Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Day-to-night heat storage in greenhouses: 3 Co-generation of heat and electricity (CHP)

Ido Seginer [a,*], Peter J.M. van Beveren [b], Gerrit van Straten [c]

[a] Technion, Haifa, Israel
[b] B-mex, Wageningen, the Netherlands
[c] WUR, Wageningen, the Netherlands

ARTICLE INFO

Article history:
Received 23 November 2017
Received in revised form
3 May 2018
Accepted 16 May 2018

Keywords:
Greenhouse environmental control
CO_2 enrichment
Heat storage
Co-generation of heat and electricity

Day-to-night heat storage in water tanks (buffers) is common practice for cold-climate greenhouses, where gas is burned during the day for carbon-dioxide enrichment. In Seginer, I., van Straten, G., van Beveren, P. (2017). *Biosystems Engineering*, 161, 188–199, an optimal environmental control approach was outlined for conventional greenhouses, the idea being that a virtual value of the stored heat (its 'co-state') could be used to guide instantaneous control decisions. The value of the co-state was heuristically adjusted to minimise the time the buffer was ineffective (being empty or full). Here the same approach is applied to greenhouses with co-generation of heat and electricity (CHP). The parameters-set and weather are characteristic of tomato greenhouses in The Netherlands. The main results are: (1) The heuristic control method is easily adapted to systems with CHP; (2) Buffers are more useful to CO_2 enrichment in the summer than to heating in the winter; (3) There is strong synergy between the two production systems – tomatoes and electricity. The tomato crop benefits from the by-products of electricity generation, namely CO_2 and heat, sharing this benefit to support low electricity prices; (4) The combined system produces less CO_2 pollution than the two production systems operating independently; (5) The contribution of the CHP and buffer to the economic performance of the system is very significant, while that of the thermal screen and boiler is marginal; (6) Flexibility in the system is important. A buffer and/or continuously controlled boiler and CHP are essential to achieving high profitability.

1. Introduction

In recent years, co-generation of heat and electricity (CHP, Combined Heat and Power) has become popular for greenhouses located in North European countries. Most of the electricity is delivered to the electrical grid and most of the heat and CO_2 is used to improve the greenhouse aerial environment (Vermeulen & van der Lans, 2011). Water tanks are often used as heat buffers (De Zwart, 1996, Salazar, Miranda, Schmidt, Rojano, & Lopez, 2014, Compernolle, Witters, Van Passel, & Thewys, 2011, Fig. 1) storing extra heat produced during the day, for night-time greenhouse heating (in winter) or easy heat dissipation (in summer). The need for a heat buffer derives from daytime over-production of heat, which is a result of the usefulness of CO_2 enrichment and the production of electricity.

* Corresponding author.
E-mail addresses: segineri@technion.ac.il (I. Seginer), peter.vanbeveren@b-mex.nl (P.J.M. van Beveren), g.vanstraten@planet.nl (G. van Straten).

https://doi.org/10.1016/j.biosystemseng.2018.05.006

Notation

Symbols

A	On-bounds adjustment rate of co-state € J^{-1}[heat] h^{-1}
B	Ventilation 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	Electrical flux J[elect] m^{-2}[ground] s^{-1}
F	Global (solar) radiation flux J [global] m^{-2}[ground] s^{-1}
f	Sunlit leaf area index m^2[sunlit-leaf] m^{-2}[ground]
G	Crop-carbon growth rate mol[C] m^{-2}[ground] s^{-1}
H	Heat flux J[heat] m^{-2}[ground] s^{-1}
$\mathcal{H}$	Hamiltonian € m^{-2}[ground] s^{-1}
I	Infiltration rate m^3[air] m^{-2}[ground] s^{-1}
J	Performance criterion (objective function) € m^{-2}[ground]
K	Capital cost of (payback for) equipment € m^{-2}[ground] y^{-1}
k	Number of iterations –
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	Grid dimension –
N	Carbon growth rate of non-fruit organic matter mol[C] m^{-2}[ground] s^{-1}
P	Gross photosynthesis rate mol[C] m^{-2}[ground] s^{-1}
p	Gross photosynthesis rate at optimal temperature mol[C] m^{-2}[sunlit-leaf] s^{-1}
Q	Ventilation rate m^3[air] m^{-2}[ground] s^{-1}
q	Temperature response of photosynthesis –
R	Respiration rate mol[C] m^{-2}[sunlit-leaf] s^{-1}
S	Stored heat J[heat] m^{-2}[ground]
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_C	Unit price of CHP heat € J^{-1}[heat]
u_B	Unit price of boiler heat € J^{-1}[heat]
u_E	Unit price of CHP electricity € J^{-1}[elect]
u_G	Unit price of gas € m^{-3}[gas]
u_Q	Unit price of ventilation € m^{-3}[gas]
u_Y	Unit market price of produce (fruit) dry matter € mol^{-1}[fruit-C]
X	CO_2 flux mol[C] m^{-2}[ground] s^{-1}
Y	Carbon growth rate of harvestable yield (fruit) 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} s^{-1}
ΔY	Loss of yield due to extreme temperatures mol [fruit-C] m^{-2}[ground] s^{-1}
ε	Efficiency of heat storage –
η_{HE}	Proportion electricity to heat in CHP J [elect] J^{-1}[heat]
$\eta_{(H+E)X}$	Proportion CO_2 to energy in CHP mol [C] J^{-1}[heat + elect]
η_{HX}	Proportion CO_2 to boiler heat mol[C] J^{-1}[heat]
η_{LX}	Conversion factor light to CO_2 (photosynthetic ‘efficiency’) mol [C] mol^{-1}[PAR]
η_{FH}	Heat coefficient of global (solar) radiation J [heat] J^{-1}[global]
η_{FL}	Conversion factor solar energy to light mol [PAR] J^{-1}[global]
ζ	Fraction of saleable fruit out of total growth –
k	Temperature correction coefficient K^{-2}
Λ	Co-state of S € J^{-1}[heat]
μ	Fraction of installed capacity above which operation is continuous –
Π	Yield damage due to extreme temperatures mol [C] m^{-2} K^{-1}
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 –
ϕ	Purchase-cost intercept € m^{-2}[ground]
ψ_B, ψ_C	Purchase-cost per unit heat flux € s J^{-1}[heat]
ψ_S	Purchase-cost per unit of storage € J^{-1} [heat]
ω	Specific payback rate y^{-1}

Subscripts

A	Atmosphere
B	Boiler
C	CHP generator
c	Installed capacity
des	Design mode
E_b	Base rate
E_p	Peak rate
F	Global (solar) radiation
G	Greenhouse
I	Indoors
max	Maximum value
min	Minimum value
n	No thermal screen
o	Outdoors
oper	Operation mode
p	Optimum for photosynthesis
r	At reference temperature
S	Heat stored in buffer
s	With thermal screen
T	Total loss from greenhouse
TS	Thermal screen
V	Ventilation

Acronyms

CHP	Combined Heat and Power (electricity generator)
FM	Fresh Matter (in fruit)
PAR	Photosynthetically Active Radiation
TS	Thermal Screen