D16: Core SME greenhouse growers final energy consumption data

(FINAL VERSION)

University of Hertfordshire (UH)

Contents

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Summary

The Energy Auditing Tool (EAT) was first tested using version 1.06 with greenhouse profiles representative of actual configurations (provided by the SME and IAG partners) as part of Deliverable 10 (main responsible partner WU). The actual energy consumption data of these configurations was compared with that simulated by the EAT version 1.06. The same greenhouse profiles have been tested again with version 1.10 of the EAT as part of Deliverable 16 and the energy consumption data from the two versions have been compared with each-other and the actual energy consumption data provided for Deliverable 10 by the SME and IAG partners.

The modifications to the EAT post version 1.06 have improved the accuracy of the simulated outputs for those greenhouse structures described as 'new constructions - laps sealed' compared to the results of initial testing for Deliverable 10. The data simulated by version 1.10 of the EAT mirrors that of the actual data accurately (≤5%). The profiles include those in Denmark (DEG potplants (2.6% difference between the actual energy consumption for heating and that simulated in the EAT version 1.10) & Venlo potplants (1.1% difference)), Finland (HKO cucumber (-1.5% difference)) and Holland (NL tomato (5.4% difference)). There was no change in the difference between the accuracy of data simulated in version 1.06 and 1.10 for England (FEC tomato (8% difference)).

An underestimation of the energy consumption for the SKI and PAE greenhouse profiles was evident in version 1.10 compared to version 1.06. The SKI and PAE greenhouses are both described as 'old constructions – poor maintenance'. Old constructions differ in their rate of air exchange due to leakage compared to a new construction with the laps sealed where such leakage is minimal. It is difficult to quantify this rate of air exchange exactly for older and poorly maintained structures and consequently a degree of uncertainty will exist for such structures which is unavoidable. The addition of a further category that increased the rate of air exchange for older structures improved the accuracy of the simulated data for the SKI and PAE greenhouse profiles.

1.0. Introduction

1.1. About this document

Deliverable 2 (main responsible partner WU) used a questionnaire to obtain the structural configurations of the SME greenhouses and their actual energy consumption. The Deliverables D6, D7, and D8 document explained the rationale and method behind the development of the Energy Auditing Tool (EAT) and outlined the calculations that are contained within the software and its main structure. Deliverable 10 described the results of the testing of the EAT and the accuracy of the output compared to the users (SMEs) actual energy consumption data obtained in Deliverable 2. Following this, Deliverable 15 then described improvements that were made to the EAT in response to comments from GREENERGY consortium partners. It included any adjustments made to the calculus to improve the accuracy of the simulations and improvements to the user interface and its overall usability.

The following document describes the final energy consumption data of the SMEs greenhouses (provided by Wageningen University in Deliverable 10) as simulated by the final version of the Energy Auditing Tool (EAT). It then illustrates with an example the potential energy savings (per kg of marketable commodity) that may be made through the implementation of small changes in configuration and operating procedures.

2.0. Description of SMEs actual greenhouses

The testing of the EAT (Subtask 6.4) used descriptions of greenhouses and actual energy consumption data from the SMEs (detailed descriptions of the greenhouses are given in Appendix 1). This data was collected by WU in collaboration with TTZ, the greenhouse profiles were then constructed in the EAT 1.06 by WU using this data. The same greenhouse profiles have been imported into the current version of the EAT and used to re-simulate the data. The changes in energy consumption data described in this document refer solely to a response to alterations to the underlying calculus within the EAT and not modifications to the structure of the greenhouses tested.

3.0. Growers final energy consumption data

3.1. Total energy consumption for heating

The total energy for heating (actual energy consumption data) for the SMEs, the energy for heating calculated by the EAT version 1.06 and the final energy consumption data calculated by version 1.10 of the EAT is given in Table 1.

Table 1. Energy consumption for heating (EH) figures for SME nurseries compared to simulated data by the EAT version 1.06, 1.10 and (in brackets) with N = 4 for greenhouses of old construction and poor maintenance. The actual energy consumption data from the nurseries and simulated data from the EAT version 1.06 is courtesy of Wageningen University as part of Deliverables 2 and 10 respectively.

Country	**Nursery & greenhouse reference**	**Type**	**Σ EH SME greenhouse ($GJ\ m^{-2}$)**	**Σ EH EAT 1.06 ($GJ\ m^{-2}$)**	**% difference actual & EAT 1.06**	**Σ EH EAT 1.10 (& N=4) ($GJ\ m^{-2}$)**	**% difference actual & EAT 1.10 (& N=4)**
Germany	SKI 1 pot and bedding	O-PM	0.50	0.46	8.0	0.42 (0.44)	16.0 (11.2)
Germany	SKI 2 pot and bedding ****	O-PM	0.62	0.43	30.0	0.34 (0.37)	45.2 (41.0)
Germany	SKI 6 pot and bedding ****	O-PM	0.51	0.43	15.0	0.34 (0.37)	33.3 (28.4)
Germany	SKI 7 pot and bedding ****	O-PM	0.59	0.60	-1.6	0.53 (0.57)	10.2 (4.1)
Germany	SKI 8 pot and bedding ****	O-PM	1.16	1.25	-7.8	1.01 (1.08)	12.9 (6.6)
Germany	PAE 3 pot and bedding	O-PM	2.60	2.76	-6.2	2.42 (2.58)	6.9 (0.6)
Germany	PAE 4+5 pot and bedding	O-PM	0.39	0.32	17.9	0.29 (0.31)	25.6 (20.5)
Germany	PAE 6+7 pot and bedding	O-PM	1.18	1.39	-17.8	1.10 (1.16)	6.8 (1.5)
Germany	PAE 8 pot and bedding	O-PM	0.72	0.76	5.5	0.61 (0.64)	15.3 (11.0)
Germany	PAE 10 pot and bedding ****	O-PM	0.99	1.00	1.0	0.85 (0.90)	14.1 (8.7)
Denmark	DEG potplants	N-LS	1.89	2.04	-7.9	1.84	2.6
Denmark	Venlo potplants	N-LS	1.86	2.08	-11.8	1.84	1.1
England	FEC tomato	N-LS	1.37	1.48	-8.0	1.48	-8.0
Finland	HKO cucumber	N-LS	4.68	4.79	-2.4	4.75	-1.5
Finland	MAR tomato	N-LU	2.02	2.19	-8.4	1.60	20.8
Holland	NL tomato	N-LS	1.30	1.39	-6.9	1.23	5.4
Spain	UAL heat tomato ****		0.87	0.84	3.4	0.83	4.6
Estonia	Tomato	N-LS					
Estonia	Cucumber	O-GM					

Σ EH SME: total actual SME energy consumption for heating
O-PM: old construction poor maintenance; O-GM: old construction good maintenance; N-LU: new construction laps unsealed; N-LS: new construction laps sealed.

In general, the energy consumption figures from heating for new greenhouse structures were closer to the actual energy consumption figure simulated within the EAT version 1.10 compared to 1.06. This improved the accuracy of output for the greenhouse profiles in Denmark (DEG potplants (2.6% difference between the actual EH and that simulated in the EAT 1.10) & Venlo potplants (1.1%)), Finland (HKO cucumber (-1.5%)) and Holland (NL tomato (5.4%)) (Table 1 and Figure 1). There was no change in the output of the greenhouse profile for England (FEC tomato (8%)). An underestimation of the energy consumption for the MAR, SKI and PAE greenhouse profiles was evident and this is addressed under section 3.1.1.

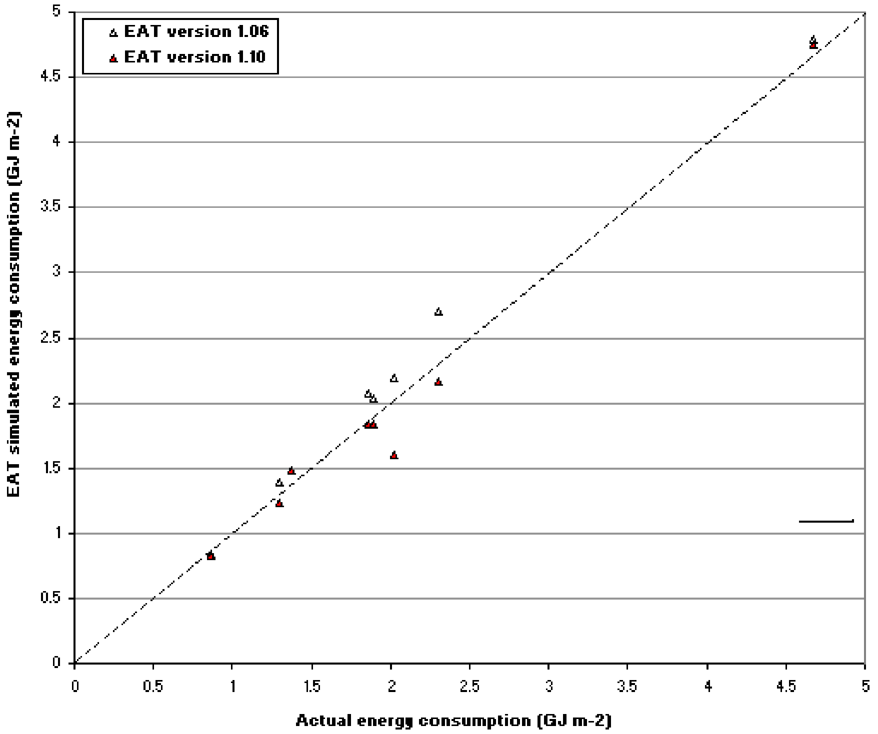

Figure 1. Actual energy consumption figures from the greenhouse profiles tested (new constructions) plotted against the calculated energy use from the EAT version 1.06 (△) and the EAT version 1.10 (▲). The dotted line shows the 1:1 relationship.

3.1.1. Key uncertainties

The accuracy of the model outputs within the EAT relative to the actual energy consumption data are subject to an element of uncertainty which, within the boundaries of the project, are unavoidable.

Firstly, discrepancies between the climate data within the EAT compared to the actual weather conditions responsible for the SME greenhouse's actual energy consumption figures. This has been overcome as much as possible with the use of a reference year representative of typical climate data in any year whenever possible. The only means to improve simulations further would be to offer a facility to import their own weather data for the year in which the energy consumption was measured. In addition to natural between year fluctuations in climate (such as temperature) the reference climate data set within the model does not account for the wind direction that may impact upon the rate of ventilation from within the structure. Differences may also arise between coastal and inland locations and between the northern and southern regions of a particular country. The increased accuracy of the simulations noted for Denmark arose in part from improvements made to the climate database for Denmark within the EAT.

Secondly, the model improved the accuracy of simulated energy for heating in those structures that were selected as 'new constructions – laps sealed' (Denmark: DEG potplants & Venlo potplants; Finland: HKO cucumber; Holland: NL tomato). There tended to be an underestimation of the energy consumption in those structures selected as being 'old construction - poor maintenance' possibly as a result of the underestimation of the rate of air exchange. The rate of natural air exchange (N) within the EAT has been quoted from ASAE (1984) (cited Bakker *et al*, 1995) and ASHRAE (2004) and is summarised in Table 2.

Table 2. Rate of natural air exchange within greenhouses used in the EAT and in brackets, range of values (from Bakker pp 181 and ASHRAE pp 22.11).

Greenhouse construction system	**Air infiltration rate (h^{-1})**
old construction - poor maintenance	3.0 (2.0 – 4.0)
old construction - good maintenance	1.5 (1.0 – 2.0)
new construction - single glass lapped (unsealed)	1.25 (0.75 – 1.5)
new construction - single glass lapped (laps sealed)	1.0

The air exchange values of old constructions, especially with poor maintenance, are subject to variation due to the contribution of multiple factors and each factor to multiple degrees of severity (for example missing or broken panes). The hourly rate of air exchange, on older structures in particular, is therefore difficult to quantify exactly as illustrated by the range of values in Table 2. Further, Table 3 and Table 1 in D10 show that the deviation from the actual energy consumption value in both versions of the EAT tested were greatest in those greenhouses where the construction was selected as being old and poorly maintained. An additional air exchange category was added: 'old construction – very poor maintenance' with an air infiltration rate (N) of 4.0 h^{-1}. The results of simulations for SKI and PAE greenhouses for this category are shown in Figure 2.

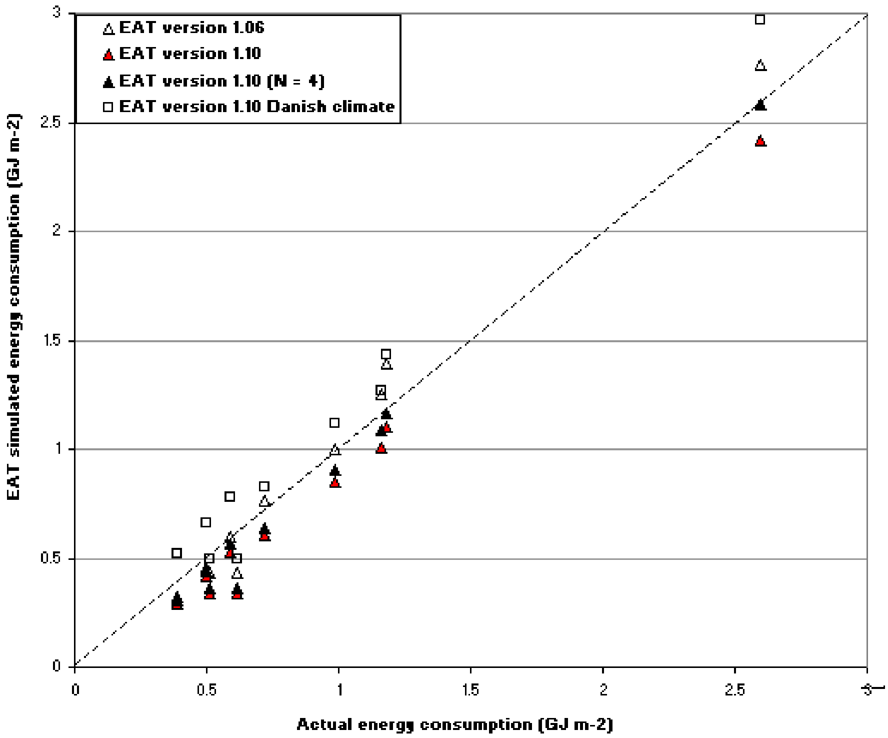

Figure 2. Actual energy consumption figures from the SKI and PAE greenhouse profiles tested plotted against the calculated energy use from the EAT version 1.06 (△), the EAT version 1.10 (▲) and the EAT version 1.10 with an additional N value of 4 for greenhouses of old construction and poor maintenance (▲). Simulations with the Danish climate are marked □. The dotted line shows the 1:1 relationship.

It should also be noted that there was no climate reference database available for Germany and consequently the simulations for the SKI and PAE greenhouse configurations were run instead with the Netherlands climate database. The glasshouses of both growers are located close to Bremerhaven and the difference in latitude is not significantly different, albeit slightly more northerly, to that of the sample points from which the Netherlands reference climate was constructed. The structures with higher hourly air exchange through leakage will however be more sensitive to differences in climate. The climate data-set immediately to the north and closest geographically was that of Denmark. Substitution of the Dutch with the Danish climate database did not improve the accuracy of the simulations that then over estimated the energy consumption for heating (Figure 2) except for SKI2 and SKI6. The most probable cause of the deviation from the actual energy consumption values for those structures in question was an under estimation of the air exchange value and this has been addressed in part by the addition of a further category for maintenance of old constructions.

The actual heating energy consumption figures for the greenhouse reference MAR in Finland were 21% higher than those simulated within the EAT 1.10. Again this may be a result of differences between the reference climate data-set within the EAT and the actual climate conditions due to the large distance an thus latitude between its most southerly and northern points. Secondly, the structure specifies that it is unsealed which is likely to result in a degree of uncertainty regarding the rate of air exchange from leakage although not to the extent of older structures (Table 2).

3.2. Total energy consumption and reduction in energy consumption after modification of the structure

Modifications to the greenhouse structure and their reduction in energy consumption are described in D10 (submitted by the partner WU). The same modifications described in D10 have been made and simulated in the current version of the EAT to provide a final calculation of the potential impact on energy consumption. The results of the simulations with the EAT version 1.10 are summarised in Table 3.

Table 3. Results from the EAT model version 1.10 testing the changes in greenhouse configurations (first analysed in D10 using version 1.06 for Dutch and 1.08 for Danish greenhouses) in comparison to a standard greenhouse (NL glass, 22801 m^2 and Denmark glass, 15000 m^2). The Danish greenhouse with an acrylic wall was calculated using 11% of the energy consumption value for a structure with an acrylic wall and glass roof with screens and 89% for a benchmark structure plus a roof and side screen (method described in D10). The percent energy saving refers to differences in the total energy efficiency (kg GJ^{-1}) between strategies.

Nursery & greenhouse reference	Σ EH (Σ EL) EAT (GJ m^{-2})	Σ EE EAT (kg GJ^{-1})	Yield (kg m^{-2})	Light capture (%)	% time above hum sp	CO_2 (t m^{-2})	% energy saving
Tomato NL Standard screen roof and side	1.27 (0)	46.42	59.15	72.3	54	0.07	baseline
Tomato NL Screen only roof	1.57 (0)	38.11	59.95	74.4	49	0.08	-17.9
Tomato NL No screens	1.77 (0)	34.69	61.33	77.8	47	0.09	-25.3
Tomato NL Poor maintenance	1.52 (0)	39.02	59.23	72.3	47	0.08	-15.9
Tomato NL Humidity to 90%	1.27 (0)	46.48	59.14	72.3	40	0.07	0.1
Tomato NL Lighting on below 250 Wm^{-2}	0.92 (0.39)	52.51	68.34	72.3	47	0.09	13.1
Tomato NL Temp sp 1°C lower	1.11 (0)	52.27	58.11	72.3	39	0.06	12.6
Denmark benchmark plus roof screen	1.77 (0.23)	17.50	34.96	75.6	53	0.12	baseline
Denmark benchmark plus roof and side screen	1.41 (0.23)	21.30	34.84	73.4	59	0.10	21.7
Denmark acrylic wall and glass roof and screens	1.40 (0.23)	21.43	34.82	73.4	53	0.10	22.4

EL: Energy for lighting; EE: Energy efficiency.

The current version of the model identifies similar trends in energy consumption in response to modifications to the greenhouse structure as versions 1.06 and 1.08. The removal of a screen on the sides and from both the roof and the sides reduces the energy efficiency (kg of yield per GJ of energy input) in the Dutch greenhouse by 18% and 25% respectively. The poor maintenance of an old structure decreases the efficiency by 16% (for an air exchange rate of 3 h^{-1}, at 4 h^{-1} as applicable to a 'very poorly' maintained structure this decrease is 22%). A reduction of the temperature setpoints by 1°C improves the energy efficiency by 13%. The use of lighting increased the yield from a predicted 59.2 kg m^{-2} to 68.3 kg m^{-2} and although there was an increase in the total energy consumption (heating and lighting) the efficiency increased by 13%.

The project aim of GREENERGY is to reduce the energy consumption in existing greenhouses by 20 - 40 % through small changes in configuration and operating procedures. A further set of simulations have been run to demonstrate the potential impact of the energy saving measures described individually in Table 3 when used in combination with each-other for tomato production in Holland (Table 4).

Table 4. Results from the EAT model version 1.10 testing the changes in greenhouse configurations (first analysed in D10 using version 1.06) in combination (as opposed to individually as shown in Table 3) for the Tomato NL greenhouse in comparison to three baselines. A worse case scenario 'very poorly maintained' old greenhouse with no screens (Baseline 1), a new construction (laps sealed) with no screens (Baseline 2) and a new construction with screens on the roof and sides (Baseline 3).

Modification	**Σ EH (Σ EL) EAT ($GJ\ m^{-2}$)**	**Σ EE EAT ($kg\ GJ^{-1}$)**	**Yield ($kg\ m^{-2}$)**	**Light capture (%)**	**% ES relative to baseline**	**% ES relative to baseline**	**% ES relative to baseline**
Old - very poor maintenance	2.49 (0)	24.64	61.21	77.8	Baseline 1	-	-
New - laps sealed, no screens	1.77 (0)	34.69	61.33	77.8	40.8	Baseline 2	-
+ screen side only	1.63 (0)	36.75	59.86	74.9	49.1	5.9	-
+ screen roof only	1.57 (0)	38.11	59.95	74.4	54.7	9.9	-
+ screen roof and side	1.27 (0)	46.42	59.15	72.3	88.4	33.8	Baseline 3
+ Lighting on below 250 Wm^{-2}	0.92 (0.39)	52.51	68.34	72.3	113.1	51.4	13.1
+ temp set point 1°C lower	0.78 (0.39)	57.77	67.25	72.3	134.5	66.5	24.5
+ humidity to 90%	0.77 (0.39)	58.02	67.24	72.3	135.5	67.3	25.0

EL: Energy for lighting; EE: Energy efficiency; % ES: percent energy saving.

Significant savings are evident through improvement to the structural maintenance of the greenhouse and the use of screens although such savings will not be available to all growers since some will have already implemented such measures. The savings will also not be as great in countries with warmer climates and savings associated with using screens will vary depending upon the size of the structure (surface area to volume ratio). For new and well sealed structures where screens are used further savings may be made through, for example, the use of lighting at night combined with a small reduction in the temperature setpoints.

4.0. Modifications to the EAT in response to requests by IAGs and SMEs during training (D19).

In the report of Deliverable 10 section 6 refers to a requirement that further testing should be undertaken within Southern Europe. An improvement to the ventilation component of the calculus applicable to Almeria type greenhouses only was provided by the partner UAL, the results of which are displayed in Figure 3.

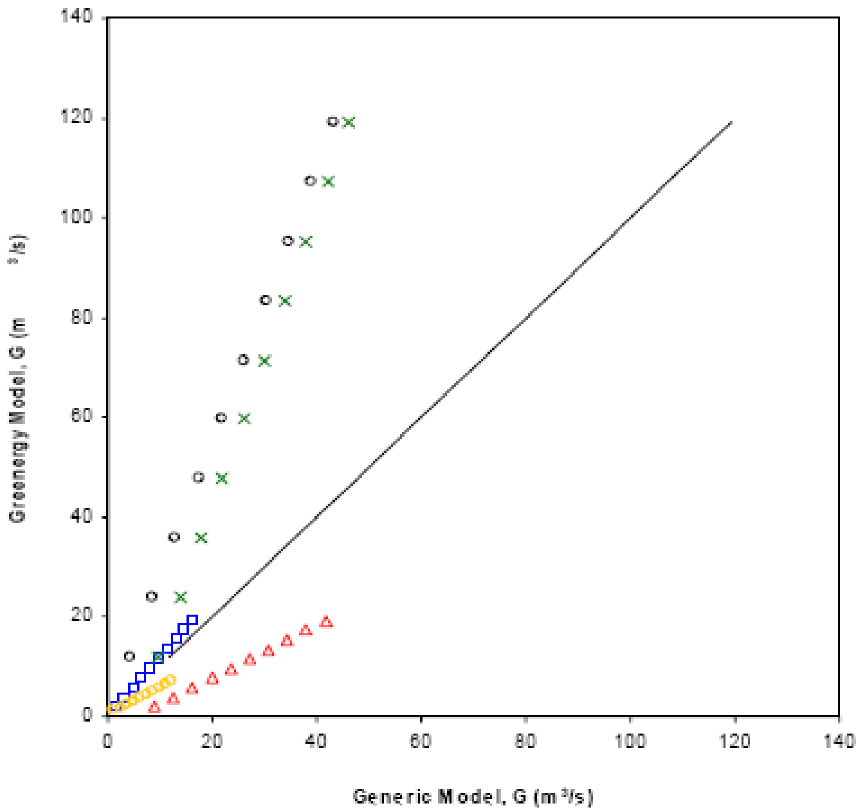

Figure 3. Results of modified ventilation calculus for Almeria widespan greenhouse (partner UAL). □ greenhouse with only flap roof windows (similar to current EAT Venlo greenhouses) with a maximum angle of 44º; ◇ roof windows with a maximum opening angle of 15º and with insect-proof screens; **O** greenhouse with rolling roof windows (opening angle of 180º) with side windows; × greenhouse with rolling roof windows (opening angle of 180º) without side windows; **Δ** greenhouse with flap roof windows with a maximum angle of 44º and with rolling side windows (opening angle of 180º).

These modifications are relevant to ventilation rather than heating and thus do not impact upon the core calculus for other greenhouse types or the energy requirement for heating. They do potentially impact the calculated yield in Southern Europe greenhouses where crop growth may be hindered at excessive internal greenhouse temperatures. The results obtained by UAL show that for a greenhouse with only flap roof windows (similar to the Venlo greenhouses currently within the EAT) with a maximum angle of 44º (□), the calculated airflow of the two models are similar. For a greenhouse with roof windows with a maximum opening angle of 15º and with insect-proof screens (◇), the current model within the EAT underestimates the ventilation airflow. For a greenhouse with rolling roof windows (opening angle of 180º) the model overestimates the ventilation airflow both with side windows (**O**) and without (×). For a greenhouse with flap roof windows with a maximum angle of 44º and with rolling side windows (opening angle of 180º) (**Δ**) the model of Energy Auditing Tool underestimates the ventilation flow (Figure 1).

Deliverable 15 describes improvements that were made to the EAT in response to issues raised during the testing of the model (D10). Further suggestions to improve the usability of the tool were made by the IAGs and SMEs during the training as part of the completion of D19. These involved relatively minor modifications and did not alter the underlying calculus. They included:

1. The partner FEC requested that vapour pressure deficit (VPD in kPa) generally used by UK growers be specified as a set-point as an alternative to % RH. The vapour pressure deficit is the difference between the actual (greenhouse) and the maximum water vapour

pressure at saturation. It was already calculated within the core calculus as a component of the humidity routine.
2. The partners COE and UAL requested an additional plastic ('Almeria') type greenhouse for Spain based upon the widespan type currently within the EAT but allowing the option of additional ventilation strips 1 – 2 m^2 in the walls.
3. The partner PAE requested a crop growth model to represent bedding plants (for example violas or poinsettia).
4. The partner WU and DEG requested facility to allow the different spacing of pot plants during the growing period.
5. The partners COE and UAL requested an additional setpoint screen for coatings where the user is able to select the percentage shading values and adjust during season.
6. The partners COE and UAL requested a facility to allow the use of insect netting on vents of Spanish greenhouses

A comment was made about the usefulness of the page where the trusses and width of the glass panes are entered. This is a necessary part of the tool in order for the model to calculate the quantity of shading by the frame and reduction of global radiation into the structure accordingly and therefore has not been modified.

A complete climate data-set from the South Eastern region compatible with the EAT is not currently available but the construction of a suitable data-set for Romania is expected to be completed within the next 12 months (co-ordinated by the partner UPT). This may be added to the EAT at a later date and made available to partners as a software upgrade.

Issues arose during the training of SMEs (Deliverable 19) of compatibility between the software and regional language settings within the EAT. This was resolved by the user setting their regional language to English in Microsoft Windows®. Further resolution of this issue through post project software maintenance may be possible however it is foreseen that if the technical changes necessary are implemented then current greenhouse / materials / comparison files will have to be reconfigured as structural changes to the storage database are required.

5.0. References

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