Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

EFFECT OF INACCURATE MEASUREMENTS ON ENERGY CONSUMPTION IN GREENHOUSE HORTICULTURE

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Abstract: The influence of inaccurate sensors, used in practice in greenhouse climate control, on the energy consumption of greenhouse horticultural production is investigated. It is shown that the inaccuracy of sensors, caused for instance by improper maintenance, leads to a higher energy use. *Copyright © 2008 IFAC*

Keywords: Greenhouse control, sensors, energy.

1. INTRODUCTION

Climate control in Dutch greenhouse horticultural production is performed by a greenhouse climate computer (Bakker et al., 1995). The grower adjusts certain temperature and humidity set points and the climate computer tries to follow these set points as good as possible, by adjusting the heating system, the window apertures and the opening of the energy screen. The climate control is using feedback control to perform this task; the set points are compared with the realised climate variables and the difference is sent through a controller to the control inputs. Also some feed forward mechanisms are used, for instance the set point for the ventilation temperature (at this temperature the ventilation by means of the ventilation windows starts) depends on the solar radiation. Also the moment to start closing the energy screens is radiation dependent. The indoor climate variables, like temperature, relative humidity, CO_2-concentration as well as the outdoor conditions like temperature and global radiation are all measured by sensors (Bakker et al., 1995). If these sensors are not accurate, for instance if they are not or not well enough maintained, this will in general lead to extra energy consumption. The cost of energy is a major part of the running costs in greenhouse horticultural production. In this paper the results of an experiment are described in which the inaccuracy of the sensors used in greenhouse climate control and its effect on the energy consumption are determined.

2. EXPERIMENTAL SETUP

The measurements were conducted at four growers (henceforth mentioned grower 1 through grower 4), of which each had a different crop, respectively eggplant, cucumber, tomato and radish. The greenhouses of the growers were located at respectively De Lier, Nootdorp, Naaldwijk and Monster, all in the Western part of the Netherlands. The measurements took place from October 1st until November 1st, 2004. Two growers had a climate computer from the same supplier, however with different types of measuring boxes for the temperature and relative humidity. All growers used the same type of solarimeter, namely a CM11 (Kipp & Zonen, Delft, The Netherlands), the CO_2-sensors of the growers were Siemens sensors of different type. The maintenance of the sensors is usually done by the supplier of the climate computer or by a dealer. The reference sensors used in the experiment were two psychrometers (ASFG, Wageningen, The Netherlands) for measuring the inside temperature and relative humidity. The two psychrometers were placed as close as possible to the measuring box of the grower. The average of the two sensors was used as the reference signal for temperature and relative humidity. The reference sensor for the global radiation was a CM22 (Kipp & Zonen); the quality of this sensor is one class higher than the CM11. For the CO_2 a Siemens Ultramat 21P was used as a reference sensor. For the outside temperature a HL2010 (Hanwell Instruments Ltd) was used. All reference sensors were calibrated before using them in the experiment.

During two or three days measurements were performed at a grower, after which the set of reference sensors was moved to the next grower. After this first series of measurements, the growers asked their supplier or dealer to carry out a standard maintenance service of their sensors, both inside and outside the greenhouse. After this maintenance, a second series of measurements was executed at the four growers.

3. MEASUREMENTS

The two series of measured data were processed using Matlab®. The difference between the sensors of the growers and the reference sensors was determined and from this signal the mean (ε_{abs}) and its standard deviation (σ) were calculated. Only for the measurements of the solar radiation the relative error (ε_{rel}) was used, since the manufacturer expresses the accuracy of his sensors in this way. From the error signal, corrected for the average, also the distribution was determined. The error distribution of the inside temperature before and after the maintenance service showed a normal distribution. A normal distribution was also found in the error in the CO_2-measurements. The distribution of the relative humidity was not a normal distribution; it had a more askew distribution. Also before maintenance, the distribution of the global radiation was not centred around zero.

In the following figures some of the measurements are shown. In each figure, the measurement from a sensor of the grower is shown together with the signal of the reference sensor.

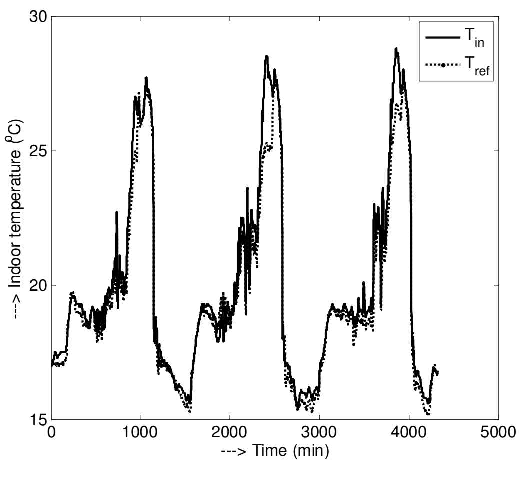

Fig. 1. Indoor greenhouse temperature at grower 1, before maintenance.

In figure 1, the error between the indoor temperature measured with the sensor of the grower (T_{in}) and the temperature measured by the reference sensor (T_{ref}) is $\varepsilon = 0.41 \pm 1.2^{\circ}\mathrm{C}$ (2σ bounds).

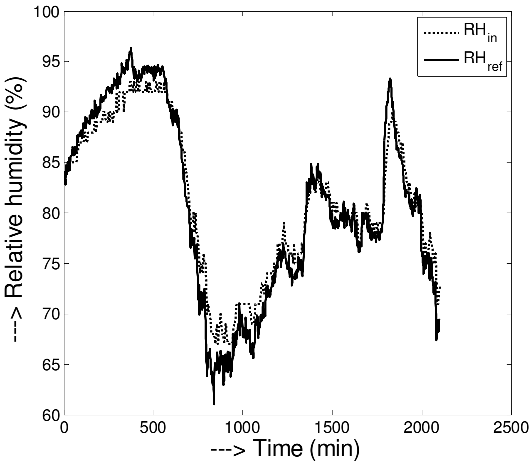

Fig. 2. Indoor greenhouse relative humidity at grower 4, before maintenance.

In figure 2 the error between the indoor relative humidity measured with the sensor of the grower (RH_{in}) and the relative humidity measured by the reference sensor (RH_{ref}) is $\varepsilon = 0.54 \pm 4.2\%$.

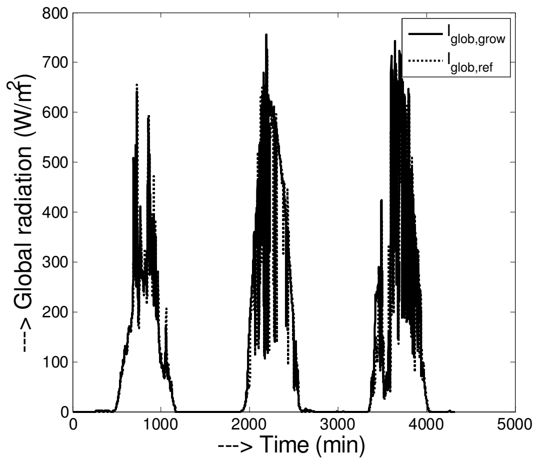

Fig. 3. Global radiation at grower 1, before maintenance.

In figure 3, the error between the global radiation, measured with the sensor of the grower ($I_{glob,\ grow}$) and the global radiation measured by the reference sensor ($I_{glob,\ ref}$) is $\varepsilon = 5.4 \pm 174 \mathrm{W/m^2}$. The relative error is $\varepsilon_{rel} = 9.3 \pm 100\%$.

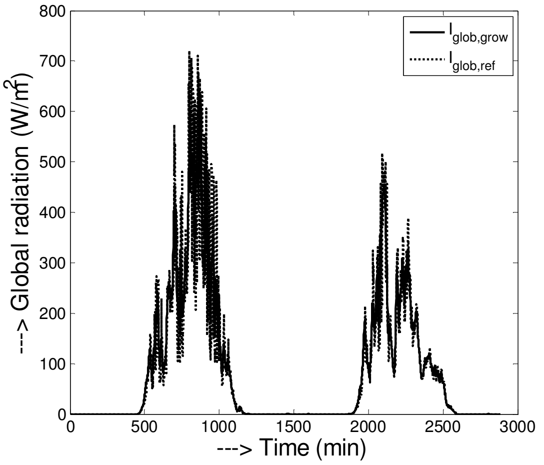

Fig.4. Global radiation at grower 2, before maintenance.

In figure 4, the error between the global radiation, measured with the sensor of the grower ($I_{glob,\ grow}$) and the global radiation measured by the reference sensor ($I_{glob,\ ref}$) is $\varepsilon = -0.5 \pm 80\text{W/m}^2$ and the relative error is $\varepsilon_{rel} = 3.9 \pm 42\%$.

After the first series of measurements at the growers, their supplier or dealer was ordered to carry out a regular maintenance service for the sensors. The results are shown in the following figures.

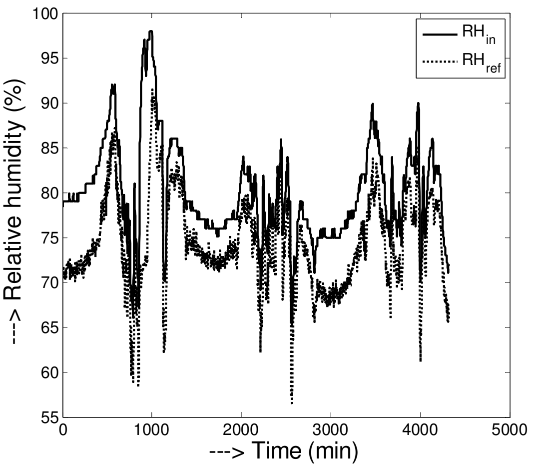

Fig. 5. Indoor greenhouse relative humidity at grower 3, before maintenance service.

In figure 5, the error between the indoor relative humidity measured with the sensor of the grower (RH_{in}) and the relative humidity measured by the reference sensor (RH_{ref}) is $\varepsilon = 5.8 \pm 6.2\%$.

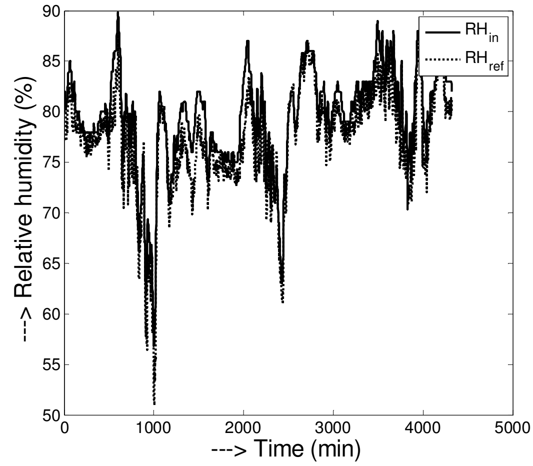

Fig. 6. Indoor greenhouse relative humidity at grower 3, after maintenance service.

After the maintenance, see figure 6, the error between the indoor relative humidity measured with the sensor of the grower (RH_{in}) and the relative humidity measured by the reference sensor (RH_{ref}) is $\varepsilon = 2.07 \pm 3.28\%$. Clearly in this case the maintenance reduced the measurement error.

In figure 4 the measurement of the global radiation at grower 2 was shown, resulting in a measurement error of $\varepsilon = -0.5 \pm 80$ W/m^2 and a relative error of $\varepsilon_{rel} = 3.9 \pm 42\%$. In figure 8 the measurements at the same grower are given after the maintenance service.

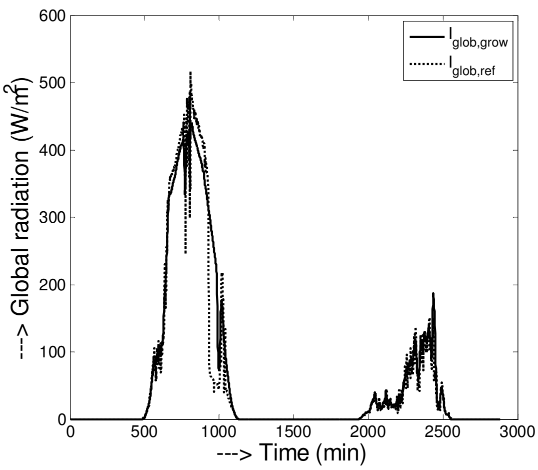

Fig. 8. Global radiation at grower 2, after maintenance service.

In figure 8, the error between the global radiation measured with the sensor of the grower ($I_{glob,grow}$) and the global radiation measured by the reference sensor ($I_{glob,ref}$) is $\varepsilon = 7.2 \pm 96.4\text{W/m}^2$ and the relative error is now $\varepsilon_{rel} = 21.3 \pm 153.4\%$. In this case the maintenance had a negative effect on the accuracy. Also the opposite effect, where the maintenance had a positive effect occurred. This is shown in the next two figures.

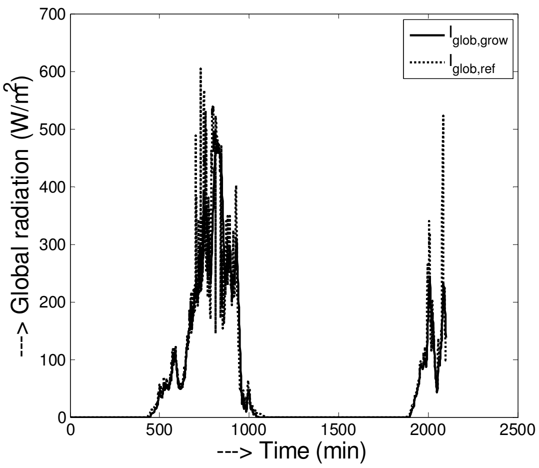

Fig. 9. Global radiation at grower 4, before maintenance service.

In figure 9, the error between the global radiation measured with the sensor of the grower ($I_{glob,grow}$) and the global radiation measured by the reference sensor ($I_{glob,ref}$) is $\varepsilon = -7.8 \pm 106 \mathrm{W/m^2}$ and the relative error is $\varepsilon_{rel} = -5.7 \pm 59\%$.

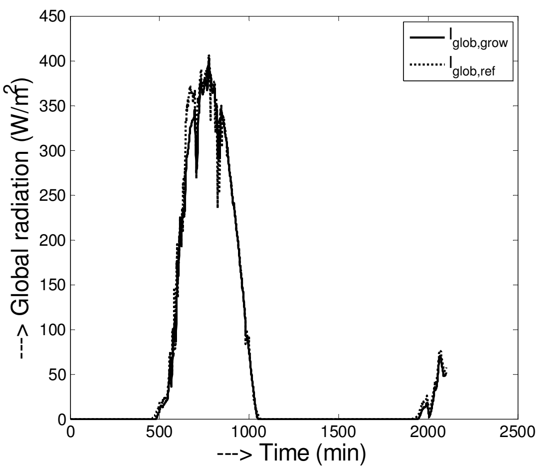

Fig. 10. Global radiation at grower 4, after maintenance service.

The maintenance increased the accuracy considerably. After maintenance, see figure 10, the error between the global radiation measured with the sensor of the grower ($I_{glob,grow}$) and the global radiation measured by the reference sensor ($I_{glob,ref}$) is $\varepsilon = -2.7 \pm 19.4 \mathrm{W/m^2}$ and the relative error is $\varepsilon_{rel} = -3.1 \pm 20.6\%$

4. ACCURACY RESULTS

The results of the first series of measurements of the relative humidity and global radiation are summarized in the next tables. In the tables the following parameters are shown: ε_{abs} is the error between the measurement from the growers' sensor and the reference sensor averaged over the whole measurement period, σ is the standard deviation of the error, σ_{des} is the desired standard deviation and σ_{ach} is the achievable standard deviation (Van den Berg and De Ruiter, 1998).

Table 1 Greenhouse indoor relative humidity, before maintenance

Grower	ε_{abs}	σ	σ_{des}	σ_{ach}
1	-0.04	2.2	2	3
2	0.46	1.4	2	3
3	5.8	3.1	2	3
4	0.54	2.1	2	3
total	2.0	3.5	2	3

At growers 1, 3 and 4 the desired accuracy is not achieved. Grower 2 has a very good result and reaches both the desired and the achievable standard deviation and also has a small absolute error. The average over all growers does not satisfy the desired or achievable accuracies.
After the maintenance services the following results were obtained.

Table 2 Greenhouse indoor relative humidity, after maintenance

Grower	ε_{abs}	σ	σ_{des}	σ_{ach}
1	-1.34	1.45	2	3
2	0.15	1.2	2	3
3	2.07	1.64	2	3
4	-1.98	2.78	2	3
total	-0.09%	2.42%	2%	3%

After maintenance the standard deviation is decreased except at grower 4. The overall average standard deviation is now between the desired and achievable accuracy.
For the global radiation we found the following results. In this case we use a relative error in order to be able to compare the results with the listed accuracy of the manufacturer (2%).

Table 3 Global radiation, before maintenance

Grower	ε_{rel}	σ	σ_{ach}
1	9.3	50	2
2	3.9	21	2
3	70	100	2
4	-5.7	29.5	2
total	23%	76.8%	2%

Clearly the solarimeter from grower 3 is not performing very well. Furthermore none of the growers' solarimeters satisfies the achievable accuracy. After the maintenance service the results are:

Table 4 Global radiation, after maintenance

Grower	ε_{rel}	σ	σ_{ach}
1	13.3	46.8	2
2	21.3	76.7	2
3	15.9	44.5	2
4	-3.1	10.3	2
total	7.7%	36.3%	2%

The accuracy of the solarimeter from grower 1 is hardly affected by maintenance, whereas the accuracy of the solarimeter from grower 3 is considerably improved by maintenance. The solarimeter from grower 4 performs the best both before and after maintenance and the accuracy is improved by the maintenance. Remarkable is the behaviour of the solarimeter from grower 2, maintenance decreases the accuracy considerably with more than a factor 3.

The summary of the results averaged over the measurements of all 4 growers together are listed in table 5 (before maintenance) and table 6 (after maintenance).

Table 5 Overall results, before maintenance

	ε_{abs}	σ	σ_{des}	σ_{ach}
T_{in}	0.2 °C	0.5 °C	0.1 °C	0.2 °C
T_{out}	-0.4 °C	1.5 °C	0.1 °C	0.2 °C
RH_{in}	2.0%	3.5%	2%	3%
CO_2	51 ppm	132 ppm	10 ppm	30 ppm
	ε_{rel}	σ		σ_{ach}
I_{glob}	23%	77%		2%

Table 6 Overall results, after maintenance

	ε_{rel}	σ	σ_{des}	σ_{ach}
T_{in}	0.1 °C	0.3 °C	0.1 °C	0.2 °C
T_{out}	-0 1 °C	1.2 °C	0.1 °C	0.2 °C
RH_{in}	-0.1%	2.4%	2%	3%
CO_2	19 ppm	116 ppm	10 ppm	30 ppm
	ε_{rel}	σ		σ_{ach}
I_{glob}	7.7%	36%		2%

5. ENERGY CONSUMPTION

To determine the effect of the inaccuracy of sensors on the energy consumption of the greenhouse production of a standard tomato crop, with standard climate settings, the whole system is simulated with the program KASPRO (De Zwart, 1996), where the inaccuracy of the measurements is taken into account. The greenhouse production system is simulated from December 11th to November 20th in the next year, the standard tomato production season in Dutch horticultural practice. The simulation was performed for 100 realisations of the errors, also with different combinations of inaccurate sensors and different speed of change of the errors. It was found that inaccuracy in the relative humidity sensor and in the sensor for the global radiation had the highest influence on the energy consumption. For the speed of change of the errors a period of 15 minutes was chosen. In the following figure the extra energy consumption due to errors in the measurements of relative humidity and global radiation is shown for 100 simulations.

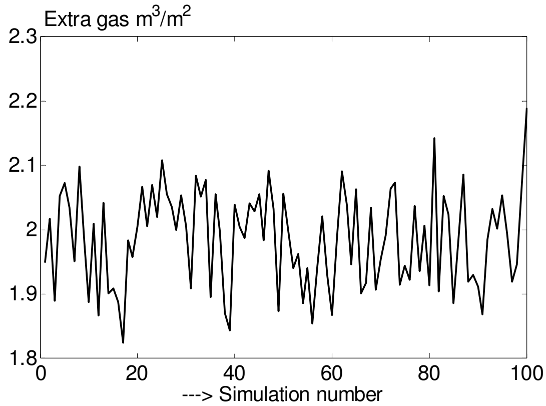

Fig. 11. The extra energy consumption (in m^3 natural gas per m^2 greenhouse surface) as a result of errors in the measurement of relative humidity and global radiation, before maintenance.

The energy consumption is 4.9 to 5.2% higher than the energy consumption without errors in the sensor signals, which is 41.4 m^3 natural gas per m^2.
If in greenhouse production more natural gas is used for heating, also more CO_2 is available, leading to higher production. This is shown in the next figure.

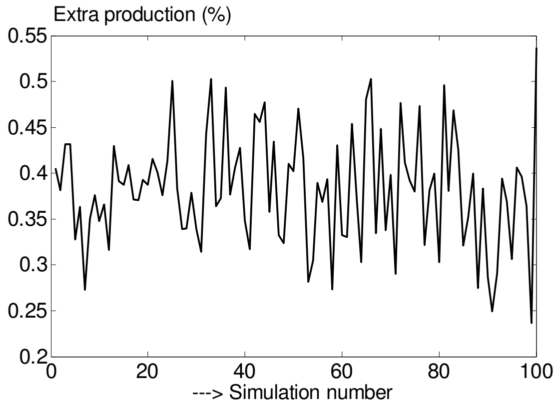

Fig. 12. The extra production (in % of the production without errors in the measurements) as a result of errors in the measurement of relative humidity and global radiation, before maintenance.

The extra production due to the inaccurate sensors is 0.3 to 0.5%. According to De Bont and Van der Knijff, 2007, the yield for fruit vegetables like tomatoes in 2007 in round figures was 40 €/m^2 and

the energy use was 10 €/m^2. The extra energy use costs the grower at most 0.5 €/m^2 and the extra production gives the grower a profit of at most 0.2 €/m^2. Using inaccurate sensors will lead for an average greenhouse of 2 ha to a loss of 6000 €/year. The cost of a maintenance service is around € 500.
The results after the maintenance service of sensors are shown in the next two figures.

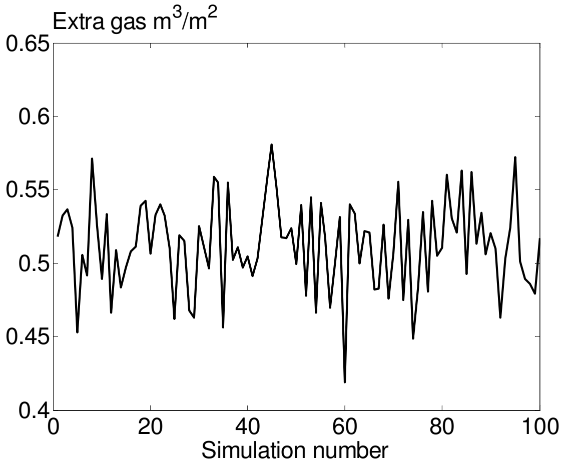

Fig. 13. The extra energy consumption (in m^3 natural gas per m^2 greenhouse surface) as a result of errors in the measurement of relative humidity and global radiation, after maintenance.

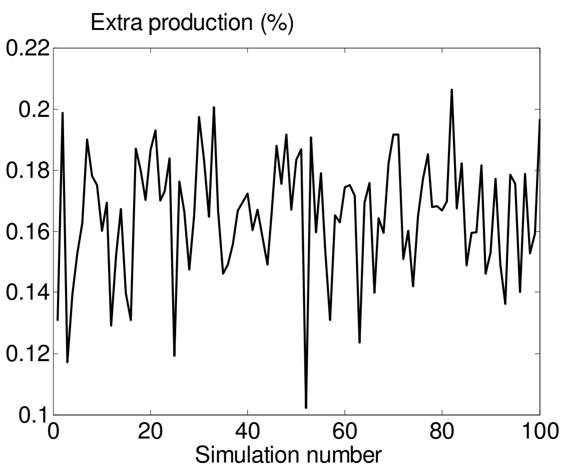

Fig. 14 The extra production (in % of the production without errors in the measurements) as a result of errors in the measurement of relative humidity and global radiation, after maintenance.

After maintenance the extra energy consumption is reduced to 1.2 to 1.3% and the extra production to 0.1 to 0.3%. The costs of the extra energy consumption is now at most 0.13 €/m^2 and the profit of the extra production is at most 0.12 €/m^2, so the loss due to inaccurate sensors is for an average greenhouse of 2 ha is now reduced to € 200/year.
Clearly maintenance has not only a positive effect on reducing extra energy consumption due to inaccurate sensors, but is also profitable for the grower.

6. CONCLUSION

In horticultural practice the sensors used for the greenhouse climate control do not satisfy the desired or achievable accuracy. Even the maintenance of the sensors as done in practice does not change this fact. The extra energy consumption, due to the inaccuracy of the sensors in greenhouse practice, is mainly caused by the sensors for global radiation and relative humidity. This extra energy consumption is around 5% of the normal energy consumption, the extra production, due to more available CO_2, is 0.4%. However, with respect to energy consumption maintenance is useful. The extra consumption is then 1.25% and the extra production is 0.2%. Besides that is it also profitable for the grower, leading to a higher profit. Maintenance can be improved by using a better protocol for the maintenance of the global radiation sensors, either by designing a device for a good on-site calibration, or by an exchange schedule, where the sensor is replaced by a reconditioned one at every service.

ACKNOWLEDGEMENT

This research was sponsored by the Dutch Ministry of Agriculture, Nature and Food Quality and the Dutch Product Board for Horticulture under project nr. PT 11937. We thank Kipp & Zonen, Delft, The Netherlands for supplying us with several reference sensors for global radiation.

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