Optimal management of energy resources in greenhouse crop production systems

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10 March 2015, Peter van Beveren[a,b]

a) Farm Technology Group, b) Wageningen UR Greenhouse Horticulture

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HortiMaX
growing solutions

Boonekamp Roses

Background

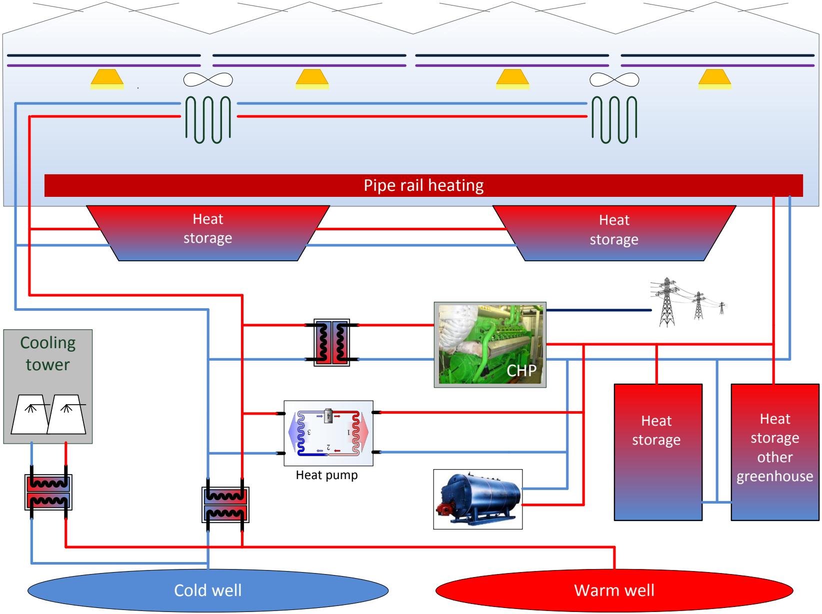
- Greenhouse horticulture is a large consumer of fossil energy.
- Growers have to reduce energy consumption and CO_2 emission
- Growers have installed a wide range of auxiliary equipment to produce, consume and store energy.
    - Increased complexity and interconnectivity of the various resources.
    - Complex management task.

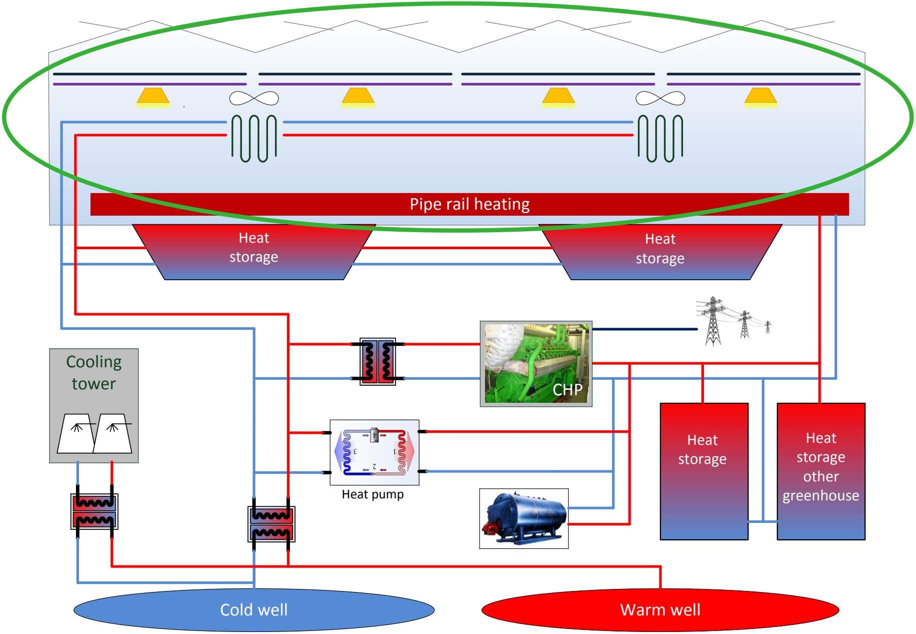
Optimal management of energy resources

Goal:

Utilize all equipment in a modern greenhouse in the most efficient manner.

Figure : 4 ha commercial rose greenhouse


Pipe rail heating
Heat storage
Heat storage
CHP
Cooling tower
Heat pump
Heat storage
Heat storage other greenhouse
Cold well
Warm well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Dual-stage approach

Stage 1: Create a desired climate in the greenhouse with minimal energy input.

Stage 2: Generate this energy as efficient as possible with the available equipment.

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Why?

- OCAP CO_2 is used
- Buffer capacity available
- Practical reasons

Stage 1: Create a desired climate using minimal energy

What is the desired climate?

- Grower knows best about the crop
- Ideal climate depends on
    - weather predictions
    - status of the crop
    - specific crop knowledge
    - production prognosis
    - product price prognosis
    - experience of the grower
    - ...

The desired climate

1. Let the grower define bounds to specify the desired climate
    - Upper and lower bounds for temperature
    - Upper bound for humidity
    - Upper and lower bounds for CO_2
    - Maximum amount of CO_2 available per day

Advantages

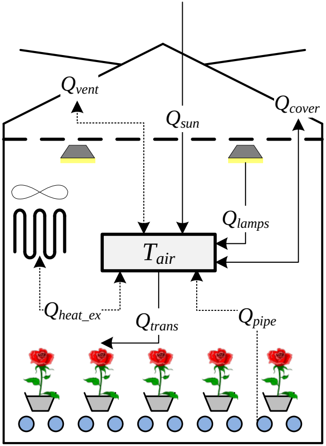
- No crop production models needed
- No predictions of market prices needed

2. Minimize total energy input by using optimal control techniques
    - Model of greenhouse climate is needed.

The dynamic model (1)

Energy balance

$$\frac{dT_{air}}{dt} = \frac{1}{c_{cap}} \left(Q_{sun} - Q_{cover} - Q_{trans} + Q_{lamps} - Q_{vent} + Q_{he} + Q_{pipe} \right) \quad (^{\circ}\mathrm{C\,s^{-1}}) \tag{1}$$



Energy fluxes ($\mathrm{W\,m^{-2}}$)

- Q_{sun} = Radiation from sun
- Q_{cover} = Cover losses
- Q_{trans} = Crop transpiration
- Q_{lamps} = Artificial lighting
- Q_{vent} = Ventilation
- Q_{he} = OPAC heat exchanger
- Q_{pipe} = Pipe rail heating

See Van Beveren et al. (2013).

The dynamic model (2)

Humidity balance

$$\frac{d\chi_{air}}{dt} = \frac{1}{h}\left(\phi_{trans} - \phi_{cov} - \phi_{he} - \phi_{vent}\right) \quad (\mathrm{g\,m^{-3}\,s^{-1}}) \qquad (2)$$

CO_2 balance

$$\frac{dCO_{2\_air}}{dt} = \frac{1}{h}\left(\phi_{c,inj} - \phi_{c,ass} - \phi_{c,vent}\right) \quad (\mathrm{g\,m^{-3}\,s^{-1}}) \qquad (3)$$

- See Van Beveren et al. (2015) for more details.
- The model is based on the work of Van Henten (1994), De Zwart (1996), Van Ooteghem (2007), and Vanthoor (2011).

External inputs of the model

- Outdoor conditions
  - Temperature (°C)
  - Relative Humidity (%)
  - Radiation $(\mathrm{W\,m^{-2}})$
  - Wind speed $(\mathrm{m\,s^{-1}})$
  - CO_2 concentration (ppm)

- Control inputs from the climate computer
  - Screen closure (%)
  - Artificial lighting (%)

Optimization procedure

- Optimal control formulation
- PROPT Matlab Optimal Control Software (Tomlab)

Optimal control problem (1)

Control variables:

1. Heating
    - $Q_{E,heat} = Q_{he,heat} + Q_{pipe}$ in $(\mathrm{W\,m^{-2}})$
2. Active cooling
    - $Q_{E,cool} = Q_{he,cool}$ in $(\mathrm{W\,m^{-2}})$
3. Ventilation
    - $g_V =$ specific ventilation $(\mathrm{m\,s^{-1}})$
4. CO_2 injection
    - $\phi_{c,inj} =$ CO_2 injection flux $(\mathrm{g\,m^{-2}\,s^{-1}})$.

Find control variables such that Eq. 4 is minimal.

$$\min_{Q_{E,heat},Q_{E,cool},g_V,\phi_{c,inj}} J = \int_{t_0}^{t_f} \left(Q_{E,heat}^2 + Q_{E,cool}^2 \right) dt \tag{4}$$

Optimal control problem (2) - Constraints

Climate variables

- Lower and upper temperature bound:

$$T_{air}^{min}(t) \leq T_{air}(t) \leq T_{air}^{max}(t) \tag{5}$$

- Upper bound for relative humidity:

$$RH_{air}(t) \leq RH_{air}^{max}(t) \tag{6}$$

- Lower and upper $\mathrm{CO_2}$ bound:

$$CO_{2,air}^{min}(t) \leq CO_{2,air}(t) \leq CO_{2,air}^{max}(t) \tag{7}$$

Optimal control problem (2) - Constraints

Climate variables

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- Lower and upper CO_2 bound:

$$CO_{2,air}^{min}(t) \leq CO_{2,air}(t) \leq CO_{2,air}^{max}(t) \tag{7}$$

These are all set by the grower.

Optimal control problem (3) - Constraints

Control variables

- Heating capacity is limited by:

$$Q_{E,heat}^{min}(t) \leq Q_{E,heat}(t) \leq Q_{E,heat}^{max}(t) \tag{8}$$

- Cooling capacity is limited by:

$$Q_{E,cool}^{min}(t) \leq Q_{E,cool}(t) \leq Q_{E,cool}^{max}(t) \tag{9}$$

- Ventilation capacity is limited by:

$$g_V^{min}(t) \leq g_V(t) \leq g_V^{max}(t) \tag{10}$$

- CO_2 injection is limited by:

$$0 \leq \phi_{c,inj}(t) \leq \phi_{c,inj}^{max}(t) \tag{11}$$

- Total amount of CO_2 available per day is limited by:

$$\int_{t_0}^{t_f} \Phi_{c,inj}\, dt \leq \phi_{c,inj}^{max,day} \tag{12}$$

Optimal control problem (4) - Constraints

Dynamic greenhouse climate model

- Dynamic greenhouse climate model:

$$(\dot{T}_{air}, \dot{\chi}_{air}, \dot{C}O_{2,air}) = f(T_{air}, \chi_{air}, CO_{2,air}, Q_E, g_V, \phi_{c,inj}, t) \qquad (13)$$

- Initial conditions:

$$T_{air}(t_0) = T_{air}(0), \chi_{air}(t_0) = \chi_{air}(0), CO_{2,air}(t_0) = CO_{2,air}(0) \qquad (14)$$

Implementation of minimum pipe temperature

- Change lower bound for heating capacity

Minimum pipe temperature

Replace the old constraint

$$Q_{E,heat}^{min}(t) \leq Q_{E,heat}(t) \leq Q_{E,heat}^{max}(t) \quad (\mathrm{W\,m^{-2}}) \tag{15}$$

with the new constraint with minimum pipe temperature T_{pipe}^{min}:

$$Q_{E,heat}^{min}(t) = \alpha_{pipe}(T_{pipe}^{min} - T_{air})(t) \quad (\mathrm{W\,m^{-2}}) \tag{16}$$

- Similar approach for implementation of *minimum ventilation* is possible.

Standard optimization settings

Table : Standard settings of the bounds for optimization

Symbol	Description	Value	Unit
$T_{air}^{min}(t)$	Lower temperature bound	$\overline{T}'_{air,meas}(t) - 0.5°\mathrm{C}$	°C
$T_{air}^{max}(t)$	Upper temperature bound	$\overline{T}'_{air,meas}(t) + 0.5°\mathrm{C}$	°C
$RH_{air}^{max}(t)$	Upper RH bound	$\max RH_{air,meas}(t)$	%
$CO_{2,air}^{min}(t)$	Lower CO_2 bound	$0.97 \cdot \overline{CO}'_{2,air,meas}(t)$	g m^{-3}
$CO_{2,air}^{max}(t)$	Upper CO_2 bound	2000 ppm	g m^{-3}
$Q_{E,heat}^{max}(t)$	Maximal heating capacity	200	W m^{-2}
$Q_{E,cool}^{min}(t)$	Maximal cooling capacity	200	W m^{-2}
$\phi_{c,inj}^{max}(t)$	Maximal CO_2 injection capacity	1200	kg h^{-1}
$\Phi_{c,inj}^{max,day}$	Total amount of CO_2 available per day	$\int \phi_{c,inj,meas} dt$	g m^{-3} d^{-1}

Table : Standard settings for optimization. $'$ = smoothed.

Optimization results

Optimization result 1 day

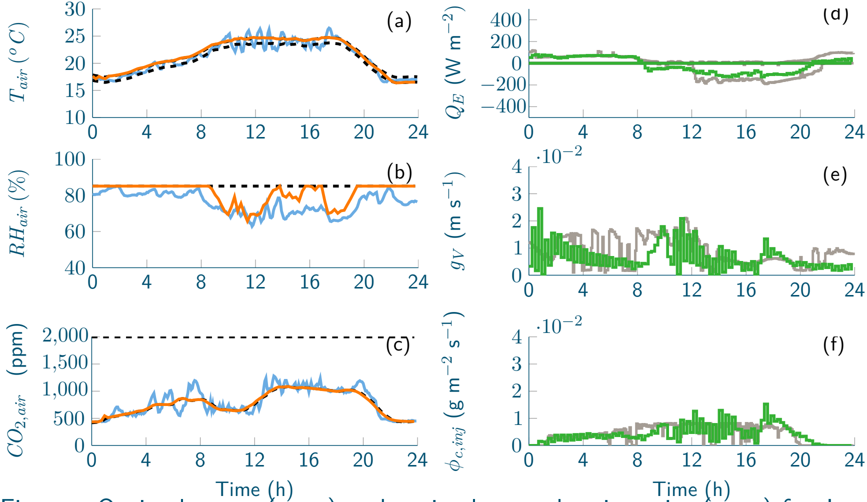


Figure : Optimal states (—) and optimal control trajectories (—) for June 16, 2012 with standard settings. The dashed lines are the bounds. The realized climate variables (—) and the control trajectories resulting from growers operation (—) are also shown.

One year optimization with standard settings

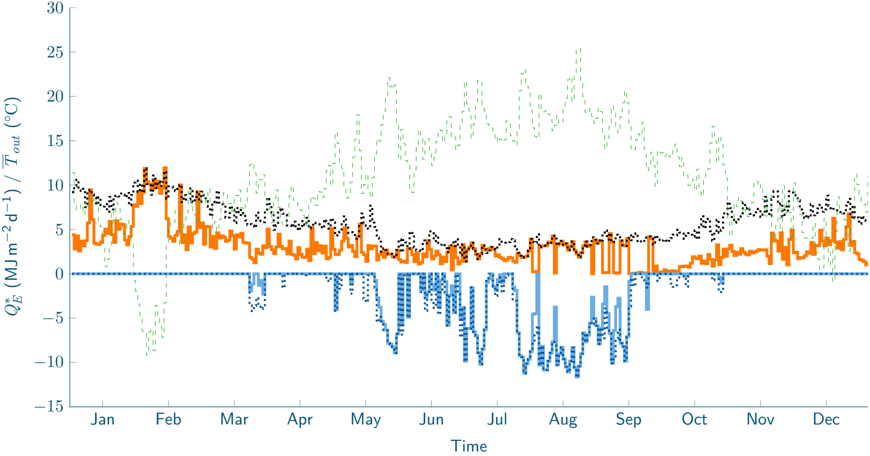


Figure : Results of daily optimization with standard settings for the year 2012. Optimal heating (▬), optimal cooling (▬), heating grower (▬), cooling grower (▬), and mean outside temperature (▬).

One year optimization with standard settings

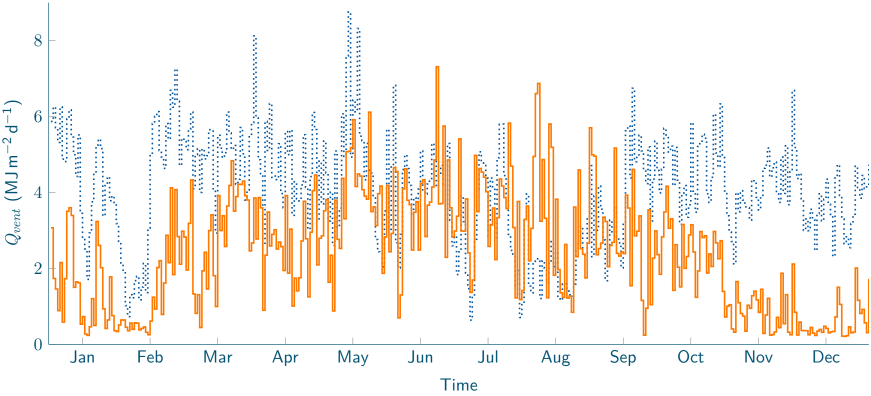


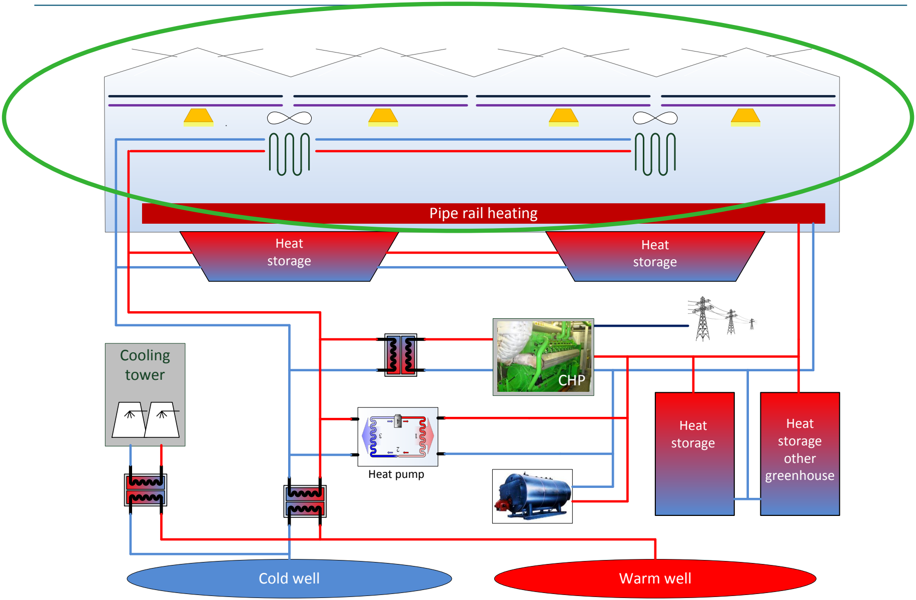
Figure : Optimal ventilation (—) and ventilation grower (—) Q_{vent} (MJ m^{-2} d^{-1}) for 2012.

One year optimization with standard settings

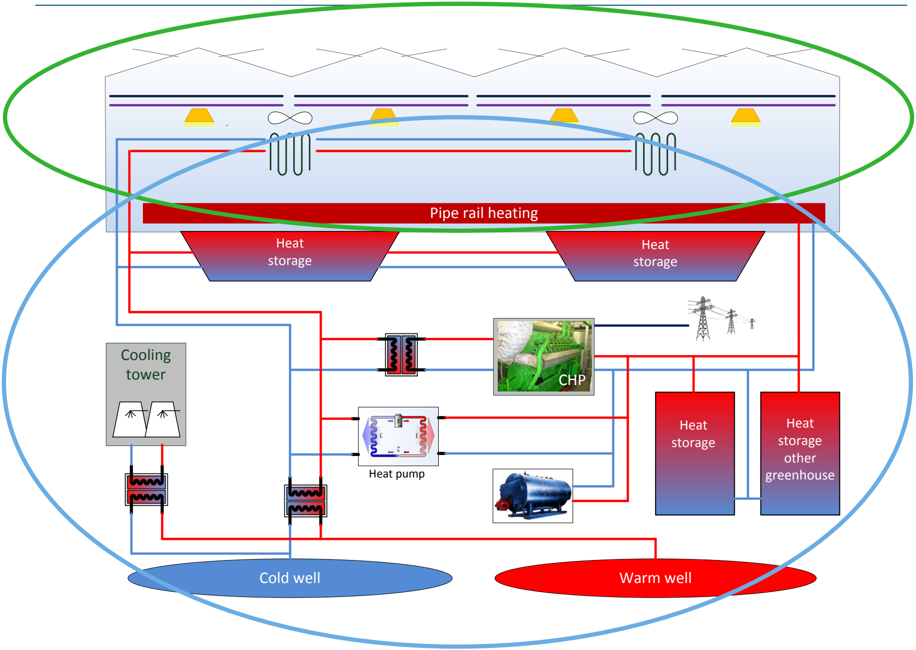
Table : Total heating, cooling, and CO_2 injection of the grower, the optimal situation with standard settings (ss), and the optimal situation with minimum pipe temperature (mp) as used by the grower for 2012.

	Grower	Optimal ss	Optimal mp	Unit
Heating	2.08	1.10	1.49	$\mathrm{GJ\,m^{-2}\,y^{-1}}$
Cooling	0.71	0.60	0.71	$\mathrm{GJ\,m^{-2}\,y^{-1}}$
CO_2 injection	95.4	85.7	85.9	$\mathrm{kg\,m^{-2}\,y^{-1}}$

Stage 2: Optimization of equipment



Stage 2: Optimization of equipment



Thanks for your attention

peter.vanbeveren@wur.nl

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