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A generic tool for quantifying the energy requirements of glasshouse food production

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ABSTRACT

Quantifying the use of resources in food production and its environmental impact is key to identifying distinctive measures which can be used to develop pathways towards low-carbon food systems. In this paper, a first-principle modelling approach is developed, referred to as gThermaR (Glasshouse-Thermal Requirements). gThermaR is a generic tool that focuses on the energy requirements of protected heated production, by integrating holistic energy, carbon, and cost modelling, food production, data analytics and visualization. The gThermaR tool employs historic data from weather stations, growing schedules and requirements specific to grower and product needs (e.g. set-point temperatures, heating periods, etc.) in order to quantify the heating and cooling requirements of glasshouse food production. In the present paper, a case study is reported that employs a database compiled for the UK. Another relevant feature of the tool is that it can quantify the effects that spatial and annual weather trends can have on these heating and cooling requirements. The main contribution of this work, therefore, concerns the development a tool that can provide a simple integrated approach for performing a wide range of analyses relevant to the thermal requirements of heated glasshouses. The tool is validated through collaborations with industrial partners and showcased in a case study of a heated glasshouse in the UK, offering the capacity to benchmark and compare different glasshouse types and food growth processes. Results from the case study indicate that a significant reduction in the heating requirement and, therefore, carbon footprint, of the facility can be achieved by improving key design and operational parameters. Results indicate savings in the peak daily and annual heating requirements of 44–50% and 51–57% respectively, depending on the region where the glasshouse is located. This improvement is also reflected in the carbon emissions and operating costs for the different energy sources considered. Furthermore, the temporal variability/uncertainty of the annual energy requirements and of the peak daily energy requirements are found to be considerably lowered through improvements to the glasshouse attributes. Overall, gThermaR proves its value in quantifying and identifying key factors that have a significant impact on energy requirements of heated glasshouses. Such valuable outputs are invaluable for stakeholders in the food industry that have an interest in mapping the sustainability and mitigating the carbon footprint of their supply chain processes.

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1. Introduction

It is projected that global food production will increase by 70% by 2050 due to population growth (FAO, 2011). Subsequently, significant stress is expected at all stages of food supply chains as attempts are made to satisfy this demand growth while also putting much stress on the associated resources. This will almost certainly lead to an increase in the energy consumption and carbon footprint of the food production sector. In alignment with the global status quo, the UK food sector is highly dependent on fossil fuels and there are ambitious targets to reducing carbon emissions (DECC and DEFRA, 2015). In this context, it is important to identify methods that can minimize the energy requirements and carbon intensity of related activities. Based on estimates provided in Carr et al. (2014) and DEEC and National Statistics (2015), the UK domestic food sector accounts for about 30% of the country's total greenhouse gas emissions. Therefore, significant improvements in this sector can

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Nomenclature

A	area, m^2
c_p	specific heat at constant pressure, kJ kg^{-1} K^{-1}
D	distance, m
e	vapour pressure, kPa
$\dot{E}$	electrical power, kW
F	flow rate, m^3 s^{-1} m^{-2}
h_{fg}	latent heat of vaporization, kJ kg^{-1}
I	solar radiation, kW m^{-2}
N	infiltration rate, s^{-1}
p	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
r	radius, m
R	gas constant
SFP	specific fan power, kW m^{-3} s^{-1}
t	time
T	temperature, K
U	overall heat transfer coefficient, kW m^{-2} K^{-1}
v	specific volume, m^3 kg^{-1}
V	volume, m^{-3}
W	humidity ratio, kg_{vap}/kg_{air}

Greek letters

β	absorbed radiation ratio
η	efficiency
θ	latitude, rad
ρ	density, kg m^{-3}
ϕ	longitude, rad

Subscripts

a	actual
b	boiler
c	cover
f	floor
i	in
o	out
p	pressure
s	time step
v	vapour

have a substantial impact in achieving the country's emissions targets (Markides, 2013). In terms of energy consumption, the UK food chain is responsible for about 18% of the country's primary energy use (Tassou, 2014), and thus it can be argued that energy security and cost uncertainty makes the pursuit of methods to reduce energy consumption a necessity to benefit businesses, society, and the environment. Similarly, food retailers are becoming increasingly interested in the optimal design and operation of their buildings (Alvarado et al., 2016; Acha et al., 2018), decarbonization and the use of renewables (Mariaud et al., 2017), and the challenging task of mapping the footprint of their supply chains to improve their robustness (ASDA, 2017; Sainsbury's, 2017; Tesco plc, 2017). This is because it is assumed that the stronger the supply chains are, the better the business longevity prospects are.

Moreover, the development of fast and refrigerated logistics has created a market where the public's expectations to consume out-of-season fresh products has grown substantially (Jones, 2002). With this increasing demand, glasshouse food production has become a promising approach for (partially) satisfying out-of-season demand (in addition to imports). Naturally, heated glasshouse food production is more energy and carbon intensive per planted area than open-field production. Nevertheless, the energy-use differences between domestic open-field production and food imports are expected to vary depending on their respective sub-processes, such as heating and ventilation for cooling in glasshouses. Other factors with a significant impact are geographical location, ambient weather conditions, installed technologies, energy resource efficiency, and food production targets (Carlsson-Kanyama, 1997), as well as the characteristics of the production system. This complexity has led to a debate over which approach is more energy intensive between food importation and local food production (Carlsson-Kanyama, 1998, 1997; Garnett, 2008; Jones, 2002). The main reason that imports from distant origins are competitive in terms of carbon footprint against national production in heated glasshouses is due to the energy intensive process associated with heating requirements (Carlsson-Kanyama, 1997). However, in order to assess and quantify the energy intensity in food production, all factors previously outlined need to be considered in a comprehensive analysis.

The quantification of the energy requirements of glasshouse food production has been investigated previously in the literature, for example in studies such as those in ASABE (2008), Chalabi et al. (2002), Gupta and Chandra (2002), Moreton and Rowley (2012), Ozkan et al. (2011a, 2011b), Papadopoulos and Hao (1997), Subić et al. (2015), Mariani et al. (2016), Luo et al. (2005) and Wass and Barrie (1984). In Papadopoulos and Hao (1997), the authors investigated the effect of the glasshouse cover material in three tomato glasshouses focusing on yields, energy requirements and productivity, whereas Gupta and Chandra (2002) focused on the effects of a glasshouse's design on its energy requirements, with a particular interest in the shape and orientation of a glasshouse in India. Furthermore, carbon dioxide enrichment strategies were considered in Chalabi et al. (2002), which extended to the development of a glasshouse energy balance model, while the American Society of Agricultural and Biological Engineers presented engineering practices based on accepted methods for designing heating and cooling systems for glasshouses in ASABE (2008).

Furthermore, a model for the calculation of the energy requirements of glasshouses was also presented in Wass and Barrie (1984). This paper focused on the effect of glasshouse dimensions, temperature regimes and weather variations on energy requirements, while Ozkan et al. (2011a, 2011b) examined the energy requirements specifically for single and double crop tomato production. Interestingly these studies observed the direct energy use in terms of fuel and electricity as well as indirect energy use due to manure and chemical fertiliser. Mariani et al. (2016) investigated the heating requirements of glasshouse tomato production in 56 sites located in Europe and the Mediterranean, while focusing on space and time variability. This paper considered the heating requirements of glasshouses over very wide territories and long times with particular emphasis on the impact of climate change. Interestingly, the study of Mariani et al. (2016) generated hourly temperature and radiation data by using only maximum and minimum daily temperatures in terms of external weather input data. This approach has the advantage of not relying on detailed weather databases and can be advantageous in performing macroscale analyses which include areas with very limited weather data. On the other hand, using real weather data can be advantageous in a more granular analysis while incorporating the impact of real weather variations and their unpredictability.

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