A SIMULATION MODEL TO ESTIMATE PROSPECTIVES OF ENERGY SAVING MEASURES IN HORTICULTURE

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Abstract

To increase sustainability and public appreciation of protected cultivation, the energy consumption of greenhouse production in the Netherlands should be decreased. To achieve this there are many options such as the improvement of greenhouse insulation, the implementation of improved climate control strategies and the application of reject heat. To estimate the potential of such measures in a horticultural context, a greenhouse simulation model was developed that includes the dynamic description of all components of the heating system (de Zwart, 1996). In this paper the model is outlined briefly. Some results concerning double glazing and combined heat and power are presented. The conclusions draw special attention to the relation between energy saving potentials and horticultural practice.

1. Introduction

Horticulture is responsible for about 5% of the national energy consumption in the Netherlands. Therefore, as for other major energy consuming sectors in economy, governmental policy aims on a decrement of energy consumption in horticulture. To contribute to this aim, horticulture has put a commitment to strive to have doubled the energy conversion efficiency from primary energy to a marketable product by the end of the millennium, compared to 1980. Anno 1993, this efficiency has increased by about 1.54 (Van der Velden et. al., 1995), but still there is a large effort to be made.

To reach the energy saving objective a lot of propositions are being made. However, the prospective of these measures are difficult to judge because they are largely dependent on the horticultural context in which they are applied. At the same time, to be able to make good decisions on investments, these figures are very important for horticultural practice. Therefore a computer model has been developed that facilitates the estimation of energy saving prospective of a large number of energy saving measures (improved insulation of the greenhouse, different climate control strategies, the application of energy saving heating devices).

In this paper, the effect of the application of a double glass cover and a combined heat and power engine are demonstrated. The customary way of growing tomatoes in the Netherlands serves as a horticultural context. To show the impact of horticultural variables, some alterations to air temperature and humidity setpoints are made. The model is outlined only briefly, mentioning references to more detailed descriptions.

2. Brief description of the simulation model

The greenhouse climate controller can be considered as the actuator that eventually determines the energy consumption of a greenhouse. Therefore, the simulation model has been developed starting at the climate controller. The controller compares the greenhouse air temperature, humidity and CO_2 concentration with setpoints for these quantities. The setpoints are time and outside weather dependent. Based on these comparisons the controller increases the temperature of the heating pipes, opens the windows or starts to supply CO_2 to the greenhouse. These actions have direct or indirect implications on energy consumption. This is obvious for the increment of the heating pipe temperature, although the primary energy to serve this heat demand can be combusted hours earlier and temporarily stored in a heat storage tank. Opening windows has an energy consuming effect when this controller action originates from the violation of a humidity threshold. CO_2 supply induces primary energy consumption when the CO_2 is obtained from exhaust gases from the boiler.

The controller actions have an impact on the greenhouse air conditions. Thus the controller and greenhouse air temperature, humidity and CO_2 concentration form a closed-loop control process. However, these primary state variables do not depend on the controller actions only, but they are also a result of interactions with the environment of the physical objects they represent. As a direct environment of the primary state variables the model distinguishes the canopy, the floor and soil and the greenhouse cover. The surfaces of these entities exchange heat with the greenhouse air. The soil beneath the floor represents a large heat storage capacity with a strong damping effect on greenhouse air temperature fluctuations. The cover is an important barrier for heat loss to the outside air, especially when it is made from double glass. Moreover, when the cover temperature is beneath the dewpoint of the greenhouse air, the cover surface adds to dehumidification of the greenhouse. The canopy surface is important with respect to heat release (gained from the sun), but even more with respect to the greenhouse humidity.

In addition to the actions of the controller, the greenhouse air conditions are severely affected by the outside weather. These boundary conditions are shown in Figure 1, together with all previously mentioned state variables. The large number of soil temperatures enables the description of a temperature gradient in the soil. The air and sky temperature affect the convective and radiative heat losses from the cover and, with that, its temperature. Outside temperature, humidity and CO_2 concentration have also a direct effect on the greenhouse air by exchange through opened windows and cracks. The wind speed is another important weather condition because it affects the convective heat exchange at the cover and largely determines the air exchange rate through windows. The fifth weather condition factor is the intensity of solar radiation. Besides being a heat source, the sun is essential for photosynthesis (computed by the model as well). The solar radiation is split into a direct and a diffuse fraction.

The heat and mass fluxes connecting the state variables are derived from the work of a number of authors. The radiative heat exchange processes, except the interception of solar radiation by the canopy, is described by general heat exchange theory (e.g. Pitts and Sissom, 1986). Interception of sunlight by the canopy was treated according to the work of Goudriaan (1977). The transmission of light through the cover was computed with a calculus presented by de Zwart (1993). The convective heat exchange at the inner and outer side of the cover was described by the relations presented by Bot (1983). The ventilation flux, based on natural ventilation, is computed with the theory presented by De Jong (1991). The canopy evaporation is modeled using the work of Stanghellini (1987). The convective heat release from heating pipes can be found in, again, the work of Bot, just like information on the convective heat exchange at the floor. The conduction of heat in the soil was treated with general heat conduction theory.

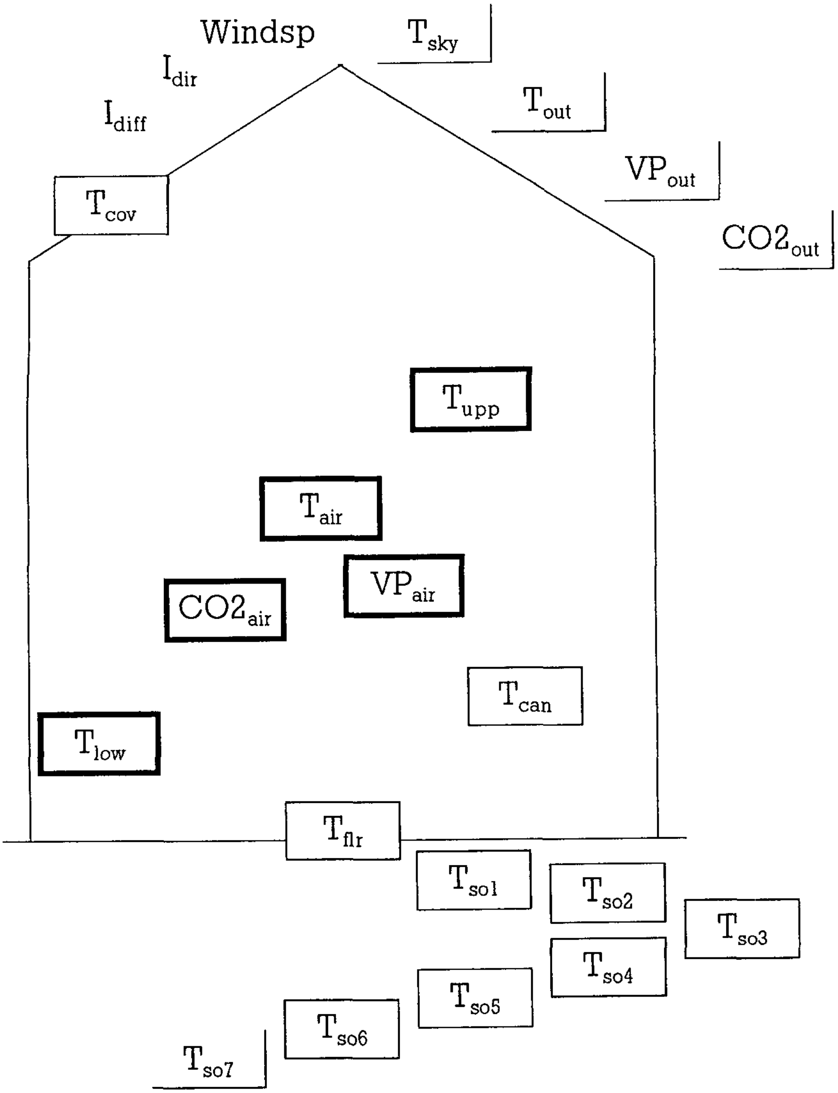

Figure 1 - State variables and boundary conditions in the simulation model

Due to the complexity and non-linearity of the model, the integration of the differential equations is performed by numeric forward integration. The step size is chosen such that the temperature change of the state variables is less than 0.1 °C. This means that the integration step size is often not more than 15 seconds. However, when outside weather conditions and climate controller actions are steady, the integration step size increases towards 2 minutes, which is the climate controller sample interval.

Comparison of the results of the model with measurements in a semi-practical greenhouse showed a very good resemblance. Differences between model computations and measurements of the air temperature for 10-minute mean values were less than ± 0.5 °C for 90% of the time. Heat consumption was simulated with an accuracy of 95% and the control actions with respect to window aperture and CO_2-supply showed good similarity.

3. Horticultural context

The performance of energy saving techniques depends strongly on the context of application. In this paper, the context is created by the definition of a one hectare Venlo-type greenhouse growing tomatoes in the Netherlands.

The greenhouse is exposed to weather typical for the Netherlands. Such a set of weather data can be found in the SEL-year (Breuer and Van de Braak, 1989). The monthly mean temperature in the SEL-year and the mean daily radiation per month are shown in Figure 2.

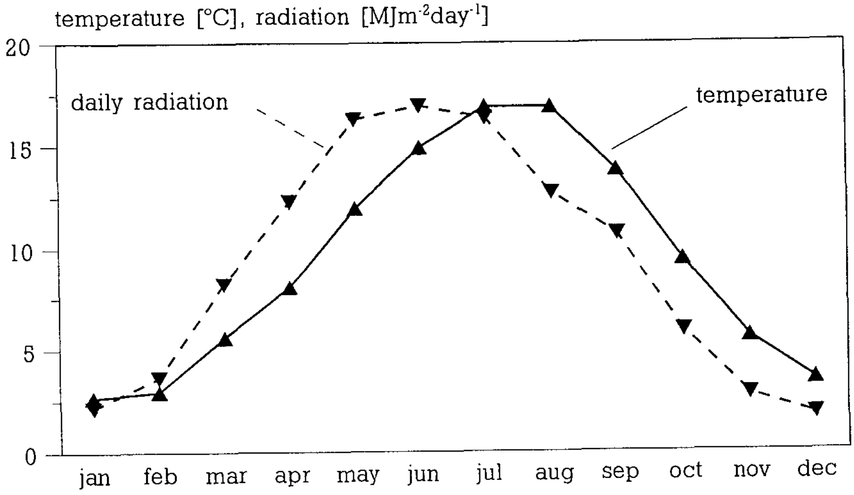

Figure 2 - Typical monthly mean temperature and mean daily solar radiation values in the Netherlands.

The growth season in the reference greenhouse starts in December when the young tomato plants are planted. During the first three weeks the daytime and nighttime temperature setpoints are 18 °C. During daytime, carbon dioxide is supplied by exhaust gases from the combustion of natural gas at a rate of 40 m^3 gas per hectare per hour, unless a maximum value of 700 ppm is reached. During periods that this way of CO_2 supply induces heat surpluses, the heat excess is stored in a heat storage tank of 80 m^3. The water in the tank can be exchanged with the water in the heating circuit. When the storage tank is completely charged the CO_2 supply is stopped.

The humidity setpoint is 85% RH. If the actual humidity in the greenhouse exceeds the setpoint the windows are opened proportional to the excess (2% window opening per percent excess of the RH). The windows are also opened when the air temperature exceeds the setpoint by 0.5 °C (15% per °C). After the first period of three weeks the daytime temperature setpoint is increased to 19 °C and the nighttime temperature setpoint is lowered to 17 °C. All other settings are left unaltered.

On the first of April the daytime and nighttime minimum pipe temperature are set at 45 °C and 40 °C respectively. The minimum pipe temperature acts as a threshold on the temperature of the lower heating pipe. During daytime, the minimum pipe temperature is lowered linearly towards the air temperature setpoint for outside global radiation in the range between 100 and 300 Wm^{-2}.

The growth season ends on 11 November. On that day the air temperature and all minimum pipe temperature setpoints are lowered to 5 °C. Humidity control and carbon dioxide supply are abandoned.

The Venlo-type greenhouse is built from a repeated sequence of 30 roof segments, each being 3.20 m wide. The gutter length of the greenhouse is 104 meter. The floor to gutter height is assumed to be 3.5 m. One window per eight glass panels is mounted in each side of the greenhouse cover. The windows are 2 m wide and half the ridge-gutter distance long. The roof slope is 25°.

When the windows are closed, the leakage of the greenhouse is assumed to be $1.25 \cdot 10^{-4}$ m^3 per m^2 floor area per unit wind speed (ms^{-1}). This figure is a mean of the leakage's determined by De Jong (1991) in four commercial greenhouses.

4. Energy saving with a double glass cover

It is known that the application of double glass decreases the heat losses of a building enormously. However, the energy saving of double glass in horticulture will be less than the energy saving of this material in ordinary buildings for three reasons. The first is the fact that an important part of the heat demand of a greenhouse (about 10%) is related to latent heat consumption of the canopy. In the second place, part of the heat consumption of customary greenhouses is associated with maintaining a minimum pipe temperature (±8%). This implies a heat demand, even when the greenhouse air temperature violates the setpoint. In the third place, part of the energy consumption (11%) is related to humidity control, which means that windows are opened to carry off moisture.

Table 1 - Energy consumption and energy saving of a greenhouse with a double glass cover compared to a greenhouse with a single glass as a function of three temperature and humidity setpoints.

		energy consumption GJ m^{-2}year			
temperature setpoint	humidity setpoint	single glazed greenhouse	double glazed greenhouse	gross saving	net saving
reference	95% RH	1.90	1.15 (-0.75)	40%	28%
reference	85% RH	1.91	1.28 (-0.73)	38%	26%
reference	75% RH	2.04	1.38 (-0.66)	33%	20%
reference +1 EC	95% RH	2.09	1.23 (-0.86)	41%	30%
reference +1 EC	85% RH	2.10	1.27 (-0.83)	40%	28%
reference +1 EC	75% RH	2.26	1.51 (-0.75)	33%	20%
reference !1 EC	95% RH	1.73	1.07 (-0.66)	38%	26%
reference !1 EC	85% RH	1.74	1.10 (-0.64)	37%	25%
reference !1 EC	75% RH	1.85	1.27 (-0.58)	32%	18%

*primary energy assuming a boiler conversion efficiency of 0.85

The simulation model, accounting for these effects, computes the energy consumption figures as stated in Table 1. To show the effect of the horticultural settings the energy saving effects are computed for different temperature and humidity setpoints. Obviously, the (absolute and relative) energy savings of a double glass cover grow as the greenhouse temperature increases. The energy saving properties of double glass are also larger when higher humidities are accepted. This is due to the fact that if a high humidity is tolerated windows are less frequently opened by the violation of the humidity setpoint. The effect of the humidity setpoint on energy consumption is larger for the double glass covered greenhouse than for the reference one because of the decreased condensation against the inner side of the double glass cover.

An important disadvantage of a double glass covering structure is the decreased shortwave transmissivity, being about the square of the single glass tranmissivity. This will lead to a decreased rate of photosynthesis. The model computed the mean rate of photosynthesis in the double glass greenhouse to be 0.84 compared to the reference greenhouse. Because, in fact the specific energy consumption ($MJkg^{-1}$fruit) is the quantity of interest with respect to energy saving, this decrement of production should be taken into account. In table 1 can be seen that, by dividing the energy consumption per m^2 per year by the relative production, the net energy saving, contributing for the larger area of a double glass greenhouses to produce an equal amount of fruit as the single glazed version is significantly less than the gross energy saving.

5. Combined heat and power

The application of combined heat and power at a nursery raises its primary energy consumption. However, the electricity produced replaces electricity production at large power plants. Because, unlike the case with CHP, as a rule the reject heat of those large power plants is not used, on a national scale, the energy conservation objective can still be served.

The year round electricity production of a CHP engine is (providing the engine runs at full capacity only) the product of electric power and the number of running hours. The latter is primary dependent on the thermal power of the engine.

To determine the relation between thermal power and the number of running hours the simulation model has been applied for 5 levels of thermal power (20, 40, 60, 80 and 100 $W_{th}m^{-2}$). The horticultural context of the simulations was described in section 3. To get an impression of the contribution of CHP to heat production the mean daily heat production of the engines is shown in Figure 3. The horticultural context is included in the figure by the gray shaded area which represents the total mean daily heat demand of the greenhouse.

The fact that even the engine of 100 $W_{th}m^{-2}$ never covers the total heat demand is attributed to the carbon dioxide supply, which forces the boiler to produce heat. Also, during peak demands, which cannot be seen in the figure due to the filtering of the data, the boiler supplies heat now and then. Obviously, in summer the heat associated with CO_2 supply severely diminishes the contribution of CHP.

To compute the extra gas consumption and the electricity production for the five cases a thermal and an electric conversion efficiency must be employed. Typically, the thermal conversion efficiency of modern engines is 0.47 with respect to the upper heating value. The electric conversion efficiency is typically 0.29 (Klimstra, 1991).

From the total heat produced by the CHP engine, as computed with the model, the electricity production, and the savings of natural gas at the power plant can be computed. The gas consumption of the CHP engine and the boiler can be computed from their conversion efficiencies which are 0.47 and 0.85 respectively. Table 2 shows the electricity production, gas consumption of the nursery, savings at the power plant and net savings of natural gas for the five levels of thermal power.

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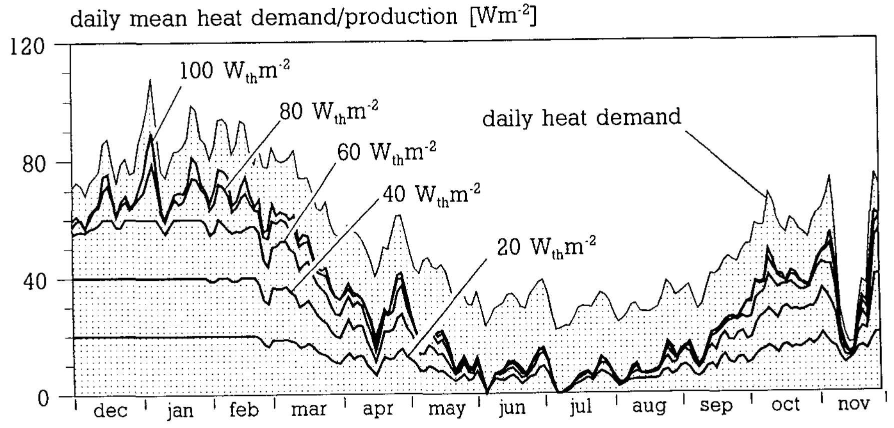

Figure 3 - Mean heat demand of the greenhouse and heat production of CHP for 5 thermal power levels (the daily mean values were smoothed by a 10 cell moving average filter).

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Table 2 - Electricity production, gas consumption of the nursery, savings at the power plant and net savings of natural gas for five thermal power levels.

	thermal power [Wm^{-2}]					
	0	20	40	60	80	100
electricity production [$kWhm^{-2}$]	0	67	120	163	193	208
nursery gas consumption [$m^3m^{-2}year^{-1}$]	57	67	75	80	84	86
power plant gas saving [$m^3m^{-2}year^{-1}$]*	0	15	27	37	44	47
net energy consumption [$m^3m^{-2}year^{-1}$]	57	52	47	43	41	39
energy saving [%]	0	9	18	25	28	32

*assuming a conversion efficiency from gas to electricity of 0.45 with respect to the upper heating value of natural gas (35.16 MJm^{-3})

Table 2 shows that the application of CHP has a considerable impact on the gas consumption of the nursery. However, on a national scale, this extra gas consumption is amply compensated by savings elsewhere. Thus, for a large combined heat and power engine, the net energy consumption drops to less than 70% of the energy consumption of the reference greenhouse.

In the simulated cases, the CHP engine does not affect canopy growth. Thus, the specific energy consumption drops parallel to the decrement of net energy consumption.

The computations show that from March until the end of the growth season, the contribution to the heating of the greenhouse is less than the potential contribution from all CHP-units. This is due to the heat generated when CO_2 is produced which causes the CHP engine to switch off. This means that, if the exhaust gases of the engine were clean enough to be used for CO_2 supply, the contribution made by a CHP engine to the heat demand can be increased strongly. Indeed, currently a number of full-scale experiments are being carried out with devices that clean the exhaust gases to such an extent that they can serve as a horticultural CO_2 source.

6. Conclusions

When determining the effect of the application of energy saving measures on energy consumption in horticulture it is very important to take account of the typical characteristics of greenhouses. For alternative cladding materials it must be recognized that only part of the heat demand of a greenhouse is associated with sensible heat loss. Also the transparency of the cladding material has a large effect on its prospective. In this context it is important to recognize that photosynthesis affects the income of a nursery, whereas energy saving decreases the costs. In the Dutch context, the is a factor 5 less important for the economic result than the former.

With respect to the application of combined heat and power engines in horticulture, the demand for CO_2 strongly limits the number of running hours of these engines during summer. Therefore the current developments on exhaust gas purification techniques are of great importance for the further development of CHP in horticulture.

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