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\textsubscript{2} enrichment in summer than the need for heating in winter.

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1. Introduction

In cold-climates, where natural gas is burned during the day to enrich greenhouses with carbon dioxide (CO\textsubscript{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\textsubscript{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...
strategy to control the operation of such systems. Attempts to solve the CO₂ 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 CO₂ 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
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