OPTIMAL DIMENSION OF A RESERVOIR FOR TEMPORARY STORAGE OF HEAT SURPLUSES FROM COMBINED HEAT AND POWER IN ARTIFICIAL LIGHTED GREENHOUSES

Refereed

H. F. de Zwart
Agricultural Research Department
Institute for Agricultural Engineering (IMAG-DLO)
Wageningen
The Netherlands

Keywords: Heat storage, Marginal costs and benefits, Combined Heat and Power

Abstract

Producing electricity with on-site combined heat and power, to feed artificial lighting implies the production of large amounts of waste heat. Quite often the heat production exceeds the actual heat demand of the greenhouse. Thus combined heat and power induces heat surpluses. However, in a large span of time (yearround), reject heat from combined heat and power is less than the heat demand of an intensive utilized greenhouse. Thus, periods with surpluses must be considered temporary and storage of these surpluses for future use is advantageous.
Another potential source of heat surpluses is the boiler, when its exhaust gases are used for carbondioxide enrichment of the greenhouse air. Carbondioxide addition is requested during the day, whereas the heat, associated with this way of CO_2-production is mostly not required during the day. A buffer can store the heat produced during the day for use during the night.
To determine the energy consumption and canopy growth of a greenhouse with artificial lighting, combined heat and power, CO_2-enrichment of the canopy ambient and a heat storage facility a simulation model was built.
In this paper the energy saving obtained by heat storage facilities with different dimensions is discussed. Comparison of the benefits with the costs related to the storage facility gives a possibility to determine an optimal storage capacity. It will be demonstrated that the amount of carbondioxide addition has a significant effect on the optimum storage capacity.

1. Introduction

Commonly, in artificially lighted greenhouses, realizing the previously defined illumination strategy receives a high priority. Thus, in case the required electricity is produced by an on-site combined heat and power unit (henceforth denoted CHP), on dull days the reject heat of the CHP, which runs to feed the lamps, induces a heat surplus. A surplus is defined as the remainder of heat production and heat demand of the greenhouse. Another important source of a heat surplus is the boiler, in case it is used to raise the CO_2 concentration of the greenhouse. When the CHP and CO_2-supply are switched off, or during cold weather, the greenhouse mostly will have a bigger heat demand than the produced reject heat (which is even zero when neither CHP is running nor CO_2-enrichment is required).

A frequent alterations between a period with surpluses to a period with shortages enables short term storage operation. The effectiveness of a storage unit depends on the dimension of the facility in relation to the extent and frequency of shortages and surpluses.

To determine heat storage operation a simulation model (de Zwart, 1994) describing energy demand and reject heat production on a minute to minute base was used. The model describes crop growth and biomass production as well.

Proc. Third Int. Symp. Artificial Lighting
Eds. T. Blacquière, H. Gude
Acta Hort. 418, ISHS 1997

With the simulation model the energy consumption as a function of buffer dimension can be studied. It can be expected that while increasing the storage capacity the additional benefits will diminish. At a certain point the expenses for additional storage capacity will not longer be compensated by additional benefits. At this point, where marginal benefits equal marginal costs, the optimal dimension of the storage tank is found.

2. Method

The model was used to compute the requirement of primary energy for a typical Dutch greenhouse growing cut-roses under artificial lighting. Recording the calculated energy consumption for a series of simulations with solely an increasing storage capacity, and rating this decrease of energy use with the price of energy results in a marginal benefits curve. Comparison of the marginal benefits curve with the curve of marginal costs associated with the storage facility yields an optimal storage facility under economic constrains.

The optimization is performed for two carbondioxide supply regimes.

2.1. A common Dutch greenhouse operation

The results of the simulations presented in this paper are based on a canopy of cut-roses in their second year. The modelled greenhouse-canopy system is exposed to the SEL-year, which is a typical Dutch weather course (Breuer, 1989), and studied for a one-year period (1 Jan - 1 Jan). The venlo-type greenhouse has a single sheet cover and two heating systems. The primary heating system is located near the floor and the secondary heating system is hung at 2 meters height. The secondary heating system is only used when the temperature of the primary heating system exceeds 50 °C.

To create a micro-climate with enough air movement, and to force canopy transpiration, during the day the minimum temperature of the lower heating pipe is bounded to 40 °C, unless the solar radiation exceeds 100 W/m^2. When the solar radiation exceeds 100 W/m^2 the minimum bound is decreased to 20 °C. During night-time the minimum temperature of the lower heating system is bounded to 30 °C.

The air temperature setpoint during the night is kept 16 °C during the whole year. The daytime air temperature setpoint is 19 °C from may to October and 18 °C for the rest of the year. Transition from night-time to daytime temperature setpoint and visa versa is performed with a tangent of (-)1 °C/h. When the solar radiation exceeds 100 W/m^2 the air temperature setpoint is raised with 1 °C per 100 Watts, up to a maximal increase of 2 °C (reached at a solar irradiation of 300 W/m^2).

When the greenhouse air temperature exceeds the setpoint with more than 0.5 °C, the windows are opened.

During winter and early spring, when during the night the outside temperature drops below 5 °C the energy screen is closed. A closed screen is not opened until sunrise. However, when during the night the relative humidity exceeds 78% or the temperature rises too much due to heat release of artificial illumination the screen is opened a crack.

The humidity in the greenhouse is attempted to be kept maximal 78%. Each percent relative humidity excess forces the windows to open one percent.

During daytime, when the windows are closed, the setpoint for the carbondioxide concentration is 600 µl/l. When the windows are opened 10 % the setpoint is decreased-linear till it reaches a minimal value, at a window opening of 20 %. The minimal value is different for the two supply regimes which were studied. In the first case, the minimal value is the outside carbondioxide concentration (340 µl/l). In the second case the minimal value of the setpoint for CO_2 is somewhat higher, namely 380 µl/l. The setpoint is attempted to be reached by addition of exhaust gases. The Distributing system is dimensioned such that, a supply rate of 1.28 mg CO_2 per m^2 per second can be achieved.

To produce this amount of CO_2 by exhaust gases, the boiler has to produce heat at 25 W/m^2.

Artificial illumination is used from halfway of august till the end of April. During that period the lamps are switched on when the solar radiation drops below 75 W/m^2. However, from 1 hour before sunset to 5 hours after sunset the artificial lighting is switched off. The intensity of illumination is set to 9 W PAR/m^2.

Heat storage is performed by raising the temperature in the tank by a temperature controlled inlet up to 90 °C. A gentle filling preserves a stratified structure in the tank.

3. Results

From the computations of the model it appeared that with the illumination strategy described in section 2.1., for the SEL year, artificial illumination was switched on for 3107 hours. For the first CO_2-supply regime, 9.7 kg $CO_2/m^2/yr$ had to be supplied, which is equivalent with the CO_2-content of 5.4 m^3 natural gas. The second regime required 13.9 kg $CO_2/m^2/yr$, which was supplied from the exhaust gases from the combustion of 7.2 m^3 natural gas.

To illustrate the performance of the storage system the heat demand of the greenhouse and the heat production of the combined heat and power engine and the boiler (running to generate CO_2), is demonstrated for a day in the end of spring (Fig. 1). The data of the picture were calculated by the simulation model.

As can be seen, during periods of surplus, the mean temperature of the storage tank increases, whereas during periods with a heat demand that exceeds the production of reject heat, the storage tank is emptied.

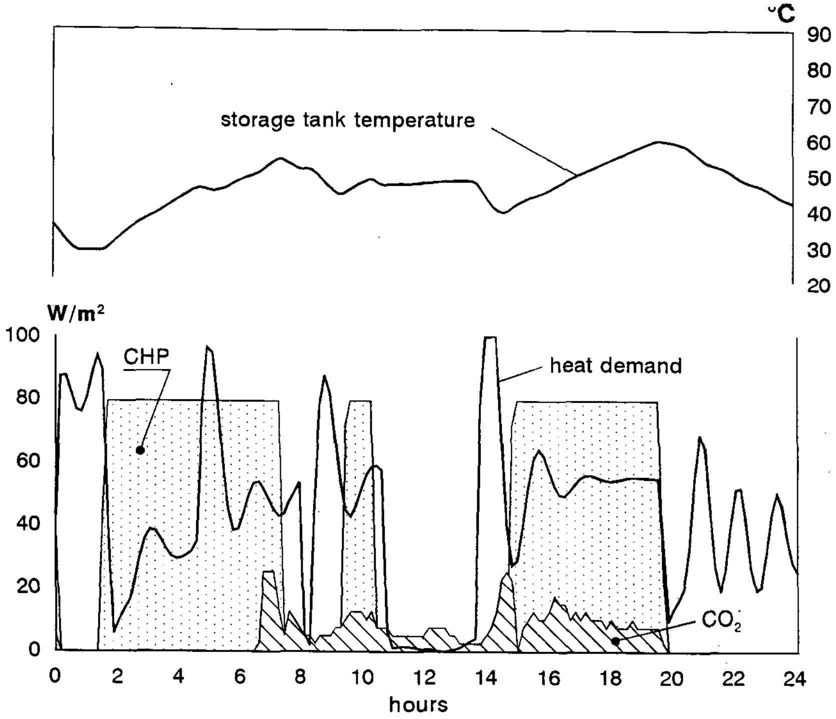


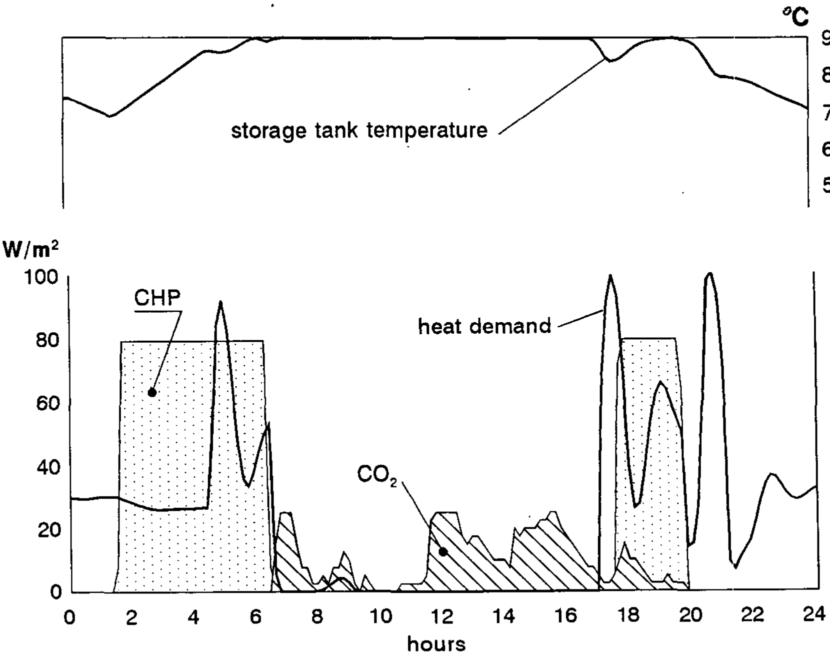
Figure 1. Performance of the storage system

In the situation depicted in Fig. 1 all heat surpluses could be stored in the tank. In Fig. 2 the situation is depicted where the tank is not large enough to store all surpluses.

Possibly, a bigger storage tank would have prevented the situation shown in Fig. 2. However, a careful study of Fig 2. learns that the total heat production exceeds the total heat demand on that day. Thus, the bigger storage tank would have given no improvement in case the day preceding the depicted one showed a similar daily heat surplus. In fact, heat that was stored, but not discharged on the same day, decreases the storage capacity of the next day. In Fig 3. the daily amount of heat that could not be stored in the tank because of overrun is depicted when no storage tank is available, when a tank of 25 m^3/ha, a tank of 50 m^3/ha and a tank of 75 m^3/ha is applied.

Obviously the effect of the enlargement from zero to 25 m^3/ha is much bigger than the effect of enlargement from 25 to 50 m^3/ha. The addition of another 25 m^3 storage capacity has hardly any effect. This can be contributed to the fact that. especially in autumn. a structural excess of heat production occurs.

Figure 2. Storage tank overrun



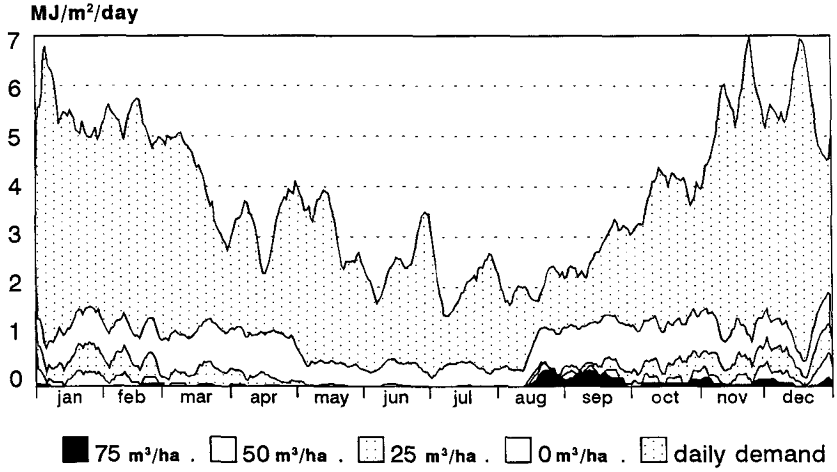


Figure 3. Daily surpluses without and with a storage facility of 25, 50 and 75 m^3/ha. For reference the daily heat demand is depicted as well.

3.1. Energy consumption in relation to the heat storage capacity

In case there is no, or insufficient storage capacity, the reject heat must be left somewhere, and the only way is to increase the temperature of the heating pipes and open the windows a bit. Thus, in fact, during periods with a surplus, the heat demand of the greenhouse is increased to match the production of reject heat.

When storage capacity is available, during surpluses the heat demand doesn't has to be increased and, during a period where the reject heat is less than the demand, accumulated heat can be used for heating. Due to both processes, a decrease of primary energy consumption can be noticed when a heat storage tank is enlarged. However, the positive effects will decrease as the storage tank increases. In Fig 4. the curve of the decreasing consumption of primary energy is presented for both CO_2-supply strategies. Note that the bigger gas consumption of the situation with the higher level of CO_2-supply for the case without a storage tank vanishes as the capacity of the tank increases. This is due to the fact that a larger storage tank is capable to transport the produced heat during daytime (which is a bigger amount for the second CO_2-regime) from the day to the night. without a storage tank. Obviously the effect of enlargement decreases with the size of the storage facility.

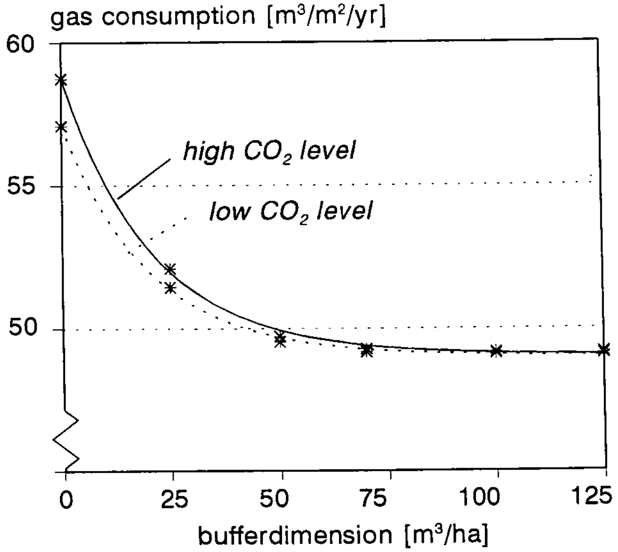


Fig 4. Total heat consumption of a greenhouse (actual demand plus surpluses) as a function of heat storage capacity

3.2 Calculating the optimal dimension

The decrement of gasconsumption of the boiler are avoided costs and, therefore, can be considered as benefits from a storage tank. Thus the derivative of the curve describing the decreasing gasconsumption, multiplied by the gasprice (0.20 Dfl per m^3) and by -1 (to convert avoided costs to benefits) yields a marginal benefits curve for energy. The derivative of the extra produce yields the marginal benefits for produce. The sum of both, yields the marginal benefits from the storage tank.
Against the benefits, a heat storage facility implies costs for investment and maintenance. According to an up to date conspectus on the costs of lasting means of production (Kwantitatieve Informatie, 1992) the initial expenses of a heat storage facility can be described by the linear function

$$\text{Costs} = 0.72\ 10^3 \times V_{storage} + 1.3\ 10^4 \qquad [\text{Dfl}] \qquad (1)$$

where $V_{storage}$ denotes the volume of the storage facility in m^3. The yearly costs of the investment comprises 7 % due to writing off, 2 % for maintenance, and 4% interest. Thus the yearly marginal costs can be described by:

$$MC = 93.6\ [\text{Dfl}/m^3/yr] \qquad (2)$$

From basic micro-economic sciences it is known that an economic optimum is found at the point of intersection of the curves of marginal costs and marginal benefits. In fig 5. three curves for marginal costs and marginal benefits are depicted.

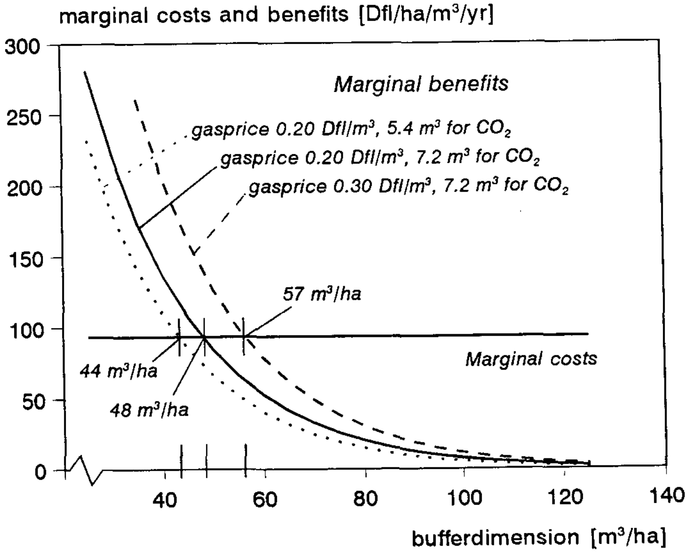


Fig 5. Marginal costs and marginal benefits of a heat storage facility.

The dotted and the full line represent the marginal benefits for respectively the first and the second CO$_2$-supply regime, both when the price of natural gas is set to 0.20 Dfl/m^3. From these curves can be seen that the optimal dimension is 44 m^3/ha for the low level of CO$_2$-addition and 48 m^3/ha for the high level. The dashed line describes the marginal benefits for the second CO$_2$ regime, but with a higher energy price (0.30 Dfl/m^3). Obviously, an increased price makes energy saving more important. The higher benefits from energy saving makes the optimum to shift form 48 m^3/ha towards 57 m^3/ha. From Eqn. (1) can be calculated that the yearly costs of a storage tank of 44, 48 and 57 m^3 are such a tank are Dfl 5.8 10^3, 6.18 10^3 and 7.0 10^3 respectively. yearly costs (13 %). From Fig. 4 the energy saving due to the 44 m^3/ha storage tank used for the case of a low level CO$_2$-supply the energy saving appears to be 57.1 - 50.1 = 7.0 m^3/m^2/yr less than the case when no storage tank is applicable. With the assumed gasprice of 0.20 Dfl/m^3, the avoided costs for that case are calculated to be Dfl 1.40 per m^2 per year. Thus the net benefit of that storage tank in that particular greenhouse is 1.40 - 0.58 = 0.82 Dfl/m^2/yr. The storage tank of 48 m^3/ha, which is the optimum for the greenhouse with the high CO$_2$level and the low energy price leads to a benefit of 1.13 Dfl/m^2/yr. Finally, the high CO$_2$-level greenhouse with a storage tank of 57 m^3/ha saves 9 m^3 of natural gas, which costs Dfl 2.70 when the price is 0.30 Dfl/m^3. A 57 m^3/ha storage tank costs 0.70 Dfl/m^2, yielding a net benefit of Dfl 2.0/m2/yr.

4. Conclusions

The implementation of a heat storage facility has an important effect on energy conservation. An economically attractive decrement of primary energy consumption with more than 10% can be achieved. With the simulation model the effect of various influencing factors can be studied.

References

Kwantitatieve informatie voor de glastuinbouw 1992-1993, Groenten, Snijbloemen, Potplanten, 1992, [In Dutch], Informatie en Kennis Centrum Akker- en Tuinbouw, Afdeling Bloemisterij/Afdeling Glasgroente en Bestuiving, Aalsmeer/Naaldwijk.

Breuer, J.J.G., and N.J. van de Braak, 1989, Reference year for Dutch greenhouses., Acta Horticulturae nr 248, pag. 101-108

Zwart, H.F. de., 1994, Prospects on combined heat and power generation and short term heat storage in Dutch horticulture, Ph.D. Dissertation, Agricultural University, Wageningen (forthcoming)