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Optimal utilization of energy equipment in a semi-closed greenhouse☆

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A B S T R A C T

Increasing variability in energy-saving equipment and systems in the greenhouse industry raises the question of how to best utilize the various equipment in such a setting. The development of adequate solutions for deployment and control of this diversity of equipment has not kept pace with the innovations in the greenhouse industry. In earlier work a two-step dynamic optimization framework was developed, where in step one energy demand for heating and cooling is optimized within the climate constraints set by the grower, and in step two energy costs are minimized of alternative equipment use to satisfy that demand. Here the aims are: (1) to develop step two; (2) to illustrate the potential cost savings of both steps by comparing optimization results with real-life data from one specific grower, as a benchmark. The energy equipment of a 4 ha semi-closed greenhouse was optimized on a daily basis using dynamic optimization for a period of one year. Predefined heating, cooling, and electricity demand patterns computed from available grower data served as input, together with realized prices for gas and electricity. The installed equipment contained a boiler, a CHP (combined heat and power installation), short term buffers for high and low temperature heat and cold water storage, a heat pump, an aquifer for long term heat and cold storage and cooling towers. Cooling towers are a new element in the field of greenhouse energy optimization.

The results show that cost optimization of the energy system is feasible and beneficial. Energy cost savings of 29% were obtained for the optimized situation as compared to the real situation at the grower. All available equipment was utilized in the optimal situation. The results show that trading of electricity and short-term forecasting of gas and electricity prices in combination with dynamic optimization has a high potential for cost savings in horticultural practice. Dynamic optimization pointed to a higher share of sustainable energy in the energy budget.

1. Introduction

A greenhouse is a permanent glass or plastic covered building for the production of fruits, vegetables, flowers, or ornamentals that has means for controlling the crop environment (Stanghellini et al. , 2019). The high energy demand of greenhouses, especially in Northern latitudes, led to the development of the closed greenhouse concept (Opdam et al., 2005; Bakker et al., 2006; Grisey et al., 2011; Vadiee and Martin, 2012; Vadiee and Martin, 2013). The main idea of the closed greenhouse is to maximize the utilization of solar energy through seasonal storage (Vadiee and Martin, 2013). It is called closed greenhouse because of the absence of air exchange with outdoor air. Heating, cooling, and dehumidification are needed to maintain temperature and relative humidity (RH) levels within acceptable bounds for plant production (Van Beveren et al., 2015). Cooling and dehumidification are usually done via heat-exchangers in the greenhouse (Bakker et al., 2006; De Zwart, 2011) as well as low temperature heating. This enables higher CO_2 concentrations in the greenhouse and consequently a higher potential plant production at lower injection rates (Dieleman and Hemming, 2011; Gieling et al., 2011). In a typical summer situation, the surplus heat is stored in the short term (diurnal) buffers or long term (seasonal) storage in underground aquifers (Van 't Ooster et al., 2007). In contrast to the summer situation, warm water from the aquifer heats the greenhouse in periods where no cooling is required. A heat pump increases the temperature of the stored water to a level that is suitable for heating.

The concept of the completely closed greenhouse evolved over the last decade in the direction of the semi-closed greenhouse concept. Semi-closed greenhouses have a smaller cooling capacity than the closed greenhouse and have ventilation windows that are opened when the cooling system has insufficient capacity (Qian et al., 2011). Next to cooling, ventilation is occasionally also needed for dehumidification. The semi-closed greenhouse can save a lot of energy by minimizing the ventilation and storing the surplus heat. In this way, natural gas consumption for heating is minimized. Several studies analyzed the performance of semi-closed greenhouses (De Zwart, 2008; Campen and Kempkes, 2011; Gieling et al., 2011; Qian et al., 2012).

However, the control of closed and semi-closed greenhouses was studied less. Molenaar et al. (2007) optimized by means of linear

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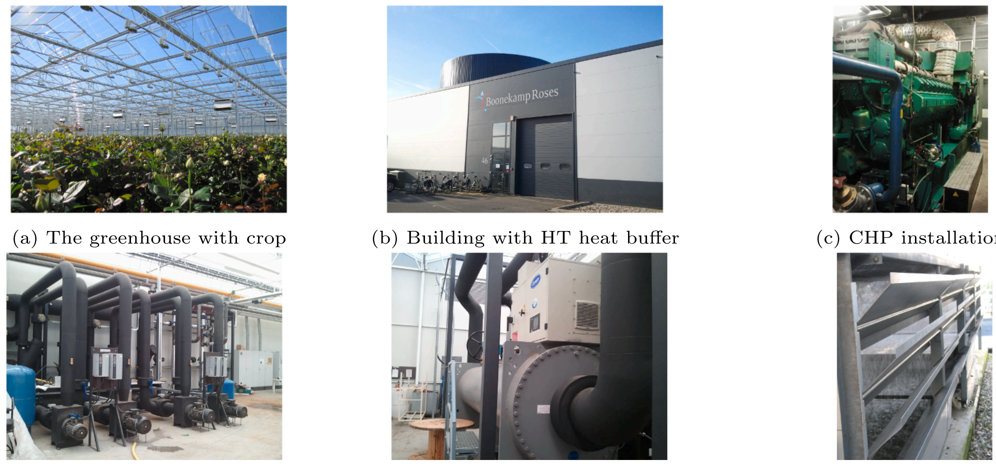

(a) The greenhouse with crop (b) Building with HT heat buffer (c) CHP installation

(d) Aquifer pumps (e) Heat pump (f) Cooling tower

Fig. 1. Photos of the greenhouse and equipment.

programming the energy costs of a closed greenhouse for a whole year using an artificially generated heat and electricity demand. Van Ooteghem (2007) presented a (receding horizon) optimal control formulation for a semi-closed greenhouse with aquifer thermal storage and a boiler. Van Willigenburg et al. (2000) proposed a three time-scale receding horizon optimal control approach to optimize a greenhouse with heat storage tank. In these examples only a limited set of equipment was considered, not fully reflecting the wide range of equipment available to greenhouse industry today. It seems the development of adequate solutions for deployment and control has not kept pace with the rapid adoption of such equipment in greenhouse industry in past years.

Scrutinizing work of Yu et al. (2015) shows that a similar kind of control issues are encountered in air conditioning of buildings using complex heating, cooling and energy storage systems. However, solutions from that application domain cannot be one to one projected on greenhouse practice due to significant differences between greenhouse systems and building systems.

Accounting for the growing complexity of the energy systems installed and fluctuating prices on the energy market, further extend the work presented in Van Beveren et al. (2015),Van Beveren et al. (2015), Van Beveren et al. (2019) and addresses the fundamental question on how to best utilize the available equipment. To deal with the complexity of the optimization and control problem, in Van Beveren et al. (2015, 2019) a two-step optimization paradigm was introduced. The first step consists of minimizing the energy input while realizing a desirable greenhouse climate, as defined by lower and upper temperature, humidity, and CO_2 bounds set by the grower. This step yields patterns for heating, cooling, and CO_2 enrichment (Van Beveren et al., 2015; Van Beveren et al., 2015). Then, the second step addresses the optimal scheduling and utilization of the equipment needed to fulfill the required demands calculated in step one and minimizing operating costs (Van Beveren et al., 2019). It is worth noting that in the second optimization step also demand patterns can be used based, in retrospect, on real-life data obtained in a practical greenhouse, thus offering the opportunity to evaluate practical system operation strategies compared to optimized strategies.

The current paper addresses the second optimization step and builds on and extends the work of Van Beveren et al. (2019). The novelty of this paper is threefold. First, while Van Beveren et al. (2019) addressed two simple yet realistic system configurations to build understanding for the optimization problem at hand, the current work addresses a realistic energy system configuration in its full complexity including, besides a boiler, CHP, short term low temperature and high temperature buffers, also a heat pump, aquifer long term energy storage and cooling towers. Addressing the optimal utilization of cooling towers in such an energy system is the second novelty of this work. Optimal control of energy systems for buildings that include cooling towers or cooling machines are presented among others by Kintner-Meyer and Emery (1995); Ma et al. (2009); Pavlov and Olesen (2012). Greenhouse systems with cooling towers have been described by Buchholz et al. (2005); Bakker et al. (2006); Blanco et al. (2014), but to the best of our knowledge optimal control of such an energy system in greenhouse cultivation has not been addressed before. Thirdly, the optimization is evaluated for a full year and compared to operational data of a real greenhouse utilizing this energy system in its full complexity.

This paper is organized as follows. First, the data of the greenhouse and equipment is disclosed (Section 2.1), then the formulation of the dynamic optimization problem addressing energy equipment and use is presented (Section 2.3). Secondly, in sections 3.1 to 3.3 optimal operation of the semi-closed greenhouse is illustrated and compared with practical operation of the studied greenhouse with the realized heating, cooling, and electricity demand of the year 2012. In addition to taking the real demands as a starting point, also the minimized energy demand of the greenhouse (Van Beveren et al., 2015) was taken as a starting point for optimization of the energy costs (Section 3.4). This demonstrates the potential cost saving of application of the optimization procedures in both the stages of energy demand and energy supply optimization.

2. Materials and methods

2.1. Data

Data was collected from a four-hectare (40709 m^2) rose producing greenhouse in Bleiswijk, the Netherlands (52 °N, 4.5 °E). Operational data from both the greenhouse process control computer and the energy control system were obtained for the whole year 2012, thus allowing comparison of the optimal control results with practice. The data from the energy control system included temperature measurements and control settings of pumps and valves. Data from both sources had a five-minute sampling interval. The outdoor climate for 2012 is shown in Appendix B. Furthermore, the real dynamic electricity and gas prices for the whole year 2012 were obtained through the energy supplier of the grower (15-min time interval). In the Netherlands, electricity produced with CHP installations is partly used for artificial lighting but mostly

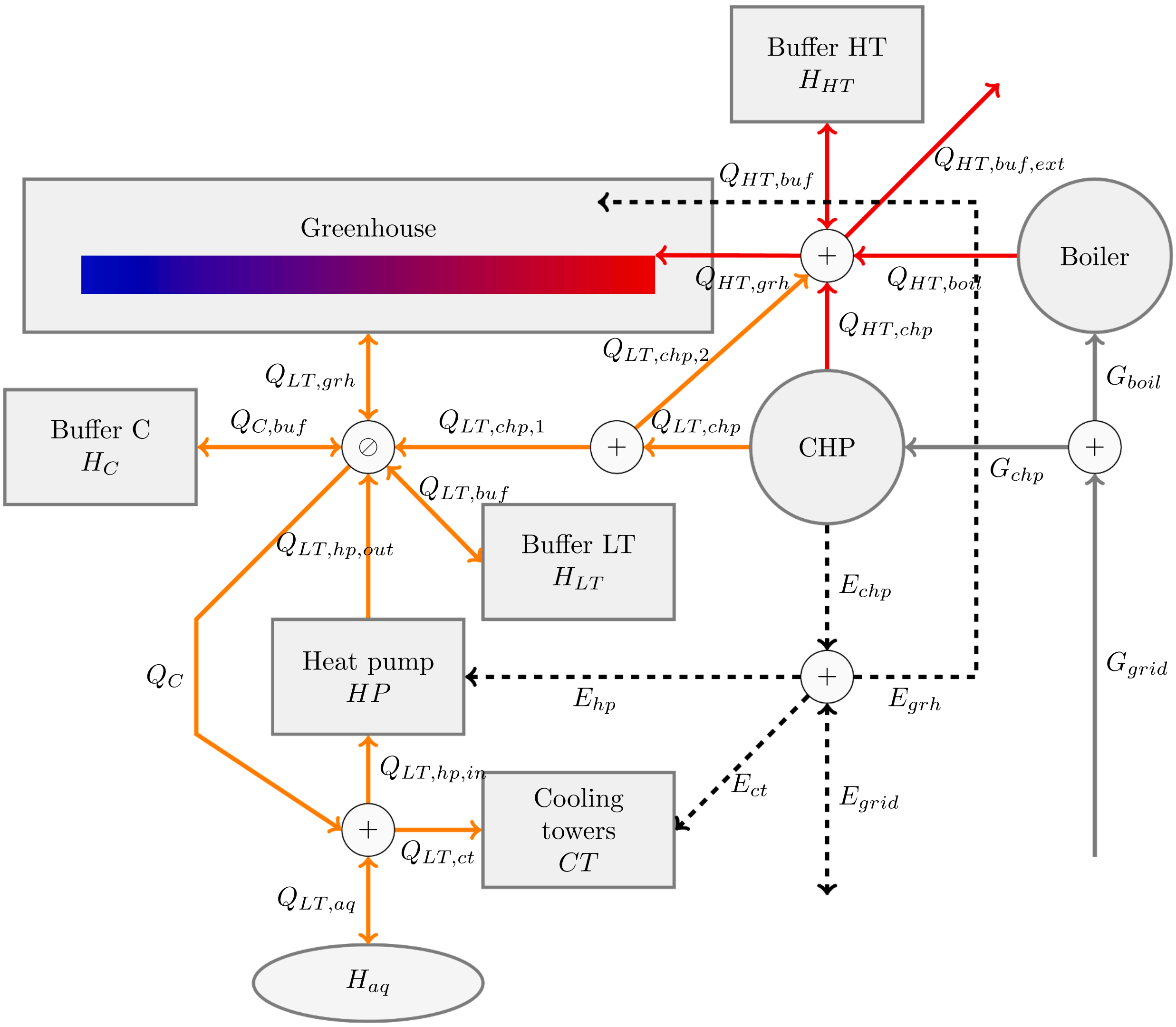

Fig. 2. System configuration for heating and cooling the greenhouse. High temperature heat fluxes (red solid line), low temperature heat fluxes (orange solid line), electricity fluxes (dashed line) and gas fluxes (grey solid line) are represented by arrows.

sold to the national power grid (Vermeulen and Van der Lans, 2011). Growers can 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. In this market, prices fluctuate every 15 min. Although rare, a negative electricity price can occur, meaning that the grower gets paid for using electricity.

2.2. Greenhouse description

The greenhouse dimensions were 281 m by 160 m, where a part of about 140 m by 32 m were office, equipment and storage space. Eave height was 6.4 m and ridge height was 7.2 m.

The following equipment was present in the greenhouse to control greenhouse climate: 1) pipe rail heating system, 2) ventilation windows, 3) water-to-air heat-exchangers for heating, cooling and dehumidification (OPAC106, De Zwart and Janssen (2010)), 4) supplementary lighting, and 5) energy and shading screens. The heat-exchangers (3) were placed above the crop. In the heat-exchangers cold or warm water was led to a large contact surface to exchange energy with the air. Air was recirculated through the unit by an internal fan. The use of such units is not common in greenhouse industry, yet. Active cooling may result in active dehumidification, so less ventilation is needed and higher CO_2 concentrations can be maintained in the greenhouse.

The available energy equipment to supply the heat and cold were an aquifer storing warm and cold water, heat pump, short term low temperature (*LT*) buffer and cold water (*C*) storage, short term high temperature (*HT*) buffers, boiler, CHP (combined heat and power installation), and cooling towers. Heat was also delivered to the neighboring greenhouse. Photos of the greenhouse and some of the equipment are shown in Fig. 1.

2.3. System configuration

A schematic overview of the system configuration is shown in Fig. 2. All symbols are explained in Appendix A.

Heating can be applied with the pipe rail heating system under the crop or with the heat-exchangers above the crop. The pipe rail heating system requires high temperature heat (>35 °C). Heating with the heat-exchangers requires low temperature heat (25 °C to 35 °C). Cooling can only be applied with the heat-exchangers.

In greenhouses without or with limited active cooling, the ventilation windows are opened to lower the greenhouse air temperature on warm sunny days. As a consequence, the CO_2 concentration drops under the desired CO_2 level because of limited CO_2 dosing capacity. The

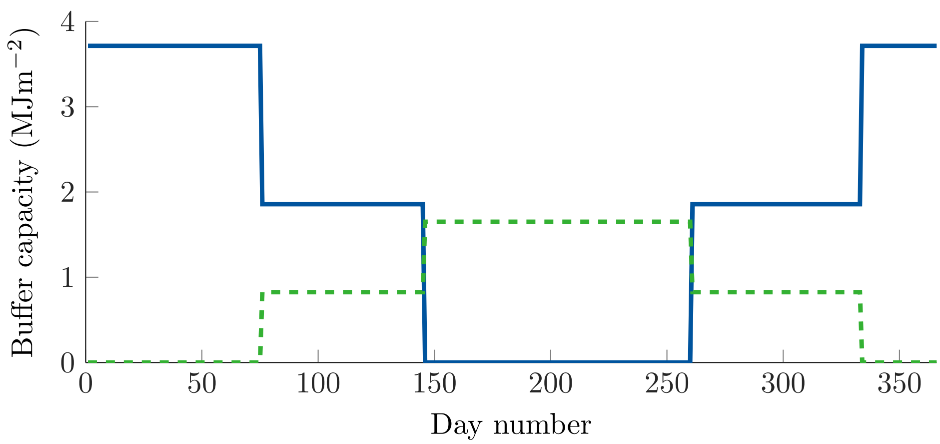

Fig. 3. Total capacity of the low-temperature heat buffer (▬▬) and cold buffer according to the practical use by the grower in 2012 (- - -). In total, two Klimrek buffers were present in the greenhouse that serve either as a low-temperature buffer (LT) or cold buffer (C).

advantage of active cooling is that ventilation loss of CO_2 is neutralized, and CO_2 remains available for assimilation which is beneficial for crop production and the environment.

Cooling is not only applied to lower greenhouse air temperature, but also to dehumidify greenhouse air. When using the heat-exchangers for cooling, vapor from the air condensates in the heat-exchanger. Dehumidification of greenhouse air is needed to prevent too high humidity levels in the greenhouse. High humidity levels increase the risk of diseases and fungi threatening crop health (Dieleman and Hemming, 2011). The need for dehumidification does occur more frequent in the late summer and autumn period in the Netherlands. Illuminated rose crops, as grown in the studied greenhouse, require a high number of dehumidification hours due to higher transpiration rates in cold and dark periods (Campen et al., 2003). It was observed in the data from the grower that heating and cooling were sometimes applied at the same time in order to correct both temperature and humidity.

High-temperature heat can either come from the boiler or the CHP. The CHP produces heat, electricity, and carbon dioxide gas (CO_2). Most greenhouses in the Netherlands use a gas-fired boiler combined with a CHP for heating the greenhouse. While burning gas, CO_2 is produced to enrich the greenhouse air. The CO_2 from the CHP was not used in the studied greenhouse. All CO_2 came from a CO_2 distribution network (OCAP, Ros et al. (2014)) in the west of the Netherlands except for a couple of days that OCAP CO_2 was not available. On those days, CO_2 from the boiler was applied. The CHP in the greenhouse was a Cummins QSV 91 G 18 bar with a total thermal capacity of 2.5 MW.

The cold water buffer and low-temperature heat buffer are two large water storages under the greenhouse floor of about 2650 m^3 each. These buffers are so-called 'Klimrek' buffers (Brand et al., 2008), and can either be used as a low-temperature heat storage (25 °C to 35 °C) or as a cold water storage (7 °C to 17 °C). As depicted in Fig. 3, buffers were initially employed by the grower as low-temperature heat storage in 2012. After 75 days, one buffer was designated as cold storage and the other as low-temperature buffer. During 16 weeks in summer, both buffers were operated as cold buffers. After this period, one buffer was in use as a low-temperature heat storage again, and finally, both buffers were used as low-temperature heat buffers.

The function of the heat pump is to bring low-temperature water to a higher temperature level, so that it is suitable for heating the greenhouse via the heat-exchangers or for temporary storage in the LT buffer. At the same time, water with a lower temperature (cold water) is leaving the heat pump. The heat pump can also be employed to fill the cold water buffer. Alternatively, the heat pump cools the warm water coming from the greenhouse or buffer. The produced cold water is then stored for later use. This is a typical summer situation.

The heat pump installed in the greenhouse was an electrical Carrier Evergreen Chiller 19XR with refrigerant type R-134a. The maximum thermal power of the heat pump was 2.5 MW. The COP (coefficient of performance) of the heat pump was determined from measured data as 5.5 (SD = 1.0).

An aquifer is a water-bearing sand layer to store warm or cold water. The aquifer used at the greenhouse consisted of four cold wells and four warm wells. The mean (measured) temperature of the water on the cold side of the aquifer was 10.7 °C (SD = 4.0 °C) and the mean (measured) temperature of the water on the warm side of the aquifer was 20.6 °C (SD = 4.8 °C).

The cooling towers were installed to fulfill governmental regulations on the storage of heat in aquifers, which state that the cold and the warm well should be in balance in the long term (Van Steekelenburg et al., 2011). This means that the same amount of heat that is extracted should be injected into the aquifer over multiple years. Rose greenhouses in the Netherlands with supplementary lighting have in general a surplus of heat. The cooling towers are intended to waste surplus heat in summer and to produce cold water to store in the aquifer in winter. These cooling towers have relatively low operating costs.

Electricity is primarily used for supplementary lighting (112.5 W. m^{-2} SON-T). The other consumers of electricity in the greenhouse are the heat pump and cooling towers. In the current case, electricity can be produced with the CHP or can be bought from the public electricity grid. Grower's in the Netherlands can also sell electricity to the grid at a dynamic market price. Electricity consumption from other equipment like pumps and controllers was not taken into account.

2.3.1. *Optimal control formulation*

In order to optimize the utilization of equipment for the presented configuration, an optimal control problem was formulated. The optimal control formulation of the semi-closed greenhouse configuration is an extension of the formulation of the second configuration (CHP, boiler and two heat buffers) in (Van Beveren et al., 2019), with a heat pump, aquifer heat storage, a cold buffer, and cooling towers.

All heat fluxes are defined as positive heat gains in the direction of the arrows in Fig. 2.

Extraction of heat e.g. from greenhouse or buffer was defined as a positive cold flux. All heat and electricity fluxes are expressed in W per square meter greenhouse floor area.

The system contains four different buffers. A buffer heat flux is either positive (unloading of the buffer) or negative (loading of the buffer). For the standard case, heat loss during transport and storage is ignored. Eqs.

Table 1
System defining parameters used for case study.

Symbol	Description	Value	Unit
η_{boil}	Boiler efficiency	0.94	–
$\eta_{E,chp}$	Electrical efficiency of the CHP	0.37	–
$\eta_{Q,chp}$	Thermal efficiency of the CHP	0.46	–
A	Greenhouse area	40709	m^2 [grh]
COP_{hp}	Coefficient of performance of the heat pump	5.5	–
H_{aq}^{max}	Maximum capacity aquifer	540	$MJ.m^{-2}$ [grh]
$H_{C,buf}^{max}$	Maximum capacity buffer C[a]	1.65×10^6	$J.m^{-2}$ [grh]
$H_{HT,buf}^{max}$	Maximum capacity buffer HT	3.14×10^6	$J.m^{-2}$ [grh]
$H_{LT,buf}^{max}$	Maximum capacity buffer LT[a]	3.71×10^6	$J.m^{-2}$ [grh]
$Q_{HT,buf}^{max}$	Maximum heat flux to buffer HT	150	$W.m^{-2}$ [grh]
$Q_{LT,buf}^{max}$	Maximum heat flux to buffer LT	150	$W.m^{-2}$ [grh]
$Q_{LT,ct}^{min}$	Minimum cooling capacity of the cooling towers	50	$W.m^{-2}$
–	Installed boiler capacity in the greenhouse	2.00	MW
–	Installed thermal CHP capacity in the greenhouse	2.52	MW
–	Installed heat pump capacity in the greenhouse	2.50	MW
$Q_{HT,boil}^{max}$	Maximum boiler thermal flux	49	$W.m^{-2}$ [grh]
Q_{hp}^{max}	Maximum heat pump thermal flux	62.5	$W.m^{-2}$ [grh]
Q_{chp}^{max}	Maximum CHP thermal flux	62	$W.m^{-2}$ [grh]
$Q_{LT,ct}^{min}$	Minimum thermal flux cooling towers	50	$W.m^{-2}$
r_{boil}^{min}	Minimum of the range for operating the boiler	0.8	–
r_{chp}^{min}	Minimum of the range for operating the CHP	0.85	–
S	Combustion heat of natural gas (upper calorific value)	35.17×10^6	$J.m^{-3}$ [gas]
t_f	Final time	86400	s

[a]Maximum capacity depends on day of the year according to Fig. 3.

(1)–(4) describe the energy content (H) of the high temperature buffer ($H_{HT,buf}$), aquifer (H_{aq}), low temperature heat buffer (H_{LT}), and cold buffer (H_C), respectively.

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

$$\frac{dH_{aq}}{dt} = -Q_{LT,aq} \tag{2}$$

$$\frac{dH_{LT}}{dt} = -Q_{LT,buf} \tag{3}$$

$$\frac{dH_C}{dt} = -Q_{C,buf} \tag{4}$$

The effect of heat loss from the *LT* and *HT* buffer was studied before in Van Beveren et al. (2019) and proved to have little effect on the optimization result. Heat loss from the aquifer is about 0.08% per day (Van Steekelenburg et al., 2011). The effect of incorporating the loss factor for the aquifer was analyzed using the same approach as in Van Beveren et al. (2019).

Since the two Klimrek buffers could be used as low-temperature heat storage or as a storage of cold water, these buffers together are treated in the optimal control formulation as one low-temperature (LT) storage and one cold water storage (C) with varying capacities throughout the year (as depicted in Fig. 3). The capacities of the low-temperature buffer and cold buffer were adapted, based on the day of the year, similar to the grower's operation in 2012. The maximal heat storage capacity for a single Klimrek buffer was 1.85 $MJ.m^{-2}$ for low temperature water and 0.82 $MJ.m^{-2}$ for cold water (Table 1). It can be seen that both Klimrek buffers contain LT heat in the first and last period of the year (day 1 to day 75 and day 334 to day 365). From day 146 to day 260, both Klimrek buffers stored cold water. In the remaining periods, one buffer served as low-temperature water storage and the other buffer served as cold water storage.

All buffers have limitations on the minimum and maximum amount of energy that can be stored in the buffer, Eqs. (5)–(8). The capacities of the buffers and aquifer are given in Table 1.

$$0 \leqslant H_{HT} \leqslant H_{HT}^{max} \tag{5}$$

$$0 \leqslant H_{aq} \leqslant H_{aq}^{max} \tag{6}$$

$$0 \leqslant H_{LT} \leqslant H_{LT}^{max}(t) \tag{7}$$

$$0 \leqslant H_C \leqslant H_C^{max}(t) \tag{8}$$

To enable a fair comparison between the grower's operation and the optimization, the heat withdrawn or stored in the buffers and aquifer over the day must be considered. Therefore, in the optimization, the initial fill status was taken from the data obtained from the grower. This leads to the following initial state constraints:

$$H_{HT,buf}(t_0) = H_{HT,grower}(t_0), \tag{9}$$

$$H_{aq}(t_0) = H_{aq,grower}(t_0), \tag{10}$$

$$H_{LT,buf}(t_0) = H_{LT,grower}(t_0), \tag{11}$$

$$H_{C,buf}(t_0) = H_{C,grower}(t_0). \tag{12}$$

The measured data of the buffers showed sometimes unrealistic values e.g. too large heat extraction in a short period for reasons not understood. Introducing a lower and upper bound with a small deviation of 1% ($f_{dev} = 0.01$) on the final state constraints of the buffers and aquifer solved this problem. This leads to the following final state constraints:

$$(1-f_{dev})H_{HT,grower} \leqslant H_{HT,buf}(t_f) \leqslant (1+f_{dev})H_{HT,grower}(t_f), \tag{13}$$

$$(1-f_{dev})H_{aq,grower}(t_f) \leqslant H_{aq}(t_f) \leqslant (1+f_{dev}H_{aq,grower}(t_f), \tag{14}$$

$$(1-f_{dev})H_{LT,grower}(t_f) \leqslant H_{LT,buf}(t_f) \leqslant (1+f_{dev})H_{LT,grower}(t_f), \tag{15}$$

$$(1-f_{dev})H_{C,grower}(t_f) \leqslant H_{C,buf}(t_f) \leqslant (1+f_{dev})H_{C,grower}(t_f). \tag{16}$$

When the low-temperature buffer is not used in summer, the heat flux to the buffer should be equal to 0. $b_{LT,buf}$ is an apriori defined boolean (no control variable) that is zero when there is no low-temperature buffer (Fig. 3). In the problem formulation this is implemented via the following constraint:

$$0 \leqslant Q_{LT,buf} \leqslant b_{LT,buf} Q_{LT,buf}. \tag{17}$$

Three different states of heating and cooling can occur in the greenhouse at the same time: (1) heating only, (2) cooling only, and (3) combined heating and cooling. The latter occurs mainly in the spring and autumn season when too high humidity levels in the greenhouse are prevented by cooling out vapor from the air with the heat-exchangers. At the same time, the indoor temperature is increased by heating so that the air can contain more water vapor and the temperature stays within the desired bounds. To cope with these three situations, a boolean b_C was calculated (apriori) from the pre-defined cooling demand and was not a control variable. When the greenhouse had a cooling demand, b_C was equal to one and otherwise, b_C was zero. When a cooling demand exists, heat could only be delivered via the high-temperature heating ($Q_{HT,grh}$). When no cooling demand exists, heat can be delivered via low ($Q_{LT,grh}$) or high-temperature heating (Eq. (18)).

$$Q_{HT,grh} + (1-b_C)Q_{LT,grh} = Q_{tot,grh} \tag{18}$$

The high-temperature heat could either come from the boiler ($Q_{HT,boil}$), high-temperature buffer ($Q_{HT,buf}$), or the high-temperature CHP outlet ($Q_{HT,chp}$) (Eq. (19)). As an extra option, the low-temperature heat produced by the CHP ($Q_{LT,chp}$) could be mixed with the high-temperature heat. The part of the LT heat from the CHP that is added to the high-temperature heat is $Q_{LT,chp,2}$. It was assumed that the resulting warm water is of sufficient temperature for heating the greenhouse. The mixing is inevitable in the summer period when both Klimrek buffers store cold water.

The division of low temperature heat from CHP is determined via Eq. (20). Eq. (21) is an additional constraint that limits the control variable $Q_{LT,chp,2}$.

$$Q_{HT,grh} = Q_{HT,boil} + Q_{HT,buf} + Q_{HT,chp} + Q_{LT,chp,2} \tag{19}$$

$$Q_{LT,chp,1} = Q_{LT,chp} - Q_{LT,chp2} \tag{20}$$

$$Q_{LT,chp,2} \leqslant Q_{LT,chp} \tag{21}$$

For reasons of efficiency and avoiding faster deterioration of parts, the boiler and CHP are preferably not run below a specific minimum operating power. To cope with this operation range of the boiler, a zero-or-range constraint was introduced (Hansen and Huge, 1989). In the case of the boiler it reads:

$$Q_{HT,boil} - Q_{HT,boil}^{max} b_{boil} \leqslant 0, \tag{22}$$

$$Q_{HT,boil} - r_{boil}^{min} Q_{HT,boil}^{max} b_{boil} \geqslant 0, \tag{23}$$

$$Q_{HT,boil} \geqslant 0, \tag{24}$$

$$b_{boil} \in \{0,1\} \tag{25}$$

where Eqs. 22 and 23 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. Eq. (24) is a trivial constraint on the heat flux from the boiler, which can only be positive.

A similar zero-or-range constraint for the CHP is given by Eqs. (26)–(29). This introduces the next boolean control variable (b_{chp}). The lower bound of the operating range of the CHP (r_{chp}^{min}) was determined from the data of the grower and turned out to be 0.85 in practice.

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

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

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

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

The low-temperature heat fluxes when $Q_{LT,grh}$ is in heating mode were calculated as:

$$Q_{LT,buf} + Q_{LT,hp,out} + Q_{LT,chp} - Q_{LT,chp,2} = (1-b_C)Q_{LT,grh}. \tag{30}$$

The low-temperature heat fluxes when the greenhouse has a cooling demand were calculated as:

$$-Q_{LT,aq} + Q_{C,buf} - Q_{LT,ct} - Q_{LT,hp,in} = b_C Q_{LT,grh}. \tag{31}$$

The electricity production of the CHP (E_{chp}) served the greenhouse (E_{grh}), powers the heat pump (E_{hp}) and the cooling towers (E_{ct}), or is sold to the grid ($E_{grid} < 0$, Eq. (32)). The cost of electricity generated by the CHP is already accounted for in the gas price.

$$E_{chp} + E_{grid} - E_{hp} - E_{ct} = E_{grh} \tag{32}$$

The electricity production by the CHP was calculated as:

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

The ratio between the electrical efficiency of the CHP $\eta_{E,chp}$ and the thermal efficiency $\eta_{Q,chp}$ was obtained from the power data of the CHP from a full year with a five minute time step. A ratio of 0.81 was found (Table 1).

The heat pump is either on or off. This is represented by the boolean control variable $b_{hp} \in \{0,1\}$ in the following equation:

$$Q_{LT,hp,out} = b_{hp} Q_{hp}^{max}. \tag{34}$$

The maximum thermal power of the heat pump Q_{hp}^{max} was 62.5 W.m^{-2}. The electric power uptake of the heat pump (E_{hp}) is

$$E_{hp} = \frac{Q_{LT,hp,out}}{COP_{hp}} \tag{35}$$

where $Q_{LT,hp,out}$ is the heat flux leaving the heat pump. The COP_{hp} (5.5) is the thermal coefficient of performance of the heat pump. The cold flux produced by the heat pump is then calculated as:

$$Q_{LT,hp,in} = Q_{LT,hp,out} - E_{hp} \tag{36}$$

Also, cooling towers have no variable control. They are either on or off. This is represented by the boolean control variable $b_{ct} \in \{0,1\}$. Minimum value $Q_{LT,ct}^{min}$ was introduced to allow cooling tower use on days when the grower did not use them. On other days the capacity was limited to the actual value observed. This was done to avoid the need for modeling the capacity of the cooling tower as a function of the external conditions; the actual operation by the grower served as a proxy. The heat flux to the cooling towers $Q_{LT,ct}$ depends on the maximum realized heat flux on that specific day.

$$Q_{LT,ct} = b_{ct} \max\left(Q_{LT,ct}^{min}, Q_{LT,ct}^{max,grower}\right) \tag{37}$$

Following the previous description, the optimization problem has twelve control variables:

$$u = \begin{bmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ \cdot \\ u_{12} \end{bmatrix} = \begin{bmatrix} Q_{LT,buf} \\ Q_{HT,buf} \\ Q_{LT,grh} \\ Q_{HT,boil} \\ Q_{HT,chp} \\ Q_{C,buf} \\ Q_{LT,aq} \\ b_{boil} \\ b_{chp} \\ b_{ct} \\ b_{hp} \\ Q_{LT,chp,2} \end{bmatrix} \tag{38}$$

where

$$b_{boil}, b_{chp}, b_{ct}, b_{hp} \in \{0,1\}, \tag{39}$$

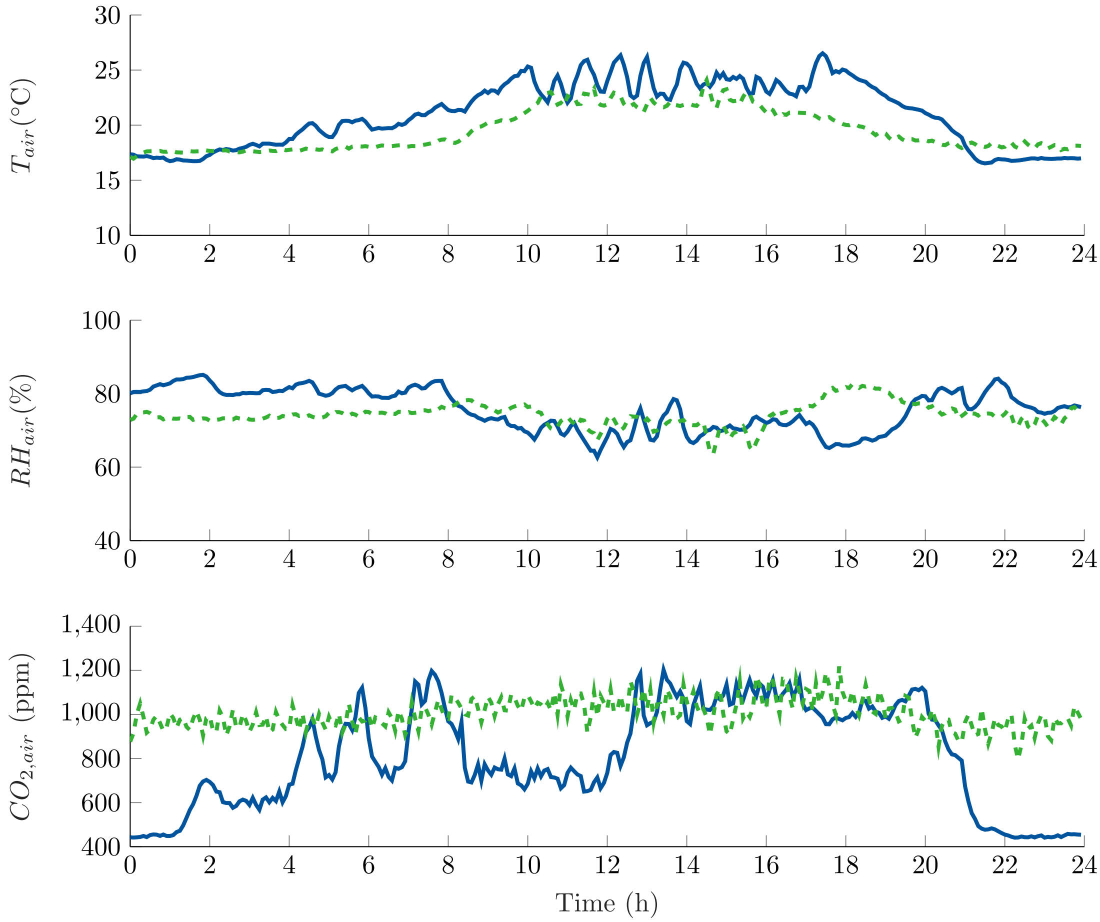

Fig. 4. Greenhouse climate for June 16, 2012 (solid line) and March 6, 2012 (dashed line): a) greenhouse air temperature (°C), b) Relative humidity (%), c) CO_2 concentration (ppm).

and the other variables are continuous and need to satisfy the constraints as described above.

The goal function to minimize the total gas costs, electricity costs for buying or selling electricity (revenues are negative costs) for the given time evolution of the gas price (Eq. (41)) and electricity price (Eq. (42)) is:

$$\min_u J = \min_u \int_{t_0}^{t_f} \left(p_G\left(G_{boil}(u) + G_{chp}(u)\right) + p_E E_{grid}(u)\right) \mathrm{d}t, \tag{40}$$

$$p_G(t), t_0 \leqslant t \leqslant t_f, \tag{41}$$

$$p_E(t), t_0 \leqslant t \leqslant t_f, \tag{42}$$

where p_G is the (dynamic) gas price (€.m^{-3}) and p_E is the (dynamic) electricity price (€.J^{-1}). The price for buying and selling electricity were equal, as for the grower. The unit of the gas consumption (G) is m^3.m^{-2}.s^{-1} and the unit of electricity bought or sold to the grid (E_{grid}) is W.m^{-2}.

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

$$G_{boil} = \frac{Q_{HT,boil}}{\eta_{boil} \cdot S}. \tag{43}$$

where η_{boil} is the boiler efficiency and S the combustion heat of natural gas. The gas consumption of the CHP (G_{chp}) is proportional to the amount of heat produced by the CHP:

$$G_{chp} = \frac{Q_{chp}}{\eta_{Q,chp} S}, \tag{44}$$

where the efficiency of the CHP for heat ($\eta_{Q,chp}$) was 0.46. This number was obtained from the total efficiency of the CHP (η_{chp}), which was determined from data from the grower's gas meter and power data.

The capacities of the buffers and aquifer, and power of the equipment are listed in Table 1. The costs of the grower were determined with measured data from the electricity and gas meters present in the greenhouse. The (dynamic) prices of electricity and gas were equal in the grower's situation and the optimized situation. The average gas price for 2012 was 0.24 €.m^{-3} (SD = 0.017 €.m^{-3}, Min = 0.21 €.m^{-3}, Max = 0.31 €.m^{-3}). The average electricity price for 2012 was 0.05 €.kWh^{-1} (SD = 0.112 €.kWh^{-1}, Min = -0.45 €.kWh^{-1}, Max = 0.54 €.kWh^{-1}).

Optimizations were performed per day ($t_f = 84600$ s) to stay as close as possible to grower's practice and to be able to compare the optimization results and control of the equipment with the control of the grower and the performance obtained. The consecutive days were optimized independently from each other. The initial buffer and aquifer filling for every day were taken from the grower. The buffer and aquifer

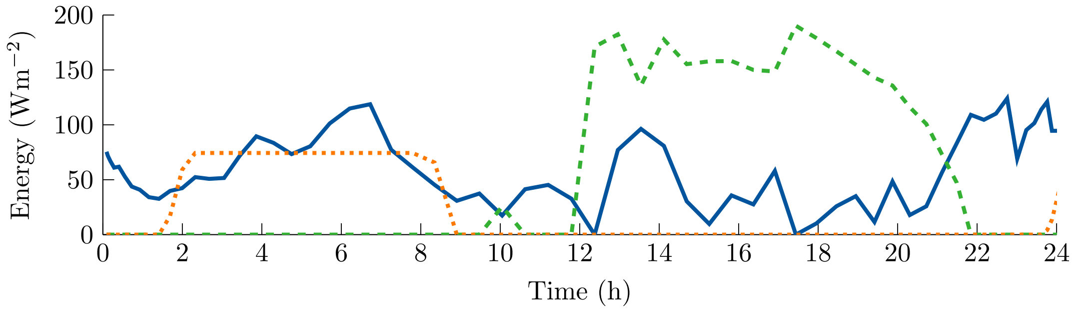

Fig. 5. Desired heating (—), cooling (- - -), and electricity (for supplementary lighting) profile (····) for June 16, 2012 (day number 168).

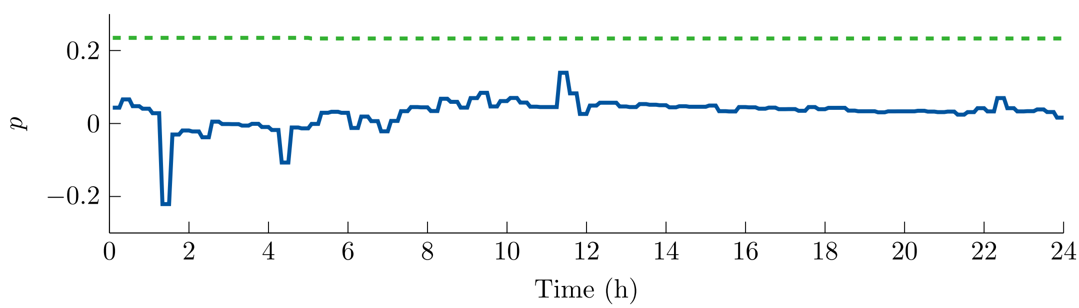

Fig. 6. Prices for electricity (€.kWh^{-1}, —) and gas (€.m^{-3}, - - -) for June 16, 2012 (day number 168).

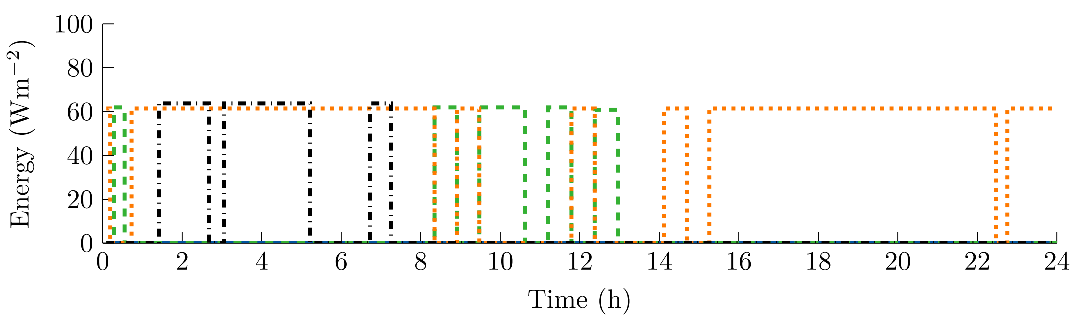

Fig. 7. Optimal result for June 16, 2012 (day number 168). Boiler (—), CHP (- - -), heat pump (····), and cooling towers (-·-·).

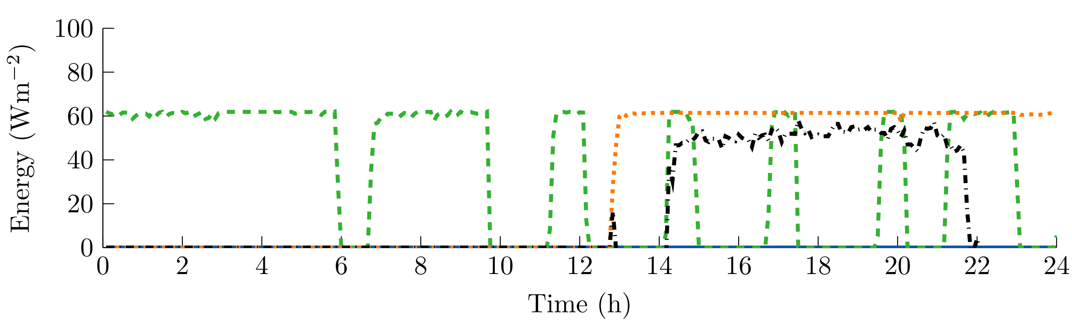

Fig. 8. Grower result for June 16, 2012 (day number 168). Boiler —, CHP (- - -), heat pump (····), and cooling towers (-·-·).

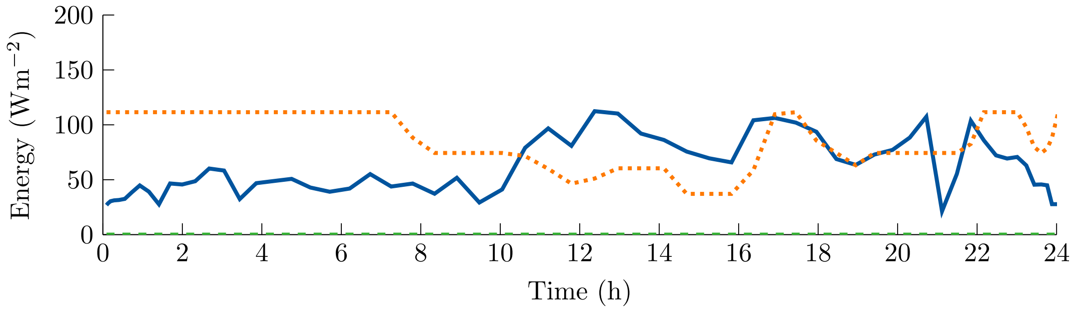

Fig. 9. Desired practical heating (solid blue line), cooling (green dashed line), and electricity profile (orange dotted line) for March 6, 2012 (day number 66).

filling at the end of the day were, as described before, allowed to deviate slightly around the grower's realization.

All optimizations in this paper were performed 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 x64 installed. The optimization problem was solved with TOMLAB/CPLEX for solving large-scale mixed-integer linear and quadratic programming problems. "Tomlab is a general-purpose development, modeling, and optimal control environment in Matlab for research, teaching, practical solution of optimization problems" (Holmstrom et al., 2010).

2.3.2. Experiments

First, in experiment 1, optimization for the 365 individual days in 2012 was performed for the given heating and cooling demand of the grower. Optimal results were compared with the grower's result. The heating and cooling demand of the grower was obtained by extending the procedure Van Beveren et al. (2019), Appendix B, with measured data from the cold storage, cooling towers, heat pump, and aquifer. Second, in experiment 2, optimizations were performed with the minimal energy input (heating and cooling) obtained from Van Beveren et al. (2015). The electricity demand remained unchanged compared to Experiment 1. The minimal energy input was obtained with the practical screen positions and supplementary lighting from the grower. It is interesting to compare the standard situation based on pre-defined demands copied from the grower to a situation where these demands themselves are optimized, within the climate constraints set around the values of the grower. This will demonstrate the potential cost saving when stage 1 (minimizing energy input) is coupled to stage 2 (minimizing energy costs).

3. Results

First, the optimization results for two individual days, one day in summer and one day in winter, are presented to demonstrate the optimization in detail. The greenhouse air temperature, relative humidity, and CO_2 concentration for these days are shown in Fig. 4. Second, the results of daily optimization of the whole year 2012 are presented and compared with the realization of the grower using the realized heating, cooling, and electricity demand as constraints. The electricity demand was the realized electricity consumption of the lamps. The heat delivery to the neighboring greenhouse was accounted for in the heat demand. Last, the daily optimization results are presented using the minimal heating and cooling demand for the year 2012 as constraints, these were obtained by optimizing the energy input to the greenhouse (Van Beveren et al., 2015).

3.1. Summer day

The practical heating, cooling, and electricity demand of a warm summer day in 2012 (day number 168, June 16, 2012) is shown in Fig. 5. The corresponding prices for electricity and gas are shown in Fig. 6. The utilization of the boiler, CHP, heat pump, and cooling towers is shown in Fig. 7 for the optimal situation and in Fig. 8 for the grower's situation. On June 16, 2012, the outdoor temperature was lower than the greenhouse air temperature for the whole day. The grower used active cooling to cool the greenhouse (12:00 to 21:00 h) and supplementary lighting (2:00 to 8:30 h). Supplementary lighting heats the greenhouse air as well. The maximum outdoor radiation was about 1000 $W.m^{-2}$. Therefore, the shading screen was closed between 11:00 and 16:00 h. The pipe rail heating system was used during the dark period, and at some moments during the day. Despite the active cooling, the ventilation windows were slightly opened, this is likely to remove water vapor from the greenhouse. Nevertheless, the grower succeeded in maintaining a CO_2 concentration around 1000 ppm during the light period (Fig. 4).

The total energy costs were -0.005 $€.m^{-2}$ in the optimal case and 0.044 $€.m^{-2}$ in the grower's operation. There was a negative electricity price for some hours in the early morning of day 168 (Fig. 6). The effect of this negative price is that it is cheaper to buy electricity from the grid than to generate electricity using the CHP, meaning that the power company rewards electricity consumption. At later hours, the price is positive, but low, thus making it beneficial to use the heat pump. Therefore, the heat pump is used for a longer period in the optimal case

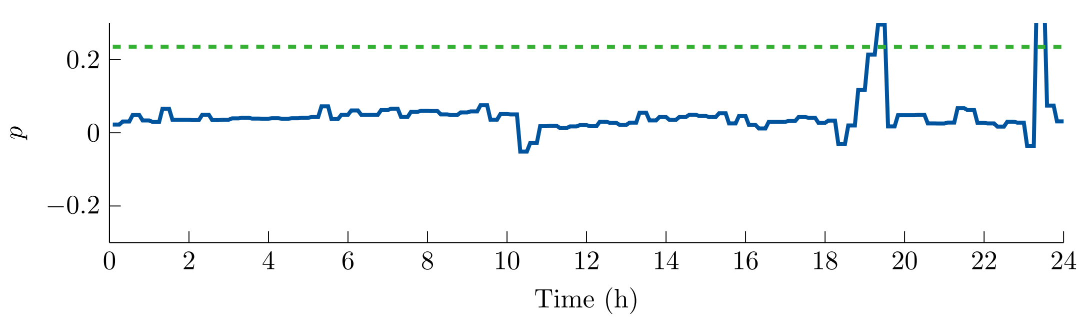

Fig. 10. electricity ($€.kWh^{-1}$, solid blue line and gas ($€.m^{-3}$, green dashed line) for March 6, 2012 (day number 66).

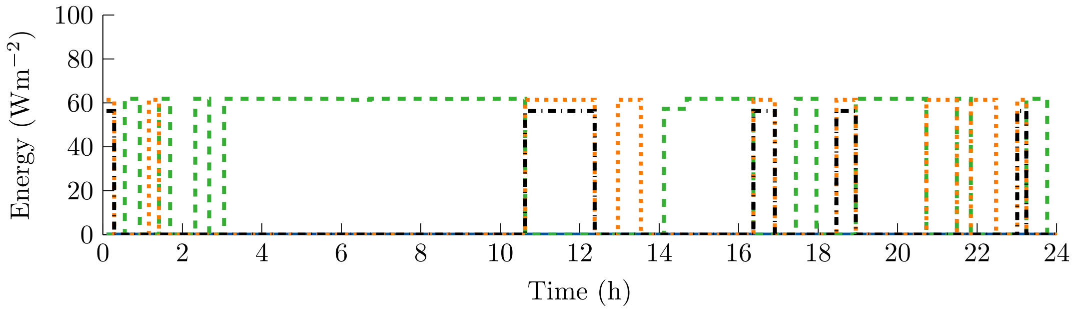

Fig. 11. Optimal result for March 6, 2012 (day number 66). Boiler, CHP (), heat pump (), and cooling towers ().

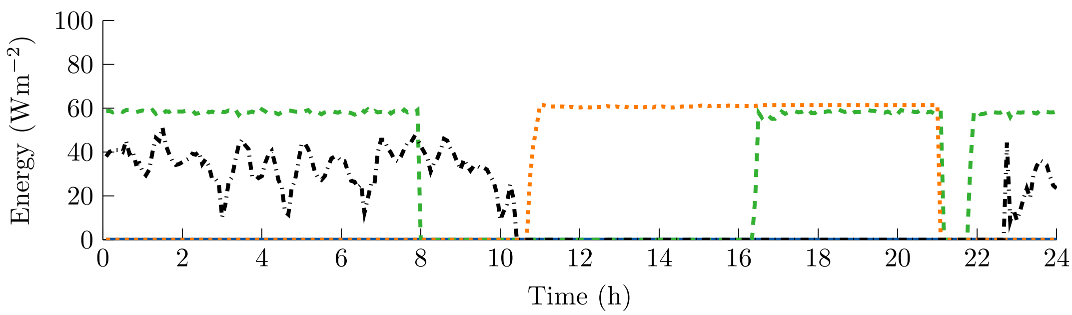

Fig. 12. Grower result for March 6, 2012 (day number 66). Boiler, CHP (), heat pump (), and cooling towers ().

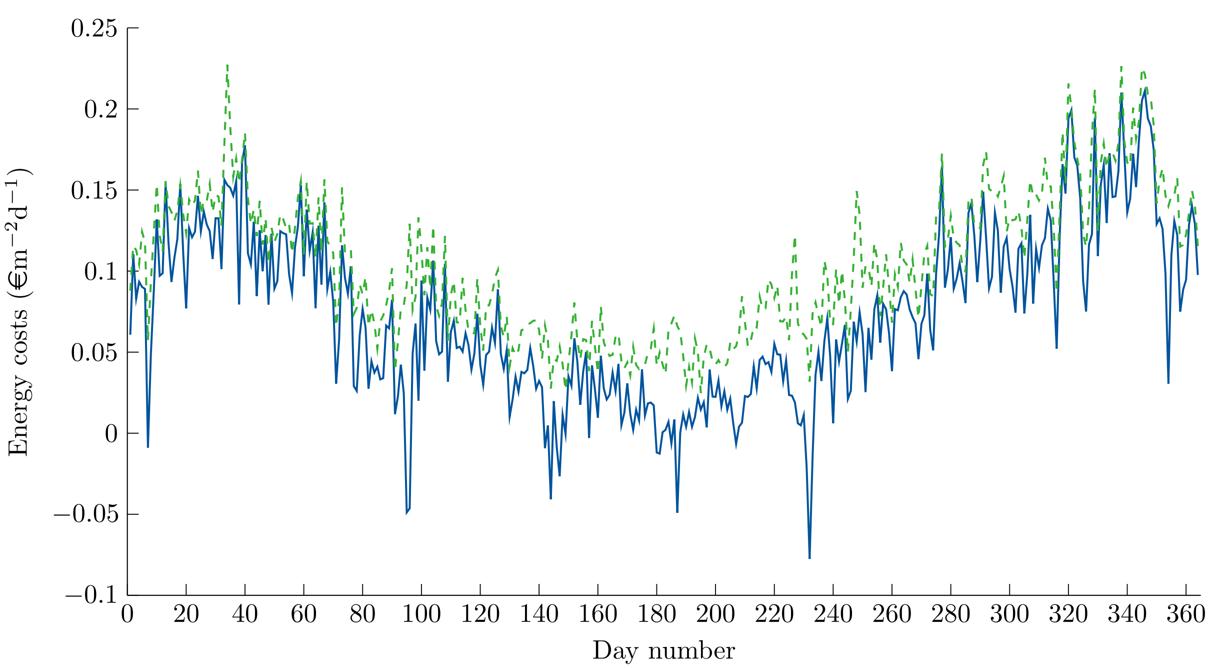

Fig. 13. Optimal goal function value and grower's result () for each day in 2012.

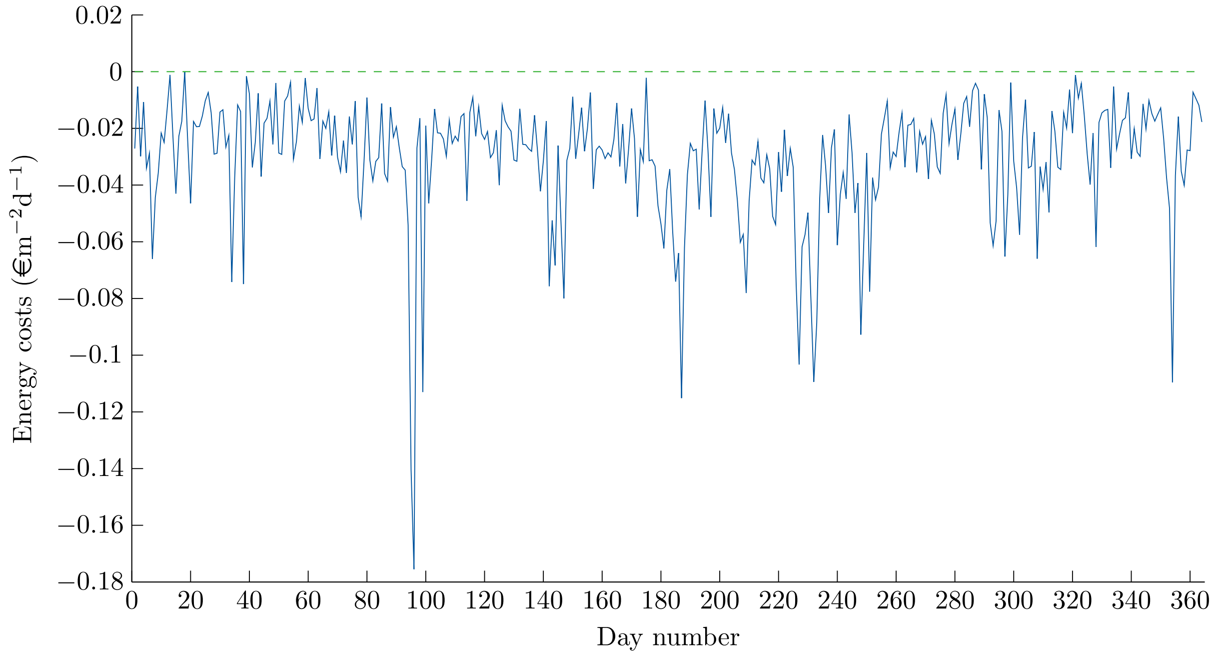

Fig. 14. Difference between the optimal goal function value and the grower's result per day in 2012.

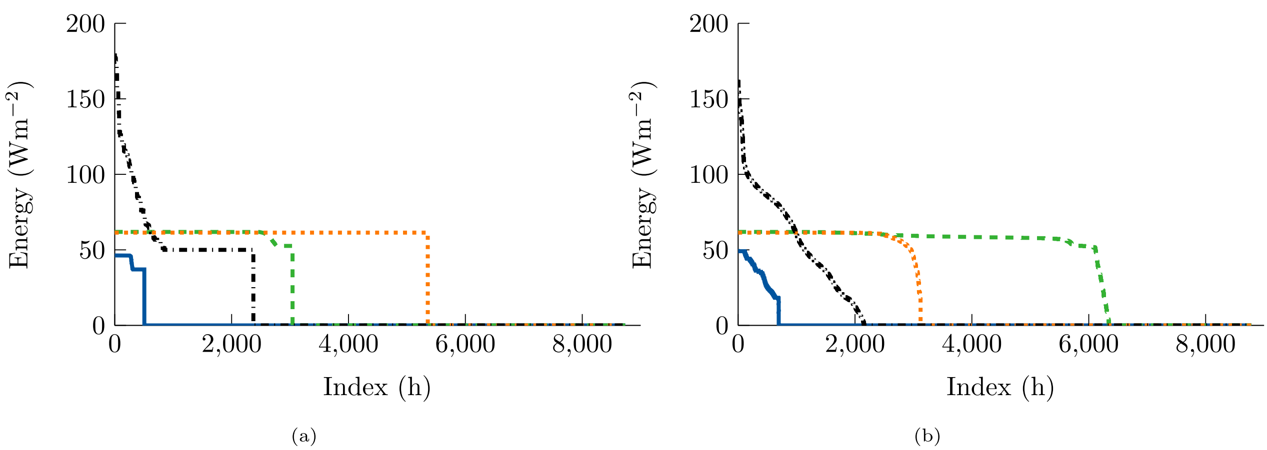

Fig. 15. Sorted curves for the optimal (a) and grower's situation (b) for the year 2012. Boiler (solid line), CHP (dashed line), heat pump (dotted line), and cooling towers (dash-dot line).

compared to the grower's operation. Heat production was not only needed for heating the greenhouse but could also be the result of electricity production with the CHP. In the optimal case, 3.3 MJ.m^{-2} of electricity was bought from the grid, while this was 1.5 MJ.m^{-2} in the grower's operation. The cooling towers were used by the grower between 14:00 and 22:00 h, while in the optimal situation they were used in the night to waste heat ahead. This is possible because the cold water could be stored in either the cold buffer or aquifer. The boiler remained switched off in both situations.

3.2. Winter day

The practical heating, cooling, and electricity demand of a cold winter day in 2012 (day number 66, March 6, 2012) is shown in Fig. 9. The outdoor light level was much lower for the day in March (8.0 MJ. m^{-2}) compared to the day in June (20.1 MJ.m^{-2}). Therefore, supplementary lighting was (partially) active for 24 h (not shown). The lamps were switched on completely between 0:00 and 8:00 h. The lamps also contribute to heating, therefore the desired heating profile is lower compared to the afternoon period. The maximum outdoor radiation was about 500 W.m^{-2} in the afternoon. Because of the lower outdoor temperature, cooling of the greenhouse was not applied. The greenhouse air

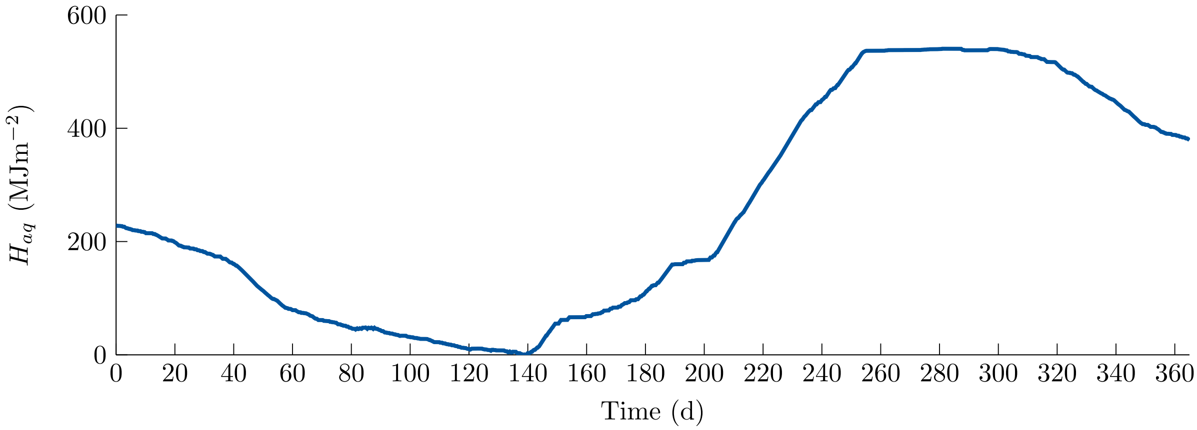

Fig. 16. Energy content of the aquifer per day for the grower's situation in 2012.

temperature was slightly lower compared to June 16 (Fig. 4). The corresponding prices for electricity and gas are shown in Fig. 10. The utilization of the boiler, CHP, heat pump, and cooling towers is shown in Fig. 11 for the optimal situation and in Fig. 12 for the grower's situation. Although there was no cooling demand from the greenhouse, the cooling towers were active in the grower's situation between 0:00 and 10:30 h and between 22:30 and 24:00 h on this winter day in order to produce cold water that is stored in the aquifer for cooling purposes in summer. The pipe rail heating system was applied the whole day (not shown). The heat-exchangers were used for heating during the dark period and at the end of the afternoon (not shown).

The total energy costs were 0.102 €.m^{-2} in the optimal case and 0.112 €.m^{-2} in the grower's operation. Around 10:00 h the electricity price was negative for a short period, but otherwise, it was rather constant on day number 66, except from two high peaks (around 19:00 and 23:00 h). The effect of the higher price is that the optimization uses the CHP on the moments that the electricity price was high. Consequently, 0.08 MJ.m^{-2} electricity was delivered to the grid in the optimal case, as opposed to no delivery of electricity by the grower. The heat pump was active between 10:30 and 21:00 h in the grower's operation, while the optimization distributed the use of the heat pump over the whole day in order to minimize the total energy costs. The cooling towers were activated more frequently for shorter periods in the optimal case. The cooling towers consume electricity, therefore, the cooling towers were active when the electricity price was low.

3.3. Experiment 1: Full year with realized climate

The mean gas and electricity price for 2012 were 0.24 (SD = 0.017) €.m^{-3} and 0.05 (SD = 0.11) €.kWh^{-1}, respectively (Section 2.3.1). The total heat demand was 2.4 GJ.m^{-2}.y^{-1}, the total cooling demand was 0.7 GJ.m^{-2}.y^{-1}, and the total electricity demand of the greenhouse for supplementary lighting was 2.0 GJ.m^{-2}.y^{-1}. The total amount of CO_2 dosing was 95.4 kg.m^{-2}.

The optimal values of the goal function (Eq. (40)) for the daily optimization for all days in 2012 with the heat and cold demand profile of the grower is shown in Fig. 13. The difference between optimal operation and the grower's operation is shown in Fig. 14.

For all days, the optimal result has lower costs than the grower. The 2012 year costs for the optimal result were 26.79€.m^{-2}, whereas the costs of the grower were 37.71 €.m^{-2}. So, the total energy costs in the optimized scenario were 29% less than the energy cost realized by the grower.

Fig. 13 shows that despite the cooling, the highest energy cost occurs in the winter period, which is not surprising. The outside temperature is lower and the day length shorter, which results in a much higher demand for heating and electricity for lighting than in the summer period. Despite this, the difference between the optimization and the grower is smaller in winter. Due to the high demands, there is apparently less freedom for the optimization to shift heat load and electricity trade within the optimization period of one day. A substantial part of the gains of the optimization is therefore obtained in summer (Fig. 14).

The utilization of the different equipment for optimal operation, sorted for the whole year 2012, is shown in Fig. 15a, and for the grower in Fig. 15b. It can be seen that in the grower's operation the CHP was used for 6348 h and operated most of the time at 100% (62.5 W.m^{-2}) and some time between 85% (53.1W.m^{-2}) and 100% of the maximum capacity. The boiler was operated for only 695 h in 2012. This is because the boiler was only used as a back-up in case of malfunction of the CHP for heat production, or as a back-up for CO_2 production in case of malfunction of the OCAP industrial CO_2 network.

The heat pump was used for 5356 h in the optimal case compared to 3122 h in the grower's operation, while the CHP was used for 3042 h in the optimal case compared to 6348 h in the grower's operation. Thus, the heat pump and the CHP exchanged the number of operating hours roughly. Supplementary lighting was active for 6318 hour in 2012. The CHP was turned on most of the time when the lamps were on in the grower's operation. The cooling towers were operated for 2371 h in the optimal case compared to 2158 h in the grower's operation. The plateau visible in the cooling tower operating curve in the optimal case is due to fixing the cooling tower capacity to a pre-defined value on days without grower data (see Table 1). The total amount of wasted heat was 0.55 GJ.m^{-2} in the optimal case and 0.45 GJ.m^{-2} in the grower's operation.

The energy content of the aquifer throughout the year 2012 for the grower's situation is shown in Fig. 16. From day number 1 till day number 140 the energy content decreases because heat is extracted and used for heating the greenhouse. From day number 140 till day number 250, the energy content of the aquifer increases because the greenhouse demands cooling and the extracted heat from the greenhouse is stored in the aquifer. After day number 250 the energy content decreases again. Although the amount of energy in the aquifer at the start of each day was equal to the grower, the cumulative net amount of heat extracted from the aquifer in the optimal situation was 100 MJ.m^{-2} higher than in the grower's situation. This is possible in the optimization because the final state constraint (per day) on the aquifer energy content (H_{aq}^{max}) was a percentage of the realized energy content by the grower. Therefore, the allowed deviation from the realized amount of energy in the aquifer at the end of the optimization period varied accordingly throughout the year.

3.4. Experiment 2: Full year with minimal energy

Instead of the realized heating and cooling demand of the grower (Section 3.3), the optimized energy demand pattern, as obtained from Van Beveren et al. (2015), was used. The electricity demand remained unchanged, as well as the begin and end constraints on the buffers and aquifer. The total heating demand was 47% lower and the total cooling demand was 15% lower compared to the grower (Van Beveren et al., 2015). With the optimized heating and cooling demand, the total energy costs were 29.9% less than in the grower's situation for the whole year 2012. The difference between 29% (cost-saving with realized climate in Experiment 1, Section 3.3) and 29.9% is rather limited. Note that the constraints on the buffers and aquifer do not necessarily match the utilization of the equipment. The optimal heating and cooling demand were not applied in practice and constraints did not necessarily match with the optimized demand. Thus, it was not possible to modify the constraints (buffer and aquifer energy content) in such a way that a fair comparison is possible.

4. Discussion

The optimization procedure in this paper is an open-loop optimization. In the current form, the optimization is done for historical days. The practical use of the optimization results is twofold: (1) analysis of the current performance of the system and (2) to demonstrate how the performance can be improved. Implementation of the optimization procedure as a forecasting tool could be done via a receding horizon optimal control approach (Tap et al., 1996; Van Straten et al., 2002; Oldewurtel et al., 2012). Such implementation requires reliable forecasts of the weather and prices of electricity and gas.

Obtaining the demands and operational constraints from the grower's data is difficult and is subject to uncertainty and measurement errors. Modern greenhouses have many different sensors and measuring systems in place. Those systems collect data with different sensors, at different time intervals, and with different accuracy (Bontsema et al., 2011). Several sources of uncertainties and possible errors arise from uncertain measured data. Another factor that introduces uncertainty is the fact that some 'measurements' are not real measurements but calculated data. For the calculations, it is necessary that all data is consistent. It turned out that this was not always the case. For example, the energy content of the buffers and aquifer at the start and end of the daily optimization were calculated from the buffer fill percentage registered by the process control computer and the known buffer capacity. It turned out that these measurements showed sometimes unrealistic values, and with these inconsistencies, it can happen that no optimal solution exists. Introducing a small upper and lower bound on the daily final state of buffers and aquifer solved this problem.

The heat and cold demand patterns of the grower were calculated based on heat and cold fluxes using common energy and mass balance based models of the greenhouse climate (Van Beveren et al., 2015; Van Beveren et al., 2015). For application in practice, it is desired to limit the number of model parameters. Also, some parameters are difficult to measure or to determine from historical data. Therefore, the models of the equipment were kept relatively simple in the problem formulation of the optimization. It turned out that the performance of the model was sufficient for optimization.

The optimization period in this study was one day. The aquifer is used in practice to store warm and cold water for longer periods (seasonal storage). The daily initial and final state constraints on the energy in the aquifer were taken equal to the realized energy content in the aquifer by the grower. There are likely other trajectories of the energy content of the aquifer that will lead to lower energy costs when longer optimization periods are used. One solution to the problem of choosing the energy content of the aquifer is to use receding horizon optimal control approach with a pre-defined reference curve for the aquifer energy content with upper and lower bounds over a longer period (Van Ooteghem, 2007). This at least would show the direction of optimality.

CO_2 for the enrichment of greenhouse air was not taken into account in this paper. The reason is that in this greenhouse an industrial CO_2 source was used. To make the proposed optimization method applicable to greenhouses that use CO_2 from the boiler and/or CHP, the required CO_2 dosing could be incorporated in the optimal control formulation. To do so, the efficiency of the boiler and CHP with respect to CO_2 production needs to be known. As flue gas from the CHP cannot be used directly in the greenhouse, the efficiency and running costs of the flue gas cleaner must be considered as well.

The difference between the cost saving of the optimization with realized climate (Section 3.3) and the optimization with minimal energy (Section 3.4) was surprisingly small at first sight. It was expected that the proposed two-stage approach would result in more savings, and it would be interesting to know which effort brings most of the benefit: minimizing energy input, or optimizing the operation of the equipment. However, because the aim was to compare the optimized costs with those of the grower, we restricted ourselves to stay close to the constraints as observed. It was demonstrated before (Van Beveren et al., 2019) that relaxing the bounds of the final state constraints will lower the total energy costs, however, to allow comparison with the grower's situation, in this study the constraints were kept equal in both experiments. Furthermore, the energy content of the buffers and aquifer that corresponds to the minimized energy input are not known since this situation was not realized in practice. It is expected that the optimization procedure is also valuable for other energy management problems in different applications e.g. animal housing, commercial buildings, storage facilities with multiple sources of heating, cooling and electricity combined with storage of heat and cold water.

The optimizations were performed for historical days where the energy demand, the realization of the grower, and prices of electricity and gas are fully known in advance. As to the weather, this is not a limitation, as weather forecasts for one single day are fairly reliable, and the optimization is fast enough to obtain the daily operation schedule. However, forecasting the electricity price is more complicated. In addition, the operational schedule calculated for the day may easily be adjusted by recalculation as soon as true prices start to deviate considerably from the pre-set prices. Moreover, the grower can learn from the optimal strategies and try to apply the lessons learned in future decisions. In any case, predictions of weather and prices of electricity and gas are of paramount importance. Finally, it is necessary to translate the optimal strategy, either automatically or manually, to settings in the greenhouse (climate) control system.

5. Conclusion

A successful optimization framework was presented for a real commercial greenhouse, taking practical constraints on the utilization of the different equipment into account. Daily energy cost optimization was demonstrated for a 4 ha semi-closed greenhouse with a complex energy equipment configuration existing of a boiler, CHP, multiple short-term buffers, heat pump with aquifer heat storage, and cooling towers.

Optimization of the utilization of advanced energy systems in greenhouses is feasible, and is a major innovation as compared to the current more heuristic approach. Application of open-loop optimization for a realistic greenhouse configuration showed a potential cost saving of 29% for the year 2012 using the heating, cooling, and electricity demand of the grower. All available equipment was utilized in the optimal situation. The heat pump was operated about 2300 h more than in the grower's situation and the CHP was operated about 3300 h less than in the grower's situation. The expected additional gains of enhancing the beneficial optimal equipment control in this paper by simultaneous optimization of the energy demand could not be demonstrated due to the forced constraints imposed in order to stay close to the climate believed by the grower to be necessary for the health of the crop. The results indicate that combining dynamic optimization with prior knowledge of dynamic gas and electricity prices is beneficial. It underlines that trading of electricity and short-term forecasting of gas and electricity prices in combination with dynamic optimization has a high potential for cost savings in horticultural practice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

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Appendix A. Nomenclature

Nomenclature

Symbol	Description	Unit
A	Greenhouse floor area	m^2
b	Boolean control variable	–
E	Electricity use[a]	$W.m^{-2}$
G	Gas use[a]	$m^3.m-2$
H	Heat content[a]	$MJ.m^{-2}$
I	Outdoor radiation	$MJ.m^{-2}.d^{-1}$
J	Goal function[a]	$€.m^{-2}$
p	Price	€
Q	Heat flux[a]	$W.m^{-2}$
r	Range of operation	–
RH	Relative humidity	%
S	Heat of combustion of natural gas[b]	$MJ.m^{-3}$
t	Time	s
T	Temperature	°C
u	Control variable	
v	Speed	$m.s^{-1}$
η	Efficiency	–
Subscript		
aq	Aquifer	
boil	Boiler	
buf	Buffer	
C	Cold	
ct	Cooling towers	
chp	Combined heat an power installation	
des	Desired	
E	Electricity	
f	Final	
G	Gas	
glob	Global	
grh	Greenhouse	
grid	Public electricity grid	
HT	High Temperature	
hp	Heat pump	
in	In	
LT	Low Temperature	
out	Out	
wind	Wind	
Superscript		
min	Minimum	
max	Maximum	
sum	Sum	

[a] per unit greenhouse floor area.
[b] upper calorific value

Appendix B. Outdoor climate

Fig. B.17.

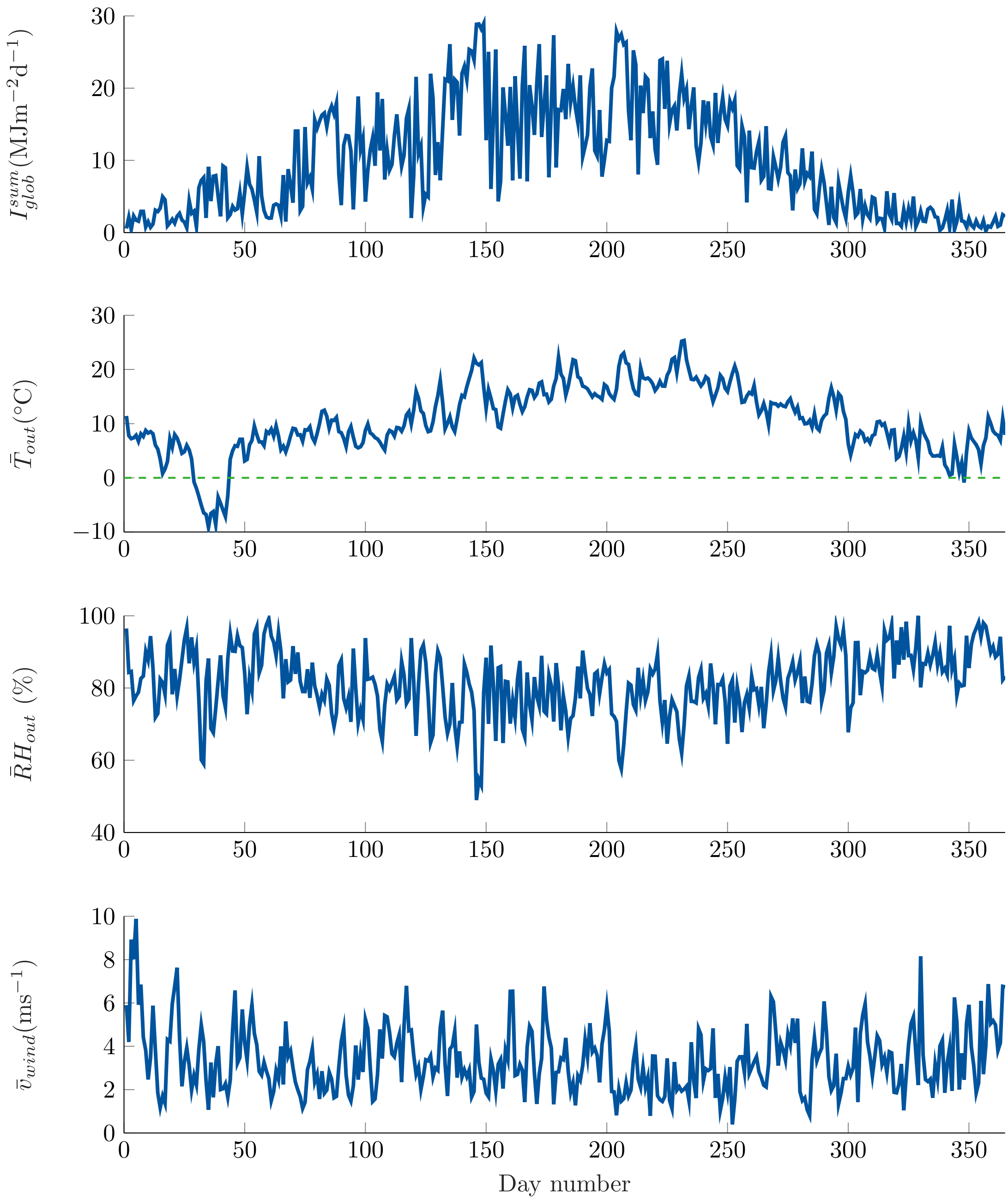

Fig. B.17. Outdoor climate for Bleiswijk, the Netherlands in 2012: a) Radiation sum ($\mathrm{MJ.m^{-2}.d^{-1}}$), b) Average temperature (°C), c) Average relative humidity (%), d) Average wind speed ($\mathrm{m.s^{-1}}$).

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