Computers and Electronics in Agriculture 162 (2019) 1035–1048

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Optimal utilization of a boiler, combined heat and power installation, and heat buffers in horticultural greenhouses☆

P.J.M. van Beveren[a,*], J. Bontsema[b], G. van Straten[c], E.J. van Henten[a]

[a] Farm Technology Group, Wageningen University, P.O. Box 16, NL-6700AH Wageningen, the Netherlands
[b] Bontsema Consultancy, Johan Kievietstraat 10, NL-6708SP Wageningen, the Netherlands
[c] Biobased Chemistry & Technology, Wageningen University, P.O. Box 17, NL-6700AA Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Greenhouse
Energy cost saving
Dynamic optimization
Zero-or-range constraint
Equipment deployment
Greenhouse operational management

ABSTRACT

In the daily operation of a greenhouse, decisions must be made about the best deployment of equipment for generating heat and electricity. The purpose of this paper is twofold: (1) To demonstrate the feasibility and flexibility of an optimal control framework for allocating heat and electricity demand to available equipment, by application to two different configurations used in practice. (2) To show that for a given energy and electricity demand benefit can be obtained by minimizing costs during resource allocation.

The allocation problem is formulated as an optimal control problem, with a pre-defined heat and electricity demand pattern as constraints. Two simplified, yet realistic, configurations are presented, one with a boiler and heat buffer, and a second one with an additional combined heat and power generator (CHP) and a second heat buffer.

A direct comparison with the grower is possible on those days where the other equipment that was at the grower's disposal was not used (63 days in the available 2012 data set). On those days overall costs savings of 20% were obtained. This shows that a given heat demand does not come with a fixed price to pay. Rather, benefits can be obtained by determining the utilization of the equipment by dynamic optimization. It also appears that prior knowledge of gas and electricity prices in combination with dynamic optimization has a high potential for cost savings in horticultural practice. To determine the factors influencing the outcome, different sensitivities to the optimization result were analyzed.

1. Introduction

Greenhouses to produce vegetables, flowers, and ornamentals require heating in colder periods. High-tech greenhouses in temperate climates, like the Netherlands and Belgium (Van Den Bulck et al., 2013), consume large amounts of fossil energy. The quest for energy saving in modern greenhouse horticulture (Van der Valk and Van der Poll, 2007) has led to investments in a wide variety of equipment. In daily operation, decisions about the best deployment of this equipment must be made. This operation is complex due to varying heat and cooling demands, and varying prices of gas and electricity and calls for effective control schemes to support the grower in this process. In current greenhouse practice the equipment is controlled by different controllers that operate based on a set of pre-defined rules. Depending on the configuration the set of rules is tailor-made. Supervision of the operation is done by the grower. If necessary the grower can overrule the controller manually.

In order to reduce the energy consumption of greenhouses a two-stage approach for optimal management of energy resources was introduced in Van Beveren et al. (2015a,b). This approach decouples greenhouse climate and the generation from the required energy input (Fig. 1). The first stage minimizes the energy input to the greenhouse for a pre-defined set of bounds to specify the desired greenhouse climate. The second stage, described in this paper, minimizes the energy costs of realizing the required energy profile (obtained from the first stage) using the available equipment. The motivation is that this approach does not rely on a complex crop model, but rather uses the grower's experience and knowledge.

Control is closely kin to dynamic optimization. Optimization of energy systems in greenhouse horticulture was studied before (e.g. Van Willigenburg et al., 2000; Tap, 2000; Van Ooteghem, 2007; Bozchalui and Cañizares, 2014; Husmann and Tantau, 2001; Vanthoor, 2011;

☆ This research is supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO).
* Corresponding author at: B-Mex B.V., Oude Eekmolenweg 71, NL-6706AN Wageningen, the Netherlands.
E-mail address: peter.vanbeveren@wur.nl (P.J.M. van Beveren).

https://doi.org/10.1016/j.compag.2019.05.040
Received 11 February 2019; Received in revised form 13 May 2019; Accepted 18 May 2019
Available online 31 May 2019

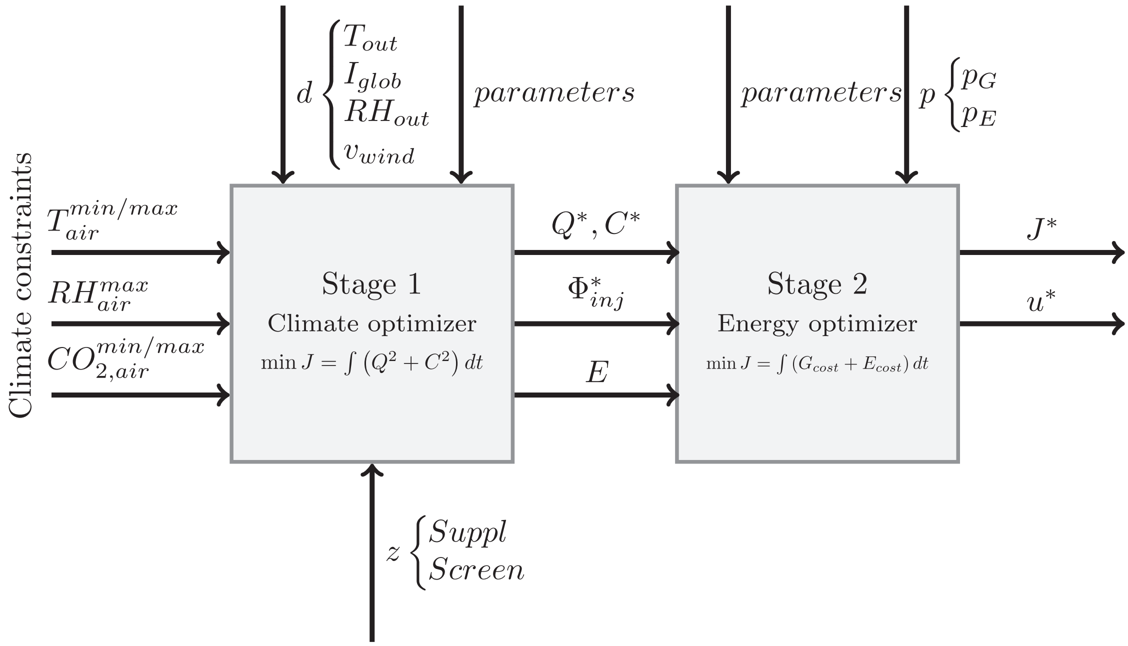


Fig. 1. Overview of the 2-stage approach. The climate optimization needs the climate constraints (set by the grower), outdoor climate measurements d, controls from the greenhouse z (here supplementary lighting *Suppl* and screen position *Screen*), and greenhouse parameters. The result of stage one is the optimal heat profile Q^*, optimal cooling profile C^*, the CO_2 injection pattern Φ_{inj}^* and, electricity need of the greenhouse E. Those are fed into the energy optimizer. Here, the prices p of gas p_G and electricity p_E and parameters of the equipment are needed. The result of the optimization in stage 2 are the optimal controls u^* such as the power of the CHP and boiler, and heat fluxes to the buffers, that lead to the optimal value of the goal function J^*.

Seginer et al., 2018), but the focus was mainly on greenhouse climate management and control. In those studies, a crop model is needed, and the operation of equipment is an integral part of the optimization and does often not comply with current practice. There are far less studies about the deployment, operation and control of all equipment that generate and store warm water (used for heating) and cold water (used for cooling) for greenhouses. Molenaar et al. (2007) presented optimization of the energy costs for a closed greenhouse using a given heat, cold and electricity demand for a typical year. The problem was solved with linear programming techniques by discretizing the model equations to an hourly time basis. However, the optimization results in Molenaar et al. (2007) were not compared with data from practice. Different energy management strategies for commercial greenhouse are summerized in Vadiee and Martin (2012, 2014). Here, the focus was not on optimization of an existing energy system, but more on the configuration and choice of different materials and equipment to improve the energy conservation of the greenhouse.

Applications of various optimization techniques and analyses of energy systems with a wide variety of equipment in similar configurations are present in other fields. For instance, applications of CHP systems and thermal storage can be found, amongst others, for residential buildings in Haeseldonckx et al. (2007), Schütz et al. (2015), Fuentes-Cortés et al. (2015),Ren et al. (2008), for a hospital in Vanhoudt et al. (2011), university campus (Pagliarini and Rainieri, 2010; Chandan et al., 2012), and industrial power plants (Mitra et al., 2013). These studies minimize total energy costs for heating and cooling based on a specified heat and cold demand. An overview of optimization techniques for thermal energy storage control of mainly office buildings, commercial buildings, and university campuses was published in Ooka and Ikeda (2015),Cho et al. (2014). Greenhouses differ from the aforementioned buildings because of different heat and electricity demands, originating from different processes and requirements and a stronger thermal coupling to the outdoor climate. Furthermore, the greenhouse industry in the Netherlands is characterized by a wide deployment of CHP systems. In 2011, for instance, a total of about 3000 MW of electrical power was installed on a total area of 10300 ha. Part of the electricity was used for lighting, but most of the electricity was sold to the public grid (Vermeulen, 2014). CHP systems are advantageous for greenhouse horticulture since the heat, electricity, and CO_2 can all be used in the greenhouse. Furthermore, these installations are important in balancing the national power grid.

The purpose of this paper is twofold: (1) The wide variety of configurations of equipment requires a formulation that is flexible in terms of type and number of equipment. Therefore, a framework for managing heat and electricity producing equipment, based on optimal control is desired. This is offered by an optimal control method that is presented here. The objective is to study the feasibility and flexibility of the method. (2) To show that for a given energy and electricity demand that satisfies minimum overall energy use, further benefit can be obtained by minimizing costs during resource allocation. If the sources and prices are fixed, there is a fixed price to pay for energy. However, the freedom to achieve further benefits is, in principle, in the possibility to shift the mix of sources to fulfil the heat and electricity demand, and the exploitation of time variation in energy market prices. In order to investigate this question, ideally an optimized energy profile, as developed in Van Beveren et al. (2015a) would be the best starting point. In this paper the starting point is different. Instead of an optimized profile, actual energy profiles as realized by the grower on days where the configuration coincides with the one in Fig. 3 are used. The motivation for this choice is that in this way a comparison with real data is possible, thus increasing the credibility of the results. The formulation and demonstration of an optimization method for energy equipment utilization applied to the horticultural greenhouse and compared to real data is novel.

In this paper we demonstrate the generality of the optimization method with two commercially used configurations of equipment: (1) A system with a heat demand from a greenhouse equipped with a boiler and a single high temperature heat buffer. This case serves as a demonstration to test and evaluate the optimization method. (2) A system with a boiler, CHP, and two buffers; one for high temperature heat storage and one for low temperature heat storage. We compare the optimization results with real heat and electricity data from a commercial full-scale greenhouse in the Netherlands.

2. Materials and methods

For 2012, greenhouse climate and energy data (five-minute time interval) were obtained from the greenhouse process control computer of a 4 ha commercial rose greenhouse in Bleiswijk, The Netherlands (see Van Beveren et al., 2015a,b for more details). The recorded data were obtained from different sensors and actuators in the greenhouse. These measurements are standard in modern greenhouses.

In addition, a time series with real gas and electricity prices (15-min time interval) was obtained via the electricity and gas supplying company of the grower. This makes it possible to compare the optimal scenarios with the grower's operation. In the Netherlands, electricity generated from horticultural CHP installations is partly used for artificial lighting, but mostly sold to the national power grid (Vermeulen et al., 2011). Growers in the Netherlands have the possibility to trade electricity on different markets that operate on different time scales. The greenhouse in this study traded electricity on the so-called unbalance market only. On this market, prices fluctuate every 15 min. Although rare, a negative electricity price can occur, meaning that the grower gets paid for using electricity.

All data were collected for the whole year of 2012. However, in the real system of the actual greenhouse there was additional equipment, such as a heat pump and aquifer, which are not considered in this study. Therefore, we could only compare the days where the configuration of the actual greenhouse was congruent with the configuration of the optimization. There are, altogether, 63 days for which the configuration was congruent with that of the grower, as explained in more detail in Appendix B.

A general optimal control formulation defines the optimization problem in a flexible and generic manner. The optimal control problem in this paper was solved using Tomlab optimization software (Edvall and Goran, 2009) in Matlab (version 7, The MathWorks Inc., Natick, USA) on a PC with core i5 CPU 660 3.33 GHz,4 GB RAM and Windows 7 × 64 installed. "Tomlab is a general-purpose development, modelling, and optimal control environment in Matlab for research, teaching, practical solution of optimization problems" (Holmstrom et al., 2010).

Tomlab requires the definition of the number of collocation points to solve the optimization problem (Edvall and Goran, 2009). All optimizations were done using a sequence of collocation points, starting from 24 collocation points per day. When an optimal solution was obtained, the result served as the initial guess for the next optimization with a higher number of collocation points. This procedure was repeated for 48, 96 and 144 collocation points per day. The raw data were resampled to the number of collocation points needed for the optimization. It was found that the result converged with the number of collocation points, and that the step from 96 to 144 points hardly gave further improvement, so 144 points are enough. The reported CPU times were recorded using 144 collocation points per day.

2.1. Case 1: Demonstration of the optimal control method with configuration of boiler and buffer

2.1.1. System configuration

The first configuration considered in this work consists of a boiler and a high temperature buffer (HT) (Fig. 2). The heat demand from the greenhouse ($Q_{des} = Q_{HT,grh}$) as a function of time is assumed to be known. This constraint follows from the two-stage approach described in Van Beveren et al. (2015b,a), but could also have another pre-defined pattern. The heat demand of the greenhouse depends amongst other things largely on the desired greenhouse climate and the outside weather. The boiler in this example has a maximum capacity ($Q_{HT,boil}^{max}$) of 3 MW (75 W m^{-2}). When the boiler is active it should be on for at least 80% of capacity. In addition, the number of switching instances should be reduced (Fransen, 2015). Both constraints have been implemented for reasons of efficiency and minimal wear of the boiler.

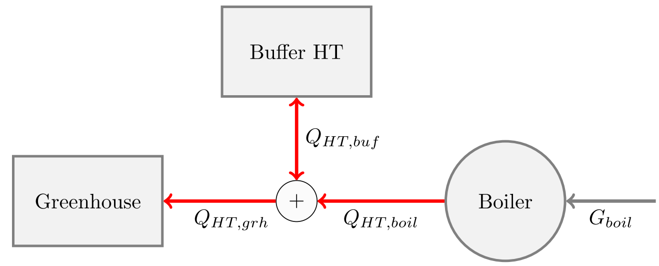


Fig. 2. Schematic overview of the system configuration using a boiler and buffer. Colors of the arrows: high temperature heat fluxes (—) and gas flux (—). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The buffer had a maximal capacity of 3.1 MJ m^{-2}. The heat flux from or to this buffer is defined as $Q_{HT,buf}$. From a physical point of view a heat flux should be considered as positive. From this perspective, two heat fluxes would have to be introduced: one for loading and one for unloading of the buffer. With such a formulation the optimal control method does not preclude the possibility of simultaneously loading and unloading. This is unwanted and in practice not possible. Therefore, here, the problem is reformulated such that the heat flux from or to the buffer is either negative (loading the buffer with heat) or positive (unloading the buffer). This definition ensures that loading and unloading of the buffer cannot occur at the same time. The total heat flux to the greenhouse (Q_{des}) is determined by the sum of the heat flux coming from the boiler ($Q_{HT,boil}$) and the heat flux coming from, or going to the heat buffer ($Q_{HT,buf}$). The properties of the heat buffer are given in Table 1. In this configuration it is assumed that CO_2 coming from the boiler is not used for CO_2 enrichment of the greenhouse. This is the practice for a growing number of greenhouses in the Netherlands that use CO_2 from industrial sources distributed via a pipe network maintained by the company OCAP (Organic Carbon dioxide for Assimilation of Plants). However, the use of exhaust CO_2 from the boiler for CO_2 enrichment can easily be included in the optimal control formulation due to its generic nature.

2.1.2. Formulation of the optimization problem

The energy content of the buffer is described by:

Table 1
Parameters for optimization of system with boiler, CHP, and buffer in Section 2.2.

Symbol	Description	Value	Unit
A	Greenhouse area	40709	m^2 [grh]
$H_{HT,buf}^{max}$	Heat storage capacity buffer HT	3.14×10^6	J m^{-2} [grh]
$H_{LT,buf}^{max}$	Heat storage capacity buffer LT	1.05×10^6	J m^{-2} [grh]
$Q_{HT,buf}^{max}$	Maximal heat flux to buffer HT	150	W m^{-2} [grh]
$Q_{LT,buf}^{max}$	Maximal heat flux to buffer LT	150	W m^{-2} [grh]
–	Installed boiler capacity in the greenhouse	2×10^6	W
–	Installed CHP capacity in the greenhouse	2.52×10^6	W
$Q_{HT,boil}^{max}$	Maximum boiler thermal flux	49	W m^{-2} [grh]
Q_{chp}^{max}	Maximum CHP thermal flux	62	W m^{-2} [grh]
r_{boil}^{min}	Minumum of the range for operating the boiler	0.8	–
r_{chp}^{min}	Minumum of the range for operating the CHP	0.85	–
S	Combustion heat of natural gas	35.17×10^6	J m^{-3} [gas]
η_{boil}	Boiler efficiency	0.94	–
$\eta_{Q,chp}$	Thermal efficiency CHP	0.46	–
$\eta_{E,chp}$	Electrical efficiency CHP	0.37	–

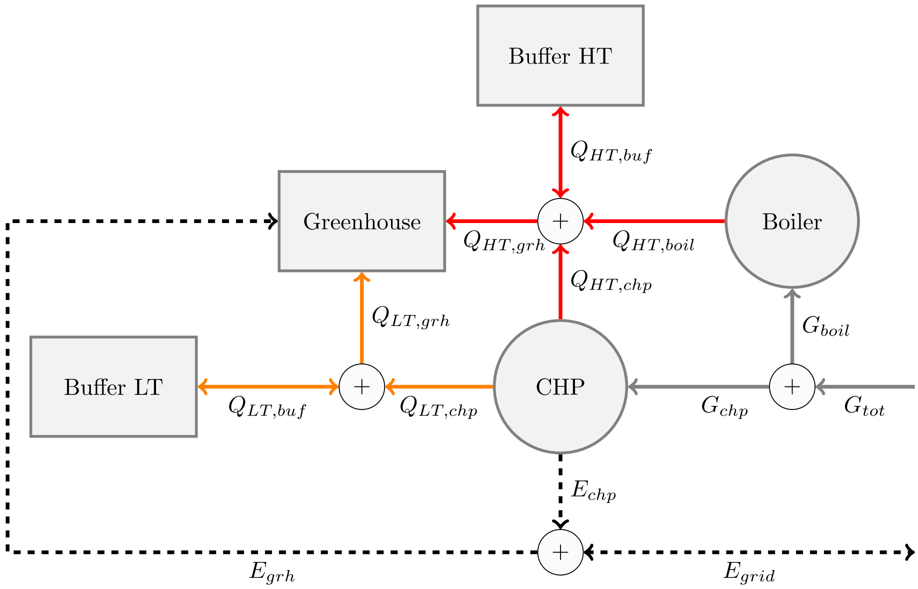


Fig. 3. Schematic overview of the system configuration using boiler, CHP, and buffers. Colors of the arrows: high temperature heat fluxes (—), low temperature heat fluxes (—) gas fluxes (—), and electricity fluxes (- - -). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\frac{dH_{HT,buf}(t)}{dt} = -Q_{HT,buf}(t), \tag{1}$$

with the known initial high temperature heat (*HT*) in the buffer from the grower ($H_{HT,grower}$),

$$H_{HT,buf}(t_0) = H_{HT,grower}(t_0). \tag{2}$$

In the sequel, for easier readability, the explicit time dependency of the variables is dropped from the notation where the dependency is evident.

The amount of heat delivered by the boiler ($Q_{HT,boil}$) and buffer ($Q_{HT,buf}$) at each moment in time is equal to the heat demand of the greenhouse (Q_{des}) (Eq. (3)). Eq. (3) acts as a constraint in the optimization.

$$Q_{HT,boil} + Q_{HT,buf} = Q_{des} \tag{3}$$

No losses from the buffer are assumed in order to keep the formulation as simple as possible. Due to their nature, all fluxes have non-negativity constraints, except for the buffer flux, since it can be positive or negative as explained before. The buffer flux is constrained by:

$$Q_{HT,buf}^{min}(t) \leqslant Q_{HT,buf}(t) \leqslant Q_{HT,buf}^{max}(t), \tag{4}$$

where $Q_{HT,buf}^{min} = -Q_{HT,buf}^{max}$. The buffer state has the following state constraint:

$$0 \leqslant H_{HT,buf}(t) \leqslant H_{HT,buf}^{max}(t). \tag{5}$$

In order to cope with the operation range of the boiler, a zero-or-range constraint was introduced (Hansen and Huge, 1989). This range constraint is represented in the optimal control problem with the following definition:

$$Q_{HT,boil} - Q_{HT,boil}^{max} b_{boil} \leqslant 0 \tag{6}$$

$$Q_{HT,boil} - r_{boil} Q_{HT,boil}^{max} b_{boil} \geqslant 0 \tag{7}$$

$$Q_{HT,boil} \geqslant 0 \tag{8}$$

where Eq. (8) is a trivial constraint on the heat flux from the boiler, which can only be positive. Eqs. (6) and (7) give the following constraint for $b_{boil} = 0$: $Q_{HT,boil} = 0$. For $b_{boil} = 1$, the constraint is $r_{boil}^{min} Q_{HT,boil}^{max} \leqslant Q_{HT,boil} \leqslant Q_{HT,boil}^{max}$. The value of r_{boil}^{min} was 0.8.

The selected control variables are:

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} Q_{HT,boil} \\ Q_{HT,buf} \\ b_{boil} \end{bmatrix}, \ b_{boil} \in \left\{ 0, 1 \right\}. \tag{9}$$

Then, the goal is to find the optimal control $u^*(t)$, $t_0 \leqslant t \leqslant t_f$ that minimizes the cost function in Eq. (10) which is the total gas cost of the boiler for the given time evolution of the gas price (p_G) in €m^{-3} (Eq. (11)). The optimization period can be any period in this formulation. When time periods longer than 24 hour are taken, the gas price varies over time.

$$\min_u J = \min_u \int_{t_0}^{t_f} (p_G G_{boil}(u))\, dt, \tag{10}$$

$$p_G(t),\ t_0 \leqslant t \leqslant t_f. \tag{11}$$

The amount of gas used by the boiler (G_{boil}) is proportional to the amount of heat produced by the boiler:

$$G_{boil} = \frac{Q_{HT,boil}}{\eta_{boil} \cdot S} \tag{12}$$

The parameters for the optimization in Section 2.1.2 are listed in Table 1.

Switching the boiler on and off too frequently should be avoided in order to save maintenance costs (Fransen, 2015). This kind of requirements can be implemented in the optimal control formulation by adding a penalty accounting for the number of switching moments to the goal function:

$$\tilde{J} = \int p_G G_{boil} + 10^{-3} \dot{Q}_{HT,boil}^2 dt. \tag{13}$$

The penalty parameter (1×10^{-3}) is hard to assess a priori and was therefore chosen empirically to obtain a realistic switching behavior.

2.1.3. Experiments

Three experiments were performed with this configuration to demonstrate the optimization procedure and to demonstrate the performance of the optimizations with different initial buffer fill status (f_0). The first two experiments were performed with goal function (Eq. (10)), to test the effect of the initial buffer status on the performance. In the third experiment the effect of the buffer switch restriction according to Eq. (13) was investigated.

2.2. Case 2: Optimization of a configuration with boiler, CHP, and buffers and comparison with real data

2.2.1. System configuration

The second configuration consisted of a boiler, combined heat and power installation (CHP), and two heat buffers (Fig. 3). The main reason to have a boiler installed next to the CHP is to serve as a back-up for heat production in case the CHP cannot run because of maintenance or repair. The CHP has a maximum thermal capacity (Q_{chp}^{max}) of 2520 kW (62 W m^{-2}); of which 70% of the heat is at a high temperature, and 30% at a low temperature. The former is gained from the exhaust gas condenser. The thermal efficiency of the CHP ($\eta_{Q,chp}$) is 0.46 and the electrical efficiency ($\eta_{E,chp}$) is 0.37. Thus, the maximum electricity production is 2060 kW (51 W m^{-2}). The thermal and electrical efficiency of the CHP were assumed to be constant for the operating range that was used, which is reasonable in view of the restricted operation range between 0.85 and 1. The thermal and electrical efficiencies are obtained from the supplier and are in line with the values reported in Vermeulen (2014). Electricity from the CHP is either used in the greenhouse for artificial lighting (E_{des}) or sold to the public electricity grid (E_{sell}). Electricity can also be bought from the grid (E_{buy}).

High temperature heat from the boiler or CHP can be stored in the high temperature buffer ($H_{HT,buf}$) or directly go to the greenhouse. Low temperature heat (LT) can be stored in the low temperature heat buffer ($H_{LT,buf}$) or directly go to the greenhouse. High temperature heating of the greenhouse air is done with the pipe rail heating system and low temperature heating is done with heat exchangers above the crop. In the analysis, we assume that there is no difference between applying greenhouse heating with heating pipes or with heat exchangers.

As explained in Section 2.1.1, the heat fluxes to or from the buffers ($Q_{HT,buf}$, $Q_{LT,buf}$) are positive (unloading of the buffer), negative (loading of the buffer), or zero. In Fig. 2 and 3 this is indicated by the two-sided arrows.

2.2.2. Formulation of the optimization problem

The energy content of the high temperature buffer (H_{HT}) is described by Eq. (1) and the energy content of the low temperature heat buffer (H_{LT}) is described by Eq. (14). The energy content of the low temperature buffer depends only on the low temperature buffer flux ($Q_{LT,buf}$). Again, no losses from the buffer are assumed. However, the effect of this assumption was investigated. Therefore, Eqs. (1) and (14) were extended as described in Section C according to the numbers given in Van Steekelenburg et al. (2011).

$$\frac{dH_{LT,buf}}{dt} = -Q_{LT,buf}. \tag{14}$$

To ensure fair comparison between grower and optimization, the heat withdrawn or stored in the buffer over the day must be considered. Therefore, in the optimization the initial and final fill status are taken like the values obtained from the data of the grower. This leads to the following initial and terminal state constraints:

$$H_{HT,buf}(t_0) = H_{HT,grower}(t_0), \tag{15}$$

$$H_{LT,buf}(t_0) = H_{LT,grower}(t_0), \tag{16}$$

$$H_{HT,buf}(t_f) = H_{HT,grower}(t_f), \tag{17}$$

$$H_{LT,buf}(t_f) = H_{LT,grower}(t_f). \tag{18}$$

The buffers have state constraints that represent the minimum and maximum storage capacity:

$$0 \leqslant H_{HT,buf}(t) \leqslant H_{HT,buf}^{max}(t), \tag{19}$$

$$0 \leqslant H_{LT,buf}(t) \leqslant H_{LT,buf}^{max}(t). \tag{20}$$

The total heat demand from the greenhouse can be satisfied by the boiler, high temperature buffer, low temperature buffer, directly from the CHP, or a combination of those. The sum of these fluxes must be equal to heat demand from the greenhouse (Q_{des}).

$$Q_{HT,boil} + Q_{HT,chp} + Q_{LT,chp} + Q_{HT,buf} + Q_{LT,buf} = Q_{des} \tag{21}$$

The heat demand from the greenhouse in this paper is obtained from the realised controls (see Appendix B). In the final two-stage approach the heat demand will be obtained by minimization of the energy input of the greenhouse as explained and calculated in Van Beveren et al. (2015a,b).

The electricity demand (E_{des}) is taken equal to the electricity consumption of the artificial lighting in the greenhouse. It can be delivered by the CHP (E_{chp}) or by the grid (E_{grid}):

$$E_{chp} + E_{grid} = E_{des}. \tag{22}$$

If the CHP produces more electricity than E_{des}, the electricity is sold to the grid (E_{grid}). E_{grid} is positive if electricity is bought from the grid and negative if sold to the grid. The cost of electricity generated by the CHP is already accounted in the gas price.

The CHP has a similar constraint as the boiler and must operate in a certain power range. Therefore, just like the zero-or-range constraint for the boiler (Section 2.1.2), another zero-or-range constraint has been implemented for the CHP. This introduces next to b_{boil} another boolean control variable (b_{chp}).X The lower bound of the operating range of the CHP (r_{chp}^{min}) was determined from the data of the grower to be 0.85.

In summary, the problem is subject to the following inequality control constraints (similar as in Section 2.1.1),

$$Q_{HT,boil} - Q_{HT,boil}^{max} b_{boil} \leqslant 0, \tag{23}$$

$$Q_{HT,boil} - r_{boil} Q_{HT,boil}^{max} b_{boil} \geqslant 0, \tag{24}$$

$$Q_{HT,boil} \geqslant 0, \tag{25}$$

$$Q_{chp} - Q_{chp}^{max} b_{chp} \leqslant 0, \tag{26}$$

$$Q_{chp} - r_{chp} Q_{chp}^{max} b_{chp} \geqslant 0, \tag{27}$$

$$Q_{chp} \geqslant 0, \tag{28}$$

$$b_{boil}, b_{chp} \in \{0, 1\}, \tag{29}$$

$$Q_{HT,buf}^{min}(t) \leqslant Q_{HT,buf}(t) \leqslant Q_{HT,buf}^{max}(t), \tag{30}$$

$$Q_{HT,buf}^{min}(t) \leqslant Q_{HT,buf}(t) \leqslant Q_{HT,buf}^{max}(t), \tag{31}$$

In Eqs. (30) and (31)$Q_{buf,HT}^{min} = -Q_{buf,HT}^{max}$, and $Q_{buf,LT}^{min} = -Q_{buf,LT}^{max}$, since it was assumed that the minimum and maximum fluxes of loading and unloading are equal.

The amount of gas used by the CHP (G_{chp}) is proportional to the amount of heat produced by the CHP:

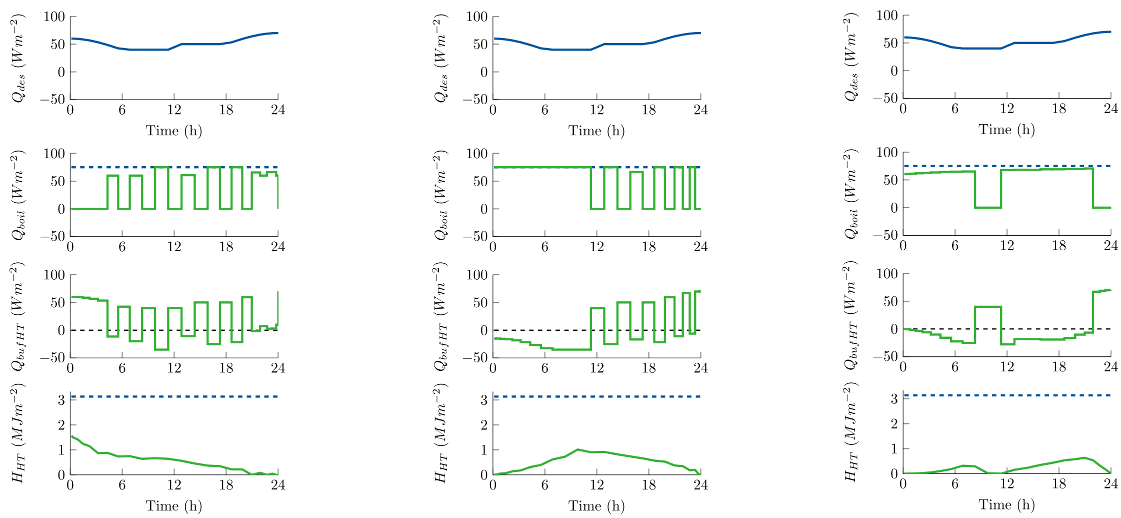
$$G_{chp} = \frac{Q_{chp}}{\eta_{Q,chp} S} \tag{32}$$

where the total efficiency of the CHP $\eta_{Q,chp} = 0.83$ was determined from data from the grower's gas meter and power data. The electricity production by the CHP is calculated as:

$$E_{chp} = \frac{\eta_{E,chp}}{\eta_{Q,chp}} Q_{chp}. \tag{33}$$

The ratio between $\eta_{E,chp}$ and $\eta_{Q,chp}$ was obtained from the power data of the CHP from a full year based on five minute data. A constant value of 0.81 was found.

For this configuration of equipment, the control variables are:



(a) $f_0 = 0.5$ (b) $f_0 = 0$ (c) $\widetilde{J} = \int p_G G_{boil} + 10^{-3}\dot{Q}^2_{HT,boil}\,\mathrm{d}t$

Fig. 4. Desired heat profile of the greenhouse (top row), optimal control of the boiler (second row), optimal buffer flux (third row), and corresponding heat stored in the buffer (bottom row).

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{bmatrix} = \begin{bmatrix} Q_{HT,boil} \\ Q_{HT,chp} \\ Q_{HT,buf} \\ Q_{LT,buf} \\ b_{boil} \\ b_{chp} \end{bmatrix}, \; b_{boil},\, b_{chp} \in \left\{ 0,\, 1 \right\}. \tag{34}$$

Then, the goal function minimizing the total costs of buying gas, and buying or selling electricity - representing the revenues as negative costs - for the given time evolution of the gas and electricity price (Eqs. (36) and (37)) is:

$$\min_u J = \min_u \int_{t_0}^{t_f} (p_G G_{tot} + p_E E_{grid})\, \mathrm{d}t, \tag{35}$$

$$p_G(t), \quad t_0 \leqslant t \leqslant t_f, \tag{36}$$

$$p_E(t), \quad t_0 \leqslant t \leqslant t_f, \tag{37}$$

$$G_{tot} = G_{boil} + G_{chp}. \tag{38}$$

And E_{grid} is given through Eqs. (21), (22) and (33) by:

$$E_{grid} = E_{des} - \frac{\eta_{E_{chp}}}{\eta_{Q_{chp}}} \cdot (Q_{des} - Q_{HT,boil} - Q_{HT,buf} - Q_{LT,buf}) \tag{39}$$

Contrary to Eq. (13), no penalty was added for frequent on/off switching of the boiler and CHP in the standard optimization runs. However, different penalty values were tested. On most days, the control was not affected by the penalty. On some days, there was a slight reduction of the number of switching events per day (i.e. six instead of seven switching events per day). The total energy costs were not influenced.

The optimization was performed over a full day period. The parameters for the optimization in Section 2.2 are listed in Table 1. The CPU time for the optimization over a day varied between 1 and 48 s, with a mean value of 6 s and a standard deviation of 7 s.

2.2.3. Experiments

Various scenarios were analyzed to assess the optimization for the configuration with boiler, CHP, and buffers all using the desired heat pattern as calculated with the procedure explained in Appendix B. In the first scenario fixed prices for gas and electricity were used.

The second scenario was to perform the optimization with real heat and electricity demand patterns. In order to determine the factors that influenced the costs most heavily, the effect of the buffer filling terminal constraints and the sensitivity for the desired heat and electricity pattern was analyzed. In order to study the sensitivity of the optimization result to the final buffer fill status, the final buffer fill status for the high temperature buffer was changed by 10%. Furthermore, the heat and electricity demand, calculated from the grower's operation, as well as the prices of electricity and gas were varied by 10%. Apart from changing the electricity price with a fixed percentage, additional scenarios were analyzed with randomly modified prices. For each value of the electricity price (time series) the price was modified by picking a random value (uniform discrete distribution) from a pre-defined interval. After obtaining the random modification factors, the values where normalized, such that the mean percentage of change was zero. A range of −10% to 10%, and a range of −50% to 50% were used and repeated five times. Lastly, the effect of extending the buffer models with a heat loss factor was investigated.

3. Results

3.1. Case 1: Demonstration of the optimal control method with configuration of boiler and buffer

The result of optimizing the utilization of the boiler and buffer is shown in Fig. 4 for three different scenarios using the same artificial heat demand profile. The gas price was fixed at 0.34 € m^{-3} for the three presented scenarios.

In Fig. 4a the result of minimizing the gas cost with an initial buffer fill status (f_0) of 0.5 is shown. The buffer is empty at the end of the optimization period (Fig. 4a). This is the expected result since the goal is to minimize the total gas cost. The effect of the zero-or-range constraint (Section 2.1.2) can be seen in Fig. 4a. When the boiler is active, it is active between 60 and 75 W m^{-2} (i.e. between 80 and 100% of full capacity). The surplus of heat is stored in the buffer as indicated by the negative buffer flux ($Q_{HT,buf}$) during these periods. When the boiler is not active, the greenhouse is heated using heat from the buffer. At 22 h the boiler is active for 90% and some heat is coming from the buffer in order to empty it completely. The total gas cost for this day was 1186 € for the whole greenhouse, and therefore equal to 2.92 × 10^{-2} € m^{-2}.

When the initial buffer fill status is zero (Fig. 4b), the only heat source available for heating the greenhouse is the boiler. The first half of the day the boiler is active, and the surplus heat is stored in the buffer. The second half of the day the buffer and boiler are active in

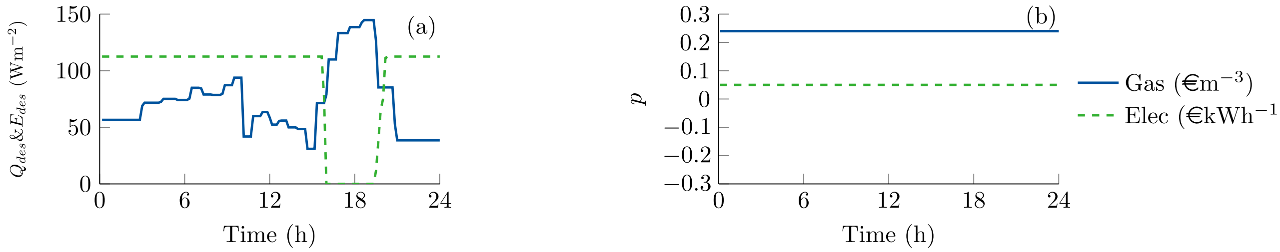


Fig. 5. Desired heat (solid) and electricity demand (dashed) (a), and gas price and electricity price (b) for November 1, 2012 with fixed prices for gas and electricity.

such a way that the buffer is empty again at the end of the optimization period. The total gas cost for this day were $4.54 \times 10^{-2}\,€\,m^{-2}$, which is higher than in the previous case because no 'free' heat was available in the buffer at the start.

In order to reduce the switching behavior of the boiler, a penalty on the switching of the control was implemented by replacing the goal function with Eq. (13) as described in Section 2.1.2.

Because the value of the goal functions is different, a direct comparison is not possible, but when we compare the gas costs component, it appears that the total gas costs remain the same. This reveals that there are several buffer control solutions for the optimization with the original goal function, meaning that the control solution found in Fig. 4b is not unique. In fact, by adding the penalty, the solution is forced to the quieter operation of Fig. 4c, without additional costs.

3.2. Case 2: Optimization of a configuration with boiler, CHP, and buffers and comparison with real data

3.2.1. Optimization with fixed prices

The desired heat and electricity demand profile to be delivered to the greenhouse and prices for November 1, 2012 are shown in Fig. 5a and b, respectively. The electricity demand is the electricity consumption of the lamps for artificial lighting in the greenhouse. The maximum capacity of the lamps was $112.5\,W\,m^{-2}$. The heat demand (Fig. 5a) was higher during the period when the lamps were off. The buffer fill status at beginning and end were fixed at the observed values.

Fig. 6 shows the results for November 1, 2012 with a fixed gas price of $0.24\,€\,m^{-3}$ and a fixed electricity price of $0.014 \times 10^{-6}\,€\,J^{-1}$ ($0.05\,€\,kW\,h^{-1}$) (equal to the mean prices for the whole year 2012). Heat fluxes of the boiler and CHP, the buffers, and the energy content of the buffers are shown in Fig. 6c for the optimal situation and in Fig. 6f for the grower's operation.

The total costs in the optimal scenario were $0.11\,€\,m^{-2}$, while in the grower's scenario this would have been $0.12\,€\,m^{-2}$ (using the same fixed prices). In the optimal scenario the CHP was always running, producing $5.3\,MJ\,m^{-2}$, while the grower produced $4.5\,MJ\,m^{-2}$ with the CHP. The remaining heat demand was produced by the boiler.

The optimization with fixed prices was also performed for a summer day (July 13, 2012) with a lower electricity and heat demand profile (not shown). The total costs were $0.037\,€\,m^{-2}$, while in the grower's scenario this would have been $0.040\,€\,m^{-2}$. The CHP was used to produce all heat in both cases. However, the moments when the CHP was on were different. Less electricity was bought from the grid, and more electricity was sold to the grid in the optimal scenario.

For both days, it appears that varying the level of the gas and electricity prices affected the total costs but did not affect the amount of heat and electricity produced.

3.2.2. Optimization with real, time variant, prices

3.2.2.1. Optimization results. Two days were selected in order to

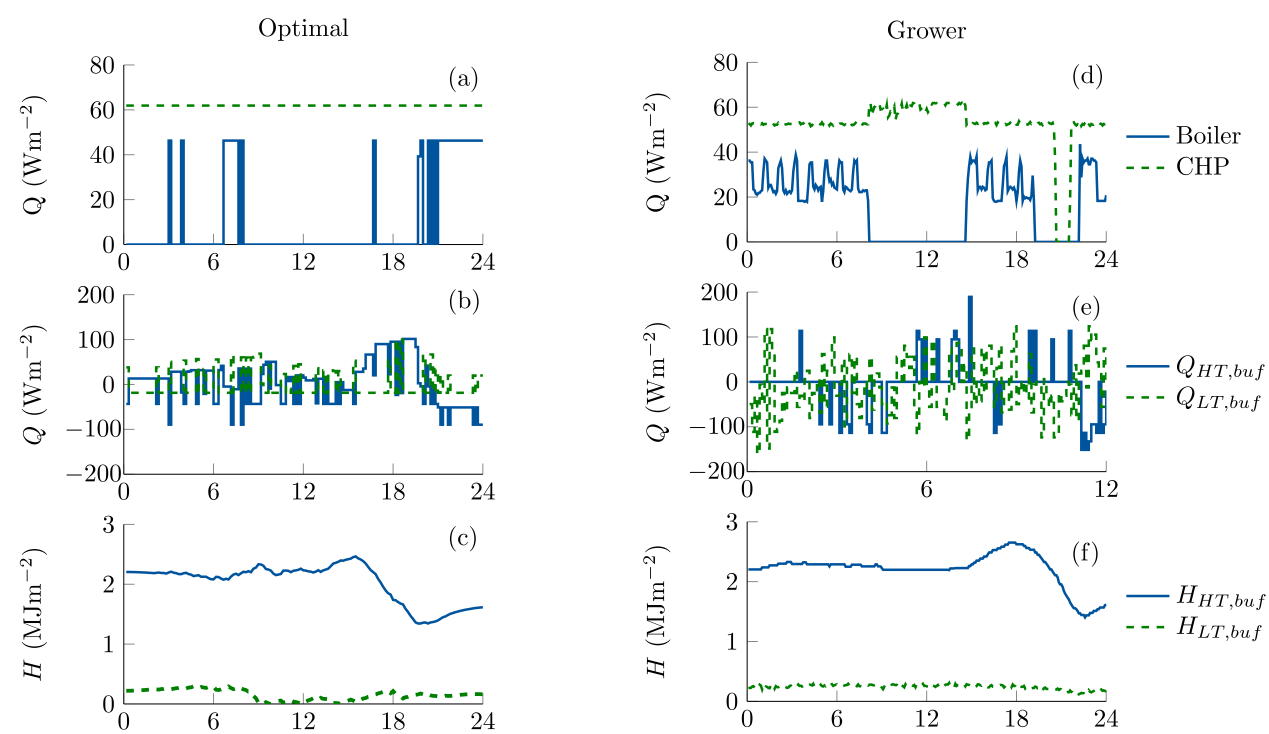


Fig. 6. Optimal (a,b,c) and grower's operation (d,e,f) of operating the boiler and CHP (a,d), buffer fluxes (b,e) and energy content of the buffers (c,f) for November 1, 2012 with fixed prices for gas and electricity.

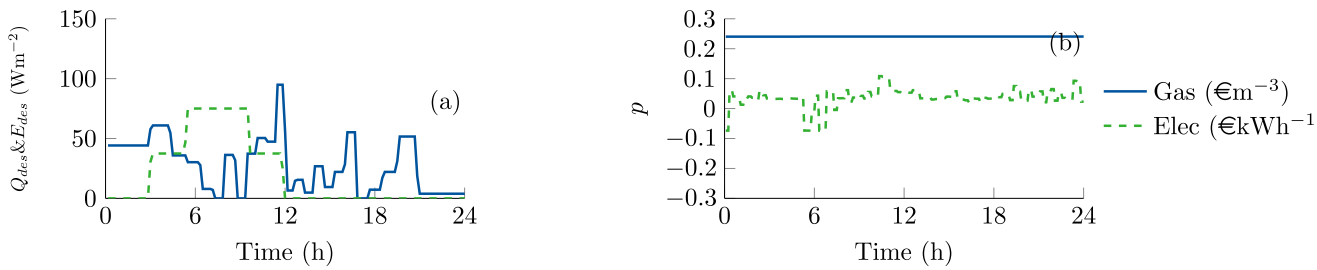


Fig. 7. Desired heat and electricity demand (a), and gas price and electricity price (b) for July 13, 2012.

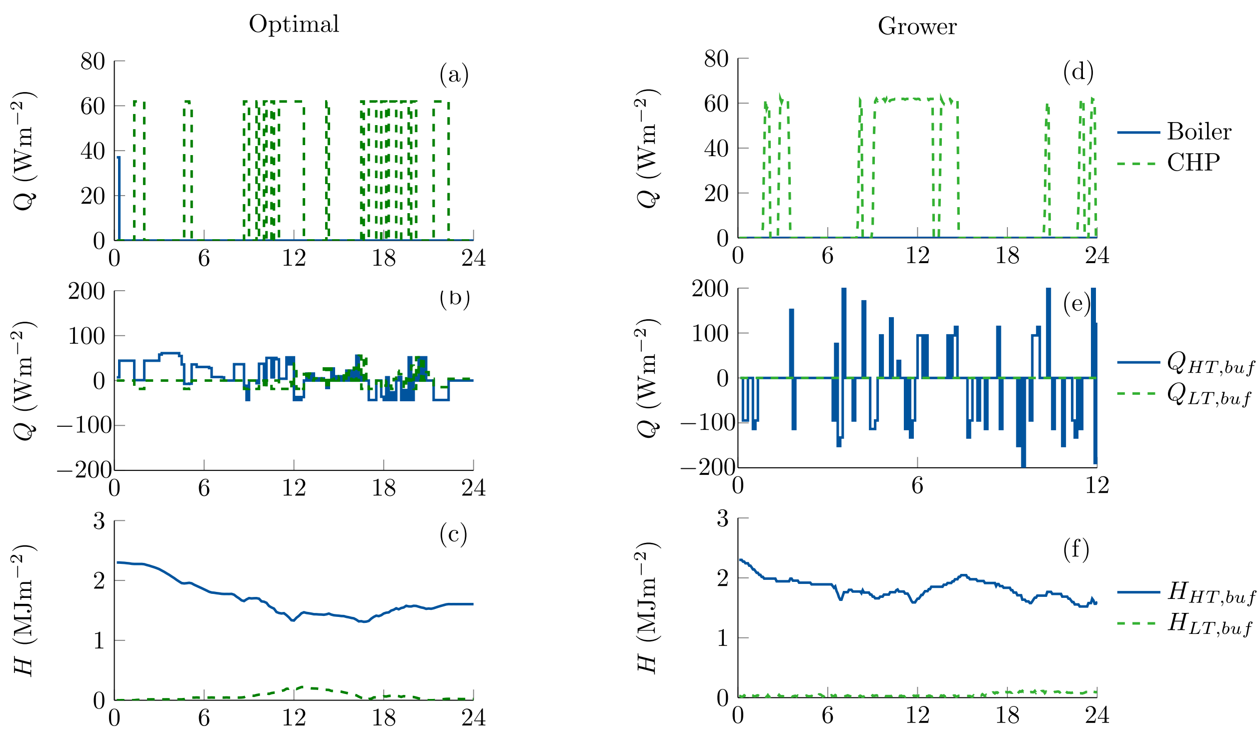


Fig. 8. Optimal (a) and grower's operation (d) of operating the boiler and CHP, buffer fluxes optimal scenario (b) and grower's operation (e), and energy content of the buffers optimal scenario (c) and grower's operation (f) for July 13, 2012.

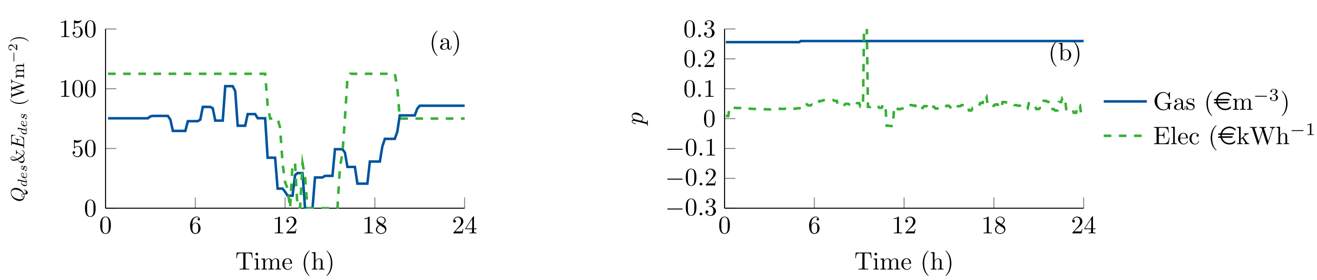


Fig. 9. Desired heat and electricity demand (a), and gas price and electricity price (b) for October 9, 2012.

demonstrate the grower's operation of the system and of the optimized operation. The first selected day was July 13, 2012, which was a day with a relatively low electricity demand. The second day was October 9, 2012, which was a day with a higher electricity demand. The heat and electricity demand and prices for July 13, 2012 are shown in Fig. 7a and b, respectively. The heat and electricity demand and prices for October 9, 2012 are shown in Fig. 9a and b, respectively (see Fig. 10).

Heat fluxes of the boiler and CHP, heat fluxes of the buffers, and the energy content of the buffers are shown in Fig. 8c for the optimal situation, and Fig. 8f for the grower's operation.

The breakdown of heat and electricity production for the selected days is summarized in Table 2. For July 13, 2012 the boiler was not used in both the optimal and grower's scenario. All heat was produced by the CHP. The total amount of heat produced by the CHP was slightly higher in the optimal scenario. More electricity was sold to the grid, while a similar amount of electricity was bought from the grid. The total costs for buying the electricity were lower and the total revenues from selling electricity were higher in the optimized scenario compared to the grower's operation. It can be seen that between the fixed initial and final values, that are identical for both optimization and grower, the time pattern of the energy content of the buffers ($H_{buf,HT}$ and $H_{buf,LT}$) were quite similar in both scenarios.

For October 9, 2012, the boiler was used in the optimal scenario but not by the grower. In the optimized scenario the CHP was used less.

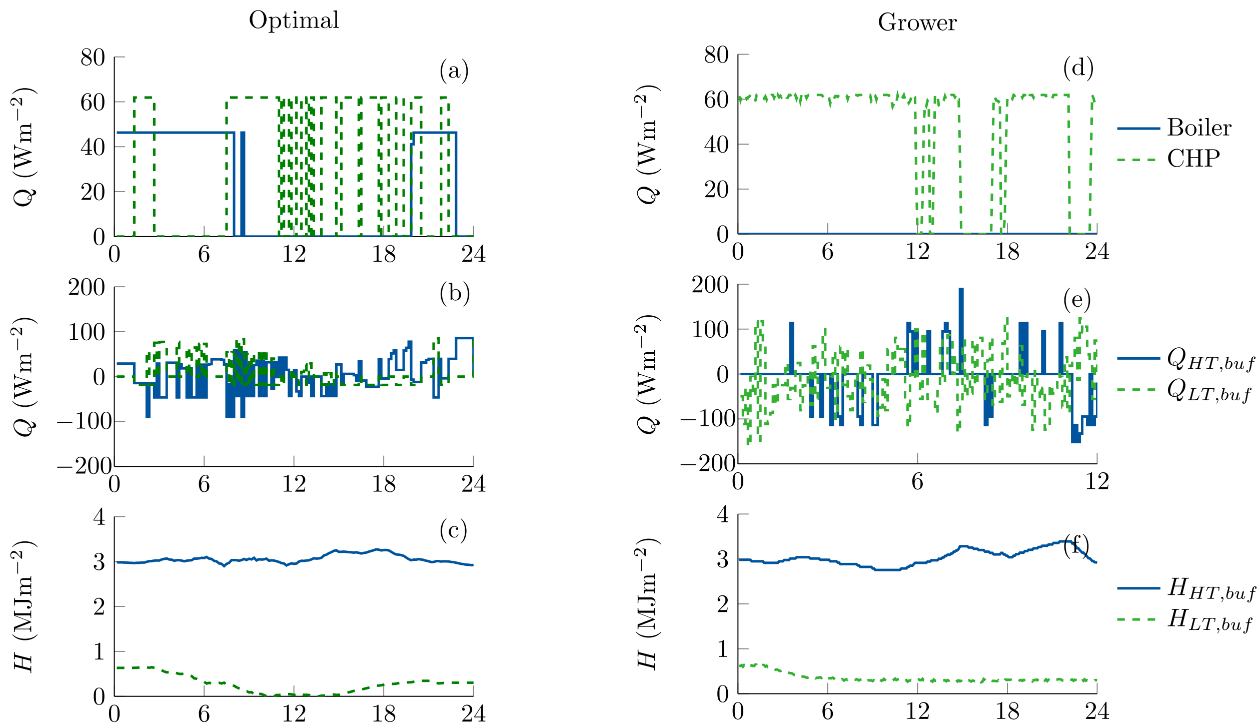


Fig. 10. Optimal (a) and grower's operation (d) of operating the boiler and CHP, buffer fluxes optimal scenario (b) and grower's operation (e), and energy content of the buffers optimal scenario (c) and grower's operation (f) for October 9, 2012.

Table 2
Performance indicators calculated from grower's operation of the greenhouse and optimization for two example days: July 13, 2012 and October 9, 2012.

Symbol	July 13, 2012		October 9, 2012		Unit
	Optimal	Grower	Optimal	Grower	
			Energy		
$\int Q_{HT,boil}^{tot}$	0.00	0.00	1.29	0.00	MJ m^{-2}
$\int Q_{chp}^{tot}$	1.69	1.64	3.00	4.22	MJ m^{-2}
$\int E_{buy}$	1.72	1.74	5.06	4.14	MJ m^{-2}
$\int E_{sell}$	0.91	0.67	0.55	0.38	MJ m^{-2}
			Costs of energy		
$\int G_{tot}$	0.025	0.025	0.058	0.070	€ m^{-2}
$\int E_{buy}$	0.007	0.008	0.057	0.051	€ m^{-2}
$\int E_{sell}$	−0.015	−0.009	−0.007	−0.005	€ m^{-2}
J	0.018	0.025	0.114	0.116	€ m^{-2}

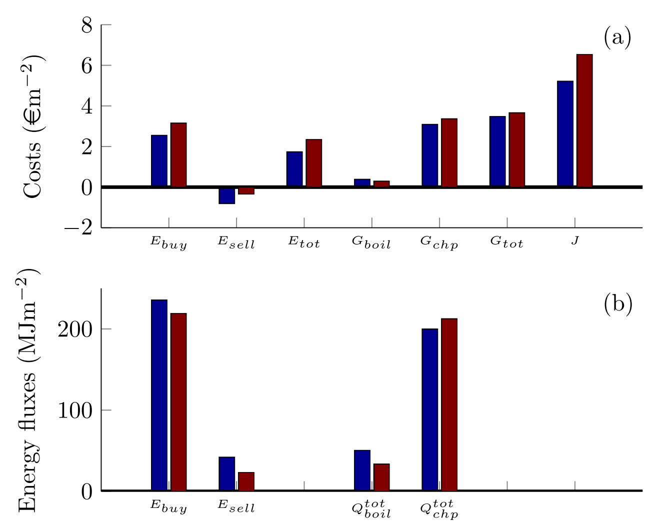


Fig. 11. Energy costs (a) and total energy fluxes (b) of the grower's scenario (red) and the optimal scenario (blue) for 63 days in 2012. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

More electricity was bought from the grid to fulfil the electricity demand. Therefore, the electricity costs were slightly higher than in the grower's scenario, but this was more than compensated by the lower expenditure for gas.

The boiler was utilized, such that the heat demand at each time is delivered and the constraints on the filling of the buffers at the end of the optimization period were fulfilled.

There is a slight difference in heat and electricity produced between the optimal scenario and the scenario of the grower (Table 2). This is because of noise in the assessment of the energy content of the buffers in the data of the grower (Appendix B). The heat profile sometimes showed negative values (Appendix B) since in the current set up it is not possible to take cooling needs into account; they were set to zero. For days with no negative values in Q_{des}, the total produced heat and electricity in the optimal scenario and grower's scenario were equal (not shown).

The optimization results for the 63 days where the configuration was congruent with that of the grower, are summarised in Fig. 11.

The cumulative cost function value (J^*) on those 63 days was 20% lower in the optimal scenario compared to the costs of the grower. This is mostly explained by the lower costs for buying electricity from the grid E_{buy} (−19%) and the higher benefits from selling electricity to the grid E_{sell} (+140%). The optimization can make use of the prior and full knowledge of the prices over the optimization horizon, in contrast to the grower. The costs for gas vary much less over time than the costs for electricity, therefore, the difference between the total costs for gas differs much less (5%) between the optimal scenario and the grower's scenario.

A comparison of energy consumption and utilization of equipment for the analyzed days is shown in Fig. 11b. In the optimal scenario the

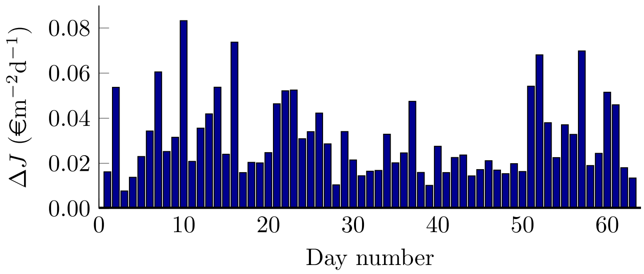


Fig. 12. Difference in the cost function value of the grower's scenario and the optimized scenario ($J_{grower} - J_{optimal}$) for all analyzed days in 2012. See Appendix B for the corresponding dates and day numbers.

amount of heat coming from the boiler is higher than in the grower's scenario. The boiler only produces heat but has a higher efficiency for heat production than the CHP. This means that less natural gas must be bought to produce the same amount of heat. Another difference between the optimal scenario and the grower is that more electricity is sold to the grid and more electricity is bought from the grid.

Fig. 12 shows the difference of the total costs between the grower and the optimized scenario for all 63 days considered. The optimal cost function value is lower on all 63 days than the costs of the grower.

3.2.2.2. Sensitivity analysis. The results of the single parameter sensitivity analysis (Section 2.2.3) on the final buffer fill status (H_{HT}), desired heat demand (Q_{des}) and desired electricity demand (E_{des}) are shown in Table 3.

A lower total buffer fill status of the high temperature buffer at the end of the optimization period of 10% led to a lower gas use of 0.7 $m^3\,m^{-2}$ and lower total costs of 0.11 € m^{-2}. A higher terminal buffer fill status led to higher gas use and costs. The total extra costs for the extra gas are relatively low because more electricity was produced that was sold to the grid. This means that a higher heat demand does not necessary lead to higher costs when the surplus electricity is sold for a price that is high enough. The same holds for overall lower and higher desired heat profile. The difference in total costs are relatively low. The costs and gas use for the case with 10% lower heat demand were about the same as in the standard scenario.

The total gas use was similar when the electricity demand profile was varied because more electricity was bought from the grid when the electricity demand was higher than the electricity production of the CHP. The total costs were much more sensitive to the electricity demand than the heat demand for the analyzed days.

Lowering the gas price always by 10% led to lower energy costs and higher gas use. This is because, compared to the standard scenario, there were more moments with electricity demand from the greenhouse for which it was cheaper to generate the electricity with the CHP instead of buying the electricity from the grid. Also, the costs of producing electricity when sold to the grid was lower. Higher electricity prices also lead to higher gas use, for the same reasons, but the total energy costs become somewhat higher. Lower electricity prices led to somewhat lower energy costs and gas use as in the standard scenario.

The effect of a perfect price forecast for electricity was investigated by random modification of the electricity price at each time with a random percentage from a pre-defined range. The standard deviation of the optimal solutions was 0.0007 € for the interval of −10% to 10%, and 0.004 € for the interval of −50% to 50%. This effect is rather small, because the mean percentage of the changed price was zero.

The effect of heat loss from the buffer for 1% heat loss per day led to an increase of 0.4% of the total costs for energy. The total costs for scenario 14 in Table 3 were 0.8% higher than the costs of the standard scenario. The gas use increased proportionally with the heat loss.

4. Discussion

4.1. Configuration

In this study, optimizations were first performed using a boiler and heat buffer (configuration 1) and secondly using a boiler, CHP, and two different heat buffers (configuration 2). Both configurations occur in Dutch greenhouse horticulture practice. Clearly, in practice, configurations may vary; for instance, in configuration 2, often just one heat buffer is installed. However, the optimal control method is flexible and can easily be adapted to the actual scenario, such as selling heat to the neighboring greenhouse or adding additional equipment.

CO_2 for the enrichment of greenhouse air was not taken into account for the two configurations optimized in this paper. The reason is that in this case an industrial CO_2 source was used. The desired CO_2 concentration or dosing strategy in modern greenhouses depends, amongst others, on the type of crop, crop development stage, light conditions, and the ventilation rate. However, by virtue of the generic character of the optimization problem this scenario can be accommodated as well, provided that like heat and electricity demand, the CO_2 demand pattern is specified in advance. CO_2 from the boiler is often used directly for CO_2 enrichment (Bailey, 2002). CO_2 from the CHP is also often used but the exhaust gas is mostly cleaned in order to prevent crop damage due to noxious gasses in the exhaust gas. To implement this in the optimization framework, the desired CO_2 must be produced by the boiler or CHP (both with their own efficiency for the

Table 3
Effect of final buffer fill status, desired heat demand, desired electricity demand, and prices of electricity and gas on the goal function (J^*) and optimal gas use (G^*_{tot}) over the selected 63 days.

#	Standard scenario	New scenario	$\sum J^*$, € m^{-2}	$\sum\int G^*_{tot}$, $m^3\,m^{-2}$
1	$H_{HT,buf}(t_f) = H_{HT,grower}(t_f)$		5.22	13.9
2	$H_{HT,buf}(t_f) = H_{HT,grower}(t_f)$	$H_{HT,buf}(t_f) \geqslant H_{HT,grower}(t_f)$	5.22	13.9
3	$H_{HT,buf}(t_f) = H_{HT,grower}(t_f)$	$H_{HT,buf}(t_f) \geqslant 0.9 \cdot H_{HT,grower}(t_f)$	5.11	13.2
4	$H_{HT,buf}(t_f) = H_{HT,grower}(t_f)$	$H_{HT,buf}(t_f) \geqslant 1.1 \cdot H_{HT,grower}(t_f)$	5.32	14.5
5	$Q_{des}(t)$	$0.9 \cdot Q_{des}(t)$	5.04	12.8
6	$Q_{des}(t)$	$1.1 \cdot Q_{des}(t)$	5.41	14.9
7	$E_{des}(t)$	$0.9 \cdot E_{des}(t)$	4.69	13.9
8	$E_{des}(t)$	$1.1 \cdot E_{des}(t)$	5.74	13.9
9	$p_G(t)$	$0.9 \cdot p_G(t)$	4.86	14.4
10	$p_G(t)$	$1.1 \cdot p_G(t)$	5.56	13.3
11	$p_E(t)$	$0.9 \cdot p_E(t)$	5.03	13.3
12	$p_E(t)$	$1.1 \cdot p_E(t)$	5.38	14.4
13	$a = 0\%$	$a = 1\%$	5.24	14.0
14	$a = 0\%$	$a = 2\%$	5.26	14.0

production of CO_2) or come from an external CO_2 source. The efficiency or costs of running the exhaust gas cleaner need to be considered in case of a CHP with exhaust gas cleaner.

4.2. Optimization

The desired heat and electricity profiles for generating the greenhouse climate were taken equal to those of the grower. These profiles of the grower were calculated from data of power production by the CHP, boiler and buffers stored in the greenhouse process control computer. In the optimization, the amount of heat stored in the buffers depends on the incoming and outgoing heat flux. Heat losses during transportation and storage were neglected, and it was assumed that all heat that was stored in the buffer was regained, which could lead to an under-estimation of the true energy consumption of about 0.4% per percent of heat loss per day as shown in the sensitivity analysis. The available measured buffer data showed very fluctuating behavior (Appendix B).

More than one buffer control solution is possible if the buffer efficiency is equal to 1, as assumed in the paper, and when the gas price is constant. Even when the efficiency of the buffer is smaller than 1, there can be multiple controls that can deliver the same amount of heat to the greenhouse. However, in that case the total costs will be slightly higher since not all heat that is put in the buffer can be regained.

The costs for electricity and gas found in the optimization were 20% lower than in the grower's scenario. An important difference is that, in the optimization, the costs of gas and electricity were perfectly known in advance. Differences between the energy fluxes in the optimized and grower's scenario were sometimes small but could result in large differences in the costs because of the strong fluctuations that occurred in the electricity price. Therefore, we emphasize that a reliable prediction of the prices, together with a proper prediction of the heat and electricity demand of the greenhouse would be very valuable for growers. Zaheer-uddin and Zheng (2000) also suggest that it is possible to take advantage of the storage possibilities and electricity prices by allowing the demand of heat and electricity to vary within acceptable limits. This is also in line with the energy savings found by widening the bounds in Van Beveren et al. (2015b).

The presented optimization is an open loop optimization. In the current form, the optimization is performed afterwards and can be used as a tool to analyze the performance and find possibilities for improvement. In order to implement the optimization procedure in the current greenhouse practice as a forecasting tool, a receding horizon optimal control approach would be suitable Tap (2000), Van Straten et al. (2002), Van Ooteghem et al. (2005) and Oldewurtel et al. (2012). In that case, a reliable weather forecast and price forecasts for electricity and gas must be available for the horizon of the optimization (e.g. one or a few days). The prediction of outdoor weather is important because the heat and electricity profiles that must be realized depend strongly on the weather conditions.

Also, in practice, the calculation time is an important aspect for implementation. The calculation times found for the optimization with fixed prices were far below the chosen time interval of one hour. Even the longest calculation time of 316 s for three successive days is still shorter than the time interval of one hour. The CPU time for the optimization with real prices were all shorter than one minute. Therefore, we do not expect problems with calculation time in practice. Another aspect for practical implementation is the prevention of frequent switching of the equipment. The current quadratic method did not provide a satisfactory solution, thus, requires further investigation.

In practice, many different configurations and combinations of equipment for heat and cold production and storage occur. This work aimed to be a starting point for optimizing and understanding optimal scheduling of these systems. Therefore, the next logical step would be to expand the optimization framework with other equipment like a heat pump, aquifer storage, cold storage in short term buffers, and cooling machines. Heat and cold storage in aquifers is typically used for long term (seasonal) energy storage. Extension of the optimization framework in such systems requires a solution to handle long term buffering.

Optimizing the configurations as described in this paper for a longer period are expected to decrease the energy use and costs since the buffers can be used more effectively. In case of a longer optimization period, the buffers have more freedom and time to anticipate to the desired heat and electricity profile. This is supported by the results of the sensitivity analysis on the final buffer filling.

If there are no constraints on the buffer capacity and final buffer filling, the cost effectivity of the CHP can be assessed as follows: The boiler has a thermal efficiency of 0.94. To produce 1 MJ of heat, 35.17 m^3 of gas must be burned. As 1 MW h is equivalent to 3600 MJ, the production of 1 MW h of heat with the boiler requires 109 m^3 gas with associated costs of p_G (€ m^{-3}) $*$ 109 (m^3). The thermal efficiency of the CHP is 0.46 for heat (Table 1). To produce 1 MW h of heat with the CHP, 223 m^3 gas must be burned, so it seems that the costs of 1 MW h CHP heat are p_G (€ m^{-3}) $*$ 223 (m^3). However, this comparison is not fair since the CHP also produces electricity. So, the total efficiency (heat + electricity) of the CHP is 0.83. With an efficiency of 0.83, 123 m^3 gas is needed to produce 1 MW h (heat + electricity), whereby, about 45% is electricity and 55% is heat. Although it seems that the CHP is not as energy efficient as the boiler, economically the CHP is in general more efficient, provided that the electricity price is high enough. For example, burning 114 m^3 gas produces 0.8 MW h electricity, in this case, the CHP is more cost-effective if the electricity price is larger than $0.14 * p_G$.

5. Conclusion

Several issues that hamper the application of the flexible dynamic framework for resource allocation in greenhouses have been solved. In particular, zero-or-range constraints were implemented in order to operate the boiler and CHP between a specified range when they are active. In addition, simultaneous loading and unloading of the buffer was prevented by defining the heat flux from and to the buffers as a single flux that can be positive or negative. It was shown that these modifications, together with a powerfull numerical tool, ensured the feasibility of the dynamic optimization approach.

The application of open-loop optimization for a realistic greenhouse configuration showed a potential benefit in the order of 20% as compared to the actual operation of the grower, at least for those days where the configurations were congruent. It shows that a given heat demand does not necessariliy come with a fixed price to pay. Rather, using price information in conjunction with dynamic optimization appears to pay off. It underlines that trading and short-term forecasting of gas and electricity prices in combination with dynamic optimization have a high potential for cost savings in horticultural practice. The total energy cost for the studied greenhouse was more sensitive to the electricity demand than to the heating demand.

The benefits of the optimization procedure implemented this way are twofold: (1) it facilitates the decision on when and how to deploy which piece of equipment, and (2) it provides an economically optimal solution.

The presented framework will be the basis for further development and extension with other equipment for heating and cooling.

Acknowledgment

The authors thank HortiMaX B.V., Lek Habo Groep B.V., Wageningen U&R Greenhouse Horticulture, and M. Boonekamp for useful discussions and for sharing their data. We thank Agro Energy for supplying the electricity and gas prices for the studied greenhouse. Furthermore, we thank the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs for their support. We would also like to thank the reviewers for their efforts to improve the quality of this paper.

Appendix A. Nomenclature

Table A.

Table A
Nomenclature

Symbol	Description	Unit
a	Buffer heat loss factor	$\%\text{d}^{-1}$
A	Greenhouse area	m^2
b	Boolean control variable	–
E	Electricity flux	W m^{-2} [grh]
G	Gas flux	m^3 [gas] m^{-2} [grh] s^{-1}
H	Heat content	J m^{-2} [grh]
J	Goal function	$€\,\text{m}^{-2}$ [grh]
p	Price	€
Q	Heat flux	W m^{-2} [grh]
r	Range of operation	–
S	Heat of combustion	J m^{-3} [gas]
t	Time	s
u	Control variable	
α	Buffer heat loss factor	$\%\text{s}^{-1}$
η	Efficiency	–
Subscript		
boil	Boiler	
buf	Buffer	
buy	Bought from the grid	
chp	Combined heat an power installation	
des	Desired	
E	Electricity	
f	Final	
grh	Greenhouse	
grower	Grower	
G	Gas	
grid	Public electricity grid	
HT	High Temperature	
LT	Low Temperature	
load	Loading	
optimal	hlOptimal	
sell	Sold to the grid	
unload	Unloading	
Superscript		
min	Minimum	
max	Maximum	
*	Optimal	

Appendix B. Derivation of the desired heat profile

In order to compare the optimization results with the operating strategy resulting from grower's operation of the greenhouse, the desired heat and electricity profiles were calculated from the realized production and delivery of heat and electricity as registered by the process control computer at the greenhouse facility (Eq. (B.1)).

$$Q_{des,grower} = Q_{HT,boil} + Q_{chp} - Q_{HT,buf,load} + Q_{HT,buf,unload} - Q_{LT,buf,load} + Q_{LT,buf,unload} \quad \text{(B.1)}$$

The greenhouse also delivered heat to a neighboring greenhouse ($Q_{buf,ext}$). This heat must also be delivered, so it was assumed to be part of $Q_{des,grower}$.

The five minute data of the buffer fill rate showed rather fluctuating behavior, while the data of the boiler and CHP were less fluctuating and more smooth. The fluctuating behavior was stronger for the low temperature heat buffer than for the high temperature heat buffer. To obtain data that better represent the inertia of the heat buffers, the high frequency was removed by taking hourly mean values for Q_{des} (Fig. B.13). A possible explanation for the behavior of the data can be the update interval of the energy content calculation and delays in the system due to the volume of the heating system.

Only days when the heat pump was not used were selected for comparison between the utilization of the equipment by the grower and the optimal scenario because the heat pump and heat buffering in the aquifer are not part of the model and optimization procedure yet. This extension will be considered in future research. In 2012 there were 64 days without heat pump usage. Some data were missing during one of the days, therefore, this day was excluded from the analysis. A list of the selected days is given in Table B.5. Within these 63 days, the low temperature heat storage was not used on 17 days. On those days the low temperature heat buffer was used as storage of cold water for greenhouse cooling. In the optimization procedure, this was implemented by adapting the maximum heat storage capacity, namely by setting $H_{LT,buf}^{max} = 0$.

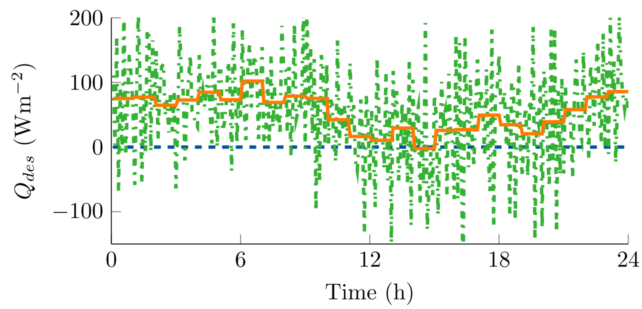


Fig. B.13. Calculated desired heat pattern using five minute data (···) and hourly means (—) for October 9, 2012.

Table B.5
Selected days for analysis.

Index	Day of year	Date	Index	Day of year	Date	Index	Day of year	Date
1	24	24-Jan-12	22	198	16-Jul-12	43	279	5-Oct-12
2	44	13-Feb-12	23	199	17-Jul-12	44	280	6-Oct-12
3	62	2-Mar-12	24	200	18-Jul-12	45	282	8-Oct-12
4	65	5-Mar-12	25	201	19-Jul-12	46	283	9-Oct-12
5	70	10-Mar-12	26	255	11-Sep-12	47	284	10-Oct-12
6	97	60-Apr-12	27	256	12-Sep-12	48	286	12-Oct-12
7	105	14-Apr-12	28	257	13-Sep-12	49	287	13-Oct-12
8	106	15-Apr-12	29	260	16-Sep-12	50	290	16-Oct-12
9	124	3-May-12	30	261	17-Sep-12	51	291	17-Oct-12
10	131	10-May-12	31	264	20-Sep-12	52	292	18-Oct-12
11	156	4-Jun-12	32	265	21-Sep-12	53	293	19-Oct-12
12	157	5-Jun-12	33	266	22-Sep-12	54	294	20-Oct-12
13	158	6-Jun-12	34	267	23-Sep-12	55	295	21-Oct-12
14	159	7-Jun-12	35	268	24-Sep-12	56	296	22-Oct-12
15	161	9-Jun-12	36	269	25-Sep-12	57	298	24-Oct-12
16	170	18-Jun-12	37	270	26-Sep-12	58	299	25-Oct-12
17	176	24-Jun-12	38	271	27-Sep-12	59	301	27-Oct-12
18	191	9-Jul-12	39	272	28-Sep-12	60	306	1-Nov-12
19	192	10-Jul-12	40	273	29-Sep-12	61	312	7-Nov-12
20	195	13-Jul-12	41	277	3-Oct-12	62	313	8-Nov-12
21	197	15-Jul-12	42	278	4-Oct-12	63	319	14-Nov-12

Appendix C. Derivation of heat loss factor buffer

The buffer without heat loss is modelled as (Eqs. (1) and (14)):

$$\frac{dH}{dt} = -Q \tag{C.1}$$

Suppose the heat loss Q_{loss} is proportional to the heat content:

$$Q_{loss} = -\alpha H \tag{C.2}$$

Eq. (C.1) then becomes:

$$\frac{dH}{dt} = -\alpha H - Q \tag{C.3}$$

Heat loss factors for different buffers used in greenhouse horticulture can be found in Van Steekelenburg et al. (2011). Suppose the heat loss for 1 day (24 h) is a% of the starting energy content. Assume $Q = 0$. Then it follows from Eq. (C.3) that:

$$H(t_f) = H(t_0)e^{(-\alpha(t_f - t_0))} \tag{C.4}$$

Since $H(tf) = (1 - 0.01 * a)H(t0)$ it follows that:

$$-\alpha(t_f - t_0) = \ln(1 - 0.01a) \tag{C.5}$$

From this it follows that with $t_f - t_0 = 24h = 24{\cdot}3600$ s, α is given by:

$$\alpha = -(\ln(1 - 0.01a))/(24{\cdot}3600) \tag{C.6}$$

In this way, the empirically known value of daily heat loss a is replaced by the parameter α, so that the optimization including heat loss can be performed by replacing Eq. (C.1) by Eq. (C.3).

References

Bailey, B.J., 2002. Optimal control of carbon dioxide enrichment in tomato greenhouses. Acta Hort (ISHS) Trop. Subtrop. Greenhouses 578, 63–69. https://doi.org/10.17660/ActaHortic.2002.578.6.

Bozchalui, M.C., Cañizares, C.A., 2014. Optimal Energy Management of Greenhouses in Smart Grids. IEEE Trans. Smart Grid 6, 827–835. https://doi.org/10.1109/TSG.2014.2372812.

Chandan, V., Do, A.-T., Jin, B., Jabbari, F., Brouwer, J., Akrotirianakis, I., 2012. Modeling and optimization of a combined cooling, heating and power plant system. In: American Control Conference (ACC), Montreal, QC, pp. 3069–3074. https://doi.org/10.1109/ACC.2012.6315606.

Cho, H., Smith, A.D., Mago, P., 2014. Combined cooling, heating and power: a review of performance improvement and optimization. Appl. Energy 136, 168–185. https://doi.org/10.1016/j.apenergy.2014.08.107.

Edvall, M.M., Goran, A., 2009. Tomlab quick start guide, Technical Report. Tomlab Optimization Inc., San Diego, CA, USA.

Fransen, J., 2015. Personal Communication.

Fuentes-Cortés, L.F., Ponce-Ortega, J.M., Nápoles-Rivera, F., Serna-González, M., El-Halwagi, M.M., 2015. Optimal design of integrated CHP systems for housing complexes. Energy Convers. Manage. 99, 252–263. https://doi.org/10.1016/j.enconman.2015.04.036.

Haeseldonckx, D., Peeters, L., Helsen, L., D'haeseleer, W., 2007. The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions. Renew. Sust. Energy Rev. 11, 1227–1243. https://doi.org/10.1016/j.rser.2005.09.004.

Hansen, P., Huge, J., 1989. Implicit treatment of zero or range constraints in a model for minimum cost foundry alloys. Manage. Sci. 35, 367–371. https://doi.org/10.1287/mnsc.35.3.367.

Holmstrom, K., Anders, O.G., Edvall, M.M., 2010. User's guide for Tomab 7.1, Technical Report, Tomlab Optimization Inc.

Husmann, H.J., Tantau, H.J., 2001. Integrated optimization of energy supply systems in horticulture using genetic algorithms. Comput. Electron. Agric. 31, 47–59. https://doi.org/10.1016/S0168-1699(00)00173-3.

Mitra, S., Sun, L., Grossmann, I.E., 2013. Optimal scheduling of industrial combined heat and power plants under time-sensitive electricity prices. Energy 54, 194–211. https://doi.org/10.1016/j.energy.2013.02.030.

Molenaar, J., Bokhove, O., Ramaekers, L., Van De Leur, J., Gvozdenovic, N., Bakri, T., Archer, C., Reeves, C., 2007. Optimizing a closed greenhouse. In: Proceedings of the 58st European Study Group Mathematics with Industry, pp. 55–68.

Oldewurtel, F., Parisio, A., Jones, C.N., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B., Morari, M., 2012. Use of model predictive control and weather forecasts for energy efficient building climate control. Energy Build. 45, 15–27. https://doi.org/10.1016/j.enbuild.2011.09.022.

Ooka, R., Ikeda, S., 2015. A review on optimization techniques for active thermal energy storage control. Energy Build. https://doi.org/10.1016/j.enbuild.2015.07.031.

Pagliarini, G., Rainieri, S., 2010. Modeling of a thermal energy storage system coupled with combined heat and power generation for the heating requirements of a University Campus. Appl. Therm. Eng. 30, 1255–1261. https://doi.org/10.1016/j.applthermaleng.2010.02.008.

Ren, H., Gao, W., Ruan, Y., 2008. Optimal sizing for residential CHP system. Appl. Therm. Eng. 28, 514–523. https://doi.org/10.1016/j.applthermaleng.2007.05.001.

Schütz, T., Streblow, R., Müller, D., 2015. A comparison of thermal energy storage models for building energy system optimization. Energy Build. 93, 23–31. https://doi.org/10.1016/j.enbuild.2015.02.031.

Seginer, I., van Beveren, P., van Straten, G., 2018. Day-to-night heat storage in greenhouses: 3 Co-generation of heat and electricity (CHP). Biosyst. Eng. 172. https://doi.org/10.1016/j.biosystemseng.2018.05.006.

Tap, R.F., 2000. Economics-based optimal control of greenhouse tomato crop production. Ph.D. thesis. Wageningen University, Wageningen.

Vadiee, A., Martin, V., 2012. Energy management in horticultural applications through the closed greenhouse concept, state of the art. Renew. Sust. Energy Rev. 16, 5087–5100. https://doi.org/10.1016/j.rser.2012.04.022.

Vadiee, A., Martin, V., 2014. Energy management strategies for commercial greenhouses. Appl. Energy 114, 880–888. https://doi.org/10.1016/j.apenergy.2013.08.089.

Van Beveren, P.J.M., Bontsema, J., Van Straten, G., Van Henten, E.J., 2015a. Minimal heating and cooling in a modern rose greenhouse. Appl. Energy 137, 97–109. https://doi.org/10.1016/j.apenergy.2014.09.083.

Van Beveren, P.J.M., Bontsema, J., Van Straten, G., Van Henten, E.J., 2015b. Optimal control of greenhouse climate using minimal energy and grower defined bounds. Appl. Energy 159, 509–519. https://doi.org/10.1016/j.apenergy.2015.09.012.

Van Den Bulck, N., Coomans, M., Wittemans, L., Hanssens, J., Steppe, K., 2013. Monitoring and energetic performance analysis of an innovative ventilation concept in a Belgian greenhouse. Energy Build. 57, 51–57. https://doi.org/10.1016/j.enbuild.2012.11.021.

Van der Valk, R., Van der Poll, W., 2007. Actieplan voor een klimaatneutrale glastuinbouw (Action plan for climate-neutral greenhouse horticulture). Technical Report, Stichting Natuur en Milieu and LTO Glaskracht (in Dutch).

Vanhoudt, D., Desmedt, J., Van Bael, J., Robeyn, N., Hoes, H., 2011. An aquifer thermal storage system in a Belgian hospital: long-term experimental evaluation of energy and cost savings. Energy Build. 43, 3657–3665. https://doi.org/10.1016/j.enbuild.2011.09.040.

Van Ooteghem, R.J.C., 2007. Optimal control design for a solar greenhouse. Ph.D. thesis. Wageningen University, Wageningen.

Van Ooteghem, R.J.C., Van Willigenburg, L.G., Van Straten, G., 2005. Receding horizon optimal control of a solar greenhouse. In: Acta Hort. (ISHS), 691. pp. 797–806.

Van Steekelenburg, A., Hoogervorst, W., Van Antwerpen, A., 2011. Inventarisatie Thermische wateropslagsystemen Inleiding. Technical Report, HAS KennisTransfer, 's-Hertogenbosch.

Van Straten, G., Van Willigenburg, L.G., Tap, R.F., 2002. The significance of crop co-states for receding horizon optimal control of greenhouse climate. Control Eng. Practice 10, 625–632.

Vanthoor, B.H.E., 2011. A model-based greenhouse design method. Ph.D. thesis. Wageningen University, Wageningen.

Van Willigenburg, L.G., Van Henten, E.J., Van Meurs, W.T.H.M., 2000. Three time-scale digital optimal receding horizon control of the climate in a greenhouse with a heat storage tank. In: Proceedings Int. Conf. Modelling and control in agriculture, horticulture and post-harvested processing (Agricontrol). pp. 184–189.

Vermeulen, P., 2014. Combined Heat and Power (CHP) as a possible method for reduction of the CO2 Footprint of Greenhouse Horticulture. J. Energy Challenges Mech. 1, 37–40.

Vermeulen, P., Van der Lans, C., van der Lans, C., 2011. Combined Heat and Power (CHP) as a possible method for reduction of the CO2 footprint of organic greenhouse horticulture. In: Proc. Rist IC on Organic Greenhouse Hort, pp. 61–68. doi:10.17660/ActaHortic.2011.915.7.

Zaheer-uddin, M., Zheng, G.R., 2000. Optimal control of time-scheduled heating, ventilating and air conditioning processes in buildings. Energy Convers. Manage. 41, 49–60.