Energy balance and climate control assessments in greenhouse projects using Hortinergy, a friendly scientifically based web tool

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Abstract

Climate management and energy consumption are major issues for greenhouse production. For the professionals of horticulture, the crucial question arising during the greenhouse design process is to define an optimal configuration adapted to both climate, crop and investment capacities. The available web solutions rarely meet all these requirements and it is the reason why an online friendly decision-making tool called "Hortinergy.com" has been developed to facilitate both accessibility and diffusion to growers worldwide. The main challenge was to reduce as much as possible the number of input parameters while keeping a high accuracy compared to greenhouse measurements. The developed software combines innovative scientific models, existing open source software, crop and material libraries, climate regulation algorithms and parameters for both classical and modern equipment (semi-closed greenhouses, buffer tank, etc.). Specific modules and algorithms were developed with scientific research centers (crop evapotranspiration, greenhouse natural ventilation, etc.) to meet all these requirements. The calculations are performed on an hourly basis and the results combine climate (temperature, humidity, radiation), thermal (heating, cooling), moisture management (humidification, dehumidification), and biological (disease risks) modules. Data results were validated in real-size facilities against greenhouse-crop measurements, showing less than 10% margin error for all examined criteria.

Keywords: modelling, decision-making tool, energy efficiency, climate control, greenhouse gas

INTRODUCTION

From the early beginning of the greenhouse's development, fossil fuels are the main energy sources used to produce heat. In Europe, with three fourths of the global energy source for heating greenhouses, natural gas is by far the main fossil fuel used by the growers. A huge amount of fossil energy is used to produce vegetables all year long: 300 kWh m^{-2} $year^{-1}$ are needed on average to produce tomatoes for the whole year in temperate climate such as in the Netherlands or France.

Therefore, it is not surprising that energy is most of the time the second expense in the grower's farming running cost (Grisey et al., 2017). Going from 7 to 12 € m^{-2} $year^{-1}$ energy consumption is a major lever regarding the cost-saving opportunities. Moreover, and even if CO_2 injection is now widely spread for vegetable production, the net greenhouse gas emissions of protected cultivation is still unsatisfactory due to its fossil fuel consumption.

For years now, technical solutions to save up energy were a significant portion of the equipment suppliers' catalogues. Energy-saving screens, modern double or triple glazing,

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even the climate computers are likely to help cutting-off the energy balance of the total bill. However, the question remains still when it comes to finding the best configuration and payback time related to the implemented equipment. Having the possibility to run different simulations going through several technical solutions is the key to forecast actual energy and cost saving. Though, calculations must be accurate and reliable as it implies huge investments, and strategic decisions for growers.

There are a few ways of running energy and thermal simulation for greenhouses. Though it gives the spatial distribution of climate and fluxes fields, the CFD (computational fluid dynamics) method is the longest and the most complex to elaborate (Boulard et al., 2017). CFD requires a huge amount of calculation resources, and it may take a few months to go through the simulation preparation step up to the results. For energy needs, global models based on the assumption of the perfectly stirred tank (Roy et al., 2002) are often more appropriate for most of the applications, particularly when the purpose is to get quick decision-making parameters that help the user to focus on the right way.

Trying to meet these requirements, software has been developed, such as HORTICERN (Jolliet et al., 1991) and GGDM (Wang and Boulard, 2000). However, they are not updated with an online version including modern equipment.

From this context, Hortinergy overcomes the gaps of other software to create a user-friendly interface (online form to fill out). The form requires as few inputs as possible, to be able to give the greenhouse energy demand according to a ±10% accuracy for a large range of technical solutions.

MATERIALS AND METHODS

The Hortinergy software/platform is a flexible tool making it possible to set as input a range of characteristics of the studied greenhouse and crop. It is also organized according to a modular structure which includes several coupled sub-models (Figure 1). The model is based on the principle of the perfectly stirred tank. It solves heat and water vapour balances for a large spectrum of crops and greenhouse equipment. Calculations are performed on an hourly basis. The model considers 2 zones: lower greenhouse and the space between screen and roof cover. Outputs are average climate in the greenhouse (temperature, humidity, radiation) as well are heating, cooling, humidification and dehumidification needs. Regulation set-points are similar as those of a climate computer including heating, cooling, humidification, dehumidification and shading set-points.

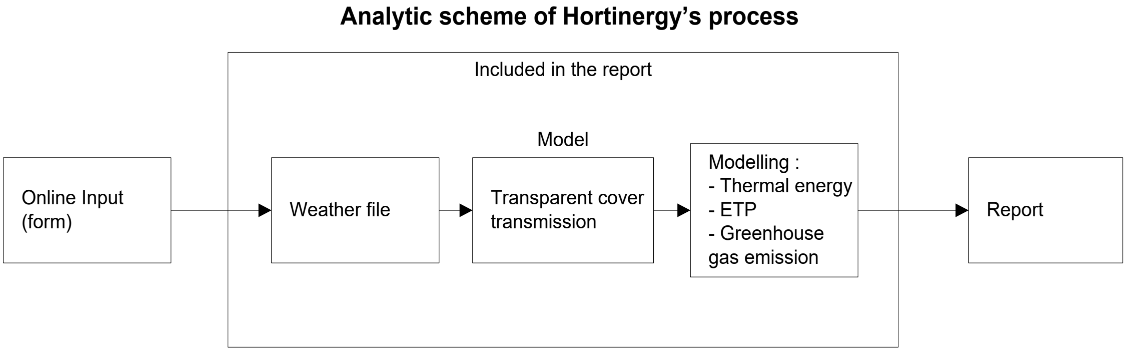


Figure 1. Hortinergy process.

Thermal and energy model description

The software input includes different general parameters to be set-up in an online form, such as geographic position, greenhouse envelop specifications, type of crop, regulation setpoints, etc. These values are used to set-up the physical sub-models. Calculations are performed on an hourly basis with iterations.

1. Weather data.

The model is based on weather data gathered from an external software: Meteonorm (Meteotest). From a given geographic location, the software proceeds with an interpolation of the 3 nearest weather station and satellite data considering the past ten years. The output is a weather file for a typical year with hourly values: air temperature and relative humidity. Global and diffuse horizontal solar radiation, wind speed and direction as well as sky temperature are also provided.

2. Transparent cover transmission.

Orientation, total width, length, number of spans and their width, gutter height and tilt of the roof cover are also considered for the calculations. Figure 2 displays the corresponding user interface for greenhouse geometry input.

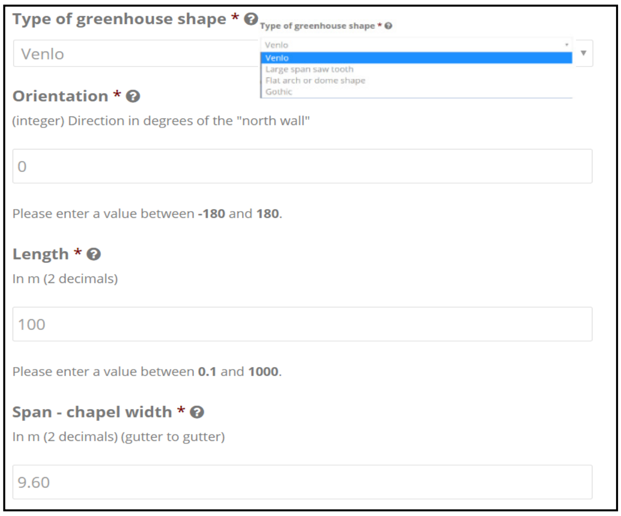

Type of greenhouse shape *
Venlo
Orientation *
(integer) Direction in degrees of the "north wall"
0
Please enter a value between **-180** and **180**.
Length *
In m (2 decimals)
100
Please enter a value between **0.1** and **1000**.
Span - chapel width *
In m (2 decimals) (gutter to gutter)
9.60

Figure 2. Available greenhouse geometry.

One of the most impactful specifications for the energy simulation is the wall and roof characteristics. About 20 different cover materials are available for the user to choose from (Figure 3), going from the single layer plastic, single/double glazing (including several thicknesses to the polycarbonate).

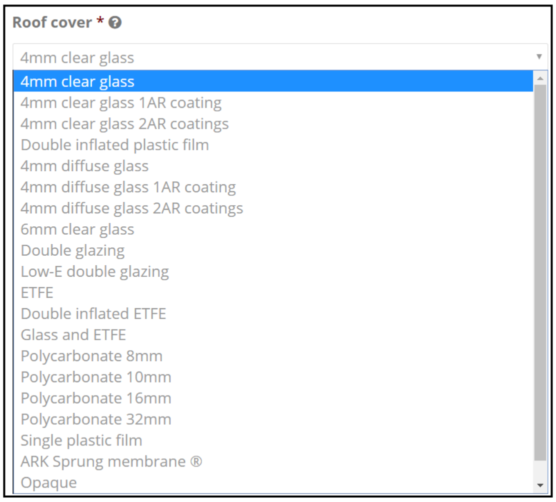
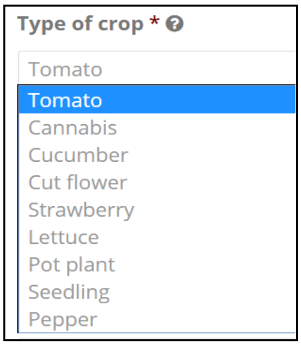

Roof cover *
4mm clear glass

Figure 3. Available roof covers characteristics.

From geographic location and meteorological data, the total insolation of the greenhouse is calculated. EnergyPlus software (Crawley et al., 2001), an open-source software, is then used to calculate the amount of radiation entering the greenhouse depending on its envelope specification. Radiation is then used as a heat input for thermal modelling.

3. Evapotranspiration model.

The evapotranspiration (ETP) modelling is based on the Penman-Monteith model. It is accurate enough for both vegetables and fruit such as tomatoes (Boulard et al., 1991) with a high ETP ratio due to their large foliar area. For each type of crop (Figure 4), Hortinergy model is based on pre-set time dependent curves to determine the leaf area index (LAI) evolution according to the plantation date. Input parameters are inner climate (temperature, humidity, radiation, air velocity) as well as inner surface temperature of ground and roof cover.



Type of crop * Tomato

Figure 4. Available crop types.

Regarding ornamental plants such as pot flowers, available data give the opportunity to compute transpiration from empirical models (Baille et al., 1994). If few data are available, the crop ETP can be directly set up at a constant value. Indeed, as their LAI is low, their ETP is less dominant in the greenhouse climate balance than for vegetable crops.

4. Thermal model.

The thermal model considers heat and mass transfer. Calculations are performed on an hourly basis with loop. The model considers thermal mass of inner air and ground. Roof and walls heat transfer consider conduction, convection and radiation. Air renewal depends on greenhouse structure type, greenhouse age and wind speed. Ground temperature and ground heat exchange are based on depth penetration considering soil characteristics, solar radiation and air temperature. Models also consider screen types (thermal, white strip, aluminium, black out) with thermal and mass transfer specification.

5. Other greenhouse characteristics of the model.

The usual energy sources (gas, fuel, biomass) may also be activated to calculate the energy balance over the greenhouse components. Finally, the software offers the possibility to consider different types of equipment, such as cooling pad and fan system, open buffer, natural ventilation or semi-closed greenhouse.

Model calibration on real greenhouses experimental data

Model calibration was performed at two locations: in Wageningen University Research centre (WUR, The Netherlands) for tomato greenhouse energy consumption (Kempkes et al., 2017) and in the Horticultural Center for Ornamental production (RATHO) in Brindas, near Lyon (France) for greenhouse climate in ornamental productions.

1. WUR experimental greenhouse.

The greenhouse used for the model validation in WUR was a single glazing Venlo greenhouse. Four 4.8 m wide spans were used on a total length of 23.6 m. Tomatoes were grown on 85% of the area – provided a 3 m wide concrete pathway on one side of the compartment. The greenhouse gutter height was 5.58 m with a roof tilting of 22°. In order to limit the heat losses during the night, a double thermal horizontal screen was used (Luxuous type). The tomato cultivar was 'Cappriccia'. Seedlings were 8 weeks old when culture began on January 27, 2015, and cultivation ended on November 18, 2015. Heating was provided by double 51 mm pipe rail system and HDPE tubes with water temperature being limited to 60°C.

Temperature sets followed standard practices with temperature integration for tomato crop. For example, on February 4: the set temperature was 20°C during the day, 17°C during pre-night, and 17.4°C during post-night. The measurement period covered the whole growing period. Energy consumption for the ten-month period was recorded as the natural gas volume consumed (31.65 MJ m^{-3}). Climate computers recorded the solar radiation, internal and external temperature and humidity as well as temperature set points. The values were used for comparison with simulated data at a daily or seasonal time scale.

2. RATHO experimental greenhouse.

In RATHO's greenhouse, potted poinsettias were grown over 609 m^2 single grazing greenhouse. Cultivation began on October 10, 2017 and measurement performed December 4 to 15. Heating was performed by two underfloor heating system (high and low temperature circuits). The greenhouse was fully computerized and climate data and state of the actuators data were recorded on a climate computer Hoogendoorn. The heating set-point was 16°C and the ventilation set-point was 26°C. Inner climate (temperature, relative humidity) and external climate (temperature, relative humidity, solar radiation) were measured with the climate computer.

A sample of poinsettias was weighed every hour during 5 selected days to measure water evaporation. Leaves area was measured every 3 weeks.

RESULTS AND DISCUSSION

Validation was performed in three stages. First, the calibration of the evapotranspiration model on poinsettia crop was performed thanks to data from RATHO. Second, the greenhouse indoor climate was validated against measurements from RATHO (poinsettia crop). Third and last, the energy consumption model was performed using the data from WUR on tomato crop.

Calibration of the evapotranspiration model from RATHO data

Based on LAI and climate measurements, the transpiration model was run and compared with lysimetric measurements on an hourly time step. Data follow the 1:1 line with R^2=0.894 and a standard error of 2 g h^{-1} m^{-2} (Figure 5). A simple equation of the transpiration of poinsettia, *Tr* (in g m^{-2} h^{-1}) was derived from measurements, as a function of the outside global radiation Ri (in W m^{-2}), and to inside pressure vapour deficit (DPV_a).

$$Tr = 0.033272 \cdot (1 - e^{-0.64 \cdot LAI}) \cdot R_i + 3.752066 \cdot LAI \cdot DPV_a \qquad (1)$$

Validation of the inside climate model in RATHO

Figures 6 and 7 provides examples of the measured and predicted time evolution of the inside temperatures during sunny and cloudy days. Globally the adjustment appears quite promising, with an average 1°C error during the sunny day and fewer than 0.3°C errors during the cloudy one.

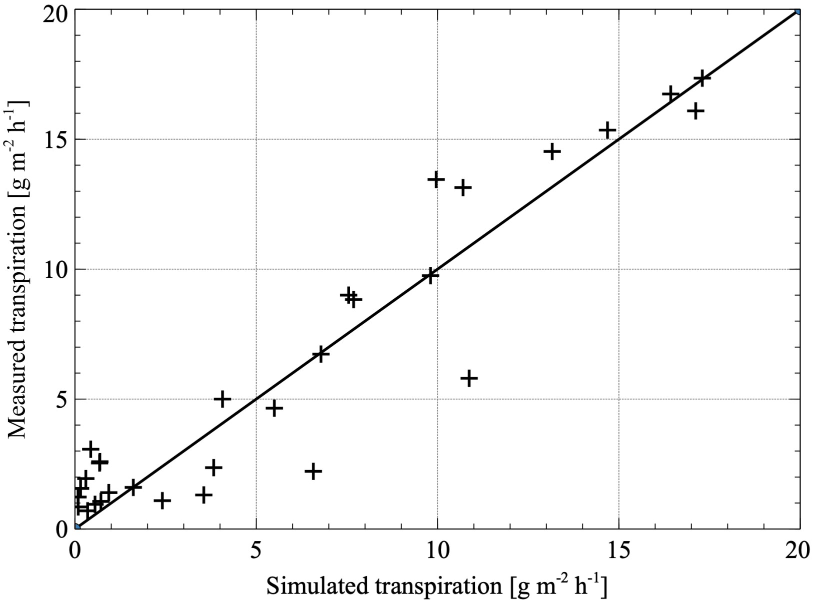


Figure 5. Comparison between measured and modelled poinsettia transpiration (g m^{-2} h^{-2}). Crosses are experimental points and the line is the first bisector.

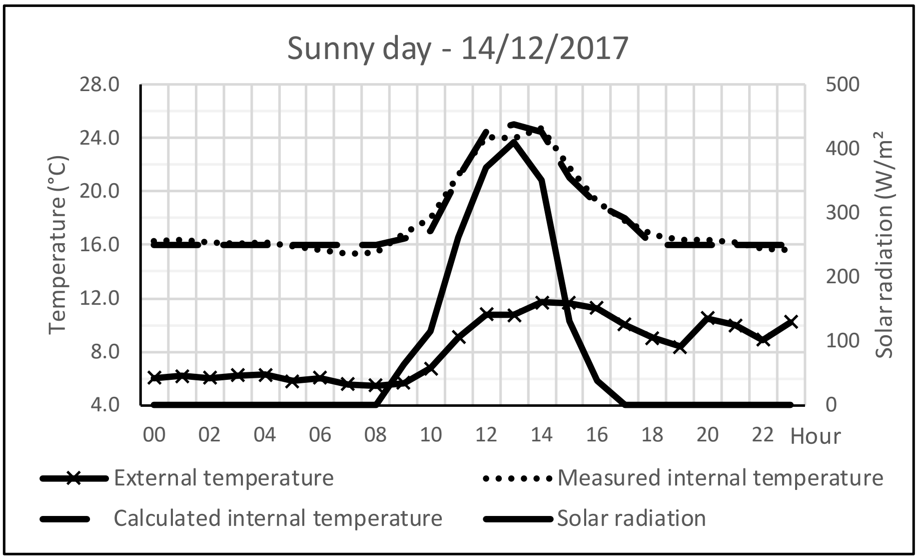


Figure 6. Comparison of the measured and modeled inside temperature course during a sunny day in a greenhouse equipped with poinsettia in RATHO (Lyon, France).

Validation of the energy model in WUR

Daily climate and heating energy measurements recorded inside the WUR's greenhouse have been used to compare simulations with experimental data. On the annual point of view, different periods were considered: 1) full winter, 2) early spring, 3) spring, and 4) fall. Globally (Table 1), for various day and night heating set-points ranging from 16 to 20°C, one observes a very good fit between modelled and measured heating consumption, the difference being only 2.5% for the yearly global heating consumption, with nevertheless a slight over estimation of the model during cold periods and an under estimation during warmer ones.

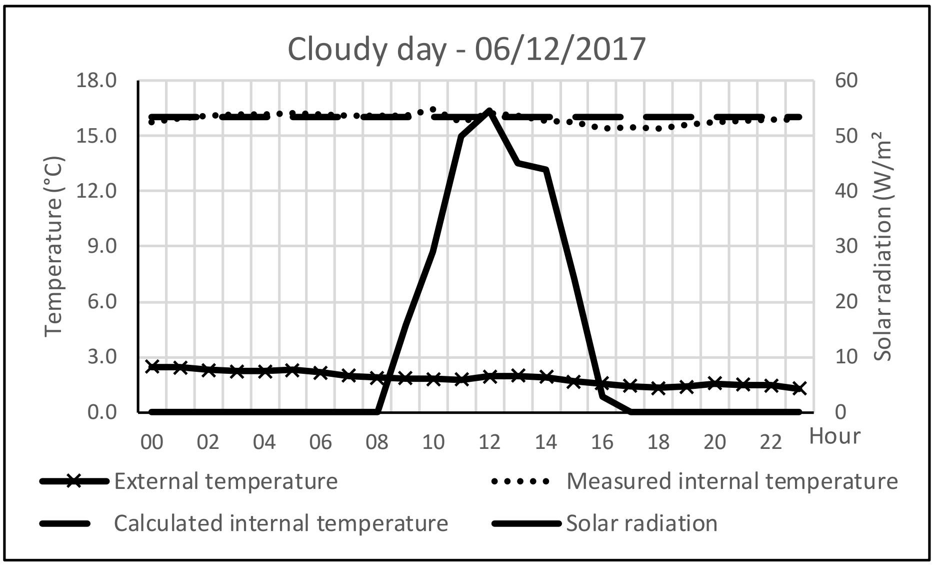


Figure 7. Comparison of the measured and modeled inside temperature course during a cloudy day in a greenhouse equipped with poinsettia in RATHO (Lyon, France).

Table 1. Greenhouse heating consumption at different periods of the year for Wageningen, The Netherlands (WUR's data).

Period	Temperature settings (°C)		Model calculation (kWh)	Real consumption (kWh)	Model-measure difference (%)
	Day	Night			
Period 1: 27/1-20/2	19.9	17.8	14,034	12,858	+9.1
Period 2: 21/2-15/3	21.6	18.3	10,389	10,719	-3.1
Period 3: 16/3-1/5	19.8	16.2	11,589	12,636	-8.2
Period 4: 2/9-18/11	17.9	15.8	16,935	15,421	+9.8
Total			**52,947**	**51,634**	**+2.5**

Based on the actual weather conditions measured on-site a comparison was performed on a day-to-day basis. Table 2 presents the measured and simulated heating consumption on a 24-h basis for winter, spring and fall days. The difference between measured and simulated heating energy data are less than 5%.

Table 2. Greenhouse heating consumption for different days (February, April, November) of the year for Wageningen, the Netherlands (WUR's data).

Day	Temperature settings (°C)		Model calculation (kWh)	Real consumption (kWh)	Weather	Model-measure difference (%)
	Day	Night				
06/02	19	19	599	579	Cloudy/cold day in February	+3.5
18/04	19.4	15.1	180	178	Sunny/cold day in April	+1.1
08/11	20	20	426	446	Cloudy/cold day in November	-4.5

CONCLUSIONS

Hortinergy, a friendly scientifically based Web tool for energy balance and climate control assessments in greenhouses. This tool was developed to meet the requirements of both new greenhouses (closed, semi-closed), climate control (pad and fan systems, natural and forced ventilation, open buffers, etc.), cladding material types (ETFE, double glazing, double inflated, etc.) in a web-based platform. The tool is based on a user-friendly interface with online forms to fill out requiring as few inputs as possible. Based on the principle of the perfectly stirred tank, a global greenhouse crop heat and water vapour balance is solved for a large spectrum of crops and greenhouse equipment. Model validation with respect to crop transpiration, inside climate and heating consumption was performed both for vegetable (tomato) and ornamental crop (poinsettia) in France and the Netherlands. Results revealed the high accuracy of the model with the crops and data presented in this paper. However, from this starting point, Hortinergy is constantly improving with new add-ons such as the real time estimation of the greenhouse gas emissions of the crop (taking account of energy consumption, nutrients, substrate, CO_2 injection and embodied energy of the greenhouse structure).

ACKNOWLEDGEMENTS

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