On the Use of Building Energy Simulation Programs in the Performance Assessment of Agricultural Greenhouses

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ABSTRACT

The paper explores possibility of using BES in performance evaluation of commercial agricultural greenhouses, focusing on the necessary adaptations and additional models required to obtain reliable results. The paper provides a high-level evaluation of relevant physical phenomena for energy performance of greenhouses. A comparison is made regarding the importance of each phenomenon in normal buildings and in greenhouses. The paper also need for models to predict the crop production and the necessary validation of BES models for the prediction of performance in greenhouses. Preliminary validation by inter-model comparison shows promising results and indicates that BES can be used for the energy performance evaluation of greenhouses.

KEYWORDS

Commercial greenhouse, greenhouse energy simulation (GES), Building energy simulation (BES), validation, ESP-r, KASPRO

INTRODUCTION

Commercial agricultural greenhouses are large low-rise structures, with shell properties rather different from usual building shells (such as high U-value and high glazed area). Greenhouses shells are designed to create more favourable condition for the crop when compared to the conditions in the outdoor environment. In spite of improvements in indoor conditions, colder climates may require the use of active heating, ventilation and air conditioning (HVAC) systems in order keep ideal conditions for the crop. Therefore the innovative greenhouse design and operation is a major challenge for energy saving.

Building energy simulation (BES) has been used in the development of innovative building shells and HVAC systems [1,2], hence BES could potentially play an important role on improving commercial greenhouses. General purpose BES

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programs can calculate dynamic interaction of heat, air, moisture and light in buildings. However, the use of such programs in the simulation of greenhouses may require: (1) some adaptations (due to the differences between buildings and greenhouses) and (2) additional models (such as models for the evaluation of crop growth, calculation of light transmittance for photosynthesis, etc.).

This paper explores possibilities of using BES in performance evaluation of commercial agricultural greenhouses, focusing on the necessary adaptations and additional models required to obtain reliable results. The paper provides a high-level evaluation of relevant physical phenomena taking place in greenhouses and the means to address them in BES programs. This is followed by a section dedicated to modifications necessary for greenhouse simulation in BES. These modifications are implemented in the BES program ESP-r, and a section is dedicated to the initial validation results by inter-model comparison. The last section summarizes the main conclusions of the paper.

EXISTING PROGRAMS FOR ENERGY SIMULATION OF GREENHOUSES

Greenhouse energy simulation (GES) has been carried out using simulation programs specifically designed to calculate the heat, air and moisture balance between greenhouse and outdoor environment. For example, "Greenhouse Simulation" is a simplified and user-friendly greenhouse energy model that allows preliminary evaluation of greenhouse design options under different weather conditions and operational strategies [3]. De Zwart (1996) developed a comprehensive greenhouse simulation program to analyse energy performance and crop productivity in Venlo-type greenhouse in the Netherlands, named KASPRO [4]. KASPRO was validated using empirical data for state-of-the-art greenhouse in the Netherland and China [5,6]. Figure 1 show an example of KASPRO validation where good agreement is observed in the daily variation of indoor air temperature.
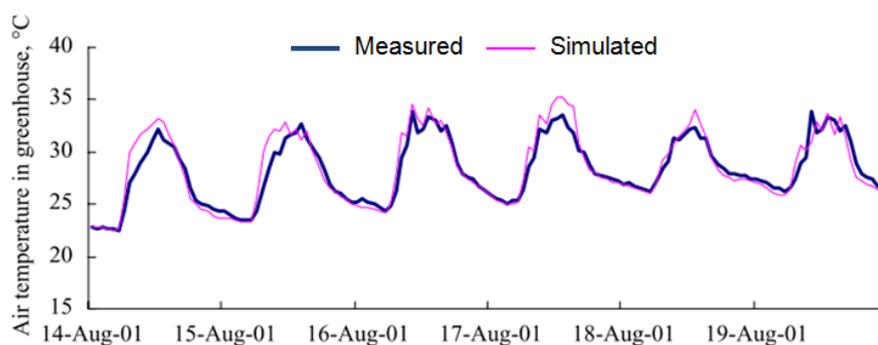

Figure 1. *Example of empirical validation of KASPRO* [5]

KASPRO is recognized as a suitable program for simulation of state-of-the-art commercial agricultural greenhouses. However, KASPRO is not the most suitable for the simulation of innovative greenhouses, as KASPRO lacks: connectivity with other simulation programs for control (such as MATLAB Simulink), extensive HVAC capabilities and airflow modelling.

Meanwhile, these features (connectivity, HVAC and airflow modelling) are commonly available in BES programs. For these reasons, BES can be used to investigate advanced materials, systems and controls of greenhouse, particularly for research purposes. The next section describes the necessary modifications in BES to properly simulate greenhouses. It is followed by a comparison of results obtained using KASPRO and a modified version of the BES program ESP-r.

REQUIREMENTS FOR GREENHOUSE SIMULATION USING BES

Crop model

There are several crop models available depending on crop type (such as tomatoes, chrysanthemum) and modelling approaches (such as steady-state, transient). Complex crop models can describe variations in the production over the year, considering effects of the variations in temperature in early stages of the crop. Initial results using BES can be obtained using simpler models, which calculates the net photosynthesis rate of the crop. The net photosynthesis rate is the amount of dry matter produced by the plant, and it can be used to calculate the crop production.

Some crop models also calculate CO_2 consumption (photosynthesis) and generation (respiration) by the crop. These are coupled to the airflow model and CO_2 balance in the zone. However, there is no feedback from the photosynthesis model to the thermal model since it is one-way coupling.

Simple crop models can be composed of two basic parts: photosynthesis model and transpiration model, as described below.

Photosynthesis model

Photosynthesis models quantify the photosynthesis rate by the crop, the energy spent to keep the crop alive, and the difference between these two values, i.e. the net photosynthesis rate or the dry matter production (which includes flowers, fruits, leaves, stems, roots, etc.). Net photosynthesis rate can be a performance indicator to the crop growth, production quality and production quantity. Photosynthetic activity is a function of CO_2 concentration, temperature and photosynthetically active radiation (PAR). The relation between solar radiation and PAR is addressed in one of the next sections of this paper.

Transpiration model

As a by-product of photosynthetic activity, crops release moisture (so-called transpiration). Transpiration increases indoor humidity and reduces crop temperature by evaporative cooling. The effects of transpiration are taken into account in the heat balance of the surface representing the canopy. Canopy temperature is then calculated by BES based on the amount of evaporative cooling by transpiration and on the heat balance between canopy and its surroundings.

Shortwave (radiation (SW)

SW radiation is closely related to photosynthetic activity and heat balance. Therefore, intensity of SW radiation in the greenhouses is one of the most significant factors to crop production and energy consumption.

SW distribution in the greenhouse

Many BES programs (such as Energyplus, ESP-r) have detailed models for calculation of solar radiation distribution, taking into account: transmission between zones, glazing properties depending on the incident angle, obstruction by neighbouring buildings, etc. Therefore, in principle BES does not require any modification to model greenhouses regarding SW distribution.

SW absorption in the greenhouse

The transmitted solar radiation into greenhouses is first absorbed by obstructions such as thermal screen, grinder, luminaries etc., and then rest of it is absorbed by the leaf of the crop. The absorptive rate on the crop has exponential relation with LAI and only small portion of shortwave radiation reflected from canopy and ground to greenhouse air, obstruction or greenhouse shell. GES generally ignores outgoing solar radiation to outside.

SW radiation in different wavelengths

For the simulation of greenhouses, it is required to divide SW radiation in photosynthetically active radiation (PAR) and near infrared radiation (NIR). PAR designates the spectral range of solar radiation from 400 nm to 700 nm that photosynthetic organisms are able to use in the process of photosynthesis. GES assume 50 % of PAR and 50 % NIR respectively to total solar radiation.

All wave lengths in shortwave are generally integrated in a single value for thermal simulation in BES. However, in order to calculate amount of photosynthesis, BES needs to be adapted to separate PAR and NIR and also requires separating glazing properties for each SW radiation.

Longwave radiation

This section addresses the two main issues involving LW radiation in GES: values of sky temperature and radiative elements of HVAC systems.

Commercial greenhouses roofs, unlike normal building, have high U-value and low heat capacity. Therefore, thermal behaviour of greenhouse is quite sensitive by LW heat losses to the sky at night time. Sky temperature is strongly influenced by cloudiness, however cloudiness is not usually included in BES models (and it is included in GES). Preliminary results show that wrong sky temperature in BES might lead to deviation up to 5.5% in the energy consumption of greenhouses in the Netherlands. Hence, it is essential to adopt proper sky temperature models in BES taking in to account cloudiness.

Greenhouse heating is usually done by heated pipes that release energy by LW radiation and convection. Heating pipes can be implemented in BES as a free surfaces floating in the zone, and the HVAC actuator in BES should be placed at these surfaces. As a simplification, the actuator can also be placed in the air node, however preliminary BES results indicate that this approach might overestimate the energy consumption up to 35% in some cases.

Convection

Greenhouses have specific convection regimes at: (1) the greenhouse saw-tooth roof surface, (2) the canopy depending on the LAI, (3) the floor depending on obstructions. These regimes are taken in to account in GES by convection coefficients calculated using empirical models specifically developed for greenhouses. Empirical models for

the calculation of convection coefficient are also implemented in BES, however they are based on experiments in buildings [7]. In spite of the differences between greenhouses and other buildings, correlations implemented in KASPRO and in ESP-r lead to similar values of convection coefficients and no modification is required in BES.

Conduction

Greenhouse shells are normally composed of one thin layer with single material and have low thermal resistance; GES only consider the conduction by floor with simplified methods. On the other hand, many BES programs use detailed model for heat flux by conduction in building structure as energy transfer depends on thermal properties of envelope layer. Therefore no modifications for conduction model are required in BES to simulate greenhouses.

Ventilation & infiltration

GES programs use fixed values of ventilation and infiltration rates calculated using simplified models based on wind speed, temperature difference and opening angle of vents. However, BES has comprehensive ventilation and infiltration modelling, which is in principle more precise and flexible than the ones used in GES programs. Nevertheless, BES requires correct values of discharge and pressure coefficients.

CO_2 balance

CO_2 balance in greenhouse depends on photosynthetic activity, screen control, ventilation (for humidity and temperature control) and infiltration rate. Many BES programs calculate inside CO_2 and its change with airflow network that might be relevant in case of open greenhouses. BES also should also consider the decrease of CO_2 concentration by crop's CO_2 assimilation.

Moisture

Evaporative cooling canopy layer

Moisture is the by-product of transpiration of crop and increases humidity inside the greenhouse. When liquid water is turned to vapour by transpiration, this activity leads to temperature drop of crop (canopy surface) by evaporative cooling. Some BES programs have evaporative cooling surfaces that can be used to model the canopy surface, but some modification in the source code are necessary to link the evaporation rate with the crop transpiration model.

Condensation glass panel

Condensation on the glass panel is common in the greenhouse and this can provide reduction of indoor humidity without ventilation. Therefore considering removed water by condensation is significant in terms of water vapour balance. GES programs calculate the saturated vapour of cover for water vapour decrease that occur by cover and screen temperature drop. Normally re-evaporation caused of condensed moisture inside the greenhouse is neglected in GES, as modern greenhouse collects the condensed water using drains.

BES programs usually do not calculate the amount of condensation on the building surfaces. Therefore condensation on greenhouse cover or screen needs to be implemented in BES.

HVAC

GES programs only include a limited range of typical HVAC systems which are frequently use in greenhouses sector. BES provides large libraries of state-of-the-art HVAC and renewable systems. BES also offers the possibility of modification and introduction of new HVAC and control system.

PRELIMINARY VALIDATION OF BES FOR ENERGY PERFORMANCE ASSESSMENT OF GREENHOUSES

Previous two section surveyed the requirements for simulation of greenhouse with BES and it turns out there is the need to add simulation model and modify some features of BES. However, it is not still unclear even after modification of required simulation model if BES can be used to evaluate energy consumption of greenhouses and crop production. Therefore, this paper conduct preliminary validation to assure quality of BES results.

For the preliminary validation of BES, this research adopted the BES program, ESP-r, which is frequently used in the building simulation research field. Inter-model comparison between ESP-r and KASPRO (as a GES) was carried out to assure quality of the result from ESP-r. The sky temperature model in ESP-r code was modified with consideration of cloudiness due to the strong influence of LW heat exchange with the sky. The comparison focuses on indoor air temperature in the greenhouse and solar radiation on the canopy surface.

Simulation settings are shown in table 1 and figure 2. Figure 2 illustrates the case used in the simulation which comprises an empty box-shape greenhouse with no crop model. In the modelling, as commercial greenhouses are large buildings (around 40 000 m^2), they are usually modelled as zones with no horizontal partitioning. Wall effects are known and differences in temperature at different regions of the greenhouses occur. These differences in temperature are usually not taken into account in the energy modelling, as it would require detailed air flow modelling inside the greenhouse. Therefore, adiabatic walls are assumed.

Table 1. *Specification of greenhouse validation model*

| Item	Specification			
Location	De-Bilt, The Netherlands			
Size (m)	100 (L)×100 (W) ×6 (H)			
Boundary condition	Wall 1~4			Adiabatic
	Top			Exterior
	Base			Ground
Optical properties of glass (perpendicular ray)	Transmittance			0.85
	Absorptance			0.00
	Reflectance			0.15
		Glass	Floor	Ground
Thermal properties	Conductivity [W/(m-K)]	1.05	0.50	0.85
	Density [kg/m^3]	2600	1050	1640
	Specific heat [J/(kg-K)]	840	837	879
	IR emissivity	0.84	0.6	-
	Solar absorptance	0.00	0.25	-
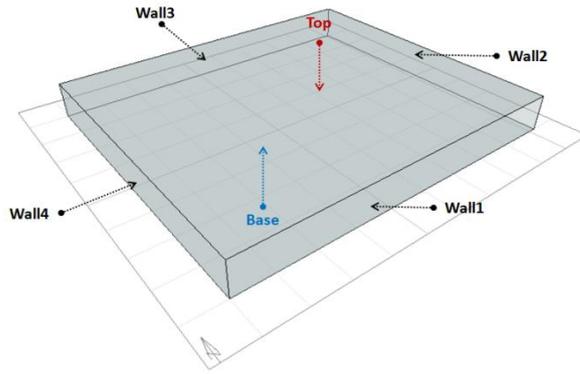
Figure 2 *. Illustration of the greenhouse adopted in the preliminary validation*

Figure 3 compares the simulation results regard air temperature in greenhouse and SW radiation on the canopy surface throughout a year. Curve fitting for both air temperature and SW radiation show that ESP-r follows well KASPRO.
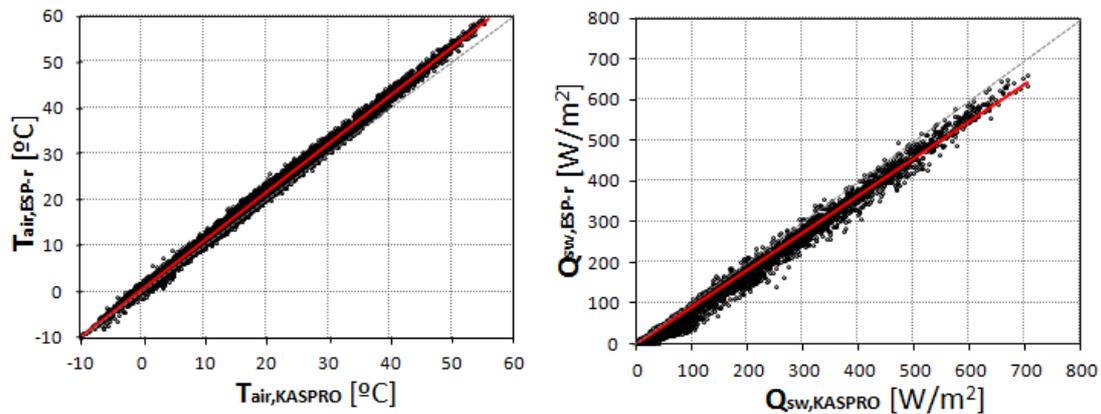

Figure 3. *Relation of air temperature and SW radiation in greenhouse*

Table 2 shows results of error analysis between results from KASPRO and ESP-r: correlation coefficient (R), mean bias error (MBE) and root mean squared error (RMSE). The R explains linear correlation between two simulation results and the MBE and RMSE show how good is the fit between ESP-r and KASPRO results. In the table, lower error value and percentage indicate better agreement of results.

Table 2. *Analysis results of error comparison between KASPRO and ESP-r for indoor air temperature and intensity of shortwave radiation*

	MBE		RMSE		R
Air temperature	1.40(°C)	8.1(%)	1.78(°C)	10.2(%)	0.998
SW Radiation	-10.39(W/m^2)	-11.51(%)	19.67(W/m^2)	21.8(%)	0.993

According to error analysis, correlations of programs for two simulation results show highly linear relation with coefficient of 0.99. Air temperature shows 1.4 °C (8.1%) errors in MBE and 1.78 °C (10.2%) errors in RMSE. SW radiation on canopy surface shows 10.39 W/m^2 (11.51%) errors in MBE and 19.67 W/m^2 (21.8%) errors in RMSE. ESP-r show reasonable result for air temperature but slightly higher error for SW

radiation. This can be attributed to discrepancies of algorithm between two programs. However, this difference is not expected to lead to high error in estimation of energy and production of greenhouse simulation so we can also conclude that BES can be used for greenhouse simulation.

CONCLUSION

This paper explored the use of BES programs in terms of the energy performance assessment for commercial greenhouses. The paper first surveyed requirements of BES programs for the greenhouse simulation. The general features of BES are not much different from GES, but BES requires modification and/or additional models for: photosynthesis, transpiration, LW radiation, CO_2 balance, ventilation and condensation.

This paper conducted preliminary validation by inter-model comparison between ESP-r and KASPRO. Results of both programs show good correlation and BES can therefore be adopted for greenhouse. Future research should focus on further validation including crop model in BES with using HVAC systems.

ACKNOWLEDGMENT

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