Decision Support for Optimising Energy Consumption in European Greenhouses

O. Körner
University of Copenhagen
Department of Agricultural Sciences
Crop Science
Højbakkegård Allé 21
2630 Taastrup
Denmark

D. Warner and J. Tzilivakis
University of Hertfordshire
Agriculture and the Environment
Research Unit
College Lane
Hatfield, Herts AL10 9AB
United Kingdom

B. Eveleens and E. Heuvelink
Wageningen University
Department of Plant Sciences
Marijkeweg 22
6708 PG Wageningen
The Netherlands

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Abstract

Improving existing greenhouse structures in terms of insulation and other features can save energy with significantly lower investment costs than building new greenhouses. Within the EU Framework VI project GREENERGY a decision support system has been developed that offers the potential to be used by the advisory services for growers all over Europe. It evaluates the impacts of either using different greenhouse materials (e.g. for the cover or screens) or building a complete new structure on the overall energy consumption and crop yield. The system is constructed as an easy to use software tool based upon a set of simulation model modules for greenhouse energy fluxes, crop growth and yield. The user defines the structure of his present greenhouse from the pre-defined menu. This greenhouse is then used as reference greenhouse that can be compared to the various modifications of it that the user selects. The entering of additional variables such as geographic location (country), type of crop, internal greenhouse climate set points etc. allow simulations of energy consumption and crop yield over a period of one year using reference climate data of the respective location as input to be performed. The system is constructed in a way such that the database of greenhouse construction materials can be updated easily to maintain its applicability.

INTRODUCTION

In addition to optimal crop production, reduction of the energy consumption within greenhouses is one of the major aims of the greenhouse horticultural industry. The majority of greenhouses in the European Union have been built within the last 20 years or so and do not conform to current standards of low energy consumption. Investing in new low-energy consuming greenhouses is very expensive, especially in Northern and Central Europe. Modern greenhouses are often well-insulated and new concepts have been developed in recent years that include the closed and semi-closed greenhouse systems. The air infiltration rate and long-wave heat losses of such greenhouses are greatly reduced thus giving a high energy saving potential. Older structures have a much higher air infiltration rate and the roof material often has a higher transmission for long wave radiation. In addition many older greenhouses do not have energy screens. Constructions in located in Eastern Europe in particular, are far below the standards existing in leading greenhouse horticultural countries such as The Netherlands. To create alternatives to new structures, a decision support system (DSS) was developed that can help the user to decide on whether various adjustments to the existing greenhouse structure (e.g. screens or roof-cover material), changes in the management regime (e.g. adjustments to the assimilation lighting or climate control set point schedules) or general maintenance (e.g. cleaning of the roof) can be done to reduce energy consumption and/or increase crop yield or energy efficiency ([crop yield][energy consumption]$^{-1}$). Since there is a large diversity of greenhouse structures with respect to age, material and shape within the EU there is no standard greenhouse even within one EU country or region. The DSS therefore must be created in a way such that it can be applied to the newer high-tech glass greenhouses that mainly exist in The Netherlands, England and Scandinavia and to older glass greenhouses that largely exist in Germany and Eastern Europe. It must also be applicable to the various plastic greenhouse structures that are predominant in Southern European countries such as Greece, Italy and Spain. In addition, the difference in climatic variables that exists between the main greenhouse production regions from central Finland (63°N lat.) to Greece and Spain (37°N lat.) must also be taken into account such that the model provides an accurate prediction of energy efficiency across Europe. In the EU project GREENERGY a DSS is created that calculates energy use and allows the user to judge on whether or how to adjust an existing greenhouse with respect to its structure, management or maintenance to improve energy efficiency. In an other line of the project a investment decision support tool for the possible improvements is developed. Both tools are accessible from a starting centre in from of a hyperlink based information system on energy saving possibilities.

MATERIALS AND METHODS

The user starts with the overview in the internet based guideline that will guide him to the Greenhouse Energy Auditing Tool (GEAT) when needed. The user of the GEAT will be confronted with a user-friendly platform where his location is first selected (to access the local climate variables) before the creation of a reference greenhouse from a number of pre-defined menus that including type (e.g. Venlo, widespan, polytunnel or paral), structure (e.g. size dimensions, roof-cover material, size of glass pane), equipment (e.g. type of lamps and power rating, type of heating), set-points and timing (temperature and humidity, assimilation lighting) and type of crop. Once this reference greenhouse has been created it is saved within the software as the user's reference greenhouse profile. It then allows the user to make subsequent alterations without having to re-create another greenhouse.

The Guideline

The guideline is in the form of a hyperlink structure. The user can find general information on energy saving and crop improvements when certain adjustments are made and this is then displayed on screen as text. The guideline information is only intended for general support and for more detailed analyses the guideline will link to the GEAT.

The Greenhouse Auditing Tool

The GEAT is the core of the GREENERGY project. It is based on simulation models on greenhouse energy fluxes and crop growth. The latter is implemented as a generic deterministic photosynthesis based crop simulation model and independent of location. The model consists of two major sub-models that interact with each other: the greenhouse climate model and the crop model. The major outputs of these two modules are energy consumption and crop yield, respectively.

1. Weather Data. For each region in Europe a weather data file is distributed with the software. Where possible the data files are representative of one year hourly climate data including air temperature (°C), relative humidity (%), sky temperature (°C), direct and diffuse global radiation (Wm^{-2}), CO_2 concentration (ppm) and wind speed (ms^{-1}). Examples of reference years include those created for the Netherlands (Breuer and Van de Braak, 1989) and Denmark (Lund, 1995). Where a reference climate year was not available a specific year was used. If any of the required data fields were absent the data was calculated using the available variables or a combination of years.

2. Greenhouse Type and Structure. The combination of the pre-defined menu and user entered variables offers the potential to create a diverse range of greenhouses. As described previously, the user can choose from a number of greenhouse variables to define his reference greenhouse and make modifications to it (Fig. 1).

3. Climate and Management Control Model. The major output of the greenhouse climate model is the energy consumption for heating and electrical energy for lighting. The model also calculates the temperature and relative humidity within the greenhouse to give the crop microclimate (temperature) on an hourly basis which is used as an input into the crop model. The calculation of the greenhouse microclimate was largely taken from Körner et al. (2007), the macroclimate calculations from De Zwart (1996) and Bakker et al. (1995). The climate part of the model consists of two sub-models: a thermal model and a vapour model. The energy losses were derived from radiative, convective and latent heat fluxes from the greenhouse cover and from conduction through the greenhouse base into the soil. The radiative exchange processes between the greenhouse cover and the crop canopy were calculated using the Stefan-Boltzmann law. The sky temperature is used, expressing the temperature of a black hemisphere that is exchanging thermal radiation with sky and greenhouse cover (De Zwart, 1996). The influx energy into the greenhouse is solar short wave radiation from outside (Q_S, Wm^{-2}) that is multiplied with the transmission factor for short-wave radiation (separated into direct and diffuse) of the cover material. Direct transmission through the greenhouse cover is calculated as a function of azimuth and elevation of the sun (De Zwart, 1996), and diffuse transmission is set to a constant as function of the cover material taken from the materials data-base within the software. When assimilation lighting is used, the amount of the different energy fluxes such as long-wave radiation and short-wave radiation (Q_L, $W \cdot m^{-2}$), or photosynthetic active radiation (PAR, $W \cdot m^{-2}$) is taken into account. The energy that is taken up by the crop is calculated and then used to calculate the crop temperature and transpiration rate. The crop net absorption of short-wave radiation ($R_{n,a}$, $W \cdot m^{-2}$) is calculated from short-wave gains (R_n, $W \cdot m^{-2}$) and long-wave losses (B_n, $W \cdot m^{-2}$). The amount of heating energy input to the greenhouse is calculated depending upon the heating source. For pipe heating it is calculated using the method described by De Zwart (1996). Energy losses through natural ventilation are calculated according to De Jong (1990) with wind speed and ventilator opening as determining factors. Latent heat production by crop transpiration is calculated according to Bakker et al. (1995). The energy losses from latent heat were either calculated by direct mass transfer to the outside air or by phase changes through condensation on the glass wall and the resulting convection losses influenced by the temperature of the greenhouse cover, outside air temperature and wind speed (Bot, 1983). From that the relative humidity within the greenhouse air is then determined. The climate is controlled using heating and ventilation and implemented with a set of simple replicas of commercially available climate controllers. Set points for the heating temperature, ventilation temperature, relative humidity, screen folding and unfolding, and assimilation lighting can be set for up to six periods within each 24-hours. Simulations can be done for a complete year or for separate sets of crops for specified growing periods separately.

4. Crop Model. Crop growth and yield is simulated with a photosynthesis driven model. First crop dry weight is simulated from crop gross photosynthesis, maintenance respiration and conversion efficiency, dry weight is then allocated to the separate plant organs as leaves, stems, and generative organs. This allocation is controlled by the temperature sum and is crop specific. The first three crops implemented are cut chrysanthemum, potted roses and truss tomatoes: 1) with cut chrysanthemum a temperature sum from planting to harvest of 1250°C days is assumed; 2) with potted roses a temperature sum from planting to harvest of 485°C days, 3) with tomato the crop is maintained at a maximum of leaf area index (LAI) 3 (i.e. older leaves are removed), and fruit production starts after 1250°C days. From then on 70% of the assimilated dry weight is allocated to the fruits. To calculate fresh weight a fruit dry weight content of 5.5% is used. A biochemical based leaf photosynthesis model (Farquhar et al., 1980) with a negative exponential light-response of photochemical efficiency and maximum gross photosynthesis (Thornley, 1976) is used for simulations. Crop gross photosynthesis is calculated for the whole crop with 3-point Gaussian integration as function of the LAI and from absorbed photosynthetically active radiation in each crop level, where the diffuse and direct beams are treated separately (Goudriaan and Van Laar, 1994). Stomatal resistance for water vapour and CO_2 exchange is simulated as function of the greenhouse climate according to Kim and Lieth (2003), the boundary layer resistance is set constant to 100 ms^{-1}.

Simulations

Simulations can be done for a complete year or for separate sets of crops for specified growing periods separately. The input climate data and simulations within the DSS tool are calculated on an hourly basis on account of the time taken for the software to run the simulations (i.e. shorter intervals as e.g. 5 minutes would be too time consuming for the user). Shorter simulation periods would require an increased operation time considered to be too long for a practical software application. A simulation study using the model conducted in MATLAB® with 5 typical cases was performed: 1) influence of the air infiltration rate on energy use and energy use efficiency; 2) influence of screens; 3) influence of increasing the transmission for short-wave radiation of the cover through cleaning; 4) influence of light installations on energy consumption and yield; 5) influence of various climate set points such as decreasing the heating temperature set point. Simulations were conducted for five countries to represent a diverse range of climate variables, The Netherlands, Denmark, Finland (north western region), Estonia (eastern region) and Spain (southern region). Simulations were performed for a complete year taking the specific cropping measures into account, e.g. year round tomato cultivation in The Netherlands and summer break in Spain. A reference greenhouse was created and used for all simulations, regardless of the country. The reference greenhouse was a single glass 1-ha Venlo-type 5 m in height, a window size when open of 2.85 m^2, with 0.078 windows m^{-2} and a maximum window opening of 44°. Additional equipment included heating pipes (51 mm, 4 pipes per 3.2 m) and no assimilation lighting. The transmission for diffuse radiation was 70%. The window opening was a function of the difference between the relative humidity set point and the relative humidity in the greenhouse, and the difference between the ventilation temperature set point and the greenhouse temperature, and wind speed. The heating energy is calculated from the requirement to increase the temperature to the desired setting when the greenhouse temperature is lower than the heating temperature set point.

RESULTS

The presence of a shelter (e.g. fence or plantations) reduces the wind speed and consequently the air infiltration rate which results in an energy saving, especially in Northern Europe (Table 1). The use of energy screens significantly reduces the energy consumption, again to a much greater magnitude in Northern Europe (Table 2). The use of screens, nevertheless, can lead to an increase in humidity at night when the screens are unfolded. The regular cleaning of the roof can prevent the decrease in the transmission of short wave radiation which is especially important in Northern Europe where a significant detrimental impact on crop yield and therefore energy use efficiency may occur (Table 3). The use of assimilation lighting increases yield and crop quality however the costs are high. The economic benefits of assimilation lighting through increased yields require careful analysis (Table 4). The application of different climate set points such as the lowering of the heating set point can further decrease the energy consumption (Table 5). This may have detrimental impacts upon plant development and quality and a cost-benefit analysis must be undertaken although this is not implemented in the simulation models of the GEAT, but it is mentioned in the guideline. In addition, when extreme conditions are simulated, the user will be warned within the GEAT that possible negative effects on crop quality are not implemented.

DISCUSSION

A DSS for improving the energy efficiency of existing greenhouses applicable throughout Europe regardless of the greenhouse type and equipment has been presented. The complex model system was constructed from previously validated models. The simulation results concur with actual energy consumption and yield data reported previously (eg. 42 kg tomato year^{-1} in The Netherlands or 12 kg in Almeria, Spain; Körner, 2000). Yield may vary considerably as a result of the agronomic experience of the grower irrespective of the energy saving measures undertaken. Therefore, the system can only be used as a guideline for improvements in the energy efficiency assuming that standard recommended agronomic variables have been observed. The exact energy savings depend upon additional factors that the system cannot calculate, such as human error. Although the exact individual reference greenhouse as it exists in reality cannot be created the system can be used to calculate the net change in energy efficiency between the original user defined reference greenhouse and any subsequent modifications that are made.

The user defined greenhouse builder allows the construction of a wide range of greenhouses. Although the greenhouse climate models used were designed for Venlo-type greenhouses (De Zwart, 1996) and thoroughly tested for this greenhouse type, the basics were adapted to other greenhouses through adjusting the model parameters that depend mainly upon the greenhouse shape, material and location. The DSS as it exists in its first version strongly focuses on energy consumption for heating although the energy consumption for cooling should also be taken into account. In reality there is hardly any energy consumption for greenhouse production in Spain (Körner, 2000). The majority of greenhouses in Southern Europe are equipped without heating, and simulated yield without heating was close to the actual achieved yields mentioned previously. In South Europe energy consumption is not the major concern, here reductions in chemical biocide use and increases of yield and quality are of more importance. Improving that would need an additional energy input. It can be concluded that the current DSS is a well structured system that has a high potential to be widely used among greenhouse grower associations in Northern Europe. However, for a better applicability in Southern Europe other modules need to be added such as water consumption, biocide consumption, water quality and crop quality. As this is out of scope of the GREENERGY project, work in future EU projects should consider these factors.

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Tables

Table 1. Simulations of the influence of air infiltration rate n (h^{-1}) on energy consumption (hec, MJ m^{-2}) and energy efficiency (ef, [kg fruit] MJ^{-1}) for a tomato crop in different EU countries with top energy screen, no assimilation lights.

N	0.5		1.0		2.0		3.0	
	Hec	ef	hec	Ef	hec	ef	hec	ef
Finland	3.1	13.3	3.3	12.3	3.8	10.8	4.3	9.5
Estonia	2.8	16.5	2.9	15.8	3.2	14.5	3.9	13.2
Denmark	2.3	19.8	2.4	18.5	2.8	16.0	3.2	14.0
Netherlands	1.9	23.5	2.0	22.7	2.2	20.7	2.4	18.7
Spain	0.7	11.6	0.7	11.2	0.8	10.5	0.8	9.9

Table 2. Simulations of the influence of a standard energy screen on heat energy consumption (hec, MJ m^{-2}) and crop yield (yield, [kg fruit]) for a tomato crop in different EU countries, in an older greenhouse with air infiltration rate n of 1.5 h^{-1}

	No screen		Top screen		Top and side-wall screens	
	hec	yield	Hec	yield	hec	yield
Finland	4.4	41.5	3.6	41.0	2.7	40.5
Estonia	3.7	46.9	3.1	46.3	2.4	45.8
Denmark	3.1	45.7	2.6	45.0	2.0	44.2
Netherlands	2.6	46.7	2.1	45.9	1.6	45.0
Spain	0.7	15.5	0.7	15.2	0.7	15.1

Table 3. Simulations of the influence of roof cleaning on crop yield (kg m^{-2}) and energy efficiency (ef, [kg fruit] MJ^{-1}) for a tomato crop in different countries, with slightly dirty and dirty cover with reduced light transmission of 5% and 20%, respectively; top energy screen, no assimilation light, in a relatively old shelter with air infiltration rate of 1.5 h^{-1}.

	Cleaned		Slightly dirty		Dirty	
	yield	ef	yield	Ef	yield	ef
Finland	41.0	11.5	39.7	11.1	35.1	9.8
Denmark	45.0	17.2	43.4	16.7	38.3	14.8
Spain	15.2	10.8	14.8	10.4	13.4	9.4

Table 4. Simulations of the influence of assimilation lighting using 400 W HPSL lamps with three different densities (0.1, 0.2, 0.4 lamps m^{-2}) on crop yield (kg m^{-2}), heating energy consumption (hec, MJ), and electrical energy (eec, MJ) consumption for a tomato crop in different EU countries, heating and ventilation set points were 18 or 20°C, top screen and side wall screen, air infiltration rate = 1.5 h^{-1}.

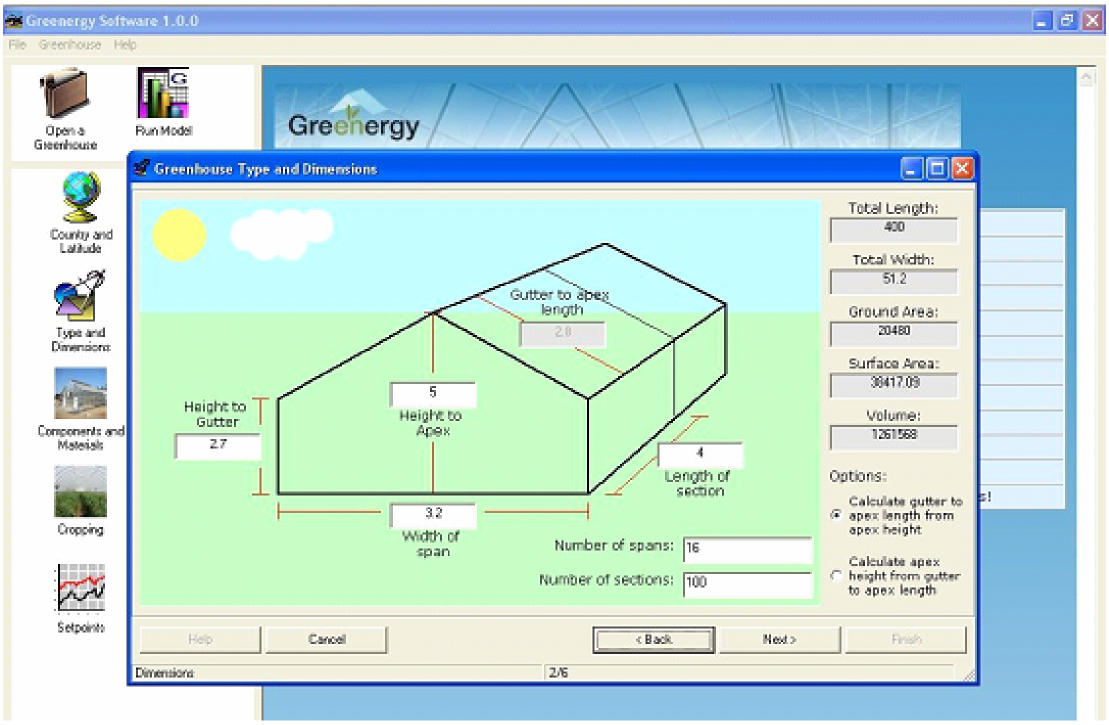
Lamps m^{-2} (*	0.1			0.2			0.4		
	yield	hec	eec	yield	Hec	eec	yield	hec	eec
Finland	45.3	3.6	0.5	52.4	3.3	1.0	63.6	2.7	2.1
Denmark	48.5	2.6	0.5	55.0	2.3	1.0	64.9	1.9	2.1
Spain	22.7	0.6	0.4	30.0	0.5	0.8	41.9	0.3	1.6

* lamps were switched on when outside global radiation was below 250 Wm^{-2} and switched on again when outside global radiation was higher 300 Wm^{-2}; no assimilation light was used between May 01st and August 30th, the rest of the year light was generally switched off between 00:00 and 06:00 a.m.

Table 5. Simulations of the influence of heating and ventilation temperature set points, T_{heat}, T_{vent}, on crop yield (kg m^{-2}) and heating energy consumption (hec, MJ m^{-2}) for a tomato crop in different EU countries.

	T_{heat} / T_{vent} (°C)					
Set points	18/20		14/24		10/28	
	yield	hec	yield	Hec	yield	Hec
Finland	34	3.4	30	2.5	24	1.7
Denmark	39	2.4	37	1.5	32	0.9
Spain	14	0.7	13	0.3	11	0.0

Figures



Height to Gutter: 2.7

Height to Apex: 5

Width of span: 3.2

Gutter to apex length: 2.8

Length of section: 4

Number of spans: 16

Number of sections: 100

Total Length: 400

Total Width: 51.2

Ground Area: 20480

Surface Area: 38417.09

Volume: 1261568

Options:

● Calculate gutter to apex length from apex height

○ Calculate apex height from gutter to apex length

Dimensions 2/6

Fig. 1. Example screen in the Greenhouse Auditing Tool.