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Research Paper

Day-to-night heat storage in greenhouses: 1 Optimisation for periodic weather

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Day-to-night heat storage using water tanks (buffers) is common practice in cold-climate greenhouses, where gas is burned during the day for carbon dioxide enrichment. In this study an optimal control approach is outlined for such a system, based on the idea that the virtual value (shadow price) of the stored heat, its 'co-state', could be used to guide the instantaneous control decisions. If this value is high, the system has an incentive to fill the heat storage (buffer), and vice versa if the co-state is low. The *optimal* co-state trajectory maximises the net income (performance criterion). To illustrate the method, a system description and a parameter-set roughly representative of tomato greenhouses in The Netherlands is used. The results, for daily-periodic weather, show: (1) The optimal co-state is constant (same value night and day), in contrast to the varying set-points and control fluxes. (2) The optimal solution is associated with minimum time on the storage bounds (minimum time of full or empty buffer). (3) The optimal *virtual* value (co-state) of stored heat is about the same as the *actual* cost of boiler heat during winter and about zero in summer. (4) The gain from installing a buffer is highest during spring and minimal in winter. (5) The intensive utilisation of the heat buffer in summer and its low utilisation in winter indicate that the justification of the heat storage practice, under the assumed conditions, is more the need for CO_2 enrichment in summer than the need for heating in winter.

1. Introduction

In cold-climates, where natural gas is burned during the day to enrich greenhouses with carbon dioxide (CO_2), water tanks (heat buffers) are often used to store extra daytime heat for heating at night (De Zwart, 1996; Salazar, Miranda, Schmidt, Rojano, & Lopez, 2014). Attempts to utilise this technique in milder climates have also been reported (Bailey et al., 2012), although our calculations (not shown) do not seem to justify its use in mild climates. The inverse approach, of night-to-day storage of CO_2 in activated carbon, has also been tried (Sánchez-Molina, Reinoso, Acién, RodrÍguez, & López, 2014).

There are several possible, and actual, configurations of such facilities; however, the focus of the present study is not on a particular configuration, but rather on an optimal

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Notation

*	units may differ among vector elements
[ground]	greenhouse ground surface

Symbols

a	light extinction coefficient, m^2 [ground] mol^{-1} [C]
B	Bowen (sensible to latent heat) ratio, –
C	CO_2 concentration, mol [C] m^{-3} [air]
c	specific heat of air, J [heat] kg^{-1} [air] K^{-1}
e	vector of exogenous (weather) variables, *
F	global (solar) radiation flux, J [global] m^{-2} [ground] s^{-1}
f	sunlit leaf area index, m^2 [sunlit-leaf] m^{-2} [ground]
f	vector function describing state rate-of-change, *
g	running (control) costs, \$ m^{-2} [ground] s^{-1}
H	heat flux, J [heat] m^{-2} [ground] s^{-1}
$\mathcal{H}$	Hamiltonian, \$ m^{-2} [ground] s^{-1}
h	termination value, \$ m^{-2} [ground]
J	performance criterion (objective function), \$ m^{-2} [ground]
L	photosynthetic light flux, mol [PAR] m^{-2} [sunlit-leaf] s^{-1} = mol [PAR] m^{-2} [ground] s^{-1}
M	carbon content of crop, mol [C] m^{-2} [ground]
N	growth rate of non-fruit organic matter, mol [C] m^{-2} [ground] s^{-1}
P	gross photosynthesis rate, mol [C] m^{-2} [sunlit-leaf] s^{-1}
p	gross photosynthesis rate at optimal temperature, mol [C] m^{-2} [sunlit-leaf] s^{-1}
p	vector of co-state variables, *
q	temperature response of photosynthesis, –
R	respiration rate, mol [C] m^{-2} [sunlit-leaf] s^{-1}
S	stored heat, J [heat] m^{-2} [ground]
S_D	daytime storage requirement, J [heat] m^{-2} [ground]
S_N	nighttime storage requirement, J [heat] m^{-2} [ground]
s	slope of stored heat trajectory, J [heat] m^{-2} [ground] s^{-1}
T	air temperature, K, °C
t	time, s
U	overall heat transfer coefficient across greenhouse cover, J [heat]m^{-2} [ground] K^{-1} s^{-1}
u_B	unit price of boiler heat, \$ J^{-1} [heat]
u_Q	unit price of ventilation, \$ m^{-3} [air]
u_Y	unit market price of produce (fruit) dry matter, \$ mol^{-1} [fruit-C]
u	vector of control variables, *
X	CO_2 flux, mol [C] m^{-2} [ground] s^{-1}
x	vector of state variables, *
Y	growth rate of salable fruit (yield), mol [fruit-C] m^{-2} [ground] s^{-1}
β	temperature exponent of respiration, K^{-1}
Γ	gain from installing a buffer ($\equiv J\{S_c\} - J\{0\}$), \$ m^{-2} [ground]
ε	efficiency of heat storage, –
η_{FH}	heating coefficient of global (solar) radiation, J [heat] J^{-1} [global]
η_{FL}	conversion factor solar energy to photosynthetic light, mol [PAR] J^{-1} [global]
η_{HX}	conversion factor heat to CO_2, mol [C] J^{-1} [heat]
η_{LX}	conversion factor light to CO_2 (photosynthetic 'efficiency'), mol [C] mol^{-1} [PAR]
ζ	fraction growth of saleable fruit out of total growth, –
κ	temperature correction coefficient, K^{-2}
Λ	co-state of S, \$ J^{-1} [heat]
ρ	air density, kg [air] m^{-3} [air]
σ	leaf conductance to CO_2, m^3 [air] m^{-2} [sunlit-leaf] s^{-1}
τ	transmissivity of greenhouse-cover to light, –

Subscripts

A	dissipated to atmosphere
B	supplied from boiler
c	installed capacity
D	day
d	discharging
F	due to global (solar) radiation
f	final
G	to greenhouse
i	indoor
max	maximum value
min	minimum value
N	night
o	outdoor
p	optimal for photosynthesis
r	at reference temperature
S	heat storage (in buffer)
T	total loss from greenhouse
t	on upper storage bound
u	charging
V	by ventilation

Acronyms

D	Dimension
PAR	Photosynthetically Active Radiation

strategy to control the operation of such systems. Attempts to solve the CO_2 enrichment problem in conjunction with heat buffers have been made before (Aikman, Lynn, Chalabi, & Bailey, 1997; Chalabi, Biro, Bailey, Aikman, & Cockshull, 2002). These, however, considered the heating needs (set-points) separately from CO_2 enrichment and did not treat the heat flux in and out of the buffer as a control variable. Here the method of optimal control is followed (Pontryagin, Boltyansky, Gamkrelidze, & Mischenko, 1962), the basic idea being that the co-state of the stored heat, namely its current virtual (marginal, shadow) value, could be used to guide the instantaneous control decisions. If this value is high, the