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Minimal heating and cooling in a modern rose greenhouse ☆

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 317, NL-6700AH Wageningen, The Netherlands
[b] Wageningen UR Greenhouse Horticulture, P.O. Box 644, NL-6700AP Wageningen, The Netherlands
[c] Biomass Refinery and Process Dynamics Group, Wageningen University, P.O. Box 17, NL-6700AA Wageningen, The Netherlands

HIGHLIGHTS

- Temperature and humidity bounds set by the grower were taken as acceptable definitions of the desired greenhouse climate.
- A newly designed dynamic model of greenhouse temperature and humidity showed good agreement with reality.
- Optimal control techniques were used to compute energy related control input trajectories that minimize total energy input.
- Computations show the energy that can be saved by relaxing bounds for temperature and humidity.

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ABSTRACT

In a modern greenhouse there are a number of alternative systems that can be deployed to control the climate, and the choice what to use and when is not easy for the grower. A novel management system is proposed, consisting of an energy input minimizing module, and a module to realise the determined input with the available equipment. The current paper describes the energy minimization part.

A dynamic optimization tool based on optimal control theory was used to obtain time trajectories of the energy flux that minimizes total external energy input over the year, while maintaining greenhouse air temperature and humidity between grower defined bounds. By giving the grower the lead in defining the bounds, the method stays as closely as possible to the grower's daily practice and experience, and no crop production models and market prices are needed. The underlying dynamic model of temperature and humidity, based on known physical principles and parameters, compared very well with unique, year round high frequent data from a commercial rose greenhouse. A relatively simple crop transpiration model was validated separately, with very good results.

It was shown that over twelve selected days, distributed over the entire year, the energy saving potential as compared to the actual grower's practice is substantial. This potential was related to the definition of lower and upper bounds, less natural ventilation at colder days, and more natural ventilation and less heating at warmer days. The prominent role of the bounds was clearly demonstrated. Relaxing the temperature and humidity bounds decreases the energy input to the greenhouse. While this is obvious, the quantification of the effect as demonstrated here is of great interest to growers, and is essential for the development of the second part of the system.

1. Introduction

Greenhouse production is, at least in the Netherlands, a large consumer of energy. Pressure on Dutch growers to reduce energy consumption in greenhouse crop production has increased over the last years. On the one hand growers need, as part of reducing production costs, to increase energy efficiency as international competition increases. On the other hand growers are forced to save energy as legislation for reducing consumption of fossil fuel and exhaust of greenhouse gas emissions becomes more strict [1]. One possible direction to realise the required energy saving is the semi-closed greenhouse, which is attractive for the greenhouse industry because of the increased CO_2 levels inside the greenhouse, reduced pesticide application, and potential water and energy savings [2]. These systems are characterized by a variety of equipment, i.e. combined heat and power generation, heat pump, aquifer seasonal energy storage, daytime energy storage

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* Corresponding author. Tel.: +31 317 483383.
E-mail address: peter.vanbeveren@wur.nl (P.J.M. Van Beveren).

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Nomenclature

Greek symbols

α	heat transfer coefficient (W m^{-2} C^{-1})
χ	absolute water vapour concentration (g m^{-3})
ϵ	ratio of latent to sensible heat content of saturated air (–)
η	ratio of electric energy from lamps transformed into heat (–)
γ	crop specific transpiration parameter (–)
ρ_{air}	density of air (kg m^{-3})
τ	transmittance (–)

Symbols

A	area (m^2)
c_{cap}	heat capacity of the greenhouse (J C^{-1} m^{-2})
$C_{p,air}$	specific heat of air (J kg^{-1} C^{-1})
Cl	closure of screen (%)
f_{on}	fraction of lamps switched on (%)
g_C	condensation conductance (m s^{-1})
g_e	transpiration conductance (m s^{-1})
g_V	specific ventilation (m s^{-1})
I_{rad}	incoming solar radiation (W m^{-2})
L	energy needed to evaporate water from a leaf (J g^{-1})
LAI	leaf area index (m^2 m^{-2})
P_E	electrical power of lamps (W m^{-2})
Q	energy flux (W m^{-2})
r_b	boundary layer resistance s m^{-1})
R_n	net radiation at crop level (W m^{-2})
r_s	stomatal resistance s m^{-1})
RH	relative humidity (%)
T	temperature (°C)

Subscripts

air	greenhouse air
avg	average
cov	greenhouse cover
crop	crop level
floor	greenhouse floor
grower	as resulting from grower's operation of the greenhouse
he, cool	heat exchangers in cooling mode
he, heat	heat exchangers in heating mode
he, in	temperature ingoing water flow to heat exchanger
he, out	temperature outgoing water flow to heat exchanger
lamp	artificial lighting
out	outdoor air
pipe	pipe rail heating system
sat	saturated
scr	shadow screen
scr2	black-out screen
sheet	sheet in heat exchanger
sun	sun
tot	total
trans	crop transpiration
vent	natural ventilation

and heat exchangers in the greenhouse for active heating and cooling. Different configurations of such systems are described and analyzed by Van't Ooster et al. [3], De Zwart [4], Courtois et al. [5], De Gelder et al. [6], Vadiee and Martin [7,8]. These systems are complex regarding the control and utilization of the energy resources. To use all equipment in an energy optimal manner, while creating a desired greenhouse climate, is a complicated task, which has shown to be very difficult, even for experienced growers. Reasons for this are the number and interconnectivity of the equipment that is used, and the uncertainty in expected outdoor weather. The ultimate objective of this project is to support the grower in his decision making process concerning the optimal utilization of energy resources in semi-closed greenhouses.

The approach to greenhouse climate management taken in this research differs from previous work on various aspects. In this research, the total energy input to the greenhouse was minimized instead of maximizing the total economic profit, as was done by [9–14]. Gutman et al. [9] used an economic criterion to minimize heating costs, while others, for example Ioslovich et al. [14] and Van Straten et al. [12] maximize profit.

However, these methods are not used in practice. This is because of the lack of reliable crop production models for the wide range of crops and species grown in horticultural practice and the need to leave part of the decision freedom to the responsibility of the growers [15]. Yet another and maybe even more important reason not to use crop models is the fact that growers do not trust the current crop models, although these models are considered reliable in academia. Also proper on-line plant measurements to correct for model errors, and proper predictions of market prices are not available yet.

In current practice, growers set bounds for temperature and humidity usually according to a predefined pattern. They use weather predictions, status of the crop, specific knowledge of the crop, production prognosis, and experience to define the desired patterns for temperature, humidity, CO_2 concentration, and light levels. The equipment is controlled based on a set of rules and settings, which may not necessarily be the most energy-efficient. The goal of this paper is to present a novel method to minimize the total energy input to a greenhouse while maintaining grower defined bounds. The reasoning is that within the believes of the grower regarding the desired climate it is still useful to minimize the energy input.

Because of the complexity of the system, the idea is to split the problem of optimal utilization of energy resources into two parts. The first part, which is described in this paper, aims at the realization of a desirable greenhouse climate with a minimal energy input, given a grower defined lower and upper temperature and humidity bound. The second part, which is not described in this paper, then focuses on the optimal scheduling and utilization of the equipment needed to fulfill the required minimal energy input to the greenhouse.

Minimizing the total energy use without an economic criterion has, as far as we know, only be done by Chalabi et al. [16], but they used a steady-state temperature model. Dynamic optimization of the total energy input to the greenhouse was previously presented in [17]. In the current work, the greenhouse climate model is extended with a dynamic vapour balance, which is imperative to obtain realistic results. CO_2 control is taken for granted.

The paper is organized as follows. First, the dynamic greenhouse climate model is described in Section 2 together with the optimization procedure. Then, in Section 3, model simulation and validation results are presented, followed by the results of the optimization. Finally, the results are discussed and some concluding remarks and points for further research are made in Sections 4 and 5, respectively.