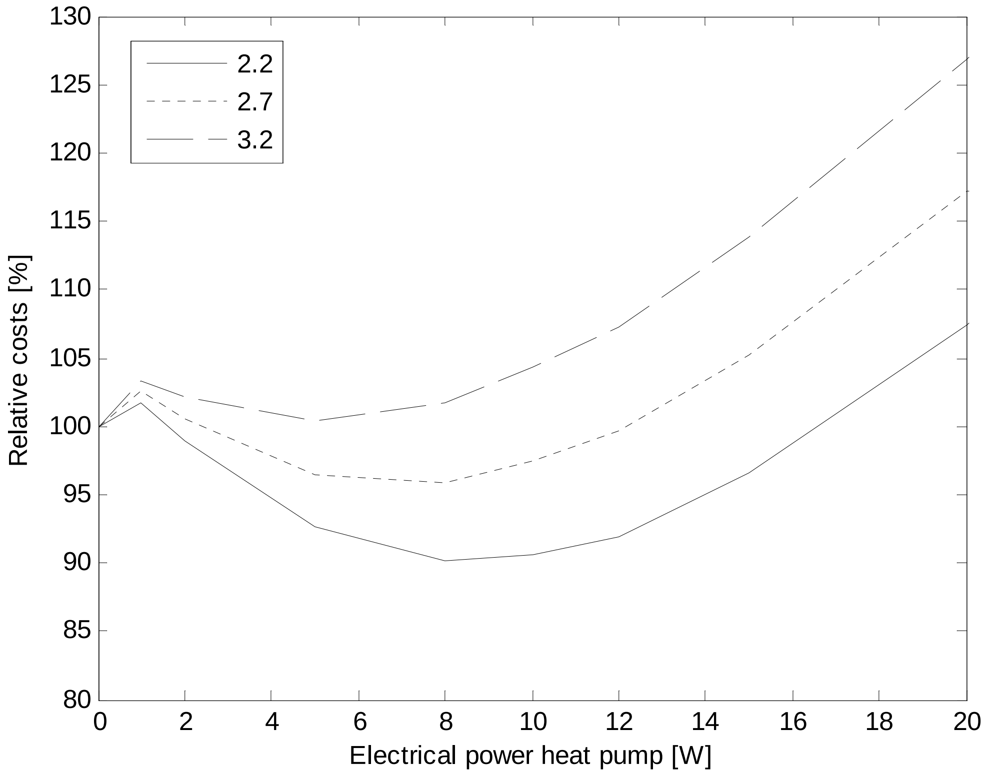

Fig. 6. The relative overall costs to a conventional boiler as a function of the electrical power of the heat pump for different electricity/fuel-price ratios

Figure 7

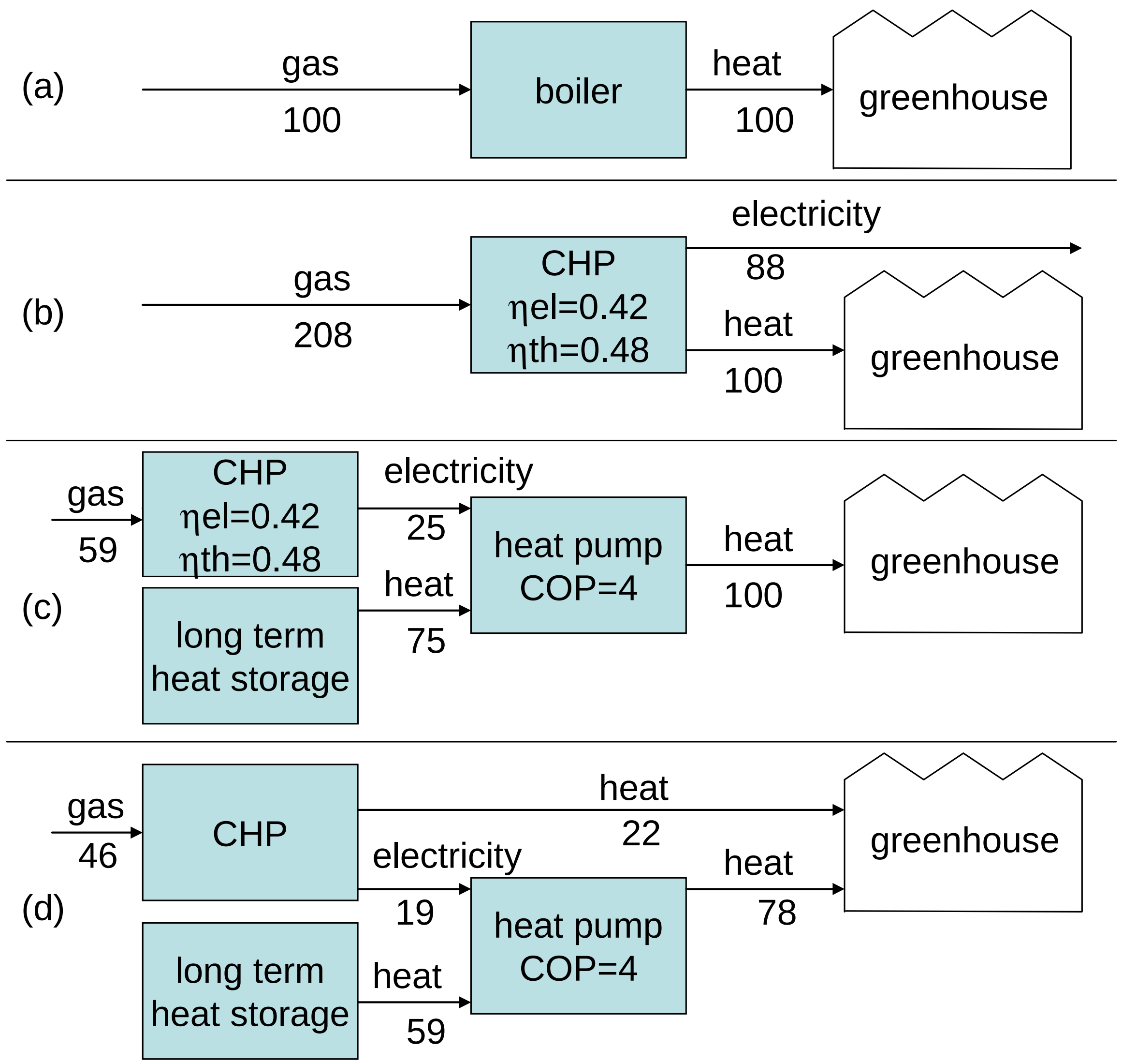

Fig. 7. Simple static calculation of the energy consumption by the energy supply systems at greenhouse heat loss of 100 units, assuming boiler efficiency of 100%, CHP electric and thermal efficiency of 42 and 48% respectively and heat pump COP of 4.

Table 1.

Installation in the greenhouse and setpoints

Setpoint	*Value*
Planting date	8 December
Removal date	25 November
Temperature below which heating is applied	
From 8 December night/day	18°C/20°C
From 15 January night/day	16°/19°C
Temperature above which ventilation is applied	
From 8 December night/day	20°C/22°C
From 15 January night/day	17°C/20°C
Relative humidity above which ventilation is applied	85%

Table 2.
Investment and maintenance costs (Woerden, 2005, Zwart, 2004)

Equipment	*Investment*	*Depreciation* *[%yr^{-1}]*	*Maintenance* *[%yr^{-1}]*
Boiler (5MW)	18 € kW^{-1}	7	1
Cogeneration (4MWe)	335 € kWe^{-1}	10	5
Heat pump (1MWth)	166 € kWth^{-1}	10	5
Aquifer (200 m^3 h^{-1})	2000 € m^{-3}h^{-1}	4	2
Short term heat storage (400 m^3)	200 € m^{-3}	7	2

Table 3

Table 3.
The yearly consumption of natural gas, electricity and pure CO2 and the dry matter production

Option	*Gas consumption $m^3 m^{-2} yr^{-1}$*	*Electricity consumption kWh $m^{-2} yr^{-1}$*	*Fossil energy consumption MJ $m^{-2} yr^{-1}$*	*Fossil energy consumption (%)*	*static fossil energy consumption (fig 6) (%)*	*Pure CO_2 kg $m^{-2} yr^{-1}$*	*Dry matter kg $m^{-2} yr^{-1}$*
Boiler	39.4	0	1247	100	100	0	7.5
CHP	76.2	-260	179	14	67.5	0	7.9
HP	19.8	24.4	835	67	60	22.2	8.2
CHP & HP	16.2	0	512	41	46	18.9	8.2

Table 4.

The operational costs of the systems

	Operational costs (€ $m^{-2} yr^{-1}$)				*Total*
Option	*Invest. and maintenance*	*Gas*	*Electricity*	*Pure CO_2*	
boiler & heat storage	0.49	9.85	-	-	10.34
cogeneration & heat Storage	5.77	19.05	-18.2	-	6.62
HP & aquifer	2.00	5.75	2.52	2.22	12.49
cogeneration & *HP* & aquifer	5.44	4.05	-	1.89	11.38