Assessing, Benchmarking and Analyzing Heating and Cooling Requirements for Glasshouse Food Production: A Design and Operation Modelling Framework

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Abstract

Growing populations, increase in food demand, society’s expectations for out of season products and the dependency of the food system on fossil fuels stress resources due to the requirements for national production and from importation of products from remote origins. Quantifying the use of resources in food production and their environmental impacts is key to identifying distinctive measures which can develop pathways towards low carbon food systems. In this paper, a modelling approach is presented which can quantify the energy requirements of heated glasshouse food production. Based on the outputs from the model, benchmarking and comparison among different glasshouse types and growers is possible. Additionally, the effect of spatial and annual weather trends on the heating and cooling requirements of glasshouses are quantified. Case study results indicate that a reduction in heating requirements of about 50\%, and therefore an equivalent carbon footprint reduction, can be achieved by replacing a single glass sealed cover with a double glass sealed cover.

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1. Introduction

It is projected that global food production will increase by 70% by 2050 as a result of population increase [1]. Consequently, huge pressure at all stages and processes of food supply chains is expected to be applied in the attempt to satisfy this growth in demand and resources requirements. This will almost certainly lead to increase in energy consumption and carbon footprint but also create a feedback effect that can further deteriorate the situation. Given that the UK food sector is highly dependent on fossil fuels and there are ambitious targets in reducing carbon emissions [2], it is important to find methods for minimizing the energy requirements and carbon intensity of such activities. Considering the fact that based on estimations from published figures by Refs. [3,4], the UK domestic food sector
accounts for about 30% of the country’s total greenhouse gas emissions, it cannot be overlooked that significant improvements in this sector can have a substantial impact in achieving the country’s emissions targets. In terms of energy consumption, since the UK food chain is responsible for about 18% of the country’s primary energy use [5], it can be confidently said that energy security and fossil fuel prices volatility make the pursuit of methods to reduce energy consumption a necessity to benefit companies, the environment, and society.

Furthermore, the development of fast and refrigerated logistics has created a market where people’s expectations to consume out of season fresh products has grown substantially [6]. With this increasing demand, glasshouse production becomes an approach for partially satisfying the out of season demand in addition to imports. As expected, in the UK heated glasshouse production is much more energy and carbon intensive per planted area than open field production and it has been found that especially heating requirements can be responsible for the greatest share of energy consumption through the whole supply chain. Nevertheless, the difference from open field production and imports is expected to vary depending on the sub-processes that take place during production such as heating and ventilation for cooling in glasshouses which in turn depend on factors such as location, technologies used, energy sources, products grown [7] as well as production system implemented. There is also a debate over which is more energy intensive between imports and local production [6-9]. The main reason that imports from distant origins are considered in the analysis.

Moreover, companies are becoming more interested in the challenging task of mapping the footprint of their supply chains in order to improve the robustness of their food supply chains. Thus, a tool which considers factors such as climate conditions, location, production systems, growing schedules, time periods intervals flexibility and more, is expected to provide a good overview in the identification of the most influential parameters for improvement through a parametric study as well as provide a relatively simple method for benchmarking and assessing existing production stakeholders of supply chains. To the best of our knowledge, there has not been a study to develop a generic tool of this kind and this paper presented a modelling framework to address this research gap.

2. Methodology

2.1. Thermodynamic model

The evaluation of energy input or output required for a glasshouse to be maintained at the required conditions is done through the quantification of the main heat gain and heat loss mechanisms. The main loss mechanisms are the losses due to convection, conduction and radiation in addition to latent and sensible heat losses due to infiltration. The main heat gain mechanisms are all aforementioned ones with the addition of solar radiation. Therefore, the heat rate input and output required ($\dot{Q}$) is determined using the following energy balance equation:

$$\dot{Q} = U \cdot A_c \cdot (T_i - T_o) + \rho \cdot N \cdot V \cdot \left(c_p \cdot (T_i - T_o) + h_{fg} \cdot (W_i - W_o)\right) - \beta \cdot I \cdot A_f$$

(1)

where $U$ is the overall heat transfer coefficient, $A_c$ is the surface area of the glasshouse cover, $T_i$ and $T_o$ are the internal and external temperatures respectively, $\rho$ is the air density assumed to be constant at 1.29 kg/m$^3$, $N$ is the infiltration rate in s$^{-1}$, $V$ is the inside volume of the glasshouse, $c_p$ is the specific heat of air assumed to be constant at 1.005 kJ/kg, $h_{fg}$ is the latent heat of vaporization of water, $W_i$ and $W_o$ are the humidity ratios in kg$_{vap}$/kg$_{air}$ of the internal and external air respectively, $\beta$ is the ratio of solar radiation per unit of area (I) absorbed by the glasshouse and $A_f$ is the floor area. Similar energy balance equations were presented in Refs. [10,11].

When $\dot{Q}$ is evaluated as positive, heating is required. To convert the heat rate required into energy consumption rate as supplied by the boiler, the efficiency of the boiler ($\eta_b$) is taken into account and the result is given in units of power. The energy can be in any form of fuel but this will make a difference mostly in the economic and carbon footprint analyses due to the variation in cost and carbon factors between energy sources. Hence, the power input from the boiler ($\dot{Q}_b$) can be determined from:
\[ \dot{Q}_b = \frac{1}{\eta_b} \dot{Q} \]  

(2)

When \( \dot{Q} \) is negative, cooling is required. Cooling in glasshouses is typically provided through natural or mechanical ventilation systems. In this model, we will estimate the ventilation rate required in terms of unit of air volume extracted per unit of time in order to maintain the ideal internal conditions of the glasshouse. Using the energy balance shown in Eq. (1) with the combination of considering the impact of external air interaction through either air supply or extract depending on the temperatures, the following expression is derived:

\[
U \cdot A_c \cdot (T_i - T_o) + \rho \cdot N \cdot V \cdot \left( c_p \cdot (T_i - T_o) + h_{fg} \cdot (W_i - W_o) \right) - \beta \cdot I \cdot A_f = \frac{-F \cdot A_f \cdot c_p}{v_1} (T_i - T_o)
\]

(3)

where \( F \) is the air flow rate through the ventilation per unit of area and \( v_1 \) is the specific volume of the internal air. In the case of mechanical ventilation, the ventilation rate required can be converted into electrical power consumption (\( \dot{E}_v \)) through the use of Specific Fan Power (SFP) variable which gives power required per unit of volume of air supplied or extracted per second as shown in Eq. (4).

\[
\dot{E}_v = SFP \cdot (F \cdot A_f)
\]

(4)

Thereafter, \( \dot{Q}_b \) and \( \dot{E}_v \) can be converted into energy consumption by integrating over the time period \( t \) considered while assuming steady state conditions using:

\[
Q_b = \int_0^t \dot{Q}_b \, dt
\]

(5)

\[
E_v = \int_0^t \dot{E}_v \, dt
\]

(6)

For the consideration over consecutive periods for the estimation of total energy requirements, if we consider discrete time period steps \( t_i - t_{i-1} \) according to the data available, the following expressions can be used:

\[
Q_b = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} \dot{Q}_{b(i)} \, dt
\]

(7)

\[
E_v = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} \dot{E}_{v(i)} \, dt
\]

(8)

Finally, if we consider taking equal time period \( t_s \) steps of one day length while the average daily values for all the variables are obtained or calculated from the database values, the energy requirements for both heating and cooling simply become:

\[
Q_b = \sum_{i=1}^{n} \dot{Q}_{b(i)} \cdot t_s
\]

(9)

\[
E_v = \sum_{i=1}^{n} \dot{E}_{v(i)} \cdot t_s
\]

(10)

2.2. Spatial model

To make sure that weather data used for the model execution and evaluation of outputs are from the best weather station available while following a standardized procedure, the station is chosen based on distance proximity to the glasshouse. The distance \( D \) between two points on the surface of the earth per their coordinates is estimated based on the law of cosine using the following equation:

\[
D = r \cdot \arccos(\sin \theta_1 \cdot \sin \theta_2 + \cos \theta_1 \cdot \cos \theta_2 \cdot \cos(\Delta \phi))
\]

(11)
where $r$ is the Earth’s radius, $\theta_1$ and $\theta_2$ are the geographical latitudes of the two points in radians, and $\Delta \varphi$ is the difference in geographical longitude between the two points. For a UK analysis, an additional step is incorporated to make the process easier and faster for organizations with a large portfolio of glasshouses. Given that it is common for the locations of glasshouses to be available in the form of postcodes, the tool accepts as a location argument the postcode of the glasshouse and using the UK postcode database it identifies the coordinates assigned to the glasshouse and executes the program.

2.3. Data model

The temperature and solar irradiation data, acquired from Ref. [12] database, are given in units that can be applied in the model after being filtered and processed. However, in the case of humidity ratio, data recorded from the majority of weather stations are given in terms of wet bulb temperature or dew point temperature [12]. Some stations might have direct humidity data recorded but because a large pool of stations is important for the provision of weather stations as close as possible to the glasshouse under analysis, the approach of dew point temperature was used for the calculation of the humidity ratio as defined in the energy balance Eq. (1). Thus, humidity ratio ($r$) is calculated based on the standard methodology presented in Ref. [13] in combination with the ideal gas law to give:

$$
 r = \frac{e_a R_d}{R_v (p - e_a)} \left[ \frac{e_a R_d}{R_v (p - e_a)} \right]^{-1+ \frac{e_a R_d}{R_v (p - e_a)}} \tag{12}
$$

where $R_d$ and $R_v$ are the gas constants for air and vapour respectively, $p$ is the atmospheric pressure and $e_a$ is the actual vapour pressure which can be calculated when the dew point temperature ($T_{dew}$) is available using:

$$
 e_a = 0.6108 \cdot \exp \left[ \frac{17.27 T_{dew}}{T_{dew} + 237.3} \right] \tag{13}
$$

2.4. Information process flow

The tool process flow with its fundamental elements are presented in Fig. 1 and as shown, the tool comprises three main databases, three fundamental models and three main outputs with the most insightful one being the end results output, namely the “Tool Outputs” from the glasshouse energy model. Finally, a feedback loop has been introduced to allow for the execution of multiple scenarios with the overriding aim of facilitating the parametric variations and studies. All models and processes are executed through Python.

![Fig. 1. High level information process flow diagram.](image-url)
3. Results

This section consists of: (a) the validation of the model based on a case study, (b) a parametric analysis pointing out the most influential variables in the model with respect to glasshouse’s energy performance, (c) the estimation and importance of daily energy requirements and (d) the variation of energy requirements based on data from multiple years with the effect of modifications on this variability.

Firstly, the energy model was tested on a UK based glasshouse used for strawberry production for the year 2015. The estimation of annual energy consumption from the model was found to be 2% lower than the actual energy consumption of the glasshouse with 248 kWh m\(^{-2}\) and 253 kWh m\(^{-2}\) respectively while considering the glasshouse characteristics, conditions required and approximate growing schedules as specified by the glasshouse operator.

The energy balance is affected by environmental variables such as radiation levels, external temperature and external humidity ratio whose variation cannot be controlled other than changing the geographical location of the glasshouse. However, there are variables both in regards to internal glasshouse conditions and equipment characteristics that have an impact on the energy requirements. Therefore, while using the methodology discussed in Section 2, a parametric analysis was carried out to observe the influence of each variable considered with respect to annual heat supply requirements per unit of area while holding all the other variables at their nominal values. The equipment performance variables that showed the greatest influence were the overall heat transfer coefficient \(U\) and infiltration rate \(N\) over their corresponding ranges applicable (0.57-6.20 W m\(^{-2}\) K\(^{-1}\) and 1.40×10\(^{-4}\)-11.10×10\(^{-4}\) s\(^{-1}\) for \(U\) and \(N\) respectively) based on the standard values given in Ref. \[10\] (see Fig. 2(a)). In terms of operation conditions variables, internal temperature was found to have a great impact on heating requirements (represented in Fig. 2(b)) even over the small range of variation considered (12 to 16 °C). This shows the impact on heating requirements that other products with different atmospheric conditions requirement might have if assessed.

Since the cover’s overall transfer coefficient and infiltration rate were identified to be the most influential variables in the model, it is also interesting to see their impact on energy performance in terms of both daily energy use as well as overall annual requirements. We take the case study’s glasshouse characteristics with the addition of mechanical ventilation to analyze energy consumption due to cooling requirements as the base case and study the impact on its energy performance by changing its cover from single glass sealed with \(U\) of 6.2 W m\(^{-2}\) K\(^{-1}\) \[10\] to double glass sealed with \(U\) of 3.7 W m\(^{-2}\) K\(^{-1}\) \[10\] and improving \(N\) from 4.2×10\(^{-4}\) s\(^{-1}\) \[10\] to 2.8×10\(^{-4}\) s\(^{-1}\)\[10\]. From Fig. 3(a), the first thing to notice is the zero values in both cooling and heating for both scenarios mainly indicating the consideration of the model in the growing schedules. Secondly, for both the base case and the improved scenario there are peak demand days in both cooling and heating which are orders of magnitude greater than most of the days. Besides the much greater energy consumption associated with these peaks, one of the main issues with these outliers is in the sizing of the heating and cooling systems to accommodate them. However, as Figs. 3(a,b) shows, through the improved case a significant reduction in terms of both the peak daily and annual demands for heating has been achieved with reductions of 45% and 56%, respectively. These reductions of course indicate an improvement in terms of efficiency of the glasshouse but they also show a more resilient system by which the external conditions have less impact on its peak energy requirements while also decreasing the risk of produce quality degradation. This fact implies that heating and cooling systems can be potentially re-sized for a smaller capacity range, thus operating closer to nominal capacity and most likely at higher efficiency. In terms of cooling while considering an \(SFP\) of 0.2 kW m\(^{-3}\) s\(^{-1}\), the impact of these two parameters was considerably less while even showing a slight increase in the overall annual cooling requirement. Finally, the number of days requiring cooling increase by 24% while the days requiring heating decreased by 25%, hence showing a shift from heating days to cooling days. However, since the impact of heating was found to be much more influential, in terms of overall energy requirements the glasshouse achieved considerably a better performance.
The impact of improving the energy efficiency of the glasshouse is also beneficial in terms of its carbon footprint and the embodied carbon of the product. However, the magnitude of these reductions depends on the energy source. For example, the aforementioned reduction in annual heating is expected to result in the curtailment of 25.67, 1.82, 0.03 kgCO₂e m⁻² for natural gas, biomass and biogas respectively based on the carbon factors given in Ref. [14]. In terms of yearly variations in annual heating and cooling requirements based on weather data from the last 20 years, the same improvement measures used in the daily analysis, Fig. 4 shows consistently significant reduction in heating requirements, resulting to a reduction in the mean (μ) by about 180 kWh m⁻² year⁻¹ and therefore a 52% decrease. However, the effect on cooling is minimal and cannot be distinguished from the graph. Also, a significant decrease in variance with respect to annual heating over the 20 years examined through the improvement measures is noticed resulting in the substantial decrease in standard deviation (σ) from 71.5 to 38.9 kWh m⁻² year⁻¹ (see Fig. 4). The minimization in annual variability is expected to assist in the improvement of resilience of the glasshouse against external weather conditions as well as in the decrease in cost uncertainty, thus providing support towards more accurate budget forecasting for both growers and retailers. On the other hand, even though the variance and standard deviation of cooling is originally lower than that of heating, the effect of the improvement measures on these metrics was found to be negligible. Nevertheless, with the introduction of other measures, such as the improvement in SFP, it is expected to see greater improvement on cooling.
4. Conclusions

The increased demand for out-of-season food availability along with its associated link to primary energy (fossil fuel) consumption act as drivers for assessing and quantifying the existing glasshouse infrastructure and the most influential factors on its performance. This paper presented a methodology comprising of multiple modules forming an integrated tool that can be used to assess the energy requirements of glasshouses used for food production, such a tool has great potential to address different type of problems and provide further insight, for example:

- Analysis and management:
  - assessment of existing glasshouses in terms of their energy performance;
  - creation of a portfolio of various glasshouses’ energy performances based on a standardized procedure;
  - analysis of glasshouse energy requirements based on products with their associated growing schedules and required internal conditions;
  - analysis on daily energy requirements and peak demand days in a season;
  - analysis on annual energy requirements;
  - forecasting the potential impact of climate variability on glasshouses’ energy requirements.

- Design and analysis:
  - analysis of the geographical location’s impact on energy requirements;
  - analysis of potential approaches for improvement through both independent modifications as well as through combinations;
  - inspection of expected yearly variations in energy requirements due to weather conditions and the impact of glasshouses’ modification on minimizing them.

Findings from this study have shown that the most influential equipment performance variable to be the overall heat transfer coefficient of the glasshouse’s cover, followed by the infiltration rate. Furthermore, the significance of ideal internal conditions, such as internal temperature on the overall heating requirements has also been pointed out. The improvement of the cover’s overall heat transfer coefficient in combination to the improvement of infiltration rate was found to significantly reduce both the annual heat supply requirement and the daily peak requirement. Results indicate that if heating loads are reduced there is large potential in better sizing of the heating systems in addition to providing more resilience of the system towards external conditions. The effect on cooling requirements was considerably less. Finally, the yearly variations based on analysis from 20 years of weather data showed the decrease in terms of variability and standard deviation with respect to heating requirements through the introduction of improvement measures, hence presenting a potential for a more stable system with less uncertainty in annual energy requirements and therefore the provision of better cost forecasting. All in all, the impact of specific characteristics of
Glasshouses used as inputs in the model as well as external weather conditions showed to have a substantial influence on the energy requirements of the glasshouse, thereby indicating the importance of quantifying these variations in an energetic analysis of a supported food production system.

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