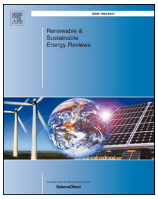
Renewable and Sustainable Energy Reviews 96 (2018) 487–501

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



A novel integrated framework to evaluate greenhouse energy demand and crop yield production

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ARTICLE INFO

Keywords:
Greenhouse
Energy demand
Crop yield model
Integrated framework
Dynamic modeling

ABSTRACT

Greenhouses are complex systems that require considerable amounts of energy. In order to optimize their performance, it is necessary to reduce the amount of energy per unit of crop produced. This requires a combined assessment of greenhouse energy balance and crop growth, as well as their interaction. In this work, more than 30 existing greenhouse models are reviewed and different algorithms are combined to propose an integrated energy-yield model. The physical model of greenhouse energy demand is based on the dynamic energy and mass balance while yield production is based on a physiological crop model.

The integrated model is validated with observed energy demand and crop yield datasets during one full tomato growing period. There was good agreement between modeled results and measured data. The key advantage of the integrated model is that it can analyze drivers for greenhouse energy losses and quantify the influence of measures on both energy demand and crop yield. Due to the model's dynamic and high temporal resolution, it is possible to study the use of renewable energy sources in greenhouse operation, as illustrated for thermal storage by means of phase change materials. A sensitivity analysis by changing day/night temperature, CO_2 indoor concentration and artificial lighting is performed. The results illustrate how the model can be used for optimizing the performance of greenhouses in terms of specific energy demand (energy per crop produced). Therefore, the integrated model can be a tool for determining the optimum design and control parameters, which is particularly relevant for growers and sustainable agriculture systems in general. This study presents a parametric decision support tool that assists planers with optimizing energy performance of greenhouses while analyzing the trade-off between energy demand and crop yield.

1. Introduction

In light of the growing worldwide population, efficiency increases in agricultural production are needed to meet the additional food demand. Food production by means of greenhouses represents a strategy to increase crop yields, by providing favorable ambient conditions of temperature, water supply and fertilization with CO_2 and nutrients [1]. This allows to prolong the cultivation period in cold regions and therefore also to avoid environmental impacts for food transport. However, providing a favorable climate in the greenhouse, especially during offseason cultivation of crops, requires more energy consumption than open field agriculture [2,3]. Therefore, increasing protected cultivation in greenhouses to achieve more yield per unit area will increase the energy consumption [4–7] and related environmental impacts [8–11], making the specific energy demand (i.e. units of energy per crop yield) of greenhouses a crucial issue [12,13]. For instance, production costs in EU greenhouses, as the largest supplier of greenhouse products, is 78% of total cost, with energy consumption being the largest share [14–17]. By shifting towards renewable energies for greenhouse operation, it is possible to reduce non-renewable energy consumption by 40% [14,16]. Hassanien et al. [18] review the utility of solar energy technologies in the greenhouse microclimate control systems specifically heating, cooling, lighting and irrigation systems. They show that advanced solar energy technologies such as solar air heaters, solar thermal collectors and photovoltaic (PV) water pumping can usually be applied very well in greenhouse and thus reduce environmental impact. Gül Bayrakci et al. [19] quantify the potentials of renewable energy sources, such as solar, biomass, wind, geothermal, and hydropower for Turkey. Greenhouses can be considered the largest commercial solar buildings [20], as they use solar energy to allow cultivation of different crops in places where previously no agriculture was possible [21].

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https://doi.org/10.1016/j.rser.2018.06.046
Received 1 November 2017; Received in revised form 20 April 2018; Accepted 20 June 2018

Nomenclature

Symbols

C_a	Specific heat of air (J kg^{-1} K^{-1})
C	Condensation on the greenhouse cover, [g m^{-2} s^{-1}]
C_{CO2}	CO_2 concentration of inside greenhouse (ppm)
$D_F(T_d)$	Function for fruit development rate (day^{-1})
E	Crop transpiration (g m^{-2} s^{-1})
$f_F(T_d)$	Function to modify partitioning to fruit vs. Average daily temperature, T_d (dimensionless)
$f_N(T)$	Function to modify node development rate as a function of hourly temperature (dimensionless)
GR_{net}	Net aboveground growth rate (g dry weight m^{-2} ground day^{-1})
h	the average height of the greenhouse (m)
LAI	Leaf Area Index (m^2 leaf m^{-2} ground)
LAI_{max}	Maximum leaf area index (m^2 leaf m^{-2} ground)
N	Number of nodes on main stem
N_b	Coefficient in expolinear equation, projection of linear segment of LAI vs N to horizontal axis (node)
N_{FF}	Nodes per plant when first fruit appears (node)
N_m	Maximum rate of node appearance rate per hour at optimal temperature (node h^{-1})
p_1	Loss of leaf dry weight per node after LAI_{MAX} is reached (g leaf node^{-1})
$PPFD$	Photosynthetic photon flux density (μmol m^{-2} s^{-1})
q_{con}	the convective and conductive heat transfer (W)
q_g	The input energy to maintain the desired temperature in the greenhouse (W)
q_l	The energy exchange of the thermal radiation from the greenhouse interior to outside (W)
q_{lamp}	Energy transfer of artificial lighting (W)
q_{trans}	the heat flux due to crop transpiration (W)
q_{solar}	The energy transfer of incoming solar radiation (W)
q_{vent}	Heat loss due to natural ventilation (W)
T	Hourly temperature (°C)
T_d	Average daily temperature (°C)
$T_{daytime}$	Average temperature during daytime hours (°C)
V_a	greenhouse volume (m^3)
V	Moisture loss through the ventilation windows, [g m^{-2} s^{-1}]
W	Above ground dry weight (g dry weight m^{-2} ground)
W_F	Total fruit dry weight (g dry weight m^{-2} ground)
W_M	Mature fruit dry weight (g dry weight m^{-2} ground)

Greek symbols

α_F	Maximum partitioning of new growth to fruit (fraction day^{-1})
β	Thermal expansion coefficient (dimensionless)
β_C	Coefficient in expolinear equation (node^{-1})
δ	Maximum leaf area expansion per node (m^2 leaf node^{-1})
κ_F	Development time from first fruit to first ripe fruit (node)
$\lambda(T_d)$	Temperature function to reduce rate of leaf area expansion (dimensionless)
υ	Transition coefficient between vegetative and full fruit growth (node^{-1})
ρ	Plant density (number of plants m^{-2} ground)
ρ_a	greenhouse air density (kg m^{-3})
ϕ_{CO2}	CO_2 flux (g m^{-2} s^{-1})
χ	Absolute water vapour concentration of greenhouse air, [g m^{-3}]
ψ	Roof slope (degree)

Subscripts

O	Outdoor condition
crop	Crop level
air,sat	Saturated air

Protected cultivation systems can be found around the world. They range from passive solar greenhouses [22,23] and low-cost greenhouses [24–29] to the high-tech greenhouses [7,30]. There is a trend towards more use of renewable energy technologies, such as PV modules, solar thermal collectors and thermal energy storages, to decrease fossil fuel consumption of conventional greenhouses [4,31,32]. Cuce et al. [31] concluded that 80% energy saving in greenhouses is achievable by appropriate application of renewable energy resources depending on climatic conditions and crop type. To consider the impact of them on the greenhouse energy consumption and yield production for designing an optimum energy system, an integrated model is required to investigate both issues, simultaneously. Such an integrated model is missing in literature, as previous models have focused on either energy demand or crop growth. Such an integrated model is missing in literature, as previous models have focused on either energy demand or crop growth.

1.1. Greenhouse energy models

Typical numerical energy demand models for buildings are not suitable for determining energy demand of greenhouses. The main reason for this is the microclimate in the greenhouse, which is determined by the crop canopy during different stages of crop growth, is constantly changing, unlike typical buildings [33]. A number of authors have developed approaches to determine greenhouse specific energy demand. Following an initial analysis of greenhouse energy balance to simulate greenhouse inside temperature [34,35], a number of dynamic models were developed. These models simulate the greenhouse climate as a function of the outdoor climate and the greenhouse's physical features [36–39]. Tiwari et al. [40], Chou et al. [41] and Singh et al. [27] used previously developed dynamic models as an analytical model to estimate energy demand by considering the impacts of different sizes and shapes of greenhouses. Sethi et al. [42] improved the previous dynamic energy models by modeling the effects of solar radiation on different greenhouse shapes. Vanthoor et al. [43] extended the model of Bot [38] and developed a greenhouse climate model to apply to four different greenhouse designs under three climatic conditions. Vadiee and Martin [20] investigated the performance of the closed greenhouses with long or/and short thermal storage technology (TES) integration. Van Beveren et al. [30] and Joudi and Farhan [26] developed and validated dynamic greenhouse microclimate models to describe the energy and mass exchanges between the inside and outside of the greenhouse, and applied the models to analyze the thermal performance in the greenhouses. Chen et al. [33] proposed a methodology to predict the energy demand of greenhouses based on the energy and mass balance. They utilized a sensitivity analysis methodology to calibrate the uncertain parameters of the energy model by using the measured data in an experimental greenhouse. Although some of the abovementioned energy models consider different basic greenhouse energy losses, none of them is able to directly account for the effects of plant growth, namely evapotranspiration with dynamic leaf area index and CO_2 assimilation. While they use some parameters from crop type as inputs, they cannot predict the impact on yield production.