DSS FOR OPTIMUM VENTILATION, THERMAL STORAGE & CO_2 MANAGEMENT FOR DIFFERENT CLIMATES & AVAILABLE SUSTAINABLE ENERGY SOURCES

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EUPHOROS DELIVERABLE 14

EUPHOROS: Reducing the need for external inputs in high value protected horticultural and ornamental crops

Dss for optimum ventilation, thermal storage & CO_2 management for different climates & available sustainable energy sources

WP2 Energy

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EUPHOROS DELIVERABLE 14
ABSTRACT

Deliverable 14 of the EUphoros project is in its whole, a decision support system to be used by growers, technical advisers or any other agents involved in high value vegetable, ornamentals or cut flower greenhouse production across Europe to optimize the greenhouse energy use, minimizing the use of fossil fuels (towards a virtual zero fossil consuming greenhouse), thus the carbon footprint, providing guidelines to make a profitable use of available sustainable energy sources.

The thermal and spectral properties of the cover material, in combination with local climate data, have been used to determine the potential productivity and the distribution of surplus/shortage of energy over the year using a greenhouse climate model specifically designed for this purpose: the HortiAlmería model. The model has been used to estimate the supplemental energy input as they relate to the properties of the cover, local climate and capacity and efficiency of thermal storage. The possibilities to cover the energy gap with locally available renewable energy has been investigated along with economically sound options for thermal storage and experimentally implemented in one of the test sites: Almería. Given the advantages of maintaining a closed greenhouse as much as possible to achieve higher CO_2 efficiency, no undesired heat loss, banning of pests, criteria have been developed for opening/closing of the vents. The minimal ventilation capacity needed to “ventilate away” any remaining surplus energy has been determined.

The work is divided into three main tasks:

EXECUTIVE SUMMARY

Introduction

Methodology

Results

INTRODUCTION

In March 2008 the EU-project "Efficient use of inputs in protected horticulture" started, abbreviated as EUPHOROS. One of the work packages of EUPHOROS deals with the efficient use of energy in European Greenhouses (WP2).

The objectives of WP2 were:

1. To obtain (at least one) glass prototype cover material with high-tech coating that improves light transmission and thermal insulation for reduction of energy losses in cold-winter climates
2. To obtain (at least one) plastic film prototype with modern additives to elongate the production period in summer in Mediterranean climates
3. To determine optimal thermal storage and optimum energy management for different climates
4. To select site-specific renewable sources for additional energy and give guidelines for their use
5. To develop decision support tools for management of ventilation and CO_2 fertilisation to optimise energy use and resource use efficiency

The work developed to achieve the first two objectives has already been completed and reported on deliverables 2, 7 and 8. The present deliverable (deliverable 14) deals with the last three objectives. The deliverable has been structured in three parts that give response to the three mentioned general objectives: Part I deals with the possibilities for thermal storage in European greenhouses; Part II is a decision support system for optimum ventilation management and Part III deals with the possibilities for usage of sustainable renewable energy sources.

PART I

1. POSSIBILITIES FOR USAGE OF THERMAL STORAGE

1.1. Introduction

During the last decades, there has been an escalation worldwide in the reliance on greenhouse products for vegetables [and for ornamentals]. This has spawned an enormous increase in production that has been achieved through intensification [productivity per unit area] in The Netherlands [Northern/Central Europe] and an increase in production area in mild environments such as the Mediterranean region. As an example, productivity of Dutch round tomatoes has increased by around 2% a year, from 42 kg/m2 in 1990 (Ruijs et al., 2001) to 64 kg/m2 in 2010 (Vermeulen, 2010) with a nearly constant greenhouse area of 11000 ha in The Netherlands. On the other hand, in Spain the greenhouse area has grown from 28,000 ha in 1990 to more than 45,000 ha in 2007 mainly concentrated in the South of Spain. The increase in productive area rather than productivity in the Mediterranean region is caused by the limited means to control the environment in the low-cost/low-tech greenhouses typical of the region.

However, both these developments are unsustainable: the Dutch greenhouse sector relies on huge amounts of energy to warrant the perfect climate that can ensure such productions (1/3 of the production costs for a typical grower, and 7% of the gas use of The Netherlands (Euphoros consortium, 2010), whereas plastic covers more than 33 % of the area of at least 4 municipalities of the province of Almería and more than 20% of the whole provincial area (Fernandez Sierra & Perez Parra, 2004). Therefore the Dutch government has required the local greenhouse sector to reduce energy use by at least 2% a year (whereas in Spain productivity will have to increase, without increasing reliance on resources. There is much scope for increasing productivity. The requirement is to find a good economic compromise between high investments in greenhouse structures and equipments and their productive performance, without notably increasing the use of inputs, especially energy, which is the main advantage most of the greenhouses in the Mediterranean area (Castilla, 2003).

In spite of the appearance, the solutions being investigated in both northern and southern greenhouse areas are based on the same principle that is a much better use of the sun energy. The greenhouse itself is by definition a sun collector (i.e. Garzoli and Shell, 1984), in which only a small fraction of the energy intercepted by the greenhouse (solar radiation) is transformed into dry matter by the plant's photosynthesis process. The greenhouse annually collects from the sun two to three times the energy needed for heating during wintertime, depending on location of the greenhouse (Heuvelink et al., 2008; Bot, 1994). The excess energy stored in the greenhouse as sensible and latent heat (water vapour transpired by the plants) is usually ventilated away (generally by means of natural ventilation) which is the cheapest and easiest method to cool the greenhouse, both at southern and northern latitudes. Therefore all the energy evacuated through the greenhouse vents, is not stored and thus not available to heat the greenhouse when needed during the winter period.

Improving temperature management in winter in the Mediterranean greenhouses can be accomplished with different methods. Passive techniques such as improving the greenhouse soil energy storage capacity during the daytime (i.e. mulching) and the use of different types of fix or movable energy saving screens to reduce heat losses are often used in Mediterranean and Northern greenhouses and the optimum combination and management of these techniques is still a matter of research nowadays.

If the excess energy could be stored away (thermal storage), there would less/no need for natural ventilation and the recovered energy could be used when needed (closed greenhouse concept). Suggested technologies for heat storage are water tanks, underground aquifers (Heuvelink et al., 2008; Opdam et al., 2005), the ground (Mavroyanopoulos & Kyritsis, 1986), or phase-change materials (Öztürk, 2005; Kürklü, 1998). As the annual solar radiation influx by far exceeds the heating demand, a fully closed greenhouse (no ventilation at all) with seasonal storage would produce surplus heat, which could be used for other buildings (Bakker et al., 2008).

Closing the air cycle of the greenhouse (reducing ventilation) provides other benefits from an environmental point of view. Reduced ventilation allows the CO_2 concentration to be increased to 1000 ppm which can increase crop yield by 22% (De Gelder et al., 2005). In addition, limiting ventilation reduces need for chemical pest control thanks to the reduced risk of contamination from outside. Van Os et al. (1994) calculated that 30-50% of the pesticides applied leave the greenhouse via ventilation. Another great advantage of limiting ventilation is the lower water use due which can be reduced by even a factor 10.

In The Netherlands, commercial greenhouses already exist which use the confined aquifers as a heat store (a cold and a warm store) combined with the use of heat pumps, cooling tower and high efficiency air/water heat exchangers inside the greenhouse. But considering the high cooling requirement for the closed greenhouse operation in the Mediterranean summers, a completely closed greenhouse might be too costly, if sizing a full capacity cooling system is required. Therefore, the concept of a semi-closed greenhouse is introduced. The percentage of time a greenhouse requires no ventilation is an indicator of the closure rate. The difference between a closed greenhouse and a semi-closed greenhouse is that the former has a 100% closure rate, while the latter has a lower closure rate.

The challenge is therefore to develop a method that can be used to calculate and design a technically feasible system based on the use of water thermal storage for the Mediterranean area which optimizes the use of energy and that is able to maintain the greenhouse closed for as much time of the growing cycle as possible. For this, the first step has been to develop a greenhouse model in a spreadsheet capable of estimating the heating and cooling requirements and design the thermal storage system.

1.2 HortiAlmeria: a greenhouse energy and climate model.

The model is based on the Horticern greenhouse energy model developed by Jolliet *et al.* (1991) and includes the treatment of humidity and transpiration used in the Hortitrans model (Jolliet, 1994). It predicts greenhouse air temperature and humidity, estimates the heating, ventilation and mechanical cooling requirements, and the water consumed by evaporative cooling. Transpiration of a tomato crop can be estimated using either a model developed at Estación Experimental de la Fundación Cajamar or the Hortitrans model. The model includes the short term storage of energy removed by mechanical cooling for subsequent heating. The model also includes modules which estimate the energy available from the wind including heat storage, and solar (photovoltaic) energy. A photosynthesis module for tomatoes is included which enables the economics of CO_2 enrichment to be assessed. Although the model is steady state, predictions of the heat transfer into and from the soil have been included based on measurements made at Estación Experimental de la Fundación Cajamar. The model calculates hourly values of the greenhouse conditions and control inputs in response to hourly values of external air temperature and relative humidity, solar radiation and wind speed, and a value for the black body sky temperature. The model is implemented in Excel.

Structure of the model

The model structure is shown in Fig. 1. The environment model requires weather data and data to characterise the greenhouse, crop and for the environmental control settings. This model interacts with modules that determine the heating and cooling necessary to create the desired environment. Energy removed by mechanical cooling can be stored and used for heating. Together these form a complete model to predict the greenhouse inputs and the environment created.

The external modules for wind energy, photovoltaic electricity and CO_2 enrichment are linked to the main model only to obtain the input data each requires. Parameters required by the modules are inserted into the area of the spreadsheet where the module is located and where the outputs are displayed. The main model is contained in the Excel file **HortiAlmeria.xls** and the applications in Excel file **Applications.xls**.

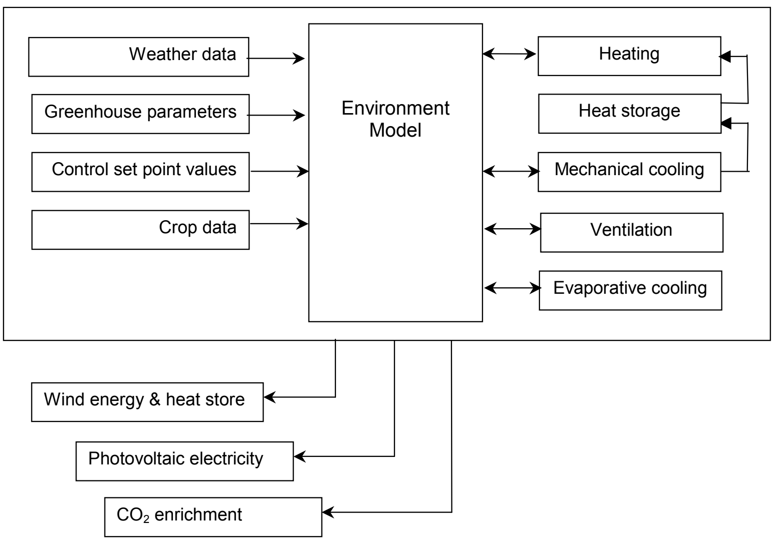


Fig. 1. Structure of the greenhouse model

Opening the spreadsheet containing the model

The spreadsheet contains three functions written in Visual Basic. One function calculates wet bulb temperature, the other two solve the water vapour mass balance equations for the vapour pressure of the greenhouse air for ventilation and mechanical cooling respectively.

Data input

The following time identification variables should be placed in spreadsheet:

year (yyyy)

month (1-12)

day of the month (1,2,3,4,…..

hour of the day (0 – 23)

The default condition is for the full extent of the weather data set to define period to be analysed.

When entering new data check if the number of records to be entered is less than currently exists in HortiAlmería. If it is then, after entering the data, delete the rows containing old values at the end of the new data. By default, the inputs are summed over rows 43 to 9000.

Meteorological data

Hourly values of the following external variables should be copied into spreadsheet:

wind speed (m/s)

relative humidity (%)

dry bulb temperature (^{o}C)

global solar radiation (W/m^2)

A weather dataset is available from Estación Experimental de la Fundación Cajamar with hourly records covering the period 1 October 2003 to 21 October 2007.

A macro is used to calculate the wet bulb temperature required for the evaporative cooling module.

The photosynthesis model requires the average daytime PAR inside the greenhouse over the previous 7 days. For simplicity the values for the first 7 days are taken as the values for the following day.

Physical parameters

The Physical Parameters Windows contains values of physical variables used in the model.

Sky temp is the value that must be subtracted from the air temperature to give the black body sky temperature. Suggested values are 8.5^{o}C when estimating inputs over a crop cycle, 20^{o}C for heating system design studies and 5^{o}C for cooling system design studies.

Physical parameters			
Specific heat air		1006.00	J/kg.K
Density air		1.20	kg/m3
Ratio PAR/Total rad		0.47	-
Latent heat of vaprstn water		2.45E+06	J/kg
Psychrometeric const (gam)		66.2	Pa/K
Atmospheric pressure		101325	Pa
Stefan's constant		5.67E-08	W/K4m2
Sky temp	Text - 8.5	C	

Greenhouse parameters

The parameters which characterise the greenhouse are inserted in the Greenhouse Parameters Window.

Greenhouse parameters			
Dimensions			
Span width		7.0	m
Length		100.0	m
Wall height		3.5	m
Roof angle		11.0	deg
Number of spans		15	
Solar radiation transmission			
Cover (Total)		0.90	
Cover (PAR)		0.88	
Shade (Total)		1.00	
Cover (net)		0.90	
House (net)		0.65	
Emissivity of cover		0.90	
Soil heat flux = A * (Sol Rad int) + B			
	A	0.2410	
	B	-21.3	W/m2
Soil heat flux factor		0.25	=1/(1+LAI)
Leak=a+b*wind speed			ac/h
Leakage rate coeff, a		0.2500	ac/h
Leakage rate coeff, b		0.0750	(ac/h)/(s/m)

Soil heat flux is estimated from a linear relationship with solar radiation derived from data recorded at Estación Experimental de la Fundación Cajamar (see Soil heat flux section).

The equation for leakage has units of air changes per hour and leakage is a linear function of wind speed.

The performance of a greenhouse covered with a **radiation selective material** can be investigated provided a value for the transmission of global solar radiation is available. If this is not known, the following can adopted. Half of the solar energy occurs in the UV and PAR parts of the solar spectrum and half in the solar infra red (IR). Thus, in energy terms, the total transmission is the sum of the (UV+PAR) and IR transmissions. Radiation selective covers change the IR component so varying the total transmission from 0.5 to 1.0, while assuming the (UV+PAR) transmission remains constant, will in effect change the IR transmission from 0 to 1.0.

The effect of **shading** applied to the greenhouse cover can be investigated if the transmission of global solar radiation by the shading is known.

If the CO_2 enrichment module is used, a value for the transmission of PAR is required.

Crop Parameters

Parameters which characterise the crop should be placed in the Crop Parameters Window.

The transpiration model is selected by inserting 1 opposite the required model and 0 opposite the other.

Crop parameters			
Crop LAI		3.0	
Transpiration model - tomatoes			
Hortitrans [yes (1) ; no (0)]			0
Las Palmerillas [yes (1) ; no (0)]			1

Control settings Parameters which characterise greenhouse environmental control should be inserted in the Control Settings Window.

Control settings			
Heating temp		**12**	**C**
Vent/Cooling temp		**27**	**C**
Evap cool efficiency		**0**	
Mech cooling rate		**200**	**W/m2**
Cooler temp		**10**	**C**
Temp adjustment when To ~ Tv			
Delta T		**1**	**C**
When Tv-To < deltaT, Ti = To + deltaT			

Setting **Evap cool efficiency = 0**, means that evaporative cooling does not operate. Setting a value **0 < Evap cool efficiency <= 1** will active evaporative cooling. Evaporative cooling efficiency is the fraction of the wet bulb depression by which the dry bulb temperature of the ventilation air is reduced.

Setting **Mech cooling rate = 0** means that the mechanical cooler does not operate. Setting a very high value (higher than will be ever be required) means that mechanical cooling will provide all cooling required. Setting an intermediate value will result in mechanical cooling taking place when the cooling requirement is less than this value, and ventilation being used at higher cooling rates for 100% of the cooling requirement.

Cooler temp is the temperature of the heat exchanger of the cooler. This temperature controls the latent heat removed by the cooler.

Delta T is the temperature by which the greenhouse temperature exceeds the external temperature when the external temperature is within Delta T of the Ventilation Temperature set point. This should only be changed if the model is used to investigate the behaviour of ventilation when the external temperature is close to the ventilation temperature.

Sky temperature

A value for the sky temperature is required by the model to calculate the thermal radiation emitted by the sky. The model assumes the sky radiates as a black body (emissivity =1) at an apparent sky temperature that can be related to the ambient air temperature. The sky temperature is generally 5 to 20°C below the air temperature and is lowest when there are no clouds.

An indication of the sky temperature was obtained from unpublished information on atmospheric radiation and air temperature measured at Estación Experimental de la Fundación Cajamar over the periods 5-7 February 1997, 13-22 March 1998 and 4-5 April 1999. The black body atmospheric radiation R_{atm} is given by:

$$R_{atm} = \sigma T^4_{sky}$$

where σ is Stefan's constant and T_{sky} the black body sky temperature. Values of T_{sky} were calculated with this equation and subtracted from the measured air temperature. The results, presented in Fig. 2, show the sky temperature was 13 to 20°C below the air temperature. No

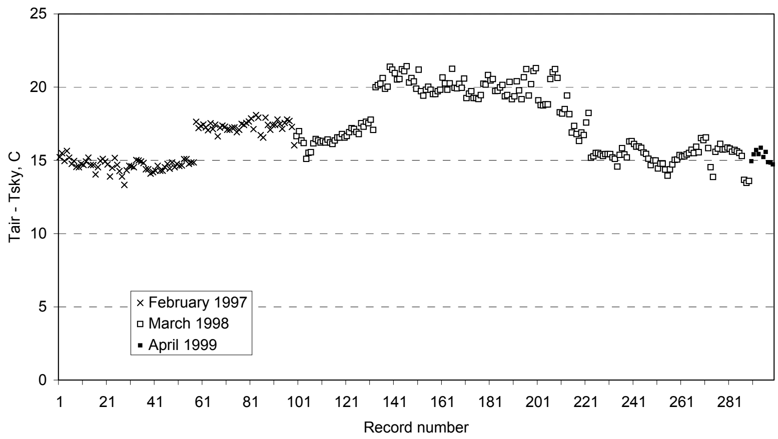


Fig. 2. Air-Sky temperature differences obtained from atmospheric radiation data recorded at Estación Experimental de la Fundación Cajamar

information on the cloud cover when these measurements were made was available, but as the lowest sky temperature occurs when the sky is clear it was assumed that the value of 20°C occurred with a clear sky and that 13°C applied to a sky with some clouds.

When the model is used to establish design heating conditions, the lowest value of 20°C should be used as this will result in the largest heating loads. However, when used to determine values of the heat input over a crop cycle, a lower value closer to the long-term average, should be used.

An estimate of the long-term average value was obtained by comparing model predictions with measured values of greenhouse heat consumption. Over the period November to February inclusive during 1997/8 and 1999/00, Lopez et al. (2006) measured total energy use of a 432 m^2 greenhouse heated to temperatures of 12 and 14°C during the night. The energy requirements predicted by the model for these temperatures, using meteorological data for the same period but for 2004/5, are presented in Fig. 3. The agreement between the measured and calculated values was closest when the sky temperature was 8.5°C below the air temperature, the model then predicted values of 129 and 237 MJ/m^2 compared to the measured values of 120 and 250 MJ/m^2. This agreement indicates that for calculating energy inputs over long periods it is appropriate to use a value for T_{air} - T_{sky} of 8.5°C.

Figure 3 also shows the variation in energy needed to cool the greenhouse in response to changing sky temperature. In this case the cooling requirement increases as the sky temperature increases. To determine the cooling requirements over a long period use of 8.5°C for the air-sky temperature difference is appropriate. However, for design conditions a higher value should be used and a value of 5°C is suggested as this forms a limit of the usually accepted range of 5 to 20°C.

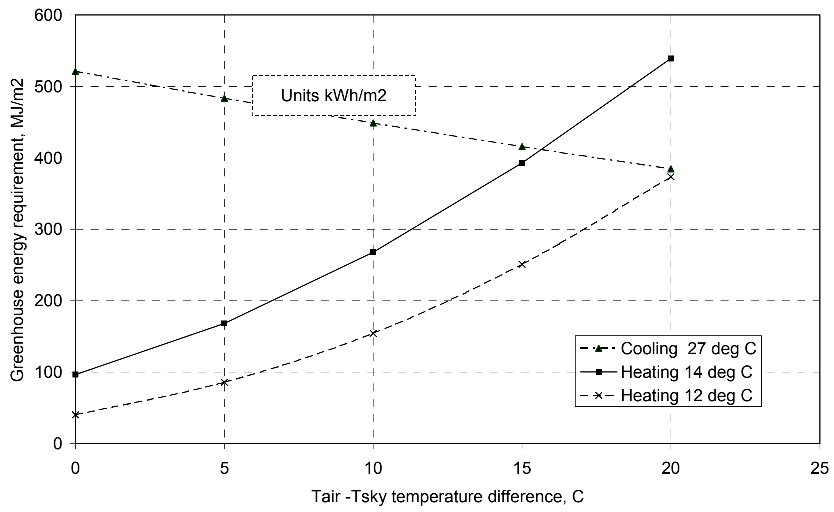


Fig. 3. Model predictions of greenhouse energy requirements over period Nov to Feb 2004/5 as affected by sky temperature

Soil heat flux

The heat transferred from the soil during the day was obtained from unpublished data on soil heat flux (measured by a heat flux plate 1 cm beneath the soil surface) and solar radiation measured in a greenhouse without a crop at Estación Experimental de la Fundación Cajamar. Data for the periods 11-22 March 1998 and 1-2 January 2005 are shown in Fig.4.

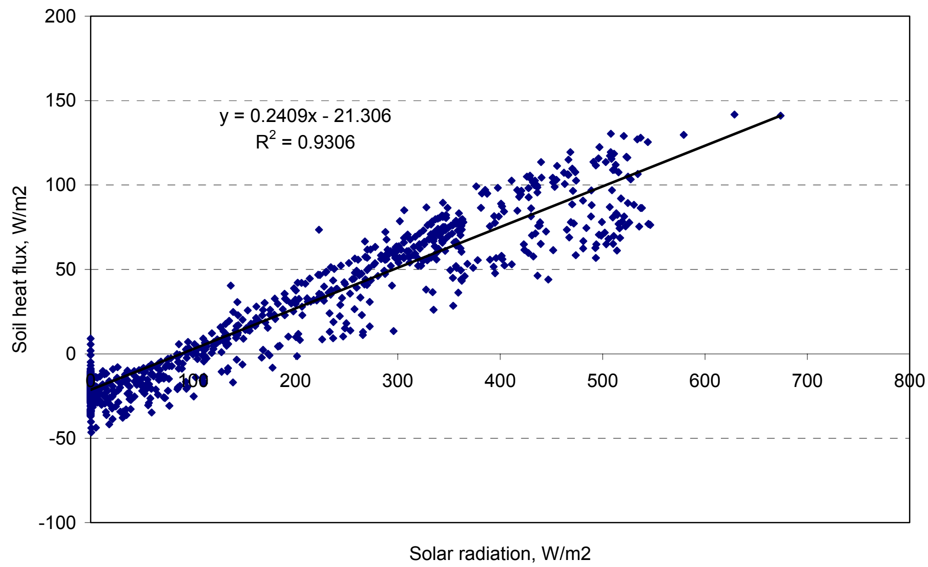


Fig. 4. Soil heat flux related to internal solar radiation in a greenhouse with no crop

Also shown is the linear regression equation fitted to the data that was used in the greenhouse model to give the heat flux from the soil. The equation indicates that when the internal solar radiation is less than 90 W/m^2 the soil acts as a heat source and above this value it becomes a heat sink; at night the heat flux from the soil is 21 W/m^2.

The above information relates to a greenhouse without a crop. When a crop is present, the soil will be shaded so less solar energy will be transferred into the ground. This was addressed using an intuitive multiplying factor equal to 1/(1+LAI) where LAI is the leaf area index of the crop. The factor is 1 when there is no crop and reduces rapidly as the LAI increases; for an LAI of 3 the factor is 0.25.

Ouputs from the model

Information on the inputs to the greenhouse summed over the whole period is displayed in the Summary of Inputs to Greenhouse Window.

The **Performance of combined cooling systems** section gives the maximum and total values over the whole period. If the No. hrs @ max RH are numerous when Max RH=100% the model is being used under conditions were it does not work correctly.

The **Contribution of mechanical cooling** and the **Contribution of ventilation** sections give the contributions made by the respective systems. In the Window shown the maximum mechanical cooling capacity was 200 W/m^2 and whenever the required cooling was greater than this, ventilation was used; mechanical cooling was used for 1222 hours and ventilation for 1579

hours.

Summary of inputs to greenhouse							
Performace of combined cooling systems							
Maximum	Cooling	Sensible	Latent	Ventilation	Temp	RH	No. hrs
values	608.1	168.4	510.3	0.1395	36.9	99.4	@ max RH
	W/m2	W/m2	W/m2	m3/m2.s	C	%	1
Total	682.8	168.5	514.3	168749	Hours		
values	kWh/m2	kWh/m2	kWh/m2	m3/m2	2801		
Contribution of mechanical cooling							
Max power	Tot cooling	Sens cooling	Lat cooling		Hours		
200	118.0	215.1	185.0		1222		
W/m2	kWh/m2	kWh/m2	kWh/m2				
Contribution of ventilation							
Max rate	Tot cooling	Sens cooling	Lat cooling	Total air	Hours		
0.1395	564.8	126.5	438.3	168749	1579		
m3/m2s	kWh/m2	kWh/m2	kWh/m2	m3/m2			
Heating							
Max rate	Total heat				Hours		
75.8	44.0	158.5			2066		
W/m2	kWh/m2	MJ/m2					
Evaporative cooling							
Efficiency	0	Max evap ra	0.0	g/m2.s	Total water	0.0	kg/m2
Leakage (over whole period)							
Max rate	0.0013	m3/m2s		Total air	12022	m3/m2	

Air leakage is included in the heat balance analysis except when the greenhouse is being ventilated. As opening the ventilators creates dominant openings it has been assumed that the passage of air through smaller openings can be neglected compared to the ventilation air flow.

Information on the predicted greenhouse air temperature and relative humidity, the hourly values of heat input, ventilation rate, mechanical cooling requirement, and crop transpiration are presented as graphs which use the record number as the x axis. Thus this axis is effectively the time in hours from the first row of data. The relative humidity is also presented in relation to temperature showing the range of humidity values when the greenhouse is heated and cooled/ventilated and when no control is required.

Heating using energy recovered from cooling

When mechanical cooling is used the energy removed from the greenhouse can be transferred to a heat store and used later for heating. This submodel can be used to investigate the effects of variables e.g. heat store capacity and heat transfer coefficients for transferring heat from the greenhouse air to the store and vice versa. Consequently, inputs that are likely to be varied in a "what if?" study, are placed in the Heat Storage section of the spreadsheet where they are displayed with the outputs.

The parameters required for the heat recovery, storage and reuse process are:

Heat storage parameters		
Heat store capacity	**5.00**	**MJ/m2**
Water heat store volume	0.080	m3/m2
Max store temp	27.0	C
Min store temp	12.0	C
Initial state of store	**0**	**%**
Max htc (heat to store)	**20.0**	**W/m2.K**
Equivalent airflow	59.6	m3 m-2 h-1
Max htc (heat from store)	**20.0**	**W/m2.K**
Equivalent airflow	59.6	m3 m-2 h-1
Mechanical cooler power	200.0	W/m2.K
Physical parameters		
Conversion from W to MJ/h	**3.60E-03**	**(MJ/h)/W**
Specific heat water	**4186.8**	**J/kg K**
Density water	**1000.0**	**kg/m3**

N.B. Only the parameters in **bold typeface** should be changed, those in normal typeface are either set elsewhere or are calculated from other inputs and are displayed for information.

The volume of the water heat store is calculated from the heat store capacity. A value of 0.1 m^3/m^2 is equivalent to a water depth of 10 cm over the whole area of the greenhouse floor.

The default maximum and minimum temperatures of the heat store are the ventilation and heating temperatures respectively.

The **Initial state of store** defines how much energy the heat store contains at the start. If this is 0% the store is empty and if 100% it is full.

1.3 Information on actual energy requirements year round for the three different test sites (for selected reference crops-tomato and/or rose).

Information has been collected to estimate the energy requirements considering two test sites: Almería, representing the Mediterranean area, choosing tomato as the reference crop, and The Netherlands, representing the northern colder European areas, choosing rose as the reference crop. In the case of Almería, unlike in northern Europe climates, heating the crop during the colder months is not strictly necessary, and if heating is applied, good results can be obtained maintaining relatively low temperature (8-10ºC) set points inside the greenhouse (López et al., 2008). In the case of Almería, the energy required for heating for a tomato crop, grown in a three spans multitunnel plastic greenhouse (960 m2) has been measured, in two growing cycles:

• Season 2003/2004: tomato crop cv. Pitenza. Temperature set point for heating: 18ºC. Medium temperature (50 ºC approx.) water heating system with double polyethylene pipes located along the rows, directly over the soil. Fuel used to heat water in the boiler: propane; Energy saving screen used inside the greenhouse. Transplant date: 26/09/2003; End of crop: 7/07/2004. Overall fuel consumption at the end of the cycle: 10.4 kg m^{-2} (482.56 MJ m^{-2})

•Season 2004/2005: tomato crop cv. Eldiez. Temperature set point for heating: 16ºC. Medium temperature (50 ºC approx.) water heating system with double polyethylene pipes located along the rows, directly over the soil. Fuel used to heat water in the boiler: propane; Energy saving screen used inside the greenhouse. Transplant date: 28/09/2004; End of crop: 7/06/2005. Overall fuel consumption at the end of the cycle: 10.2 kg m^{-2} (473.28 MJ m^{-2})

The rest of energy consumption in the greenhouse corresponds to the electricity consumed by the motors that opened and closed the four roof vents, the two side vents and both and energy saving screen and an outside shading screen, and a pump of the circulation of the hot water (season 2003/2004: 0.19 kWh m^{-2}; season 2004/2005: 0.22 kWh m^{-2})

About the energy requirement of a rose crop in Holland, it must be pointed that following data correspond to a typical Venlo type greenhouse with 2 roofs (4.8 m wide each) on one trellis bar with a wide of 9.6 meter.

Artificial lighting is used because without it's not possible to grow a quality crop which is needed for the export. Artificial lighting is operated it in the following way.

Power of bulb: 115 Wm-2 electric input.

	from	until	Initial value	
Max global radiation to switch off lighting	01/09	15/04	200	W m^{-2}
	15/04	01/09	40	W m^{-2}
Max radiation sum above this value lighting is not switched on again during day time	01/09	15/04	1000	J cm^{-2}
	15/04	01/09	10	J cm^{-2}
Minimum time lighting is switched off	15/09	15/04	4	hours
	15/04	01/06	8	hours
	01/06	01/09	10	hours
	01/09	15/09	8	hours

Time switch off time is started 20:00

Electric input of bulb is split up in 30% PAR light, 30% NIR energy and 40% sensible heat.

To avoid too many heat losses, a part of the required energy (electric) is produced using a CHP with a capacity of 75 Welectric/m2. This provides maximum availability of CO2 supply to the greenhouse. The difference between produced and required electricity is sold to the market. In summertime some-times the boiler is used for heating and CO2 production.
There is a heating system (besides the lighting) of 6 x 51 mm pipes per roof (12 / trellis bar)

Electricity production CHP 318 kWh m-2
Used by the artificial lighting 489 kWh m-2
Gas use by boiler 7.6 m3 m-2 (296.4 MJ m-2)
Gas use by CHP 86.1 m3 m-2 (3357.9 MJ m-2)

Besides the measured data, which can only be referred to the specific greenhouse where it has been measured (dimensions of the greenhouse, type of greenhouse glazing, exposition to the wind, presence/absence of energy saving screens, etc.) and the temperature set point/s used, simulations have been performed for the three experimental sites using a model called Hortialmería, varying the temperature set point to extend the information to other management criteria. The model is based on the Horticern greenhouse energy model developed by Jolliet et al. (1991) and includes the treatment of humidity and transpiration used in the Hortitrans model (Jolliet, 1994). It predicts greenhouse air temperature and humidity, ventilation and mechanical cooling requirements, the water consumed by evaporative cooling and it also estimates the heating. Transpiration of a tomato crop can be estimated using either a model developed at Estación Experimental de la Fundación Cajamar or the Hortitrans model. Although the model is steady state, predictions of the heat transfer into and from the soil have been included based on measurements made at Estación Experimental de la Fundación Cajamar. The model calculates hourly values of the greenhouse conditions and control inputs in response to hourly values of external air temperature and relative humidity, solar radiation and wind speed, and a value for the black body sky temperature. The model is implemented in Excel.

Comparison of HortiAlmeria model predictions with values measured at EEFC

Measurements of the propane used to produce tomato crops in Venlo and Multitunnel greenhouses were made for the 2003/4 and 2004/5 crop cycles. For the 2003/4 crop (29 September 2003 until 7 July 2004) the heating temperature was 18oC, and for the subsequent crop (28 September 2004 until 7 June 2005) it was 16oC. Thermal screens (Ludvig Svensson XLS18 Revolux) were used in both greenhouses for both crops. The measured propane consumptions are given in Table 1.

Table 1. Measured propane consumption

	2003/4	**2004/5**
Heating temperature [^oC]	18	16
Venlo [kg/m^2]	9.7	8.9
Multitunnel [kg/m^2]	10.4	10.2

HortiAlmeria was used with weather data recorded at EEFC over the two crop cycles and the relevant heating temperatures to estimate the greenhouse energy requirements for the two cycles.
The results are given in Tables 2 and 3. The calorific value of propane (net or lower value) was taken as 46.4 MJ/kg. The table shows the propane consumption for a range of heater efficiencies (efficiency of combustion plus transport of heat to the greenhouse) and the reduction in heat loss provided by the thermal screen

Table 2. Calculated propane consumption (kg/m2) for 2003/4 tomato crop cycle (18ºC heating temperature)

Reduction of heat loss by thermal screen	Efficiency of heating					
	60%	65%	70%	75%	80%	85%
20%	12.5	11.5	10.7	10.0	9.4	8.8
30%	9.8	9.0	8.4	7.8	7.3	6.9
40%	7.4	6.8	6.3	5.9	5.6	5.2
50%	5.4	4.9	4.6	4.3	4.0	3.8
60%	3.6	3.3	3.1	2.9	2.7	2.6
70%	2.2	2.1	1.9	1.8	1.7	1.6

Table 3. Calculated propane consumption (kg/m2) for 2004/5 tomato crop cycle (16ºC heating temperature)

Reduction of heat loss by thermal screen	Efficiency of heating					
	60%	65%	70%	75%	80%	85%
20%	12.1	11.2	10.4	9.7	9.1	8.6
30%	10.8	10.0	9.3	8.7	8.1	7.6
40%	9.5	8.8	8.2	7.6	7.1	6.7
50%	8.2	7.6	7.1	6.6	6.2	5.8
60%	6.9	6.4	5.9	5.6	5.2	4.9
70%	5.6	5.2	4.8	4.5	4.2	4.0

Comparison of energy requirements for greenhouse heating at different locations.

The timing of crop cycles depends on local conditions which complicates a comparison of greenhouse energy use. Crop cycles frequently start in one calendar year and end in the following year. In this analysis greenhouse energy consumption was calculated using the HortiAlmeria model with weather data for 2007 for three locations (Spain, Netherlands and Hungary). The estimates were made for the complete year of 365 days.

Table 4. Energy (MJ/m2) required to provide a minimum greenhouse temperature for each day during 2007

	12°C	14°C	16°C	18°C	20°C
Spain	120	210	340	500	680
Netherlands	660	1110	1130	1400	1690
Hungary					

1.4 Semi-closed greenhouse: observations on design and estimates of performance of a water thermal storage system

The analysis was made using the HortiAlmeria greenhouse model for the following conditions:

i. Almeria weather data from 1 August 2005 to 31 May 2005 (weeks 1 to 44).
ii. Greenhouse with 6, 8 m spans 20 m long, 4 m to gutter, roof angle 30°.
iii. Tomato crop with LAI=3, assumed to be in a steady state condition.
iv. Time step of model 1 hour.
v. Perfect heat transfer between greenhouse and energy store i.e. no restrictions on heat transfer coefficients and no losses from the energy store.
vi. Greenhouse CO_2 concentration 1000 vpm during the day except when ventilation is required when the concentration is 380 vpm.
vii. Heating temperature 12°C, ventilation temperature 27°C.
viii. Greenhouse light transmission 75%.
ix. Shade screen providing 30% shade (when used).
x. Prices: propane 0.8 €/kg, electricity 0.2 €/kWh, CO_2 0.18 €/kg, tomatoes 0.6 €/kg, tomato crop production 15 kg/m^2.

1.4.1 Winter use

1.4.1.1 Single energy store no heat pump

This uses a single energy store to provide cool water for cooling the greenhouse. During the day the water temperature rises and the cooling rate reduces. At night the warm water is used to heat the greenhouse which reduces the water temperature so the store can provide cooling during the following day. The cooling system in the greenhouse acts as both cooler and heater.

a) Energy store

The influence of energy store capacity on the energy provided for heating is shown in Fig. 5. The optimum size of store is 3 to 4 MJ/m^2 which provides 83 to 87% of the energy required for heating a long tomato crop cycle during 2004/05.

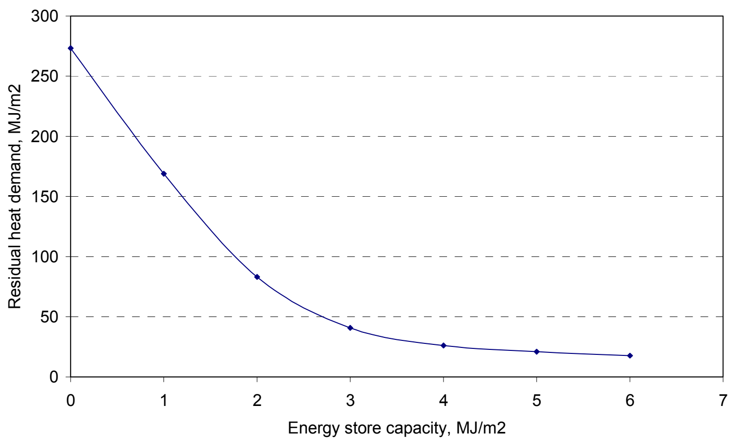


Fig 5. Influence of energy store capacity on heat demand of experimental greenhouse

The greenhouse covers a ground area of 960 m^2, so the capacity of an energy store for the whole house is 3.5 x 960 = 3360 MJ. Using water as the heat storage medium and assuming the temperature difference between the full and empty store is 15^{o}C, requires a store with a volume of 46 m^3. For a cylindrical store the dimensions could be:

Height	2 m
Diameter	5.8 m

Initially only one compartment of the greenhouse will be heated and cooled. With a tank of this diameter the depth of water required for one compartment will be 0.33 m.

b) Insulation of energy store

The heat transfer from the surface of this size of tank when full would be approximately 100 W/K assuming the tank is not exposed to the sun. There would be a heat gain when the store temperature was lower than ambient air and vice versa. Simulations showed that insulating the tank reduced the heat requirement from 108.5 to 99.8 MJ/m^2 (reduction of 6%) but also reduced the profit from CO_2 enrichment from 0.54 to 0.52 €/m^2 (reduction of 3%).

1.4.1.2 Heat pump with hot and cold energy stores

This system uses a cold store to absorb energy from greenhouse cooling and a hot store to provide energy for heating. Energy is transferred from the cold to hot stores by a heat pump which operates continuously whenever the cold store is not empty and the hot store is not full.

a) Heat pump

The power (Qp) used to drive a heat pump is given by:

Qp = Qd/COP (1)

where Qd is the energy delivered to the hot store and COP is the coefficient of performance of the heat pump. (2)

In practice the COP can be expressed as:

$$COP = \eta \; 0.5 (Th + Tc) / (Th + \Delta Th – (Tc - \Delta Tc)) \quad (3)$$

where η is an efficiency factor, Th and Tc the absolute temperatures of the hot and cold stores, and ΔTh and ΔTc the temperatures differences associated with the heat pump condenser and evaporator heat exchangers. The COP is highest if the denominator in this equation is made as small as possible. The operating cost of the heat pump is directly related to its power consumption (Qp).

b) Heat Store Capacity

The effect of energy store capacity on greenhouse energy consumption, which includes energy to drive the heat pump and to meet shortfalls in the energy available from the heat store, is shown in Fig. 6. The two curves are for different sizes of heat pump which transfer heat at different rates between the cold and hot stores. The energy used to drive the heat pump was obtained using Eq (1) with COP values of 4 and 8. The latter is higher than is usual for heat pumps used in space heating, however, it was chosen because of the low temperature differences possible with the Heat exchange units. Equation (1) shows that the product of COP x Qp is the energy delivered to the hot store. For the conditions of this analysis the latter is a constant (equal to 32 W/m^2) which is defined by the conditions. Thus if the Cop is 6, the power require for these conditions will be 32/6 = 5.3 W/m^2.

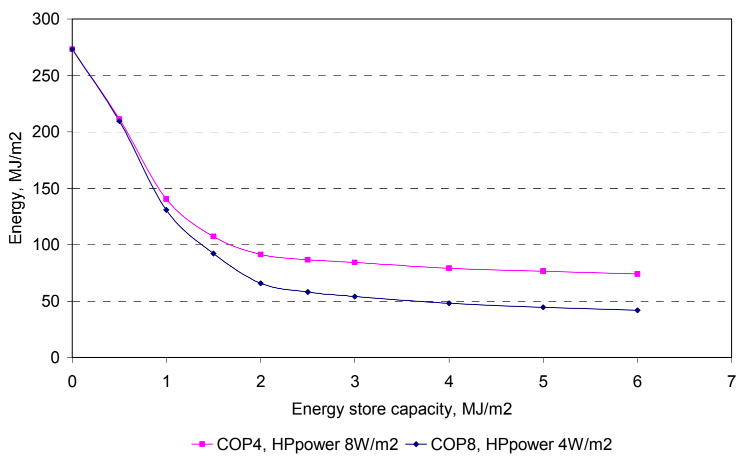


Fig. 6. Influence of energy store capacity on heat demand of experimental greenhouse

The cost of energy with the heat pump system is the cost of the electricity used to drive the heat pump plus the cost of gas used to provide heating which cannot be met by the hot store. Figure 7 shows the energy costs for:

(i) reference greenhouse – with a conventional propane fuelled heater
(ii) greenhouse with single energy store of 3.5 MJ/m^2
(iii) greenhouse with the two different heat pumps.

The air leakage rates were calculated as 0.5 + 0.25w air changes per hour. The energy costs do not include the operating cost of the fans and pumps required for heat collection and reuse in (ii) and (iii). These costs are likely to be similar for both options.

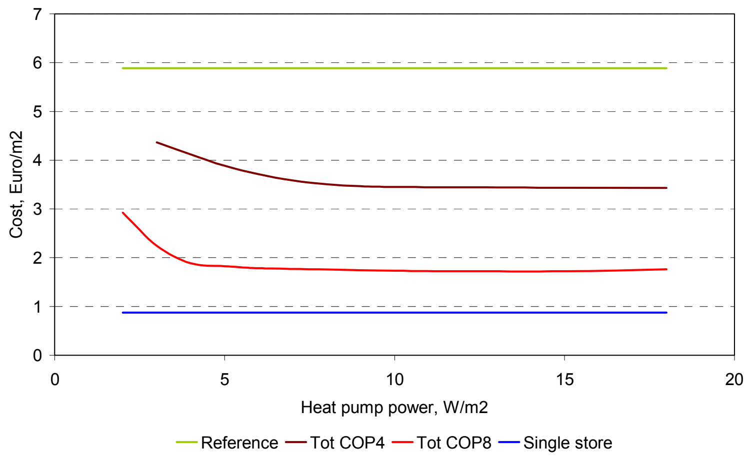


Fig.7. Cost of energy for heating

1.4.2 CO_2 enrichment

When the cooling system provides sufficient cooling and ventilation is not required the greenhouse is enriched with CO_2 to 1000 vpm. When the cooling requirement exceeds the capacity of the cooler, ventilation then provides all the cooling and the CO_2 level is equal to the external concentration of 380 vpm. The influence of the energy store capacity (single energy store option) on the total amount of net photosynthesis during the whole period is shown in Fig. 8. If it is assumed that tomato yield is proportional to total net photosynthesis this suggests the potential yield increase is approximately 8%.

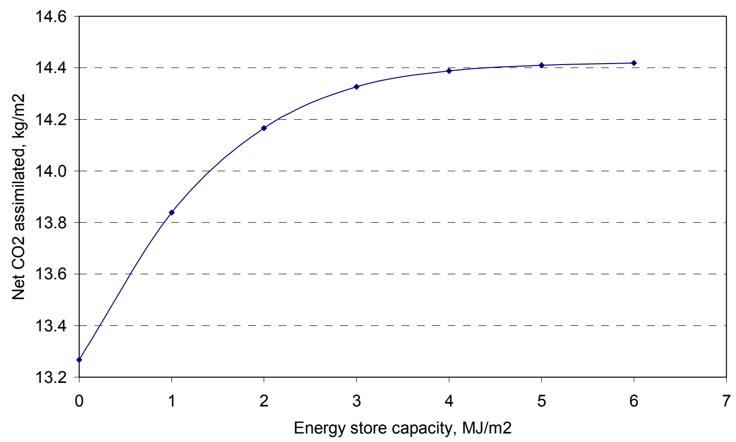


Fig. 8. Increase in net CO_2 assimilated with increasing energy store capacity

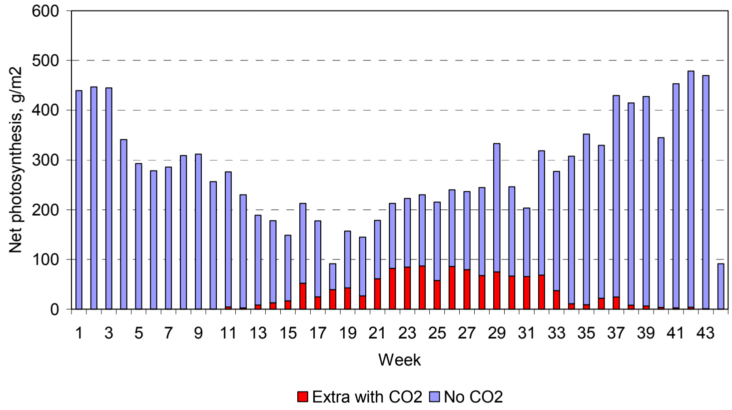


Fig. 9. Increased photosynthesis permitted by partial closure of the greenhouse

Figure 9 shows that in this crop cycle the benefits of CO_2 enrichment would have been obtained from week 13 (25 October 2005) until week 39 (1 May 2006).

The cost of the CO_2, the increase in crop value given by the enrichment and the resulting financial margin are shown in Fig. 10. The following values were used in the analysis, cost of CO_2, 0.18 €/kg; tomato crop yield, 15 kg/m^2 and value of tomatoes, 0.60 €/kg. Figure 6 presents results for greenhouse light transmission of 65% and 75%. It shows clearly that the economics of CO_2 enrichment are influenced very strongly by the greenhouse air leakage rate and also by its transmission of solar radiation. The air exchange rates shown result from leakage rates of respectively, zero, 0.125+0.0625w, 0.25+0.125w, 0.375+0.1875w and 0.5+0.25w where w = wind speed. For leakage rates higher than 0.25+0.125w air changes per hour CO_2 enrichment appears not to be economic with current CO_2 and tomato prices. This diagram is intended only to show the relative changes between the enrichment made possible by closing the greenhouse during the periods when energy can be collected and removed from the greenhouse thus eliminating ventilation. The reference condition is a greenhouse without heat collection for which enrichment is only possible for daylight hours when ventilation is not required. In this respect there is little difference between greenhouses with 65% (0.65) and 75% (0.75) light transmission. When heat recovery was used the biggest profit is obtained from the 65% transmission house, which is a consequence of the larger cooling requirement of the house with the higher light transmission. As the heat recovered is fixed by the greenhouse heating demand the enrichment time is reduced in the greenhouse with the higher light transmission.

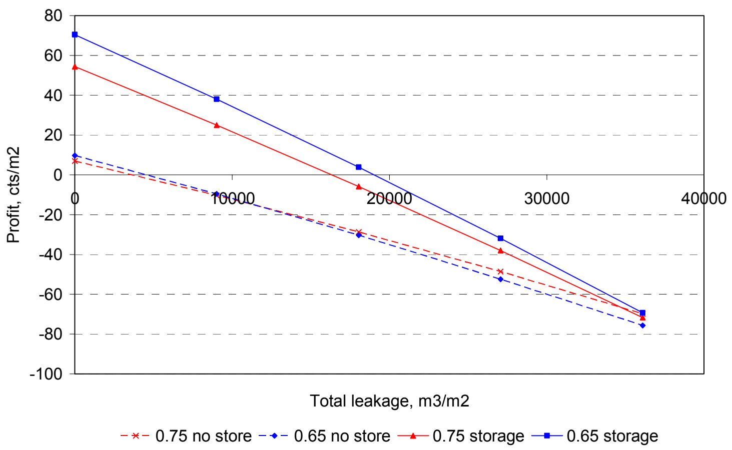


Fig. 10. Influence of greenhouse light transmission and air tightness on profit from CO_2 enrichment

The times of day when the cooling, heating and CO_2 enrichment take place are shown in Fig. 11. The bars represent the total operating times over the 44 week period. Collection of energy from the greenhouse is biased towards the morning as the energy store becomes full in the afternoon. Heating occurs predominantly at night and supplementary heating is required in the early morning when the energy store becomes empty. CO_2 enrichment can occur during the whole day but is biased towards the early mornings and late afternoons.

The response of the greenhouse to CO_2 enrichment when heat pumps are used is similar to that with the single energy store. This is because the heat pump is used only to transfer energy between the cold and hot stores and the store capacities are based only on the greenhouse heat requirement.

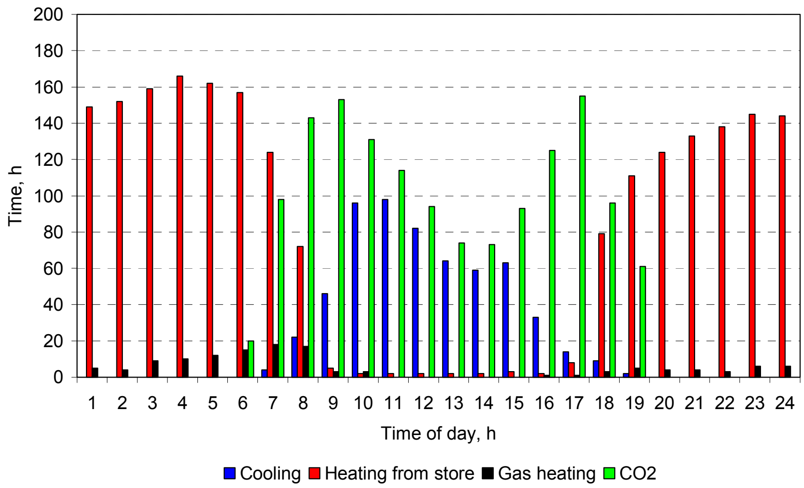


Fig.11. System operating times over the 24 hour period

1.4.3 Economic assessment

This analysis was made using the cost of energy for heating, the cost of electricity to drive the heat pump, the cost of CO_2 and the price and yield of tomatoes over a long crop cycle. The greenhouse was assumed to have a leakage rate of 0.2+0.02w air changes per hour; a value measured in a film plastic covered multispan greenhouse at Las Palmerillas. The light transmission was assumed to be 75%. The single energy store had a capacity 3.5 of MJ/m^2 and the hot and cold stores used with the two heat pump systems were each of 2 MJ/m^2. The heat pump with a COP of 4 had an electricity consumption of 8 W/m^2 and the one with the COP of 8 consumed 4 W/m^2. The energy costs and net income from CO_2 enrichment are given in Table 1.

Table 4. Energy costs and income from CO_2 enrichment

	Gas	Electricity	Profit from CO_2	Net cost
	€/m^2	€/m^2	€/m^2	€/m^2
Reference house	5.513	0	-0.072	5.584
Single energy store	0.568	1.134	0.305	1.397
Heat pump COP 4	0.330	3.336	0.232	3.435
Heat pump COP 8	0.454	1.629	0.268	1.815

Although this analysis has covered the whole crop cycle, the heat recovery system only operated when there was a need for heating and energy was removed from the energy store, at all other times the store was full so the cooling system could not operate. Therefore the results in Table 1 result from the winter period when the greenhouse required heating.

These results show that the most promising option is to use a single energy store with a capacity of 3.5 MJ/m^2. The heat pump with a COP of 8 gives an energy cost which is close to the Single energy store option, but it would have a higher investment cost.

It should be noted that the cost of operating fans and pumps used in the collection and reuse of energy were not included. No account has been taken of investment costs.

1.4.4 Heat exchange cooler/heater units

1.4.4.1 Number of units required

The information obtained on the performance of the heat exchange units were the heat transfer rates (W/K) for cooling and heating at the maximum (400 W fan power) and 75% of the maximum (150 W fan power) air flow rates. In operation the fan speed and the flow rate of water from the energy stores are both varied to match the output to the greenhouse cooling and heating requirements.

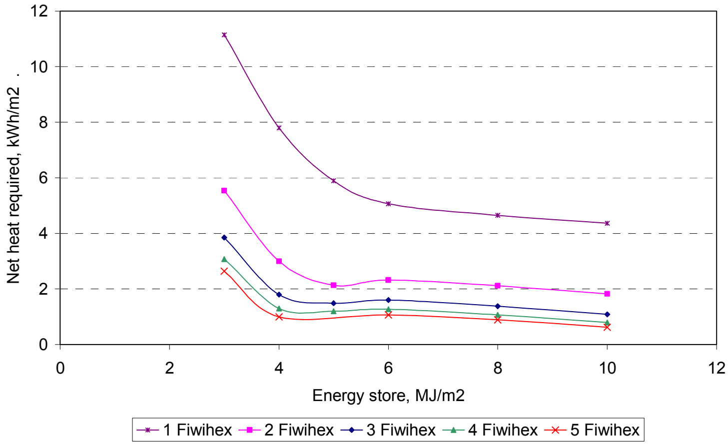


Fig.12. Number of heat exchange units required per 160 m^2 in the experimental greenhouse requirements. Because of this limited information, the analysis was restricted to determining the number of units required in the greenhouse.

Figure 12 shows the additional heating energy required by the greenhouse is influenced by the number of heat exchange units per span (160 m^2) of the experimental greenhouse. Most of the potential benefit is obtained using three units. The figure also indicates that the optimum size of heat store may be higher than the value of 3.5 MJ/m^2 deduced from Fig. 5.

1.4.4.2 Number of units required

Based on the flow of isothermal air jets the distance the flow of 4000 m^3/hr of air from the 1.06 x 0.102 m outlet of a heat exchange unit (speed 10.3 m/s) will travel before the centre line speed falls to 0.5 m/s is approximately 50 m. Therefore the air emerging from a Heat exchange unit should travel the length of the greenhouse unless there is interference with air from another unit. However, fan speed is one of the control variables and is reduced to lower fan power when less cooling/heating is required, therefore the distance travelled by the air will be reduced. With an air flow of 40% of the maximum, the air jets would just reach the far end of the greenhouse. The air jet leaving the outlet of the heat exchange unit will diverge at an angle of approximately 22^o in both the horizontal and vertical planes.

An important aspect of forced air movement in greenhouses is the air speed in the vicinity of the crop. Research has shown that the productivity of plants is reduced if they are subjected to air speeds higher than 1 m/s. In practice this means that while some movement of plant leaves is acceptable they should not be moved strongly by the air flow.

The following section presents information on the possible air flows created by different positions and numbers of heat exchange units in the horizontal plane containing their air outlets. To reduce the possibility of high air speeds in the crop zone the units should be placed as high as possible. The Heat exchange manufacturer considered that a vertical distance of 1.5 m between the top of the crop and the air outlet was suitable.

a) 2 Heat exchange units

The units should be place in diagonally opposite corners of the compartment. They should be arranged so the plane of the air outlet is vertical and oriented so that the air flow is directed towards the centre of the opposite end wall. This will require the unit to be positioned so the centre line of the outlets is inclined at 11^{o} with the 20 m side wall.

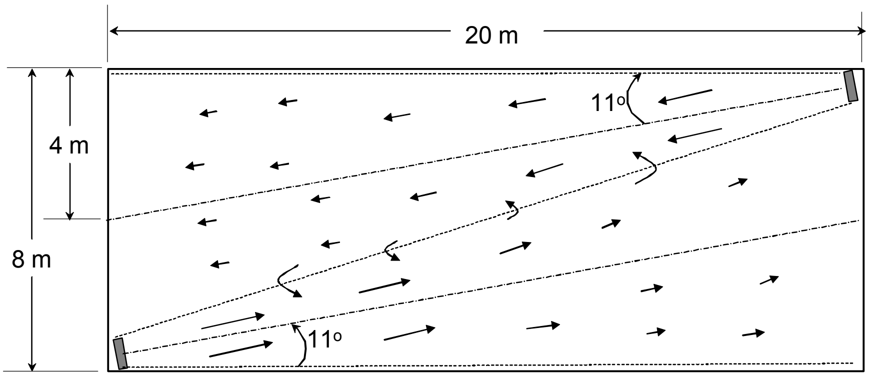


Fig. 13 Possible air flows in plane of outlets when two units used

With this arrangement the air flows from the two units should not interfere strongly with each other and the whole cross section of the greenhouse should experience positive air flow. However, at low fan speeds there may not be very positive air flow at the ends of the greenhouse.

b) 3 heat exchange units

Positioning three heat exchange units is not straightforward and four possibilities have been considered:

i. <u>Two units at one end of the greenhouse 2 m from each side wall and one unit at the opposite end under the ridge. Outlet faces parallel to the end walls.</u>

The interference of the air jets from units at opposite ends of the greenhouse is likely to result in regions with poorly defined air flow in the corners adjacent to the single unit (Fig. 14). In addition there could be smaller areas without positive air flow on both sides of the units at the other end of the greenhouse.

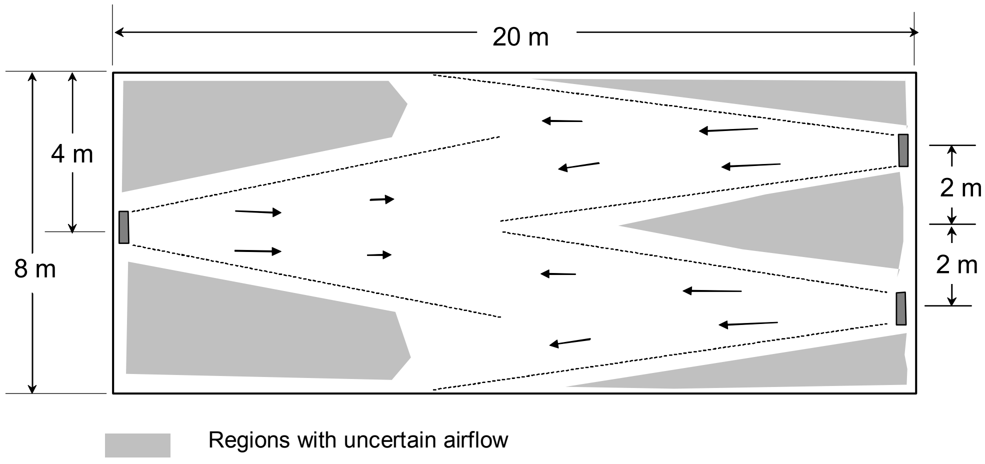


Fig. 14 Three heat exchange units option (i) – possible air flows in plane of outlets

ii. Two units at one end of the greenhouse 2 m from each side wall and one unit at the opposite end under the ridge. All units 5 m from an end wall. Outlet faces parallel to the end walls.

The possible air flow pattern is shown in Fig. 15. Compared to the previous option the number of regions with uncertain airflow is reduced but still large areas still exist.

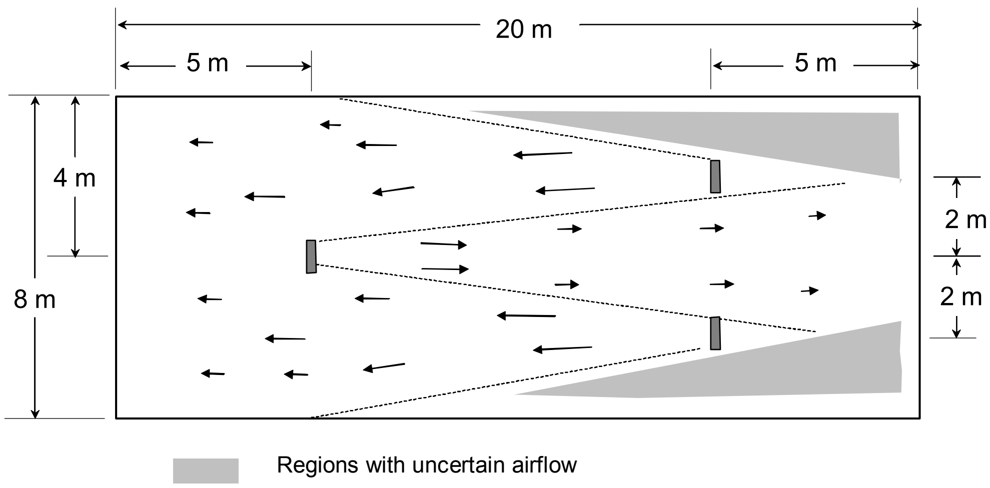


Fig. 15 Three heat exchange units option (ii) – possible air flows in plane of outlets

iii. Two units at one end of the greenhouse 2 m from each side wall and one unit under the ridge 5 m from the opposite end wall. The centre line of the outlet of the single unit is parallel to the greenhouse ridge. The centre lines of outlets of the two units are inclined at 5-6^o away from greenhouse ridge direction to reduce the interaction between the air flows.

The regions with uncertain air flow are small (Fig. 16). However at low fan speeds the climate control in the space behind the single unit at the left side of the greenhouse may be less well controlled than in the rest of the house.

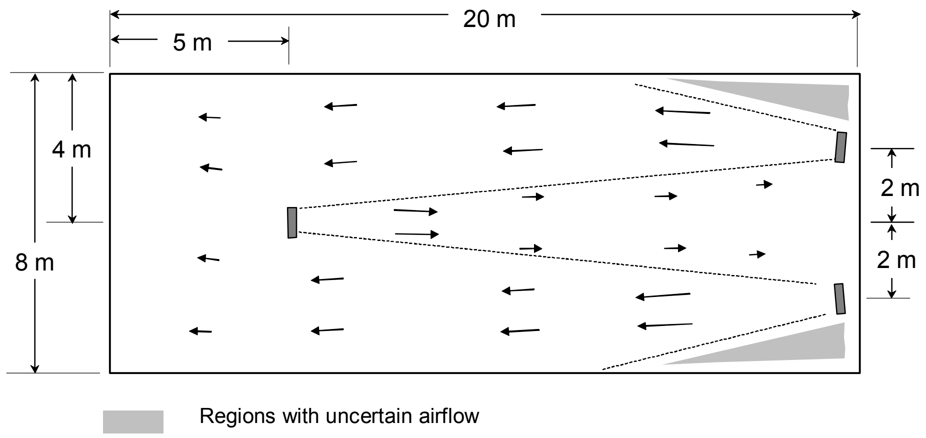


Fig. 16 Three Heat exchange units option (iii) – possible air flows in plane of outlets

iv. Two units at one end of the greenhouse 2 m from each side wall and one unit at the opposite end under the ridge (as option i). However, the centre lines of outlets of the two units are inclined at 5-6^{o} away from greenhouse ridge direction to reduce the interaction between the air flows (as option iii).

This arrangement (Fig. 17) should reduce interference between the air jets travelling in opposite directions.

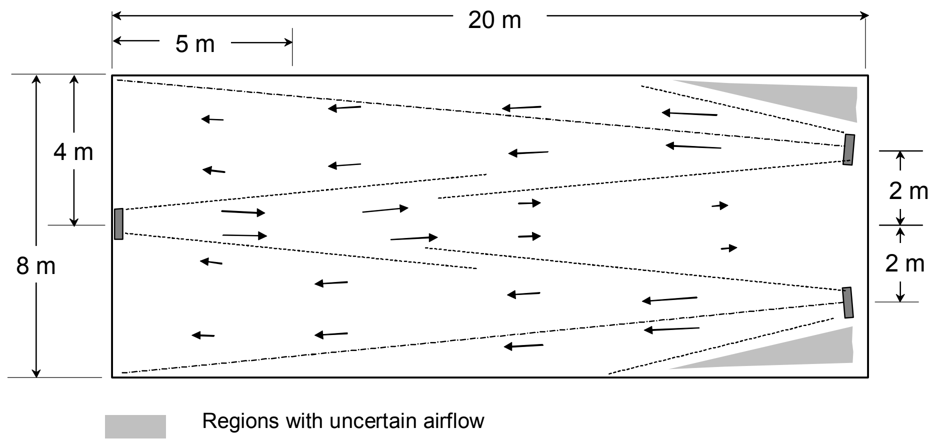


Fig. 17 Three Heat exchange units option (iv) – possible air flows in plane of outlets

It is suggested that a practical test of the Heat exchange units should be carried out in the greenhouse to determine the orientation that gives effective air circulation. If this is not possible option (iv) seems to be the most suitable and it is suggested that the units should be mounted so the direction of discharge can be adjusted by a few degrees in the horizontal and vertical directions. Vertical adjustment will enable the air to be directed upwards away from the crop should a problem with high air speeds be experienced when the tomato crop is fully grown.

1.4.5 Summer operation

Energy recovered from the greenhouse during the day which is not required at night for heating must be dissipated so the energy store has capacity to accept more energy the next day. In summer no heating is required and so all the energy collected has to be removed from the energy store.

1.4.5.1 Cold and hot energy stores with heat pump

The cold store provides water to cool the greenhouse and the heat pump transfers the energy to the hot store in order to maintain the cold store temperature. The heat transferred to the hot store has to be transferred to the outside air during the night.

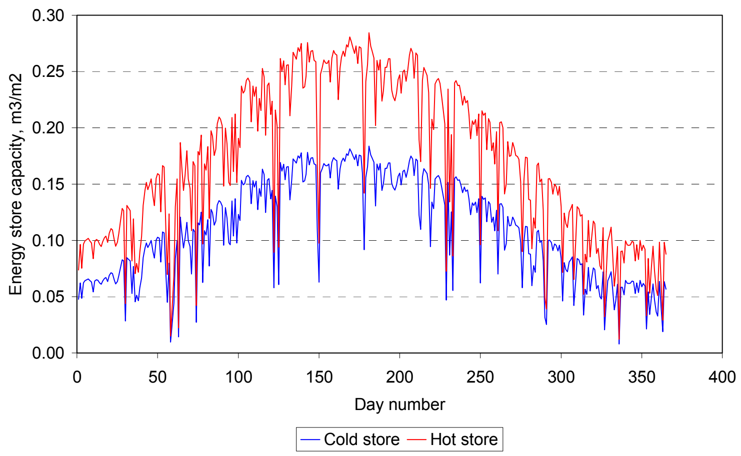


Fig. 18. Sizes of hot and cold water stores required for greenhouse cooling

Figure 18 shows how the store capacity depends on the daily integral of the solar radiation entering the greenhouse. The hot store has a higher capacity than the cold one because it has also to accommodate the energy used to drive the heat pump. The hot store capacity was based on a heat pump with a COP for heating of 4. Figure 18 can be used to determine the required store capacity. The day with the highest solar radiation during the period when the greenhouse is to be cooled is used to identify the capacities of the hot and cold stores. The downward spikes in the curves (days with clouds) should be ignored and values taken from the maximum values which relate to radiation from clear skies.

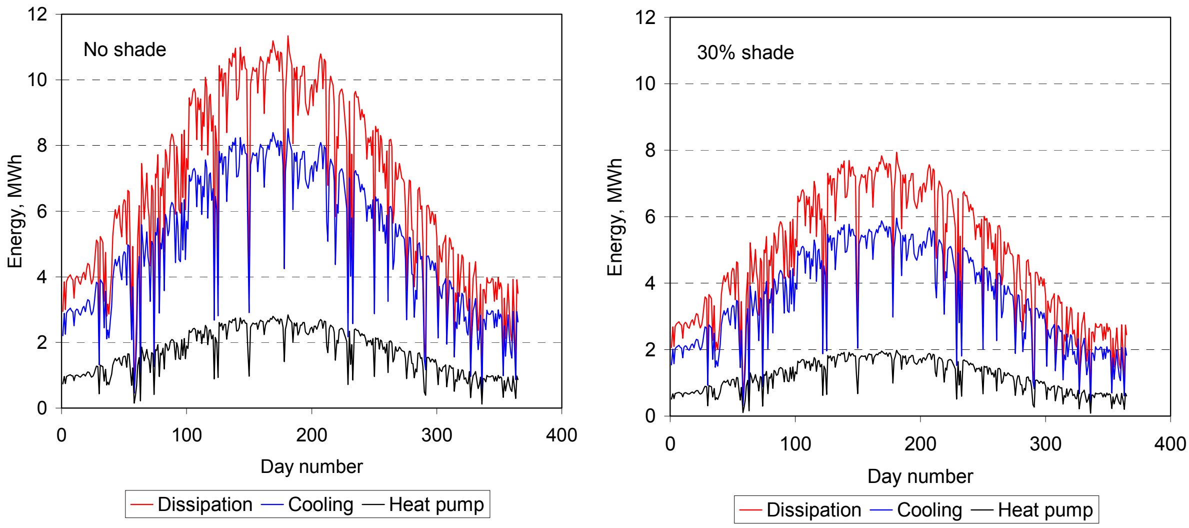
1.4.6 Experimental greenhouse at Estación Experimental

The results presented in this section refer to a greenhouse covering an area of 1000 m^2 which is approximately the size of the greenhouse to be built at the Estacion Experimental.

1.4.6.1 Energy stores

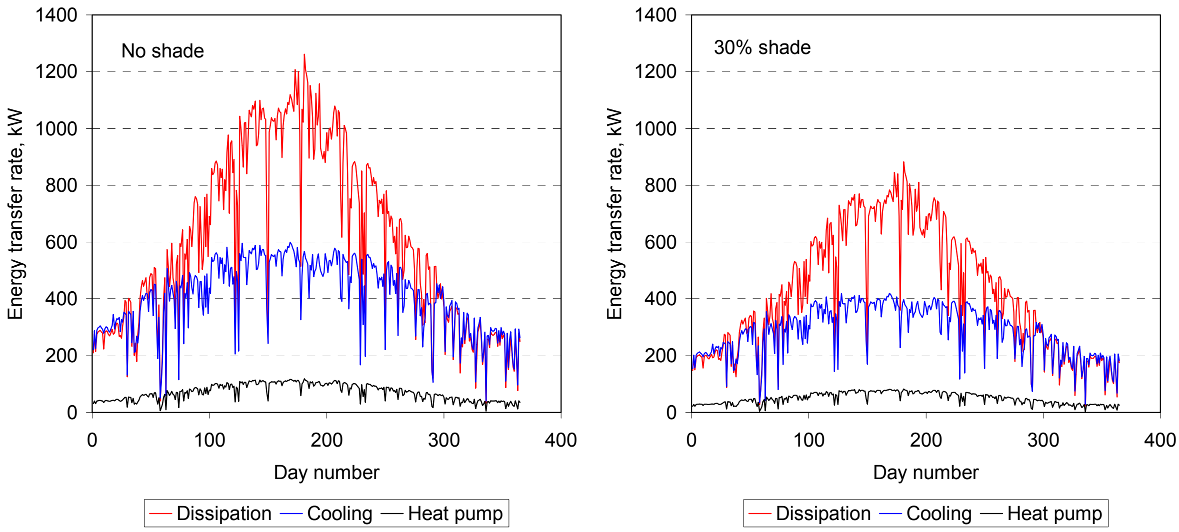
Daily values of the energy recovered by cooling the greenhouse, consumed by the heat pump and transferred to the outside air without and with 30% shading are shown in Fig. 19 and the heat transfer rates in Fig. 20.

The energy stores have to accept energy from the greenhouse cooler which is a maximum at mid-day while the heat removal rate by the heat pump is constant over 24 hours. The energy store capacities for operation in mid summer are given in Table 5.



(a) (b)

Fig. 19. Energy collected from the greenhouse, consumed by the heat pump (COP 4) and dissipated to the outside air from a 1000 m^2 greenhouse (a) with no shading and (b) with 30% shade.



(a) (b)

Fig. 20. Average rates of energy collection from the greenhouse, consumed by the heat pump (COP 4) and dissipated to the outside air from a 1000 m^2 greenhouse (a) with no shading and (b) with 30% shade

Table 5. Capacity of energy stores for 1000 m^2 greenhouse in mid summer

	No shade		30% shade	
	MWh	m^3	MWh	m^3
Cold store	5.2	300	4.6	265
Hot store	6.4	365	5.2	300

The heat transfer rates for cooling and dissipation were obtained using the durations of the day and night; the heat pump operated continuously provided the stores permitted energy transfer.

These stores are capable of accepting all cooling energy produced during a summer day provided this energy plus the energy used to drive the heat pump can be dissipated during the following night.

1.4.6.2 Heat pump

n summer the heat pump has to transfer all the energy collected from greenhouse cooling from the cold to the hot stores so the heat pump capacity is determined by the total daily solar radiation received in the greenhouse. By operating the heat pump continuously its capacity is minimised. Table 3 shows the amount of energy that has to be transferred from the cold to the hot stores during a day in mid summer for a greenhouse of 1000 m^2 and the rate of heat delivery by the heat pump (COP = 4) to the hot store when operated continuously.

Table 6. Energy transferred by heat pump in 1000 m^2 greenhouse in summer

	No shade	30% shade
Maximum energy to be upgraded, MWh/day	8.0	5.5
Rate of heat transfer by heat pump, kW	110	75

From this Table the capacity of the heat pump required for a 1000 m^2 greenhouse is shown to be 110 kW if there is no shade or 75 kW when there is 30% shade.

1.4.6.3 Dissipating energy from the hot store using a cooling tower

A cooling tower transfers energy from water to ambient air which is moved through the tower by a fan. Some cooling towers can be operated in both dry and wet modes. In the latter, water is sprayed over the cooling coils to increase the rate of heat transfer which increases the cooling rate but some water is evaporated. The tower normally operates in the dry mode and changes to the wet mode when the performance becomes low; which makes for efficient use of water. The additional cooling obtained in the wet mode is related to the wet bulb temperature of the ambient air. Figure 21 shows the dry and wet bulb temperatures of the ambient air for Almeria and indicates that using a wet cooling tower provides an additional 4 to 5^o C for cooling.

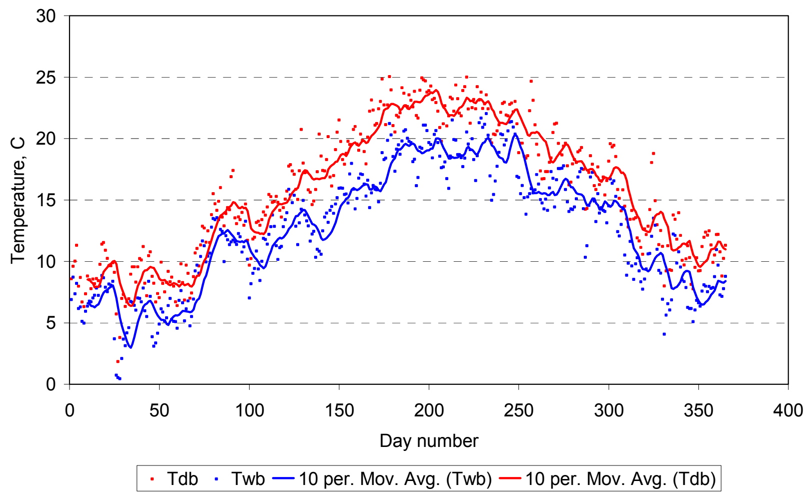


Fig. 21. Averages of dry and wet bulb air temperatures at night (Almeria weather data 2005)

Estimates were made of the energy which needs to be rejected from a greenhouse with an area of 1000 m^2 with no shading and with shading of 30% using Almeria weather data for 2005. The solar radiation received inside the greenhouse (light transmission 75% with no shading and shading of 30%) during the day was used to determine the total energy to be rejected (Fig. 21) and the average energy rejection rate (Fig. 22) during the night. The COP of the heat pump was 4. The store capacities for specific time periods can be obtained from Fig. 13.

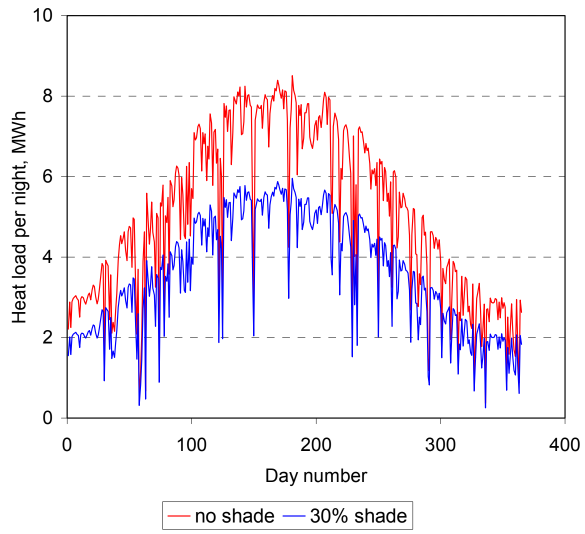


Fig. 21. Energy to be dissipated at night for a 1000 m^2 greenhouse with and without a 30% shade screen (Almeria weather data 2005)

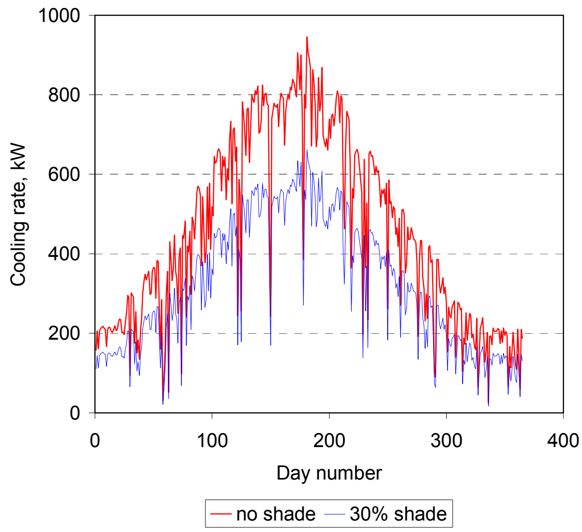


Fig. 22. Night cooling rates for 1000 m^2 greenhouse with and without a 30% shade screen (Almeria weather data 2005)

1.4.7. Conclusions

1. Cooling and heating the 160 m^2 experimental compartment in winter

    1.1. It is estimated that 3 Heat exchange heat exchangers are required in the 160 m^2 compartment when a single energy store is used.

    1.2. Placing one Heat exchange unit under the ridge at one end of the greenhouse with the air directed along the greenhouse axis, with the other two units at the opposite end of the greenhouse 2 m from the side walls and angled so that the air is discharged at an angle of 5-6^o from the greenhouse axis appear to be suitable locations for the Heat exchange units.

    1.3. As there is limited space in the experimental compartment above the crop and between adjacent Heat exchange units it suggested that the units should be mounted so their outlets can be adjusted by 5^o in the vertical and horizontal planes to enable adjustments to be made based on the air flows achieved in practice.

2. Cooling and heating a 1000 m^2 greenhouse in winter

    2.1. Using a single heat store to provide both cooling and heating appears to be more economic than using two heat stores and a heap pump.

    2.2. The optimum capacity of the single energy store is 3500 MJ which is provided by 56 m^3 of water (tank 2 m high and 6.0 m diameter).

    2.3. With this size of energy store, cooling the greenhouse during the heating season reduces the duration of ventilation from 1480 to 930 hours, a reduction of 550 hours.

    2.4. The estimated increase in tomato crop value resulting from raising the CO_2 concentration to 1000 vpm when the greenhouse requires no ventilation is €300.

    2.5. The economics of CO_2 enrichment depend strongly on the air leakage of the greenhouse.

    2.6. The reduction in heating cost is estimated to be €3800, but the cost of electricity used in the collection and reuse of energy has not been included.

3. Cooling a 1000 m^2 greenhouse in summer

    3.1. The capacity of the cold energy store is 5.2 MWh (300 m^3 water) if the greenhouse has no shading and 4.6 MWh (265 m^3 water) with 30% shade.

    3.2. The capacity of the hot energy store is 6.4 MWh (365 m^3 water) with no shade and 5.2 MWh (300 m^3 water) with 30% shade.

    3.3. The heat pump output is 110 kW with no shading and 75 kW with 30% shade.

    3.4. The heat transfer rate of the cooling tower is 1100 kW with no shading and 750 kW with 30% shade.

1.5 Performance of a Day/Night Water Heat Storage System for Heating and Cooling of Semi-Closed Greenhouses in Mild Winter Climate Areas

In the Experimental Station of the Cajamar Foundation, and based on the predictions and estimations obtained from the HortiAlmería model, a novel system for cooling/heating semi-closed greenhouses with high efficiency fine wire heat exchangers, based on short term heat storage in a water tank was designed and implemented in a small greenhouse compartment. The main part of the system (control room, storage tank, cooling tower, etc.) was designed to condition 960 m2 in the future. But for preliminary tests, only one compartment of 160 m^2 has been conditioned the first year with in total three heat exchange (Fiwihex) units and a total water circulation capacity of 5.25 m3 h^{-1}

The water in the storage silo is always in "open" contact with air; therefore the material used for piping and system components is stainless steel, PVC or other non corrosive materials. The main parts of the system have been installed in a sea container and assembled previously to the final location of the equipment.

The main goal is to keep the greenhouse as closed as possible, which is necessary to keep the CO_2 concentration at high levels during the daytime (800-1000 ppm). To avoid humidity problems the water evaporation is condensed in the heat exchange units. Therefore the greenhouse has been provided with a condensate collecting system. The collected condensate is very clean and is being re-used for watering plants. The following scheme is an overall diagram of the system including the open cooling tower, the water silo, the mixing group and control system and the heat exchangers (Fig. 23).

Three fine wire exchangers, which basically are a combination of a heat exchanger and a cross flow ventilator for forced air movement, mounted inside a galvanised steel frame. They were installed 1 metre above the top of a well developed tomato crop, with condense collector as shown on Figure 24. With these heat exchangers, large quantities of heat can be transferred with only a small temperature difference as each heat exchanger is equipped with a large surface area for contact between air and water. The units have a maximum cooling capacity under practical circumstances of 300-400 W/m2 (more technical details in http://www.hsh-fiwihex.com/)

A one time used sea container with the following dimensions was used as control room (Figure 24). For the storage of both cold and warm water a silo (Figure 24) was mounted in situ with the following basic dimensions: (60 m3; Diamete 4.55 m; Height 3.88 m). The bottom ring of the silo is coated with a durable Duplex coating; this was done in the factory under specific controlled conditions. After placement, the silo was insulated with curved Polystyrene plating, type EPS 100 RE, thickness 50 mm; these plates were placed between the silo foil and the galvanised steel plating. Also the floor was insulated in this way. On top of the water surface an insulating green PVC foil was installed providing a certain slope for rainfall water evacuation.

The silo is furthermore equipped with a wall cover and an Aquatex (PVC) silo sleeve.To maintain and enhance thermal stratification in the thermal store, water has to be added and removed a way that minimises disturbances. This requires two diffusers, one to withdraw cold water from the bottom of the store and the other to introduce warm water at the top. The diffusers should permit a uniform flow across the entire horizontal plan area of the store. The diffuser designed, constructed and implemented in the silo consists of an octagonal "ring" made from sections of perforated plastic pipe joined by 45º bends, see Fig. 32. These sections have regularly spaced openings along their lengths through which the water enters or leaves. The water is supplied by a pipe which divides into four pipes, each connected to one quarter of the octagonal diffuser. This means that each quarter of the octagonal diffuser is supplied with one quarter of the total flow and also ensures the flow into each end of a diffuser section is only one eight of the total. Each side of the octagonal diffuser contains the same number of openings, so their lengths differ to accommodate the T junctions. The upper and lower diffusers are identical, but when installed in the thermal store the upper diffuser is positioned horizontally with the openings facing upwards, while those in the lower diffuser face downwards.

Diffusers of this type have been described by Zurigat et al (1988), Fiorino (1991) and Ndlouv and Roy-Aitkins (2004).

The silo used as the thermal store has a diameter of 4550 mm and is 3880 mm high. With the "diameter" of the octagon = Dt/ √2, where Dt is the tank diameter, the horizontal areas of the tank inside and outside the diffuser ring are equal. The nominal diameter of the octagon is 3217 mm and the total length is 10108 mm. Length of each side of octagon is 1264 mm. The nominal overall length of a bend is 146 mm and 265 mm for a T junction. The pipes extend 60 mm into sockets at each end of a bend or T. Length of pipe for sides with bends which can have openings is 1264-146 = 1118 mm. Length of pipe for sides with bends and T which can have openings is 1118-265 = 853 mm. To balance the system so the same amount of water is discharged from each portion of the octagonal diffuser the lengths of perforated pipe sections with and without the T junctions are made equal to the average of the two i.e. (1118+853)/2 ~ 986 mm. Overall length of pipe for side with only bends is 986+120 = 1106 mm. Overall length of the two pipes for side with bends and a T is 986/2+120 = 613 mm. This means the octagonal shape of the diffuser is no longer regular, but its total length is unchanged. The spacing between openings in the diffuser pipes should be a practical distance but as short as possible order to maximise the number of openings, a distance of 20 mm was selected. Total number of openings per octagon side is 49.The total area of openings per octagon side will be taken as twice the pipe cross sectional area. Based on 49 openings per pipe the area of each opening is 3.40 cm2. The openings were made by drilling pairs of 15 mm diameter holes whose centre lines are inclined at 120o to each other at 2 cm intervals along each pipe. The maximum water flow rate, taken as the design value, to pass through the diffuser is 14 litre/sec.

The double diffuser was constructed (Figure 33) and later implemented in the silo. Additional 110 mm pipes were used to fabricate the network supplying water to the diffuser ring. The bottom of the lower diffuser pipe was placed 20 cm above the base of the tank and the top of the upper diffuser pipe is 20 cm below the water surface.

The Richardson number (Ri) is used to characterise the stability of thermoclines in fluid thermal stores.

Ri = g h (ρ c - ρ h) / ρ v2

where g is the acceleration of gravity, h the vertical distance between store inlet and outlet, ρ c and ρ h the densities of the fluid in the cool and warm parts of the store, ρ the mean fluid density and v the inlet velocity of the fluid at the inlet. In the present case h =3.69 m (for a capacity of 60 m3) and V = 0.105 m/s.

The values of Ri shown in Fig. 34 were obtained for a range of water temperature differences and the corresponding density differences. In this application Ri represents the ratio of the buoyancy force to forced convection. If Ri < 0.1, forced convention is dominant while if Ri > 10 the buoyancy force is dominant. Wilden and Truman (1985) reported a value of 1 as the minimum value of Ri for acceptable thermal store performance. Zurigat et al (1988) reported that 5 was the lower limit below which diffuser design and layout became an important factor in thermal store performance; they suggested that the value of 1 proposed by Wilden and Truman (1985) may have been influenced by the imposition of additional requirements. Wilden and Sohn (1993) reported the upper limit of the Reynolds number for optimal performance of a chilled water store was between 400 and 600.

In the present case it is likely that a stable thermal gradient will occur when the temperature difference exceeds 8oC, but for lower differences it may become unstable.

. The silo has 4 temperature sensors (thermopars) at different heights to monitor thermal stratification

A 4 kW open cooling tower (Figure 24) with a capacity of 40 litres/second (35 ºC in-29 ºC out) was installed and connected to the system for heat transport from the condensed to the ambient. This cooling tower allows for cooling of the hot water accumulated at the top of the silo when night temperatures do not allow for delivering the heat inside the greenhouse, providing an extra period for cooling and keeping the greenhouse closed.

The system was controlled with a complete free programmable steering and control unit to control all functions of the Fiwihex system. The system has 4 operation modes:

Mode 1: Standby; Mode 2: Cooling greenhouse using the heat store; Mode 3: Heating greenhouse using the heat store; Mode 4: Cooling heat store using the cooling tower.

The energy exchange inside the greenhouse (convection plus conduction due to water condensation) is realised by the three Fiwihex heat exchangers. In cooling situation, mode 2, cold water is removed from the lower part of the energy store and transferred to the Fiwihex heat exchangers. Simultaneously, the warm air runs through the Fiwihex and can be cooled by the cold water flowing from the energy store. The heated water flows back to the upper part of the energy store. During the day evolves a gradient in water temperature between the lower and upper part of the energy store. When, for example at night, heating is required the water can be removed from the upper part and returned to the lower part after heating the greenhouse (mode 3). When night temperatures are above the heating set point, and water temperature in the storage tank ins 4 ºC above the exterior temperature, mode 4 is activated to cool the water in the heat store and gain cooling capacity for the next day.

The most significant set points established for the system have been:

(i)Ventilation set point: 30 ºC (ii) Cooling set point: 20 ºC in winter (at this temperature the system starts sending cold water flow which progressively increases depending on the inside temperature and the cold water temperature). This set point was established slightly low to collect enough energy (warm water) for the night during the winter. In the spring time, it was increased to 24 ºC (iii) Heating set point: it was set to 12 ºC except during a period (one hour before dawn and one hour after dawn) which was increased to 15 ºC to activate the plant. (iv)CO_2 injection to 800 ppm for vents completely closed, 400-800 ppm if vents open less than 10% and 400 ppm for vents open>10%.

The heat exchanger fans were activated every time the system started cooling or heating and were switched off if conditions were different. On cloudy nights they were switched on to move the air in the compartment and prevent condensation on plants and fruits.

Inside the compartment, dry and wet bulb temperatures (aspirated psychrometer with 2 thermistors 3k) and CO_2 concentration were continuously monitored and averaged every 5 minutes. In one of the Fiwihex units, temperature of the air and water before and after the heat exchange process were continuously monitored as well as all the energy consumed by the heat exchanger, circulation pump and cooling tower, and CO_2 consumed during the whole cycle.

Due to several leakage problems in the water silo which took long to find and repair (the double diffuser had to be disconnected, a crane had to take it out the silo, etc.) the system could only be activated after the first months of the crop cycle (the tomato crop was transplanted on July 14th 2009, and it was intended to start using the system in October). The system started working on the 28th of November, being able to keep the greenhouse compartment completely closed during the daytime (vents only opened at night to decrease humidity and less than 10% during the daytime) until 30th of May, in which the system started to be unable to maintain 30 ºC during the central hours of the daytime, and therefore, less CO_2 was injected, as vents opened more than 10 %. On the 23rd February a second tomato crop was interplanted in the compartment, and the previous crop eliminated on the 3rd of May The 2nd crop cycle ended the 30th June.

Performance of the system during the winter months

The behaviour of the system in winter was very different on clear days than on cloudy days. After clear days, the system stored energy in the silo and good thermal stratification was achieved (Fig. 25). Data shown correspond to December 4th 2009. In order to know better how the water was stratified more sensors are planning to be implemented in the silo. However, Fig. 25 shows that the double diffuser system seems to be performing according to the expected without creating much turbulence, hence allowing for a good separation between hot and cold water. Fig 25 also shows that during the daytime, when cooling mode is active, the returning hot water accumulates mainly at the top and especially, at the middle part of the tank, which within few hours increases its temperature from around 9 ºC to almost 14 ºC. It can also be observed that until midnight, there was no heating demand from the greenhouse as the temperature was not below 12 ºC. After several cloudy days, since the system is collecting very little or no energy at all (last winter in Almería was unusual due to the large number of completely cloudy days), the thermal stratification tends to disappear in the silo, but on cloudy days followed by a cloudy night, for the Almería conditions, neither cooling nor heating is required in the greenhouse (system under mode 1, temperatures comprised mostly between 12 and 20 ºC).

The following Figures (26, 27, and 28) summarize how the heat exchangers are affecting the climate inside the closed compartment for the 28/01/2010, which was a clear day, as well as its night.

Under most circumstances, the daily evolution of the relative humidity inside the closed compartment during the winter (also during the spring) followed the trend shown on Figure 4 together with the outside relative humidity. Since the greenhouse vents are closed, the relative humidity values are high and range between 70 and 90 %, but saturation is never achieved: during the day the heat exchangers are condensing a large part of the water vapour transpired by the plants and that prevents saturation and during the night the air was heated and saturation is never achieved neither.

According to Figure 27, during the night the system had the heating mode activated and the set temperature of 12 ºC was maintained along the whole night, with a gradient of around 3 ºC in relation to the outside temperature. The adjacent ventilated compartment maintained a temperature almost equal to the outside temperature. During the daytime the cooling mode was active and the temperature was kept below 25 ºC and to very similar values to an adjacent naturally ventilated compartment (5 spans). After the sunset, the heating mode activates again making use of the energy accumulated during the day and, unlike in the adjacent open compartment, the temperature drop is not as fast as in the ventilated unheated adjacent greenhouse. The plant temperature remains at very similar values to the ambient temperature during the night, and 1-2 ºC lower during the daytime, showing a good transpiration from the crop which seems not to be affected by the high RH values, stimulated by the high CO2 concentration and the airflow created by the fans inside the compartment.

Figure 28 shows the temperatures of the air just before it enters the heat exchange units and the temperature just after the air leaves the heat exchanger. During the night period the air leaving the heat exchangers has a temperature between 12 and 13 ºC, which is approximately the average ambient temperature that was maintained (Figure 28). During the period the pump was supplying water at a high rate (80 %). During the daytime, the pump was not supplying such a high water rate (49.5%) since it was not necessary as the ambient temperature was maintained at values well below the ventilation set point and that is the reason why the difference between the air in and the air off temperatures is very low on this period. During the night the water delivers very little energy to the air since the temperature gradient to be maintained is not very high (≈3 ºC), therefore, the "water out" temperature is only slightly cooler than the "water on" temperature. However, during the day, a large amount of energy is transferred to the water from all the sensible and latent heat accumulated in the closed compartment, and at the peak the water is cooled to almost 6 ºC.

Performance of the system during the spring months

On the 7th April the cooling tower was activated, so that the warm water accumulated in the silo would be could, dissipating heat to the air at an energy cost, in order to have cold water available for the next day. The cooling tower mode was activated whenever the average temperature of the water in the silo was ≥ 2 ºC than the ambient wet bulb temperature and was programmed to work for 1 hour at least. In most cases, 1 hour was enough to cool the whole volume of the tank, except the very top water layer (Figure 28).

Figure 28 shows the water temperature at four different heights in the silo from bottom to top for the 1st of May 2010. It can be observed that the cooling tower was activated twice on this day: one hour just before noon, in which the water was cooled only 1 ºC in almost the whole volume, to the wet bulb external temperature and once more in the afternoon, this time being the water cooled up to 3 ºC in almost the whole volume, remaining from this point temperature due to the lack of heat demand from the greenhouse and the good insulation of the tank. During the hours in which the cooling mode was on, we can observe that the temperature of the water in the tank was increasing from the mostly in the two medium sensors, first in the lower one and then in the upper one, and more slowly in the bottom and top layers. As the warm water was delivered from the greenhouse, since the diffuser is located at a certain height from the bottom of the tank, this warm water creates warm layers that stratify slowly along the day.

In relation to the climate inside the closed compartment during the spring, it was possible to maintain the greenhouse almost completely closed until the 30th of May. During the month of May, some very clear days, the vents had to open during short periods (temperature>30 ºC) around noon, but always less than 10 % so the CO_2 injection was not affected very much and the heat exchangers remained active. Figure 29 shows the climate inside the closed compartment on an average clear spring day of Almería (1/05/2010). It can be observed that the temperature in the closed compartment reached values close to 30 ºC (a maximum temperature gradient of 8.7 ºC in relation to the outside temperature, and 5.1 ºC in relation to an adjacent 5 spans very well ventilated greenhouse with same crop), but the system was capable of maintaining the temperature below this ventilation set point, allowing for the CO2 concentrations to remain very high during the daytime (between 750 and 1000 ppm) allowing for higher net photosynthesis to be achieved (data not shown).

Unlike in winter, during the daytime, under cooling mode, the water absorbs a lot of energy and increases its temperature to a maximum of 5.3 ºC (heat absorbed by convection and due to water condensation) and the air is cooled to a maximum of 3.2 ºC (Figure 30). The large amount of energy absorbed by the water during the high radiation months explains why a cooling tower is necessary if the greenhouse is to be maintained closed during the early spring and possibly autumn months, at the expense of the energy consumed by the cooling tower.

A novel system based on the use of high efficiency heat exchangers (FiwiHex), a day/night single thermal storage tank and an open cooling tower has been tested for the Almería conditions during the winter and spring months in a small (160 m2) greenhouse compartment. The system has been able to keep the greenhouse almost completely closed during the daytime (during the night the vents opened to decrease humidity when heating mode was not active) from the beginning of December until the end of May. In general terms, the climate inside the compartment was warmer and more humid during the day and the night in winter (due to the use of heat accumulated during the day) than in an analogue-adjacent greenhouse managed with natural ventilation. During the spring, the cooling tower had to be used during the night to provide cooling "power" for the next day, again with a warmer and more humid climate than in the analogue-adjacent greenhouse.

The single storage tank, with double diffusers for water collection/delivery from/to the greenhouse, respectively, performed according to the expected, with good stratification achieved during clear days, which allowed for the use of the energy at night during the winter.

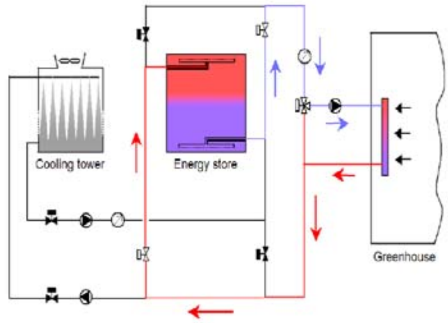


Figure 23. Overall diagram of the system

Figure 24. Picture of one heat exchanger with the condensate water collection device.

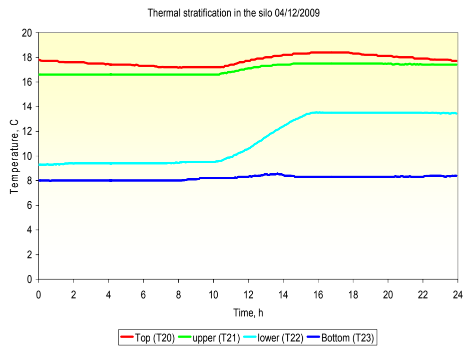


Figure 25. Thermal stratification in the storage tank on a clear winter day (4/12/2009)

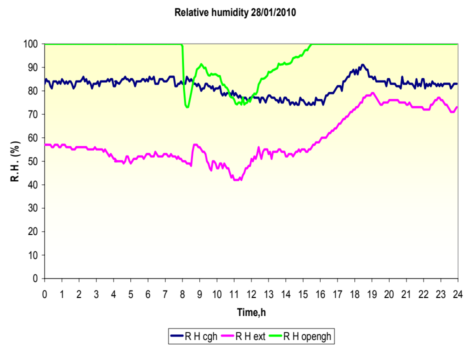


Figure 26. 24 hours evolution (28/1/2010) of the relative humidity in the closed compartment, open compartment and exterior.

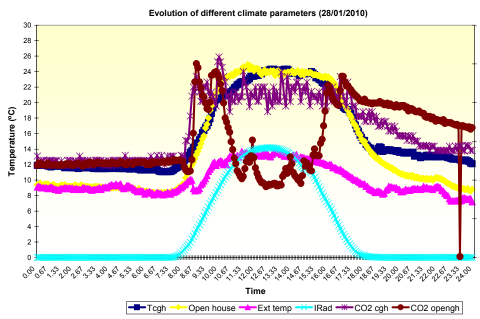


Figure 27. 24 hours evolution (28/1/2010) of ambient temperature, radiation and CO_2 concentration in the closed and open compartments on a clear winter day

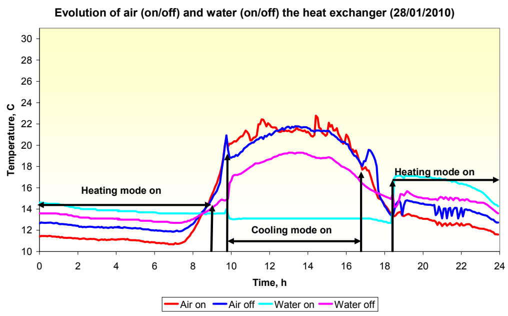


Figure 28. 24 hours evolution (28/1/2010) of the air and water (before and after the heat exchanger) on a clear winter day.

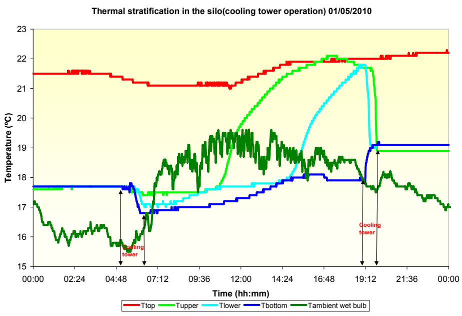


Figure 29. Thermal stratification in the storage tank on a clear spring day (1/5/2010)

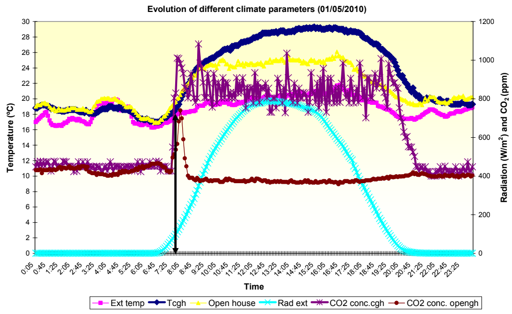


Figure 30. 24 hours evolution (01/05/2010) of ambient temperature, radiation and CO_2 concentration in the closed and open compartments on a clear spring day

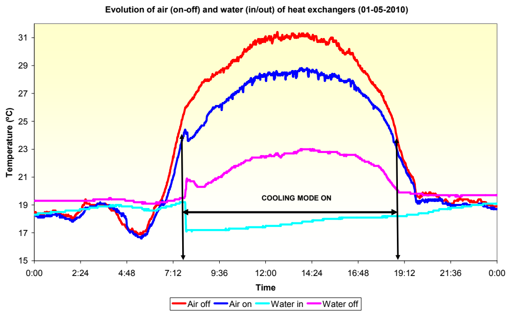


Figure 31. 24 hours evolution (01/05/2010) of the air and water (before and after the heat exchanger) on a clear winter day.

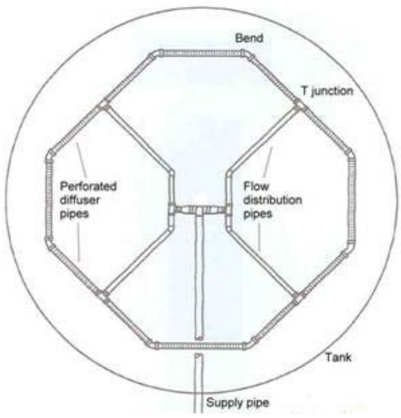


Fig. 32. Plan view of upper octagonal diffuser

Fig. 33 Double diffuser finally constructed before final implementation in the silo

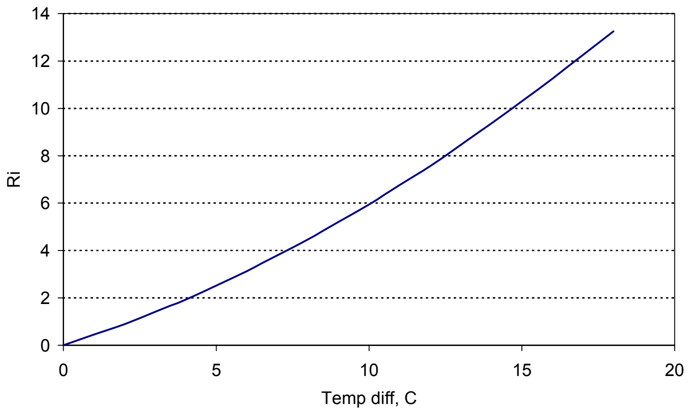


Fig. 34 Richardson number for the installed thermal store

1.6 Other greenhouse thermal storage methods.

A deep literature review was done last year to identify the best technologies for heat storage. The review paper from Sethi & Sharma (2008) is a very comprehensive detailed descriptor of this kind of systems: The different technologies were grouped in two main categories selecting those more commonly used commercially or most promising for greenhouse use in the future. This year a rough estimation of the implementation costs associated to each system and scientific results of those most used nowadays are presented:

1. Energy/heat stores integrated into the greenhouse

Greenhouse soil: the soil of a greenhouse is in itself a heat store, the heat delivery from the greenhouse soil leads to a considerable reduction of the heat demand and must not be neglected in case of low heating set points. In the EEFC, a research project is being carried at the moment in which the effect of sand mulch (and other types of plastic film mulching) are being evaluated to determine the effect on the day/night energy balance (heat store capacity with both systems) of the greenhouse.

To evaluate the potential to store heat in the greenhouse soil, at the Experimental Station of the Cajamar Foundation, micro-climate measurements in the system soil, air and greenhouse cover were performed, considering the soil system as the set integrated by the natural soil and in its turn by the “enarenado” (sand mulch) and/or plastic mulch. This activity began in October 2008 and ended by the middle of April 2009. Later, during the summer of 2009, the same evaluation of energy store potential for soils disinfected by solarization.

The different conditions evaluated (scenarios) were: bare soil, soil with thick sand mulch, soil with fine sand mulch, soil with thick or fine sand mulch covered with black plastic film, and soil with thick or fine sand mulch with transparent mulch. Regarding solarization, a black and transparent plastic mulch were evaluated, and the direct implementation of them in contact with the sand or leaving an air layer in between them.

The “enarenado” soil types studied were selected based on the most commonly used in the area of Almería (previously evaluated). These were: “thick enarenado” which corresponds to fine gravel, and a “fine enarenado” which corresponds to thick gravel, according to the USDA classification. The different scenarios were tested in a multitunnel greenhouse, which was divided into two equal sections of 10 x 22.5 m2 (zones A and B), separated also laterally to avoid the border effect.

A distinct behaviour has been found for the “enarenado” soil warming depending on the plastic material used as mulch over the sand.

The average temperature in the first 10 cm of the soil system was 4 ºC higher during the daytime period in the “enarenado” soil than in the bare soil, however, the night values were similar. In the soil area, where most of the roots concentrate (0.15-0.35 cm) an increase of temperature in the “enarenado” soil occurred during a period of 14 days, whereas this temperature decreased in the bare soil (without sand mulch), with differences of up to 2 ºC. The ambient temperatures inside the greenhouse, measured at several heights, were clearly higher in the “enarenado” soil compartment, than in the bare soil compartment, with maximum differences of 5 ºC during the daytime period. However, the night temperatures were similar or slightly lower in the “enarenado” soil compartment.

The temperature in the thick sand layer covered with black plastic mulch was higher than in the non mulched soil, during the day, and especially during the night. During the day, when the greenhouse vents remained open, the temperature of the sand mulch layer covered with black plastic film was higher than in the “enarenado” without plastic film, but the differences were lower. In the soil layer, a higher and faster temperature increase occurred when using black mulch, in relation to the “enarenado” not covered with plastic.

On the other hand, the temperature of the sand layer was higher when it was covered with black plastic film than when it was covered with the transparent film, both during the daytime and during the night. The use of black plastic mulch increased more temperature of the soil than the transparent mulch, with our experimental conditions.

The night temperature of the “enarenado” was slightly higher in the thick sand compartment than in the fine sand compartment. The average temperature of the soil area where the roots usually are was similar in both types of sand mulch, with the same trend.

The sand mulched soil was able to store more energy, providing a higher temperature to the roots and the greenhouse environment, with respect to a bare soil. Equally, in the sand mulched soil with black plastic stored more energy than the soil without mulch.

Soil: 2.000 m³/ha x 5 €/m³ = 10,000 €/ha = 1 €/m²

Manero: 250 m³/ha x 24 €/m³ = 6,000 €/ha = 0,6 €/m²

Sand: 1.000 m³/ha x 10,5 €/m³ = 10,500 €/ha = 1,05 €/m²

Plastic mulch: 2.000 €/ha = 0.2 €/m² (average value that might change depending on the material)

Total for “enarenado”: 2.65 €/m² + 0.2 €/m² with plastic mulch

Figure 35. Bare soil (a), “thick enarenado” mulched soil (b) and soil with black plastic mulch (c).

Figure 36. Solarization of the sand mulched soil covered with transparent plastic in contact with the soil (a) and with an air layer (b).

• **Water under porous concrete floor**: the main reasons to discard the systems is that it is not only adaptable to already existing greenhouses with high associated costs: the necessary works to build a basin below the greenhouse plus the porous concrete floor, whereas the system based on heat exchangers and an insulated external water tank/basin outside the greenhouse involves a much lower investment on works plus the equipments and simple and cheaper works for piping and wiring the system.

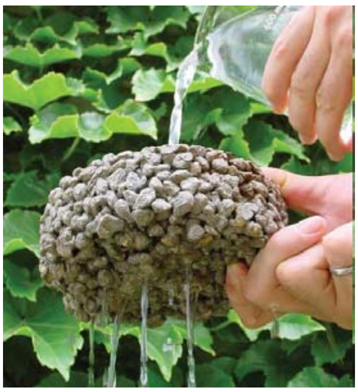
 a)	 b)

Figure 37. Detail a) of a piece of porous concrete floor and b) of the layout of this material in the greenhouse soil, previous to its construction.

2. Separate energy/heat stores linked to the greenhouse

• **Rock beds**: the average volume that must be occupied by rocks to obtain good heat storage under Mediterranean is from 3 to 4 times the volume of the greenhouse to be cooled/heated. The most efficient is to build the bed under the greenhouse, so once again, this system involves a large investment in works and also difficult adaptation to already existing greenhouses. The high energy costs associated to the large air flows needed by the system to properly exchange the heat through the whole rock bed volume also limit their implementation in

relation to other heat storage systems with lower energy cost associated (i.e. water tanks/basins or aquifers)

Figure 38. Picture of the filling with pebbles of the thermal store volume under the future greenhouse.

• **Water tanks**: this is the system which can be considered most promising for the Mediterranean conditions to store energy respectively cooling and heating a closed greenhouse on a day/night basis. The main reasons are its easy implementation on an existing greenhouse provided that there is enough height in the greenhouse to place the heat exchangers at least one meter above the top of a well developed vertically trained crop (to avoid direct impact of the jet of air on the top of the plants). Another advantage is that many growers already have a water basin to irrigate their crops. If the basin is deep enough, it could be used as a substitute of the water tank (saving investment), ensuring a good thermal stratification by installing proper diffusers to avoid turbulences. Another option could be to separate two compartments in the basin, one for the warm water and one for the cold water. An example of the investment costs associated to this system for 1000 m2 of greenhouse are presented below. Obviously, some of the elements would remain more or less at similar cost (i.e. control system, sea container) so the price per m2 for a larger surface would become much lower and money would be saved too if the water basin is used instead of buying a new silo.

The prices below exclude:

• Piping and cables outside the sea container.

• Water treatment system supply water cooling system.

• Insulation of all the Piping.

• Break, digging, carpentry, masonry, and painting.

• All materials and mounting witch are not mentioned in this quote.

• V.A.T., all local taxes and insurance's.

• All expenses for assays of the installations, which may be demanded by the local energy company or government.

• Expenses for costume-house, import duties, etc.

12	Heat exchanger units (Fiwihex units). One for each 80 m2	€ 24,000
1	Sea container with air conditioning	€ 5,942
1	Water connections and mixing group in the sea container	€ 11,891
1	Electric connections and main panel in the sea container	€ 7,500
1	Storage silo	€ 6,589
1	Total Control System (TCS)	€ 20,000
1	"Open" cooling tower	€ 12,000
	TOTAL	€ 87,922

• **Solar ponds**: discarded also for expensive works or investment to build and especially due to very complicated maintenance of the salinity gradient in the pond.

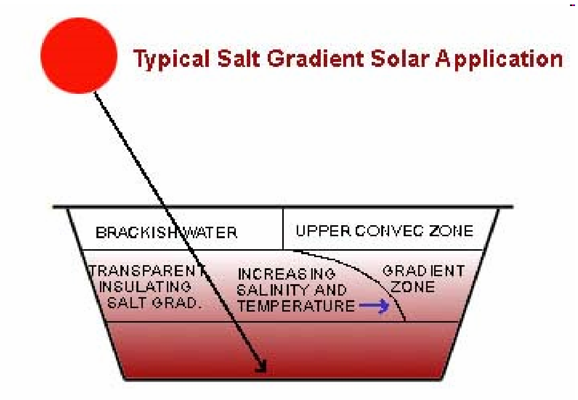


Figure 39. Scheme of a typical solar pond and its different areas.

•**Aquifers**: the best option for seasonal storage if confined aquifers are available near the greenhouse (i.e. many areas of The Netherlands) although investment is also quite high. The flux of water necessary for a glasshouse in The Netherlands varies from 40 to 200 m3/ha. An equation has been derived from those used in the building industry which allows for the estimation of the costs including:

Frequency controlled pumps, piping, excavation works, wiring, heat exchangers with a ∆T of 2 ºC capacity, engineering on site, control system, 10% of other costs, etc.

Costs= 1930*maxflow+78000 [euros]

• Phase change materials (PCM): promising but research still in development. Most important problems are lack of good values of thermo physical properties in the literature of the **PCM's**. They are quite necessary for appropriate and accurate design of the thermal storage units. Solid-liquid PCM's are the most promising candidates for its use in greenhouse (low-medium) temperature applications.

In many industries, there might be some residues or sub products which could have good properties for their use as PCM´s and it would be worth investigating this to lower prices. The desired characteristics of a PCM material for its use on a heat absorb/storage system are:

- Melting point (solid-liquid phase change) between 10-50 ºC.
- Long chain hydrocarbons, branched or not, saturated or not, of the paraffin type, olefins, etc.
- Mix of hydrocarbons of different chain length.
- High latent or melting heat.
- Without disintegration or separation of phases in the melting-solidification processes.
- Do not present harmful or toxic substances, and if they are present, they must be easily eliminated by simple separation processes.
- Fusion enthalpy and heat capacity in liquid and solid states.
- Viscosity and density.
- Thermal conductivity coefficient.
- Others…

The energy collected in the greenhouse air will be blown during the daytime will be blown to the pipes containing the PCM (energy store), which will change the phase of the material and then, at night, will be delivered back to the greenhouse as the material changes phase back.

PART II

2. DECISION SUPPORT SYSTEM FOR OPTIMUM VENTILATION MANAGEMENT

The aim of this task is to develop a decision support system for minimizing the necessity of ventilation (energy and pest management), while improving crop productivity, also through CO_2 fertilisation.

2.1 Development of a method to determine required natural ventilation capacity in view of the local climate conditions and the properties of the cover.

2.1.1. Introduction

Greenhouses frequently require ventilation to prevent overheating during the day and to reduce humidity. The majority of greenhouses employ natural ventilation in which the ventilation airflow occurs through ventilators in the roof and walls. The flow of air is created by the difference between the inside and outside air temperatures and by the external wind. The important characteristics of a greenhouse natural ventilation system are, the total area of the ventilators, their position on the greenhouse i.e. only in the roof or in the roof and walls, and their location relative to the direction of the wind. This ventilation decision support system is intended to assist in making the following decisions:

(i) What area of ventilators is necessary in relation to the local climate and required ventilation temperatures?
(ii) What benefit is obtained by shading in reducing the ventilation requirement?
(iii) During which months can acceptable temperatures be achieved?

An energy balance model is used with local climate data to determine the ventilation airflow required to maintain a greenhouse at selected ventilation temperatures. Ventilation models which relate the airflow through greenhouse ventilators to the internal and external temperatures and wind speed, and to ventilator geometry are then used to determine the area of ventilators necessary to provide the required airflow.

The effect of applying shading to the greenhouse in summer to reduce the cooling requirement and thereby improve the effectiveness of ventilation is included.

The information on the required ventilation area is presented as the number of hours (per calendar month and per year) in which the greenhouse temperature exceeds the selected ventilation temperature.

2.1.2 Ventilation requirement

The greenhouse energy balance model is based on the HortiCern and HortiTrans models described by Jolliet et al. (1991) and Jolliet (1994) and is executed in a spreadsheet. The energy balance of a greenhouse is expressed as:

Qsolar + Qconduction + Qsoil + Qventilation = 0

where Qsolar is the solar energy transmitted into the greenhouse, Qconduction the heat conducted through the greenhouse cover, Qsoil heat transferred to/from the soil and Qventilation the energy removed by ventilation.

Qsolar is calculated using the external global solar radiation, a transmissivity value for solar radiation which depends on the greenhouse cover material and an allowance for solar energy absorbed by the cover.

Qconduction is calculated from the energy exchanges between the cover and the sky, the cover and the external air and between the cover and the inside air.

Qsoil is obtained from data recorded in an uncropped greenhouse at Estacion Experimental de la Fundación Cajamar.

Qventilation is obtained from energy and water vapour balances of the ventilation air.

Qventilation = Qsensible heat + Qlatent heat

and

Qtranspiration = Qlatent heat + Qcondensation

where Qsensible and Qlatent heat are the sensible heats transferred by the ventilation air respectively, Qtranspiration is the energy contained in the water vapour transpired by the greenhouse plants and Qcondensation is the energy transferred to the greenhouse cover by the condensation of water on the inner surface. Transpiration was calculated using a model developed at Estacion Experimental de la Fundación Cajamar for a tomato crop. Condensation was estimated using the method developed by Jolliet (1994) in which the cover temperature was calculated assuming the internal air was saturated and then a correction applied based on the actual internal vapour pressure. Condensation occurred when the internal vapour pressure exceeded the saturated vapour pressure at the cover. If the external temperature exceeded the ventilation temperature, the greenhouse temperature was calculated using a maximum value for the ventilation heat transfer coefficient of 100 W m^{-2} K^{-1} (equivalent to a ventilation rate of 0.82 m^3 m^{-2} s^{-1}).

The effect of shading is included by changing the solar radiation transmission of the greenhouse cover.

The model is used with weather data sets consisting of hourly values of air temperature, solar radiation, relative humidity and wind speed to calculate hourly values of greenhouse temperature and the ventilation airflow required to maintain the greenhouse at selected ventilation temperatures. The ventilation airflow rates are expressed per m^2 of greenhouse ground area.

2.1.3 Ventilation models

Numerous models have been developed to predict ventilation air flow through different designs of ventilators, ventilator positions and types and sizes of greenhouse. Some include both the effect of temperature difference and wind speed in creating the ventilation air flow, others only include the wind effect. Models have been created for flap and rolling ventilators in curved roof and pitched roof greenhouses and also in the sidewalls. Three different models have been used to develop this decision support system. Between them they encompass flap ventilators in the roofs and walls, curved and pitched roof greenhouses, and the use of temperature difference combined with wind speed and wind speed on it own.

The model of Boulard and Baille (1995) was developed for a 416 m^2, 2 span, film covered greenhouse with continuous ventilators on one side of each curved roof. It used both temperature difference and wind speed in predicting the ventilation air flows. The primary wind direction was parallel to the longest side walls.

Kittas et al (1997) created a model for the above greenhouse but included air flow through both the roof ventilators and continuous flap ventilators in the two 32 m long sidewalls. This model also included both temperature difference and wind effects.

The model of Bailey et al. (2004) was developed using a 1/3 scale model Venlo greenhouse with discrete panel ventilators spaced along alternate sides of each ridge and then validated on 200, 5200 and 37,800 m^2 Venlo greenhouses. Sidewall ventilators are not included and the model uses only wind speed in estimating the air flow.

The ventilation rates predicted by each model were expressed per m^2 of ventilator area.

2.1.4 Results

The energy balance model and the ventilation models were used with weather data recorded at hourly intervals during 2007 at the Estacion Experimental de la Fundación Cajamar, in southern Spain and weather data for the Netherlands also for 2007. By dividing the required ventilation rate (m^3 / m_g^2 s) given by the energy balance model by the ventilation rate given by the ventilation models for the same temperature and wind value (m^3 / m_v^2 s) the ventilator area required to provide the ventilation air flow for that hour is obtained (m_v^2 / m_g^2).

The transmissivity of the greenhouse cover for solar radiation was taken to be 90% which applies to glass and standard greenhouse covering films. This resulted in a transmissivity for the greenhouse of 65%. When shading in the form of whitening applied to the cover, the cover transmissivity was 28% which gave the greenhouse a transmissivity value of 25%.

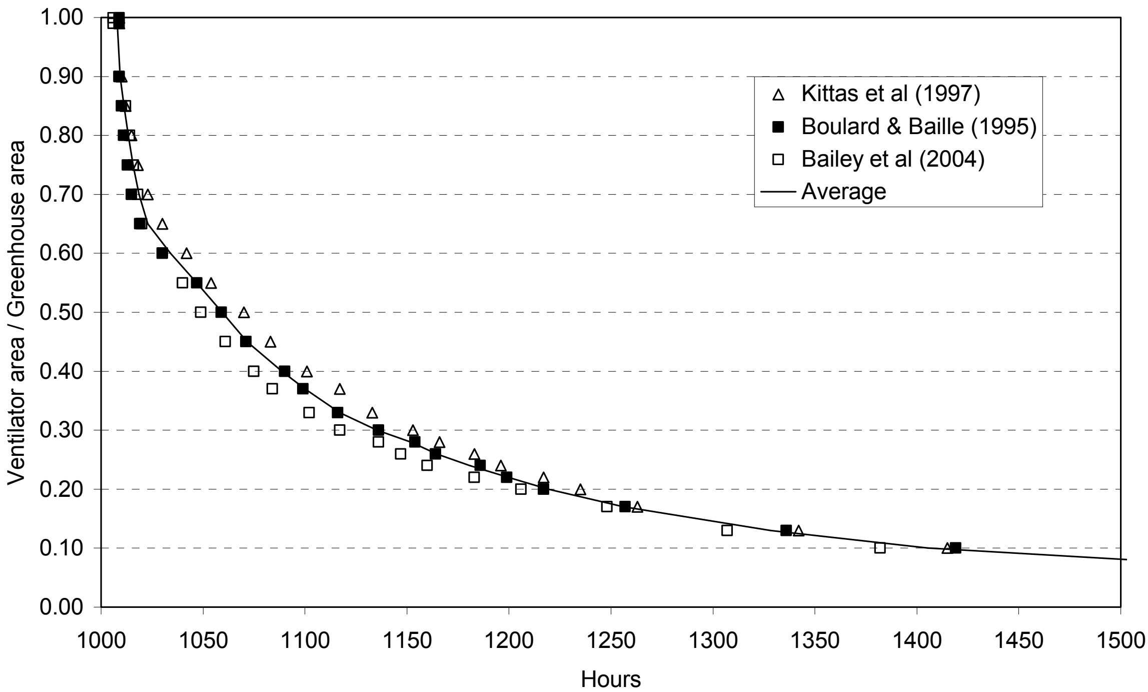


Fig. 40. Ventilator areas required to achieve 26^{o}C in a greenhouse in Southern Spain in 2007

Figure 40 shows how the total number of hours in the year when the greenhouse temperature exceeds the ventilation temperature (in this case 26^{o}C) reduces as the total ventilation area increases. There is reasonable agreement between the results from the different ventilation models so the average of the three values is used.

The results, given in the Appendix, are presented in tabular and are grouped according to:

(i) location i.e. climate data
(ii) ventilation temperature
(iii) shade / no shade.

Table 7 is an example of one of the tables. For the specified ventilation temperature, location, shade configuration and range of total ventilator area / greenhouse ground areas between 0 and 1, the number of hours when the temperature during each month exceeds the ventilation temperature is shown. The number of hours when the external temperature exceeds the ventilation temperature during each month is shown at the top of the Table. The final column gives the number of hours during the year when the greenhouse temperature exceeds the ventilation temperature for each ventilator area ratio.

Table 7. Typical output table, enabling assessment of ventilator areas

Ventilation temperature 26 C

Almeria 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	0	52	138	324	373	140	9	0	0	1036
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	209	211	287	306	378	386	403	397	321	284	228	212	3622
0.005	154	172	235	247	341	363	397	371	292	238	188	140	3138
0.010	96	146	197	201	306	348	391	357	274	210	149	99	2774
0.025	17	89	99	126	267	313	362	342	240	162	74	25	2116
0.050	0	45	33	64	222	301	349	334	226	133	14	2	1723
0.075	0	18	9	37	196	280	341	327	210	103	4	0	1525
0.100	0	5	4	21	175	268	337	323	199	76	0	0	1408
0.120	0	2	3	14	164	256	337	320	189	68	0	0	1353
0.140	0	0	2	4	148	247	335	312	187	61	0	0	1296
0.160	0	0	0	2	139	243	332	310	183	55	0	0	1264
0.180	0	0	0	2	135	239	331	307	180	54	0	0	1248
0.200	0	0	0	0	131	235	328	301	178	51	0	0	1224
0.225	0	0	0	0	129	230	327	295	169	45	0	0	1195
0.250	0	0	0	0	128	227	325	290	164	42	0	0	1176
0.275	0	0	0	0	128	220	323	284	159	41	0	0	1155
0.300	0	0	0	0	124	216	321	277	156	39	0	0	1133
0.333	0	0	0	0	123	215	316	275	153	38	0	0	1120
0.367	0	0	0	0	120	214	308	269	150	38	0	0	1099
0.400	0	0	0	0	118	214	305	264	148	38	0	0	1087
0.450	0	0	0	0	117	212	301	258	146	38	0	0	1072
0.500	0	0	0	0	115	211	298	253	145	36	0	0	1058
0.550	0	0	0	0	115	211	293	247	144	36	0	0	1046
0.600	0	0	0	0	115	209	290	241	142	36	0	0	1033
0.700	0	0	0	0	114	207	284	237	141	36	0	0	1019
0.800	0	0	0	0	114	207	281	234	141	36	0	0	1013
0.900	0	0	0	0	113	207	280	232	141	36	0	0	1009
1.000	0	0	0	0	113	207	277	232	141	36	0	0	1006

Similar Tables are presented in the Appendix for greenhouses in southern Spain and the Netherlands for a range of ventilation temperatures and with and without shading in summer months.

These provide information to aide making decisions on:

(i) What ventilation area is required in a new greenhouse?

(ii) What temperatures can be achieved in an existing greenhouse with existing ventilators?

(iii) During which months can the greenhouse be used to grow plants which have a known upper temperature tolerance?

2.1.5 Effect of greenhouse size and ventilator position

The forgoing deals only with determining the total area which can be opened to provide ventilation, the position of the ventilators has not been considered. In greenhouses with areas of less than a few thousand m^2 it is known that having ventilators in the sidewalls and in the roof gives increased cooling. Figure 41 shows how the relative areas of roof and sidewall ventilators influence the ventilation rate [note the total ventilation area is constant]. It is clear that the highest ventilation occurs when both ventilators have the same areas (Kittas et al, 1997).

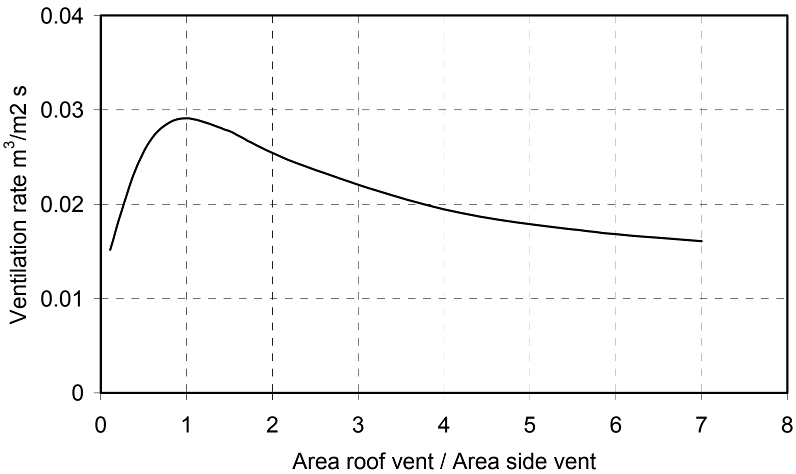


Fig. 41. Influence of sidewall and roof ventilator areas on ventilation rate.

Note the total ventilation area is the same.

Therefore, in designing a natural ventilation system for greenhouses covering small areas the aim should be to have equal areas of sidewall and roof ventilators.

However, as the size of greenhouse increases this is no longer possible. The total area of roof ventilators increases and the sidewall ventilators form a decreasing proportion of the total ventilation area. Figure 42 shows the how the ratio of roof to sidewall ventilator areas influences the ventilation performance. When this ratio exceeds 10 there is little additional benefit to be gained in having ventilators in the sidewalls.

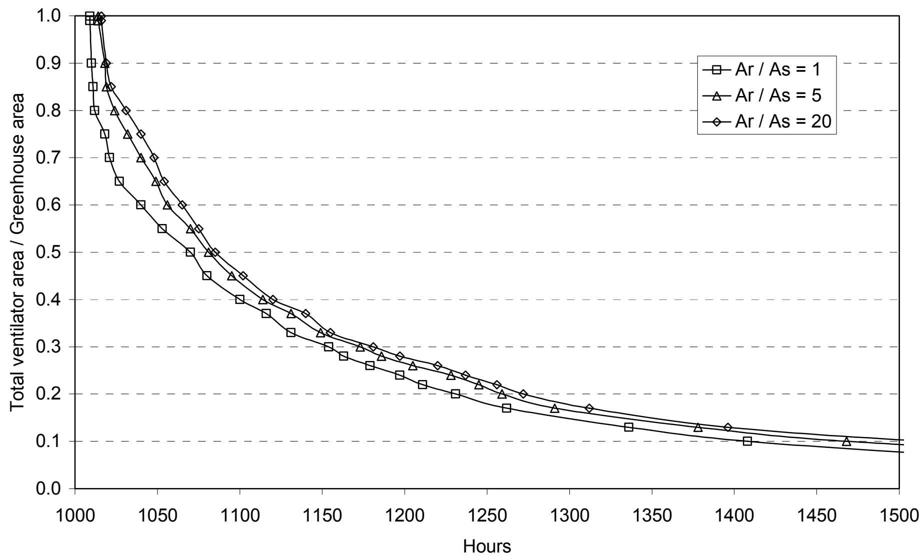


Fig. 42. Total ventilation areas required to achieve 26°C in a greenhouse in Southern Spain in 2007 with different ratios of roof (Ar) to sidewall (As) ventilator areas

However, sidewall ventilators can have a strong influence on greenhouse ventilation when exposed to the prevailing wind as air entering the sidewall ventilator can have a controlling influence on the airflow in the greenhouse. This situation can adversely affect plants adjacent to the sidewall particularly if there are large differences in temperature or humidity between conditions in inside and outside the greenhouse. Deflectors have been used to direct the entering air upwards to create a region in which the air mixes with the greenhouse air before impinging on the crop. It has been suggested that the effects of sidewall ventilation can extend 20 to 40 m into a greenhouse, however, this distance will be reduced markedly by the presence of a tall crop.

2.1.6 Windward and leeward ventilation

Glasshouses usually have ventilators on both sides of the roof of each span. This can provide either leeward ventilation, windward ventilation or a combination of both. However, curved roof greenhouses often have continuous ventilators along the roof which all face in the same direction when open. Depending on the wind direction, these will provide either leeward or windward ventilation.

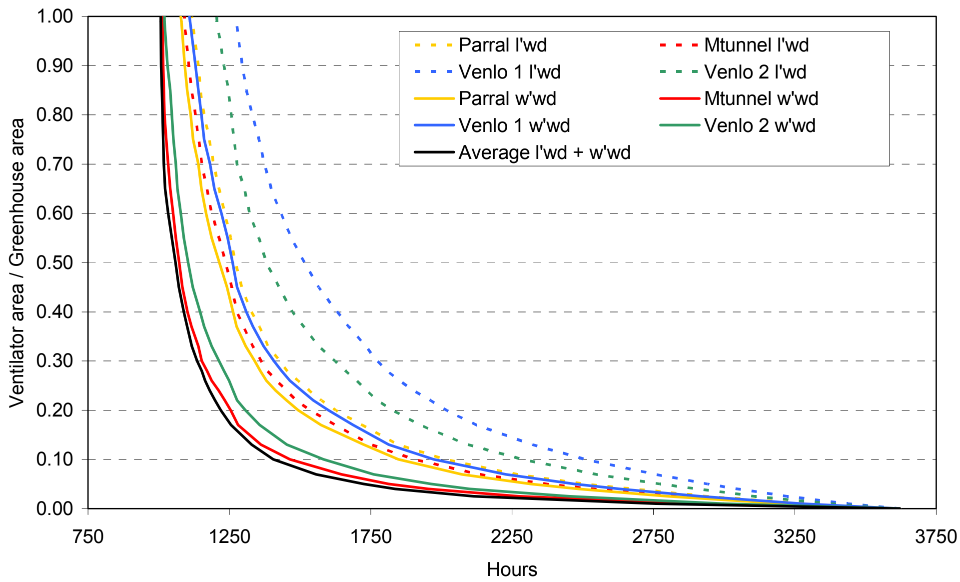


Fig. 43. Performance comparison of leeward, windward and combined windward and leeward ventilation.

Figure 43 shows clearly that combining leeward with windward ventilation gives the highest performance since it requires the smallest ventilator area. Leeward ventilation is the least effective and windward ventilation is better than leeward but not effective as combined leeward and windward ventilation. It is also clear that there are large variations in the predictions of different models, for both leeward and windward ventilation. Consequently, it is only possible to conclude that for the same ventilator area using combined leeward and windward ventilation gives the highest ventilation rate, followed by windward ventilation, with leeward ventilation giving the lowest ventilation rate.

When ventilation is first required in a glasshouse it is common practice for the ventilators on the leeward side of the roof to be opened first and for those on the windward side to be opened when the leeward vents do not provide sufficient cooling. With leeward ventilation, the pressure distribution over the greenhouse surface created by the wind causes air to enter through ventilators in the down wind part of the greenhouse and leave via the ventilators in the upwind part. The flow of air inside the greenhouse is in the opposite direction to the external wind. At low wind speeds there are no regions of high air speed in the greenhouse. As the wind speed increases the internal flow increases and in greenhouses with typically 5 or more spans, recirculation of the incoming air can occur in the most down wind span of the greenhouse. This reduces ventilation effectiveness as a region of stagnant air is created between the re-circulating flow and the flow in the remainder of the greenhouse which is in opposite direction. As the greenhouse increases in size to 12, 18 and 24 spans, this region without positive air flow moves away from the down wind part towards the centre of the greenhouse (Kacira et al 2004). The slow removal air from these stagnant areas can lead to increased temperatures.

Appendix – Tables showing the hours that greenhouse ventilation temperatures are exceeded for a range of ventilator areas

Table	Greenhouse location	Ventilation temperature	Shade / no shade
8	Southern Spain	22 °C	No shade
9	"	24 °C	"
10	"	26 °C	"
11	"	22 °C	75% Shade
12	"	24 °C	"
13	"	26 °C	"
14	Netherlands	20 °C	No shade
15	"	22 °C	"
16	"	24 °C	"
17	"	26 °C	"

The shading consists of whitening applied to the greenhouse roof and reduces the greenhouse transmissivity to 25% during the period July to September inclusive.

Table 8

Ventilation temperature 22 C

Almeria 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	3	5	19	214	372	584	663	420	151	3	2	2436
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	244	227	322	328	396	394	425	420	346	306	248	230	3886
0.005	183	193	266	281	369	387	407	400	321	278	213	180	3478
0.010	149	176	240	256	354	383	406	390	310	263	197	146	3270
0.025	85	146	195	203	323	367	399	372	297	237	157	93	2874
0.050	30	110	127	158	302	351	388	366	284	220	111	39	2486
0.075	6	82	82	126	290	344	386	364	278	201	79	20	2258
0.100	1	71	59	104	286	341	383	363	277	192	65	11	2153
0.120	0	60	49	96	281	339	380	362	268	189	49	7	2080
0.140	0	54	39	91	276	337	380	360	263	188	43	5	2036
0.160	0	47	31	91	273	334	378	359	260	185	37	5	2000
0.180	0	42	25	89	265	331	376	358	259	185	34	5	1969
0.200	0	38	24	84	263	326	373	357	258	183	34	4	1944
0.225	0	32	20	79	259	324	372	352	258	181	30	4	1911
0.250	0	31	20	76	259	322	370	347	253	175	29	4	1886
0.275	0	29	20	75	256	318	368	344	251	173	29	4	1867
0.300	0	29	19	73	255	316	367	339	251	171	29	4	1853
0.333	0	27	19	71	255	313	365	334	245	168	29	4	1830
0.367	0	27	18	71	253	309	362	329	238	167	29	4	1807
0.400	0	27	18	70	250	305	361	321	233	163	29	3	1780
0.450	0	27	18	70	249	304	356	317	230	160	29	3	1763
0.500	0	27	18	70	249	303	352	312	226	160	29	3	1749
0.550	0	27	18	70	248	300	347	309	222	159	29	3	1732
0.600	0	27	18	70	248	296	342	304	220	158	29	3	1715
0.700	0	27	18	70	247	290	333	294	218	157	29	3	1686
0.800	0	27	18	70	247	290	328	287	215	157	29	3	1671
0.900	0	27	18	70	247	288	326	285	214	156	29	3	1663
1.000	0	27	18	70	242	286	317	280	212	156	29	3	1640

Table 9

Ventilation temperature 24 C

Almeria 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	0	120	274	438	505	269	59	0	0	1665
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	225	218	304	316	385	388	406	406	329	296	238	222	3733
0.005	165	180	247	265	354	382	401	390	311	260	203	158	3316
0.010	124	164	219	234	334	372	395	373	297	238	175	122	3047
0.025	52	118	144	164	291	341	380	359	272	200	120	57	2498
0.050	3	73	70	108	270	324	375	349	258	167	57	13	2067
0.075	0	52	41	77	241	320	369	346	251	156	22	4	1879
0.100	0	32	20	63	230	313	365	345	243	150	13	2	1776
0.120	0	21	13	53	223	310	360	344	242	140	6	2	1714
0.140	0	17	10	46	214	305	358	343	239	134	4	2	1672
0.160	0	11	7	39	210	302	357	340	237	125	3	0	1631
0.180	0	8	6	35	205	300	355	335	233	121	0	0	1598
0.200	0	7	5	32	201	296	353	331	231	118	0	0	1574
0.225	0	7	4	29	197	294	350	327	225	114	0	0	1547
0.250	0	6	4	28	197	291	345	320	221	112	0	0	1524
0.275	0	4	4	27	196	287	345	313	217	109	0	0	1502
0.300	0	4	4	27	194	285	343	306	210	109	0	0	1482
0.333	0	4	4	27	192	282	339	296	205	109	0	0	1458
0.367	0	4	4	27	187	278	335	289	204	109	0	0	1437
0.400	0	4	4	27	184	276	332	284	201	107	0	0	1419
0.450	0	4	4	27	184	276	322	280	200	106	0	0	1403
0.500	0	4	4	27	184	274	322	276	198	106	0	0	1395
0.550	0	4	4	27	183	271	316	271	196	104	0	0	1376
0.600	0	4	4	27	183	266	309	263	194	103	0	0	1353
0.700	0	4	4	27	182	263	300	257	190	101	0	0	1328
0.800	0	4	4	27	181	263	294	252	189	101	0	0	1315
0.900	0	4	4	27	180	262	294	250	189	101	0	0	1311
1.000	0	4	4	27	180	262	283	244	189	101	0	0	1294

Table 10

Ventilation temperature 26 C

Almeria 2007 weather

No shading

Vent area / g'house area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	0	52	138	324	373	140	9	0	0	1036
	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	209	211	287	306	378	386	403	397	321	284	228	212	3622
0.005	154	172	235	247	341	363	397	371	292	238	188	140	3138
0.010	96	146	197	201	306	348	391	357	274	210	149	99	2774
0.025	17	89	99	126	267	313	362	342	240	162	74	25	2116
0.050	0	45	33	64	222	301	349	334	226	133	14	2	1723
0.075	0	18	9	37	196	280	341	327	210	103	4	0	1525
0.100	0	5	4	21	175	268	337	323	199	76	0	0	1408
0.120	0	2	3	14	164	256	337	320	189	68	0	0	1353
0.140	0	0	2	4	148	247	335	312	187	61	0	0	1296
0.160	0	0	0	2	139	243	332	310	183	55	0	0	1264
0.180	0	0	0	2	135	239	331	307	180	54	0	0	1248
0.200	0	0	0	0	131	235	328	301	178	51	0	0	1224
0.225	0	0	0	0	129	230	327	295	169	45	0	0	1195
0.250	0	0	0	0	128	227	325	290	164	42	0	0	1176
0.275	0	0	0	0	128	220	323	284	159	41	0	0	1155
0.300	0	0	0	0	124	216	321	277	156	39	0	0	1133
0.333	0	0	0	0	123	215	316	275	153	38	0	0	1120
0.367	0	0	0	0	120	214	308	269	150	38	0	0	1099
0.400	0	0	0	0	118	214	305	264	148	38	0	0	1087
0.450	0	0	0	0	117	212	301	258	146	38	0	0	1072
0.500	0	0	0	0	115	211	298	253	145	36	0	0	1058
0.550	0	0	0	0	115	211	293	247	144	36	0	0	1046
0.600	0	0	0	0	115	209	290	241	142	36	0	0	1033
0.700	0	0	0	0	114	207	284	237	141	36	0	0	1019
0.800	0	0	0	0	114	207	281	234	141	36	0	0	1013
0.900	0	0	0	0	113	207	280	232	141	36	0	0	1009
1.000	0	0	0	0	113	207	277	232	141	36	0	0	1006

Table 11

Ventilation temperature 22 C

Almeria 2007 weather

Whitening - 25% transmission, July - Sept inclusive

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	3	5	19	214	372	584	663	420	151	3	2	2436
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	244	227	322	328	396	394	407	414	328	306	248	230	3844
0.005	183	193	266	281	369	387	388	373	286	278	213	180	3397
0.010	149	176	240	256	354	383	375	358	257	263	197	146	3154
0.025	85	146	195	203	323	367	349	323	221	237	157	93	2699
0.050	30	110	127	158	302	351	334	309	197	220	111	39	2288
0.075	6	82	82	126	290	344	330	302	185	201	79	20	2047
0.100	1	71	59	104	286	340	325	296	176	192	65	11	1926
0.120	0	59	49	96	282	338	324	293	171	188	49	7	1856
0.140	0	53	39	91	277	337	320	281	165	187	43	5	1798
0.160	0	46	31	91	275	334	316	275	159	185	37	5	1754
0.180	0	41	25	89	268	331	315	269	150	185	34	5	1712
0.200	0	37	24	84	266	330	312	259	144	183	34	4	1677
0.225	0	31	20	79	261	328	310	250	135	181	31	4	1630
0.250	0	30	20	76	261	326	302	245	126	177	30	4	1597
0.275	0	28	20	74	256	321	292	239	124	175	30	4	1563
0.300	0	28	19	72	255	320	290	233	120	174	30	4	1545
0.333	0	26	19	69	254	318	277	220	117	171	29	4	1504
0.367	0	26	17	68	252	315	264	212	114	169	29	4	1470
0.400	0	26	17	67	249	306	254	199	109	166	29	3	1425
0.450	0	26	17	67	249	303	244	186	107	164	29	3	1395
0.500	0	25	17	67	249	301	237	180	101	164	29	3	1373
0.550	0	24	17	67	249	298	231	175	100	161	29	3	1354
0.600	0	24	17	67	249	295	229	174	99	160	29	3	1346
0.700	0	23	17	67	247	291	221	170	99	159	29	3	1326
0.800	0	23	17	67	246	290	220	169	99	158	29	3	1321
0.900	0	23	17	67	246	288	218	168	99	157	29	3	1315
1.000	0	23	17	67	244	286	214	168	99	157	29	3	1307

Table 12

Ventilation temperature 24 C

Almeria 2007 weather

Whitening - 25% transmission, July - Sept inclusive

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	0	120	274	438	505	269	59	0	0	1665
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	225	218	304	316	385	388	392	384	310	296	238	222	3678
0.005	165	180	247	265	354	382	370	351	254	260	203	158	3189
0.010	124	164	219	234	334	372	353	330	221	238	175	122	2886
0.025	52	118	144	164	291	341	326	304	186	200	120	57	2303
0.050	3	73	70	108	270	324	317	286	165	167	57	13	1853
0.075	0	52	41	77	241	320	311	277	150	156	22	4	1651
0.100	0	32	20	63	230	313	309	275	137	150	13	2	1544
0.120	0	21	13	53	223	310	306	266	131	140	6	2	1471
0.140	0	17	10	46	215	305	299	261	123	134	4	2	1416
0.160	0	11	7	39	210	302	295	250	114	125	3	0	1356
0.180	0	8	6	35	205	301	289	238	103	120	0	0	1305
0.200	0	8	5	32	202	298	284	229	98	117	0	0	1273
0.225	0	7	4	29	199	296	276	227	91	112	0	0	1241
0.250	0	6	4	28	199	293	269	219	85	111	0	0	1214
0.275	0	4	4	27	198	291	264	213	80	109	0	0	1190
0.300	0	4	4	27	196	288	259	203	76	109	0	0	1166
0.333	0	4	4	27	196	284	250	198	73	107	0	0	1143
0.367	0	4	4	27	193	280	238	184	69	107	0	0	1106
0.400	0	4	4	27	189	280	232	178	68	106	0	0	1088
0.450	0	4	4	27	189	279	228	167	64	106	0	0	1068
0.500	0	4	4	27	188	277	223	163	63	105	0	0	1054
0.550	0	4	4	27	188	271	221	161	63	103	0	0	1042
0.600	0	4	4	27	188	268	217	159	63	103	0	0	1033
0.700	0	4	4	27	188	266	212	156	63	103	0	0	1023
0.800	0	4	4	27	188	265	208	156	63	103	0	0	1018
0.900	0	4	4	27	187	264	203	156	63	103	0	0	1011
1.000	0	4	4	27	187	263	199	155	63	103	0	0	1005

Table 13

Ventilation temperature 26 C

Almeria 2007 weather

Whitening - 25% transmission, July - Sept inclusive

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	0	52	138	324	373	140	9	0	0	1036
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	210	211	287	306	378	386	386	362	282	284	228	212	3532
0.005	154	172	235	247	341	363	347	332	220	238	188	140	2977
0.010	96	146	197	201	306	348	331	303	187	210	149	99	2573
0.025	17	89	99	126	267	313	305	270	137	162	74	25	1884
0.050	0	45	33	64	222	301	286	250	107	133	14	2	1457
0.075	0	18	9	37	196	280	275	241	87	103	4	0	1250
0.100	0	5	4	21	175	268	268	232	76	76	0	0	1125
0.120	0	2	3	14	164	257	261	224	70	68	0	0	1063
0.140	0	0	2	4	149	250	258	216	67	61	0	0	1007
0.160	0	0	0	2	139	248	256	207	63	54	0	0	969
0.180	0	0	0	2	135	244	251	195	55	53	0	0	935
0.200	0	0	0	0	131	240	249	190	51	50	0	0	911
0.225	0	0	0	0	129	233	242	179	49	44	0	0	876
0.250	0	0	0	0	127	227	238	171	46	42	0	0	851
0.275	0	0	0	0	126	222	233	163	44	40	0	0	828
0.300	0	0	0	0	122	219	227	153	43	38	0	0	802
0.333	0	0	0	0	122	218	213	144	41	35	0	0	773
0.367	0	0	0	0	120	217	208	127	40	34	0	0	746
0.400	0	0	0	0	119	217	202	125	40	33	0	0	736
0.450	0	0	0	0	118	216	194	114	40	33	0	0	715
0.500	0	0	0	0	117	213	192	113	40	33	0	0	708
0.550	0	0	0	0	116	212	190	113	40	32	0	0	703
0.600	0	0	0	0	116	210	189	112	40	32	0	0	699
0.700	0	0	0	0	115	209	186	112	40	32	0	0	694
0.800	0	0	0	0	115	209	182	112	40	32	0	0	690
0.900	0	0	0	0	115	209	177	111	40	32	0	0	684
1.000	0	0	0	0	115	209	174	111	40	32	0	0	681

Table 14

Ventilation temperature 20 C

Netherlands 2007 weather

No shading

Vent area / g'house area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	98	58	158	130	159	15	0	0	0	618
	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	39	77	205	341	358	398	403	365	274	190	74	29	2753
0.005	6	23	135	306	310	365	368	333	225	138	12	0	2221
0.010	0	6	90	277	266	338	345	312	193	108	1	0	1936
0.025	0	0	41	222	211	284	299	286	144	64	0	0	1551
0.050	0	0	15	169	166	256	256	260	96	34	0	0	1252
0.075	0	0	3	146	130	234	225	239	74	20	0	0	1071
0.100	0	0	0	131	118	220	202	223	67	11	0	0	972
0.120	0	0	0	125	109	209	193	218	62	4	0	0	920
0.140	0	0	0	124	97	204	184	209	51	2	0	0	871
0.160	0	0	0	122	96	198	179	204	47	2	0	0	848
0.180	0	0	0	117	93	196	175	201	43	2	0	0	827
0.200	0	0	0	117	90	191	173	196	42	2	0	0	811
0.225	0	0	0	114	89	191	169	193	39	2	0	0	797
0.250	0	0	0	113	87	186	167	191	37	1	0	0	782
0.275	0	0	0	111	85	182	164	189	36	0	0	0	767
0.300	0	0	0	110	84	178	164	187	36	0	0	0	759
0.333	0	0	0	110	82	174	163	181	35	0	0	0	745
0.367	0	0	0	110	82	172	160	178	35	0	0	0	737
0.400	0	0	0	110	82	170	158	177	35	0	0	0	732
0.450	0	0	0	109	81	166	156	174	35	0	0	0	721
0.500	0	0	0	109	80	165	151	173	35	0	0	0	713
0.550	0	0	0	109	80	164	147	171	34	0	0	0	705
0.600	0	0	0	108	80	164	147	171	34	0	0	0	704
0.700	0	0	0	108	80	161	147	170	34	0	0	0	700
0.800	0	0	0	107	80	159	147	170	34	0	0	0	697
0.900	0	0	0	105	80	159	147	170	34	0	0	0	695
1.000	0	0	0	104	80	159	147	170	34	0	0	0	694

Table 15

Ventilation temperature 22 C

Netherlands 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	63	19	63	64	73	3	0	0	0	285
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	31	63	197	331	347	383	388	346	262	179	57	20	2604
0.005	1	16	109	289	273	324	340	309	197	121	2	0	1981
0.010	0	2	69	261	237	290	302	284	155	78	0	0	1678
0.025	0	0	20	183	165	239	236	242	91	38	0	0	1214
0.050	0	0	1	129	115	191	176	189	45	10	0	0	856
0.075	0	0	0	109	85	162	145	164	28	3	0	0	696
0.100	0	0	0	97	71	150	130	151	15	1	0	0	615
0.120	0	0	0	96	68	143	114	138	14	1	0	0	574
0.140	0	0	0	88	64	130	109	130	12	0	0	0	533
0.160	0	0	0	87	61	125	105	123	10	0	0	0	511
0.180	0	0	0	82	61	124	104	117	9	0	0	0	497
0.200	0	0	0	80	61	123	102	114	9	0	0	0	489
0.225	0	0	0	78	57	119	101	111	9	0	0	0	475
0.250	0	0	0	75	55	116	101	111	8	0	0	0	466
0.275	0	0	0	70	54	115	98	108	8	0	0	0	453
0.300	0	0	0	69	53	112	95	105	8	0	0	0	442
0.333	0	0	0	68	53	111	91	103	8	0	0	0	434
0.367	0	0	0	68	53	110	90	101	8	0	0	0	430
0.400	0	0	0	67	53	108	86	101	8	0	0	0	423
0.450	0	0	0	67	52	108	83	101	8	0	0	0	419
0.500	0	0	0	67	52	107	80	99	8	0	0	0	413
0.550	0	0	0	67	52	106	79	98	8	0	0	0	410
0.600	0	0	0	67	52	104	79	98	8	0	0	0	408
0.700	0	0	0	67	52	102	78	97	8	0	0	0	404
0.800	0	0	0	67	52	102	78	97	8	0	0	0	404
0.900	0	0	0	67	52	102	78	97	8	0	0	0	404
1.000	0	0	0	67	52	99	78	97	8	0	0	0	401

Table 16

Ventilation temperature 24 C

Netherlands 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	41	5	27	19	30	0	0	0	0	122
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	23	59	184	322	330	360	375	334	239	167	39	14	2446
0.005	0	7	89	269	253	292	309	283	162	97	1	0	1762
0.010	0	0	50	230	198	251	262	257	126	61	0	0	1435
0.025	0	0	7	144	123	183	168	182	47	17	0	0	871
0.050	0	0	0	94	69	127	115	130	13	3	0	0	551
0.075	0	0	0	76	48	109	83	99	6	0	0	0	421
0.100	0	0	0	64	37	90	67	83	3	0	0	0	344
0.120	0	0	0	59	29	82	56	76	3	0	0	0	305
0.140	0	0	0	58	22	75	53	65	2	0	0	0	275
0.160	0	0	0	53	21	67	46	62	1	0	0	0	250
0.180	0	0	0	52	21	62	43	55	1	0	0	0	234
0.200	0	0	0	49	20	58	43	53	1	0	0	0	224
0.225	0	0	0	47	20	54	41	51	1	0	0	0	214
0.250	0	0	0	47	20	52	41	50	1	0	0	0	211
0.275	0	0	0	47	20	51	40	50	1	0	0	0	209
0.300	0	0	0	47	20	50	39	50	1	0	0	0	207
0.333	0	0	0	47	19	50	37	49	1	0	0	0	203
0.367	0	0	0	46	18	49	35	48	1	0	0	0	197
0.400	0	0	0	46	18	47	34	48	1	0	0	0	194
0.450	0	0	0	46	17	47	33	47	1	0	0	0	191
0.500	0	0	0	46	17	46	32	46	1	0	0	0	188
0.550	0	0	0	46	17	46	32	46	1	0	0	0	188
0.600	0	0	0	46	17	45	32	46	1	0	0	0	187
0.700	0	0	0	46	16	43	32	46	1	0	0	0	184
0.800	0	0	0	46	16	42	32	46	1	0	0	0	183
0.900	0	0	0	46	16	42	32	46	1	0	0	0	183
1.000	0	0	0	46	16	42	32	46	1	0	0	0	183

Table 17

Ventilation temperature 26 C

Netherlands 2007 weather

No shading

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
	Hours when external temperature is higher than ventilation temperature												
	0	0	0	18	0	10	8	11	0	0	0	0	47
Vent area / g'house area	Hours when greenhouse temperature is higher than ventilation temperature												
0.000	18	49	174	313	319	348	358	321	222	152	32	10	2316
0.005	0	3	75	255	217	264	282	267	140	76	1	0	1580
0.010	0	0	32	195	166	223	212	217	85	40	0	0	1170
0.025	0	0	1	104	88	134	117	132	17	5	0	0	598
0.050	0	0	0	61	39	83	55	80	5	0	0	0	323
0.075	0	0	0	46	24	64	30	51	0	0	0	0	215
0.100	0	0	0	41	17	42	21	37	0	0	0	0	158
0.120	0	0	0	40	14	35	19	32	0	0	0	0	140
0.140	0	0	0	39	14	33	17	29	0	0	0	0	132
0.160	0	0	0	36	11	30	17	28	0	0	0	0	122
0.180	0	0	0	34	9	28	16	25	0	0	0	0	112
0.200	0	0	0	34	8	27	15	24	0	0	0	0	108
0.225	0	0	0	33	7	25	15	23	0	0	0	0	103
0.250	0	0	0	33	6	24	15	23	0	0	0	0	101
0.275	0	0	0	33	6	24	14	22	0	0	0	0	99
0.300	0	0	0	33	5	23	14	21	0	0	0	0	96
0.333	0	0	0	33	5	21	14	20	0	0	0	0	93
0.367	0	0	0	32	5	21	13	19	0	0	0	0	90
0.400	0	0	0	32	5	21	13	19	0	0	0	0	90
0.450	0	0	0	32	5	20	11	19	0	0	0	0	87
0.500	0	0	0	31	5	20	11	19	0	0	0	0	86
0.550	0	0	0	31	5	20	11	19	0	0	0	0	86
0.600	0	0	0	31	5	20	11	19	0	0	0	0	86
0.700	0	0	0	31	5	20	11	19	0	0	0	0	86
0.800	0	0	0	31	5	20	11	19	0	0	0	0	86
0.900	0	0	0	31	5	20	11	19	0	0	0	0	86
1.000	0	0	0	31	5	20	11	19	0	0	0	0	86

2.2 A Decision Support System for the calculation of ventilation rate in obstructed and unobstructed greenhouses.

2.2.1. Ventilation in obstructed greenhouses.

Greenhouse ventilation can be strongly affected by the existence of a windward obstruction, which can produce a significant change on the air pattern and pressure field around the greenhouse. This situation is typical from dense growing areas where greenhouses are located very close to each other.

One of the tasks of the Euphoros project is the "Development of distance indicators for optimal ventilation in presence of neighbouring/greenhouses. To undertake this task a number of actions have been taken:

1. Use a simplified model for the calculation of ventilation rate of unobstructed greenhouses.
2. Run CFD simulations to determine a set of "adjustment functions" that relates the ventilation rate of the obstructed and unobstructed greenhouse with the distance between them.
3. Apply the "adjustment functions" to the ventilation rate obtained by the simplified model. This allows knowing the ventilation of the obstructed greenhouse.
4. Develop a user friendly spreadsheet with the simplified ventilation model and the adjustment functions

2.2.2 Ventilation model

The flow of air is created by the difference between the inside and outside temperatures and by the external wind. In most occasions wind driven ventilation overrides thermally induced ventilation and therefore most simplified models only consider wind driven ventilation. A general equation to calculate ventilation rate was given by de Jong, (1990) among others (Eqn 1) in which it is assumed that half of the ventilators are inlet air and the other half outlet air.

$$\Phi = \frac{S}{2} C_d \, C_w^{1/2} \, u \qquad \text{Eqn. 1}$$

Where ϕ is the total inlet or outlet greenhouse air flow (m^3/s), S is the total greenhouse ventilator area (m2), C_d is the discharge coefficient of ventilators (dimensionless) C_w is the global wind pressure coefficient (dimensionless) and u is the outside air wind speed (m/s). Suitable values for discharge coefficients of ventilators as a function of their aspect ratio (length divided by height) can be found in literature (Perez-Parra et al, 2004).

In many occasions greenhouses in warm areas use insect-proof screens to protect crops from insect invasion. Insect-proof screens create a drop in pressure which leads to a significant ventilation reduction with associated high temperature risks. A simplified equation that accounts for ventilation reduction as a function of screen porosity was given by Perez-Parra el al (2004)

$$\phi_{sc}/\phi = \varepsilon\,(2-\varepsilon) \qquad \text{Eqn 2}$$

Where ϕ_s is the ventilation flux of screened greenhouses, ϕ is that of the unscreened greenhouse and ε is the screen porosity.

Eqns 1 and 2 were used for the calculation of ventilation rate of unobstructed greenhouses.

2.2.3. Adjustment functions.

This task was undertaken by running CFD analysis on two groups of multi span greenhouses. The distance between both greenhouses was increased from D=2m to D= 60 m (Figure 44). In this report we will call greenhouse A to the one on the windward side (unobstructed greenhouse) and B to the one on the leeward side (obstructed greenhouse)

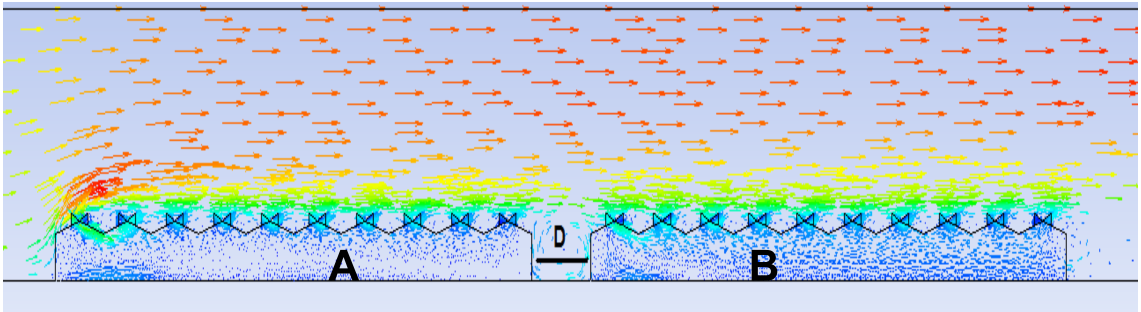


Figure 44. Scheme of greenhouses A and B separated a distance D.

Two different greenhouse structures were included in this analysis: double sided roof ventilators and single sided roof ventilators.

Figure 45. Double sided and single sided roof vents.

For each type of greenhouse structure four case studies were simulated:

- Five span greenhouses with roof vents open and side vents open
- Five span greenhouses with with roof vents open and side vents closed.
- Ten span greenhouses with roof vents open and side vents open

- Ten span greenhouses with roof vents open and side vents closed.

This produced a total of four case studies for each greenhouse type (double sided and single sided roof vents). For each case study the distance D was increased and the ventilation rate of greenhouse B was compared to that of the greenhouse A, which was considered as the reference ventilation rate.

Figure 46 refers to the case study of the ten-span greenhouse and side ventilators open. It can be seen that there was a strong correlation between distance D and ventilation rate. For all case studies a statistical regression such as the one shown in Figure 3 were produced and later implemented in the spreadsheet for adjusting the ventilation of the unobstructed greenhouse.

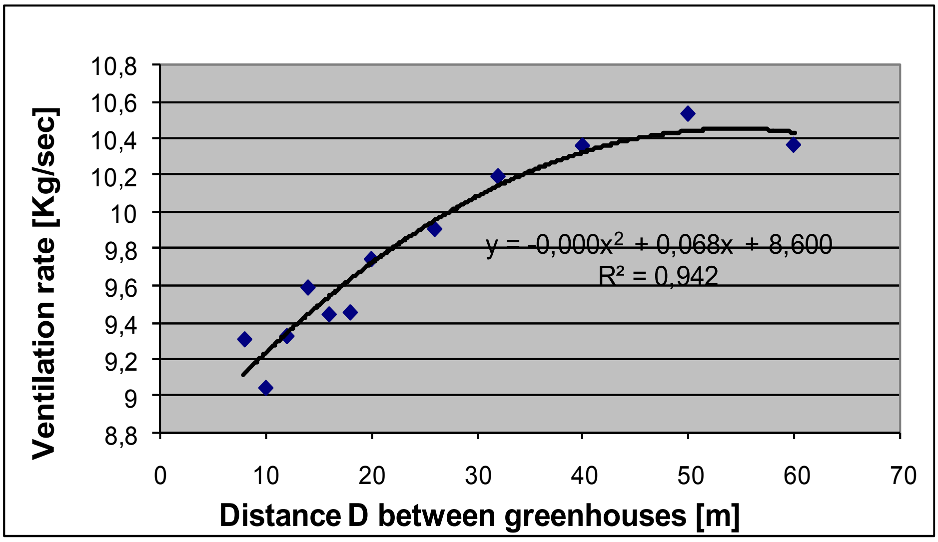


Figure 46. Ventilation rate of greenhouse B as a function of its distance to obstruction A. Ten-span greenhouse and side ventilators open.

As a general conclusion it can be said that the negative effect of the obstruction is much lower for the double sided than for the single sided vent structure: if the greenhouse has very good ventilation the distance to the windward obstruction does not produce a big reduction in the ventilation rate. On the other side, for single sided vent greenhouses even for a distance D as high as 60 m. the ventilation reduction could be nearly 50% that of the reference greenhouse. This study reinforces the need of having big ventilator surface for proper climate management in greenhouse clusters.

2.2.4. User friendly spreadsheet.

After a short introduction the Excel file includes three sheets. The first sheet requires entering the following data:

1. Greenhouse geometry: number of spans, span width and length, gutter and ridge height.
2. Opening characteristics: number of roof vents, number of side vents, dimensions of roof and side vents, insect-proof screen porosity.
3. Wind speed and direction (windward and leeward direction. Other cases are not considered)
4. Distance between greenhouses.

The user has to choose the type of greenhouse structure: double sided or single sided roof vents. Then, firstly the ventilation of the unobstructed greenhouse is calculated. Secondly the ventilation of the obstructed greenhouse is considered by applying a correction factor which depends on the distance between the obstructed and the unobstructed greenhouses. After this, results are presented on two separated sheets for the double sided and single sided greenhouses.

By changing the ventilator size and ventilation parameters the user can find a suitable combination of ventilators to compensate the effect of the windward obstruction. The main final output is the number of air exchanges per hour. Following good engineering practises it is desirable to keep ventilation rate above 30 Volumes per hour under sunny conditions. When ventilation rate is below 30 Vols/hr a warning message is issued, so that the spreadsheet can help to detect potential situations of excessive heat.

2.3 Identification of periods of zero greenhouse ventilation

The HortiAlmeria greenhouse heat and mass transfer simulation model was used with a weather data set for 2007 for Almeria, southern Spain to identify the conditions when there was finite solar radiation, but zero ventilation. Using the hourly weather data for the complete year it was found there were upper limits to solar radiation and external air temperature below which ventilation was not necessary for temperature control, Fig. 47. The external conditions are bounded by a linear relationship.

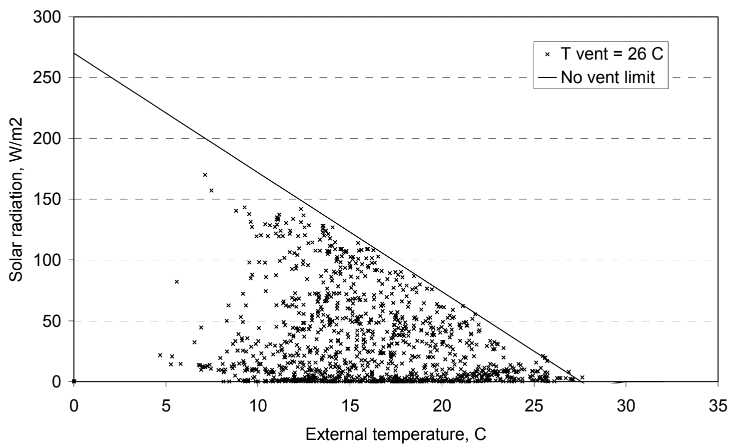


Fig. 47. Solar radiation and external air temperature conditions when greenhouses do not require ventilation; Almeria weather data 2007

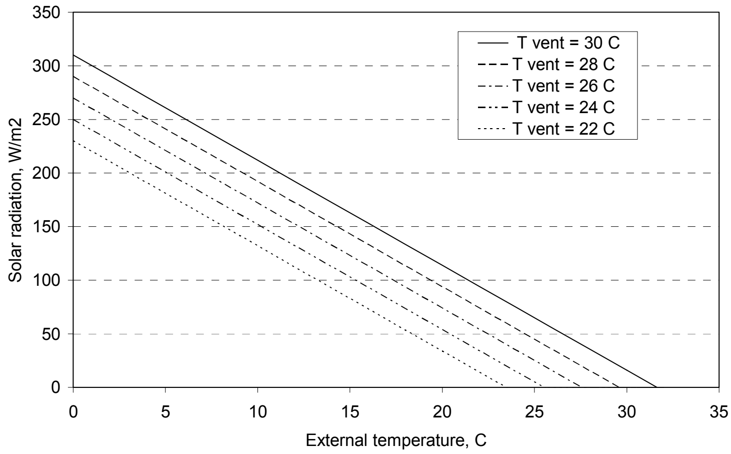


Fig. 48. Limits on solar radiation and external temperature above which greenhouses require ventilation; Almeria weather data 2007.

This relationship also depends on the temperature at which the greenhouse is ventilated and Fig. 48 shows the upper bounds for a range of ventilation temperatures. The upper bound is defined by Eqn (1) for which values of the coefficients α and β are given in Table 18.

$$SR = \alpha - \beta T \quad (1)$$

where SR is the external solar radiation and T the external air temperature. In practical applications the coefficient β can be considered to be independent of temperature and have a constant value of 9.8 W m^{-2} K^{-1}.

Table 18. Coefficients for Eqn (1) defining the upper limits of external solar radiation and air temperature when greenhouses do not require ventilation.

Ventilation temperature	Coefficient α	Coefficient β	Coefficient β in practice
^{o}C	Wm^{-2}	W m^{-2} K^{-1}	W m^{-2} K^{-1}
30	310	10.0	}
28	290	9.9	}
26	270	9.8	} 9.8
24	250	9.7	}
22	230	9.6	}

The times when zero ventilation occurs during the day are concentrated in the periods just after and just before sunrise and sunset respectively. Table 19 shows the hours of the day for which there is finite solar radiation and zero ventilation.

Table 19. Hours of the day with finite solar radiation and zero ventilation (ventilation temperature 26 ^{o}C)

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	3	0	0	0	0	0	3
4	0	0	0	0	0	0	0	0	1	1	0	0	2
5	0	0	0	17	31	30	28	29	5	0	0	0	140
6	0	2	31	25	6	1	1	0	26	30	8	28	158
7	30	28	11	7	0	0	0	0	1	11	30	20	138
8	27	8	0	4	0	0	0	0	0	1	6	3	49
9	5	5	0	2	1	0	0	0	0	1	2	1	17
10	0	2	1	1	0	0	0	0	0	0	1	0	5
11	0	2	0	0	0	0	0	0	0	1	0	1	4
12	0	2	0	0	0	0	0	0	0	1	0	1	4
13	1	2	2	0	0	0	0	0	0	0	1	2	8
14	1	2	0	0	0	0	0	0	0	0	1	6	10
15	3	5	1	0	0	0	0	0	1	1	1	29	41
16	25	8	2	3	0	0	0	0	2	6	25	2	73
17	22	27	26	9	1	0	0	0	6	27	8	0	126
18	0	0	24	29	11	2	0	4	20	0	0	0	90
19	0	0	0	0	15	30	29	8	0	0	0	0	82
20	0	0	0	20	0	0	0	0	0	0	0	0	20

21	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0
Month	114	93	98	117	65	63	61	41	62	80	83	93	970

2.4 Calculation of the optimal co$_2$ supply rate

The flow of supplied CO_2, *S*, must balance the CO_2 that is assimilated, *A*, and the CO_2 that is lost to the external ambient, *V*:

$$S = A + V = f\left(I_{sun}, CO_{2,in}\right) + g_V\left(CO_{2,in} - CO_{2,out}\right) \qquad \text{mg m}^{-2}\text{ s}^{-1} \text{ (1)}$$

where g_V is the volume exchange by ventilation, per unit surface area of the greenhouse, m^3 m^{-2} s^{-1}, that is: m s^{-1}, and CO_2 is the CO_2 concentration, mg m^{-3}, *in*side and *out*side, respectively. Since *n* volume changes per hour means replacing in one hour as many cubic meters as the mean height, *h*, of the greenhouse, for each square meter of floor area, $g_V = n \cdot h/3600$.

The assimilation rate is a function *f* of sun radiation, I_{sun} and inside carbon dioxide concentration. For the purpose of this work we have selected a simple two-variables model that does reproduce the trend and the level of the more complex model proposed by Nederhoff (1994):

$$A = f\left(I_{sun}, CO_{2,in}\right) = 2.2 \frac{1}{1 + \dfrac{230}{CO_{2,in}}} \left[1 - \exp\left(-0.0015 I_{sun}\right)\right] \qquad \text{mg m}^{-2}\text{ s}^{-1} \text{ (2)}$$

where CO_2 is the ambient carbon dioxide concentration, here in in vpm and I_{sun} is the photon flux density of Photosynthetically Active Radiation (PAR), μmol m^{-2} s^{-1}. For sun radiation, I_{sun} can be estimated as twice the value of sun radiation in W m^{-2}, if one prefers to use sun radiation in W/m^2 then the coefficient is obviously 0.003 instead of 0.0015. Avogadro's law gives the conversion from volume to mass: in the case of CO_2, 1 vpm ≅ 2 mg m^{-3}. 2.2 mg m^{-2} s^{-1} is the "maximal" assimilation rate of a tomato crop, according to Nederhooff's extensive measurements in commercial farms, which may be reduced by suboptimal values of radiation and/or carbon dioxide. Both factors of eq(2) are always less than unity.

The worth of 1 kg assimilated CO_2 can be calculated as follows: the conversion efficiency of CO_2 fixation into dry matter is about 70% and the ratio of molecular weights of CH_2O and CO_2 is 68%, which means that each kg assimilated CO_2 yields about 500 g dry matter (Stanghellini and Heuvelink, 2007). The value of each kg dry matter depends obviously on the crop, its value and harvest index. It will be indicated in the following as P_{yield} and its units are €/kg of dry matter.

Thanks to the ongoing implementation of the Kyoto protocol into a system for trading emission rights, current world prices of bottled or piped CO_2, P_{CO2}, are between 0.1 and 0.2 €/kg of carbon dioxide, which is comparable to the cost of producing carbon dioxide by burning gas (as done in the heated greenhouses of Northern Europe, for instance).

The optimal concentration of carbon dioxide is then the one that maximizes profit, which is the value of assimilated CO_2 minus the cost of the supply. Indeed, maximizing the profit implies that supply should be modulated in order to maintaining the internal carbon dioxide concentration that ensures that the value of *A* minus the cost of *S* is maximal:

$$0.5P_{yield}\,A - P_{CO_2}S = \left(0.5P_{yeld} - P_{CO_2}\right)f\left(I_{sun}, CO_{2,in}\right) - P_{CO_2}g_V\left(CO_{2,in} - CO_{2,out}\right) \Rightarrow MAX \qquad \text{€ m}^{-2} \quad (3)$$

Where obviously if *A* and *S* are in mg m^{-2} s^{-1}, the prices must be €/mg and CO_2 must be in mg m^{-3}. Taking into account that 230 vpm = about 460 mg m^{-3} and substituting:

$$F_I = 2.2\left[1 - \exp\left(-0.0015 I_{sun}\right)\right] \quad \text{and} \quad 0.5P_{yield} - P_{CO_2} = R\,P_{CO_2}$$

$$\frac{\partial}{\partial CO_{2,in}} P_{CO_2}\left[R\frac{F_I}{1+\dfrac{460}{CO_{2,in}}} - g_V\left(CO_{2,in} - CO_{2,out}\right)\right] = 0$$

$$R\,F_I\frac{460}{\left(CO_{2,in} + 460\right)^2} - g_V = 0$$

$$460\,R\,F_I - g_V\left(CO_{2,in} + 460\right)^2 = 0$$

$$CO_{2,in} + 460 = x$$

mg m^{-3} (4)

$$x = sqrt\frac{460\,R\,F_I}{g_V}$$

$$CO_{2,in,OPT} = 21.5\sqrt{\frac{R\,F_I}{g_V}} - 460$$

Divide by 2 to transform in vpm.

And the optimal supply is:

$$S_{OPT} = A_{CO_2,in.OPT} + V_{CO_2,in,OPT} = F_I\,\frac{CO_{2,in,OPT}}{CO_{2,in,OPT} + 460} + g_V\left(CO_{2,in,OPT} - CO_{2,out}\right) =$$

$$= F_I\,\frac{21.5\sqrt{\frac{R\,F_I}{g_v}} - 460}{21.5\sqrt{\frac{R\,F_I}{g_v}}} + g_v\left(21.5\sqrt{\frac{R\,F_I}{g_v}} - 460 - CO_{2,out}\right)$$

mg m^{-2} s^{-1} (5)

Rearranging, the optimal supply, in mg m^{-2} s^{-1} is:

$$S_{OPT} = F_I\left(1 - \frac{460}{21.5}\sqrt{\frac{g_v}{R\,F_I}}\right) + 21.5 g_v\sqrt{\frac{R\,F_I}{g_v}} - g_v\left(460 + CO_{2,out}\right) =$$

$$= F_I - g_v\left(460 + CO_{2,out}\right) + 21.5\left(F_I\,g_v\right)^{\frac{1}{2}}\left(R^{\frac{1}{2}} - R^{-\frac{1}{2}}\right) \cong$$ mg m^{-2} s^{-1}(6)

$$\cong F_I - g_v\left(460 + CO_{2,out}\right) + 21.5\left(F_I\,g_v\right)^{\frac{1}{2}} 1.2\ln R$$

The approximation being very good in the range 1< R < 10.

With the outside CO_2 concentration in mg m^{-3}, g_v in m^3 m^{-2} s^{-1} and the prices in € mg^{-1}. The optimal supply will probably need to be limited to be >=0 and the coefficient 2.2 mg m^{-2} s^{-1} of the assimilation rate may be made crop dependent.

PART III

3 POSSIBILITIES FOR USAGE OF SUSTAINABLE ENERGY SOURCES

3.1 Introduction

Across Europe, we can clearly distinguish between two main greenhouse production agro-systems, the “northern or Dutch agro-system”, typical from northern Europe, which requires a great initial investment (in the greenhouse structure and its equipments) and that is characterized by a great energy use (mainly dependent on fossil energy), and the “Mediterranean greenhouse agro system”, characterized by a low investment and a lower energy consumption, which is typical from the Mediterranean basin countries. Between both agro systems, of extreme technological levels, there are different gradations.

In the “Dutch agro system” the productive strategy has been to optimize the greenhouse microclimate, whereas in the Mediterranean countries the adaptation of the crops to sub-optimal climates has prevailed, all of which has meant less yield and in some cases, limited quality, but also lower production costs than in the “Dutch agro system (Castilla, 1994).

There is an increasing concern on the effects on the climate due to the man’s activity and one of the main factors involved in the so called “climate change” is the fossil energy use (Fletcher, 2001). This resource is also limited and more and more difficult and expensive to extract, so its use must be restricted in a near future both due to environmental and economic concerns. This situation affects agriculture, and particularly, intensive horticulture that in some cases (cold climates) involves agricultural systems with high-energy consumptions. In the technified greenhouses of temperate climate areas, such as The Netherlands, horticultural production requires the use of large amounts of energy for maintaining the desired temperature. Traditionally, fossil fuels such as oil, coal or natural gas have been used (Jordbruksverket, 2010b; Taragola, 1996; van der Velden & Verhaegh, 1992). Conventional greenhouses heated by natural gas are estimated to generate 800 ton of CO2ha-1 a-1 (in Dutch conditions). Carlsson-Kanyama (1998) reported emissions of around 4 kg of CO2-eq per kg Dutch or Swedish tomatoes, including emissions from transportation to the retailer and production of fertilisers. However, the increasing cost of fossil energy and the debate on climate issues associated with the use of fossil fuels has intensified the search for alternative ways of heating (Lagerberg & Brown, 1999). Electric energy is also used in substantial amounts in greenhouse horticulture, the two major uses being: i) electricity needed for the operation of technical systems, and ii) electricity used for artificial lighting. The compromise of Dutch growers to improve the energy efficiency in 65 % for the period 1980-2010 has been partially achieved adopting co-generation technology for the glasshouse horticultural production, together with the construction of tighter greenhouses (Bot et al., 2005; Sonneveld & Swinkels, 2005) and the generalization in the use of energy saving (thermal) screens (Tantau, 1998; Campen, 2009).

On the other hand, in mild winter climate greenhouses, such as in the Mediterranean area, the energy question is not so problematic as in temperate climate areas, as the fossil fuel consumption is minimum (Stanhill, 1980), although there is still a certain electricity consumption associated to the irrigation systems, opening and closing of the greenhouse vents and in some cases the energy consumed by the evaporative cooling systems (mainly fog systems), in any case much lower than the heating or cooling requirements of the greenhouse. However, at certain periods quality and yield have problems, and different strategies can be followed to solve this. Some of these strategies (such as heating or active cooling) would involve the use of fossil energy, although more attempts are made on trying to improve the climate in both the warm and cold season with passive systems (improvement of natural ventilation, improvement of light transmission in winter, use of energy saving screens or black mulching, improvement of the greenhouse insulation, etc).

Considering the previous situation, the clear alternatives to lower energy consumption are to use different energy saving techniques (more insulated greenhouses, more transparent covers to use more efficiently the sun light, use of energy saving screens, improving the energy storage capacity of the greenhouse soil by means of mulching, etc.) or to use alterative energy sources. Figure 49 summarizes the renewable energy sources than can be used nowadays in greenhouse horticulture (Source: www.growsave.co.uk):

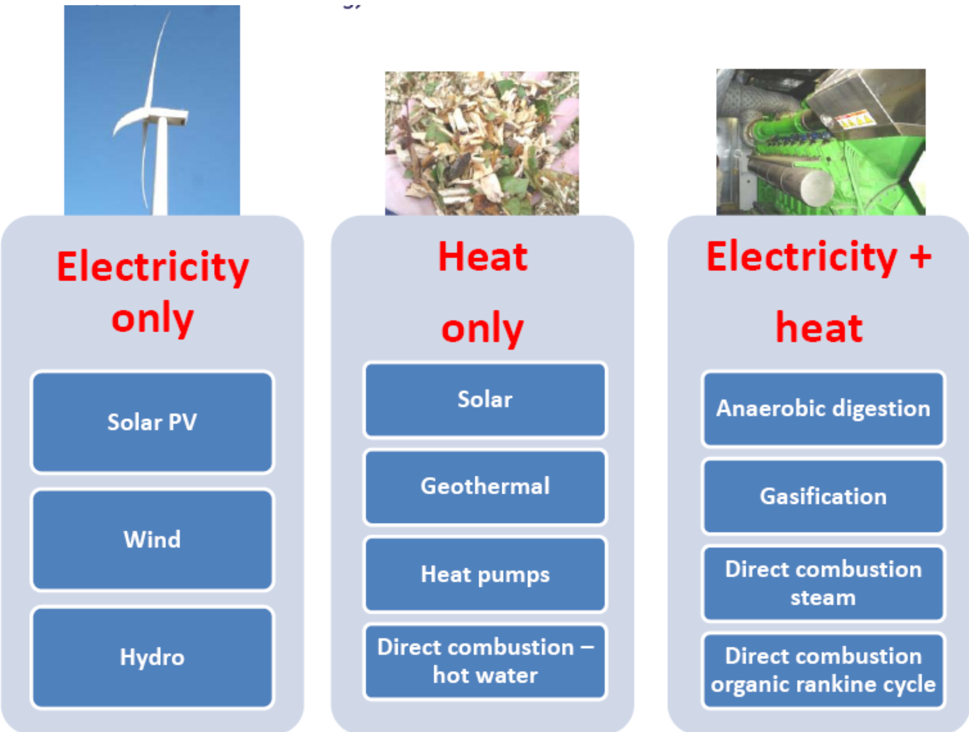


Figure 49. Different sources of renewable energies potentially applicable to cover energy use in greenhouse horticulture

Obviously, the following report will not deal in detail with all the options gathered in Figure 1, but will focus on those that have more options to be applied in any greenhouse despite of its location (i.e. geothermal energy or hydro energy will be an option depending on the greenhouse location close to such sources). Others will not be treated in detail since they have been studied in detail in other parts of the Euphoros project (i.e. Thermal storage of excess sun energy collected from the closed or semi-closed greenhouses). The sector of greenhouse agriculture can contribute to reach the European objectives on energy efficiency and energy saving on the base of three main strategies: i) reduce demand for fossil energy either by increasing renewable energy utilization for cooling and heating or by optimizing plant production and acclimatization technologies; ii) changes in plant production characteristics towards to plant species more local, more seasonal, and based on energy friendlier crop management, in order to save energy for transportation, handling, and plant disease protection; iii) utilization of renewable energy (photovoltaic, solid/residues biomass, geothermic fluids) for acclimatization of greenhouses; iii)contribute to reduce CO2 emissions and to make agriculture more viable and resilient as energies (oil, gas and electricity).

Table 20 shows the advantages of using renewable energy sources instead of traditional sources of fossil energy (Campiotti et al., 2010).

Table 20. Benefits of renewable energy if compared with traditional energy (Campiotti et al., 2010)

Avoiding environmental damages, such as the destructive effects of ecosystems and climate change.
Avoiding the high costs of energy imports.
Increasing the security of energy supply by securing independent and more decentralized energy sources.
Avoiding subsidies for atomic and fossil energies, which amount around 300 billion USD annually world-wide.
Avoiding health damage and fatalities.
Avoiding political, economic and military conflicts over limited fossil fuels.
Providing economic opportunities for new industries and services.
Source: Project INCO 2002-C.1.3 n. 012066.

According to von Zabeltitz (1994) the following questions have to be answered before making decisions about the use of renewable energies for greenhouse energy demands (heating, cooling, etc.):

- How much energy is available from renewable sources in the different seasons?
- How much energy is required in the greenhouse in the different months of the growing season?
- Can this energy be delivered only on certain days, in certain seasons or throughout the year?
- What is the temperature level of the energy?
- What is the expected expenditure for the use of renewable energies?
- What is the amount of energy, which cannot be covered by renewable energies?
- What are the consequences for grower, greenhouse construction and crop cultivation?

In a first analysis we are going to focus on the two most widespread renewable energies sources nowadays, this is, solar PV and wind energy. In principle, they both are electricity-producing energies, so their greenhouse application is subject to the following previous considerations:

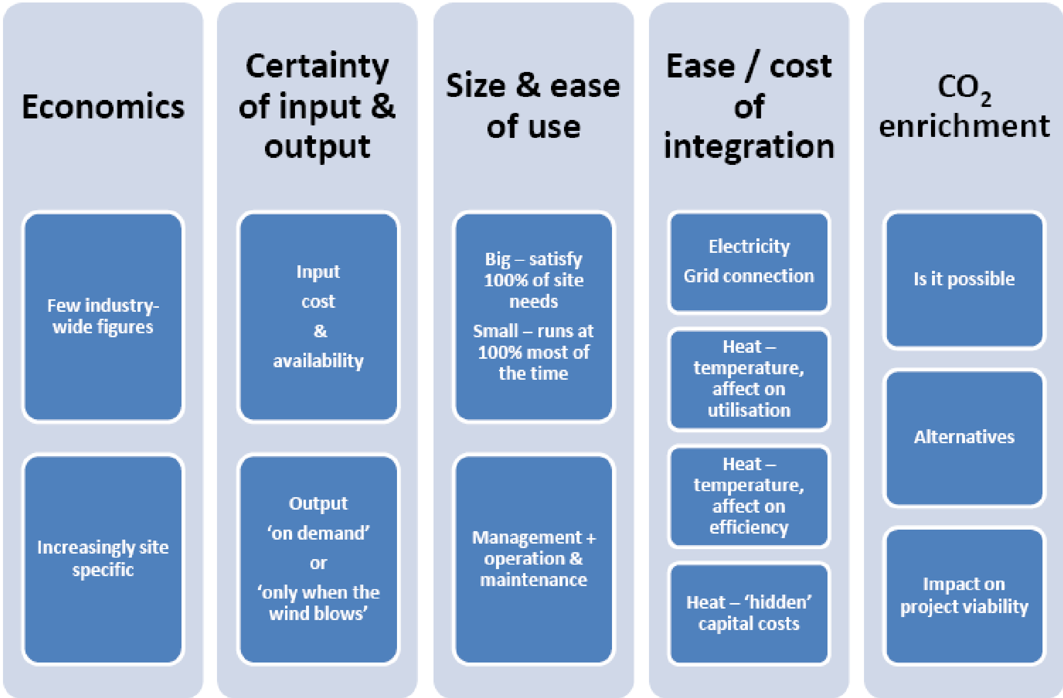


Figure 50. Considerations to be discussed previously when attempting to use wind or solar PV renewable energy sources for greenhouse operation.

We are then going to answer to these questions for two locations Almería (Spain) and The Netherlands (reference year weather data set) and for two of the most used renewable energy systems (photovoltaic and wind energy).

3.2 Study on renewable energies (Solar PV and wind) for their use in Mediterranean greenhouses.

In the present report a methodology has been used in which the calculation of the amounts of energy available has been as important as to analyze in which moment this energy is available (avoiding the accumulation). Having a matrix that reports how much energy is available at each moment of the day and along the months establishes the framework over which we can decide which kind of technology could be used to cover some the greenhouse energy requirements.

In order to do this work, meteorological data obtained during a period of ten years at the Experimental Station of the Cajamar Foundation. The length of the data set and the location of the meteorological in the core of the largest greenhouse area in the Mediterranean area provide this study an excellent reliability

3.2.1 Data sets

1990	1991	1992	1993	1994	1995
31/Jan	1/Jan a 17/Jan	1/Jan a 13/Mar	1/Jan a 3/Feb	1/Jan a 25/Feb	1/Jan a 25/Jan
1/Feb	21/Jan a 26/Jan	16/Mar a 18/Dec	4/Feb a 22/May	1/Mar a 31/Dec	1/Feb a 2/Feb
22/Apr	28/Jan a 29/Jan	21/Dec a 31/Dec	24/May a 31/Dec		4/Feb a 18/Ago
	2/Feb a 7/Feb				21/Ago a 1/Dec
	9/Feb a 12/Mar				4/Dec a 14/Dec
	14/Mar a 22/May				19/Dec a 31/Dec
	24/May a 18/Sep				
	20/Sep a 26/Sep				
	1/Oct a 24/Dec				
	27/Dec a 31/Dec				

1996	1997	1998	1999	2000	
2/Jan a 27/Feb	1/Jan a 24/Nov	1/Jan a 8/Jan	1/Jan a 6/Ago	1/Jan a 1/Oct	
1/Oct a 23/Oct	4/Dec a 31/Dec	22/Jan a 2/Feb	31/Ago a 31/Dec		
26/Oct a 28/Oct		5/Feb a 16/Feb			
30/Oct a 15/Nov		18/Feb a 27/Apr			
16/Nov a 13/Dec		30/Apr a 16/May			
15/Dec a 31/Dec		18/May a 6/Jun			
		9/Jun a 60/Jun			
		23/Jun a 27/Jun			
		29/Jun a 1/Jul			
		1/Oct a 31/Dec			

During 1990 and 1991 the data were stored every 10 minutes, the rest of the year were stored every 30 minutes (average of values measured every two seconds)

3.2.2 Renewable resources

3.2.2.1 Solar energy (W/m^2)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
6:00	0,00	0,00	0,00	41,98	93,09	123,79	97,37	33,13	0,00	25,85	0,00	0,00
7:00	0,00	26,19	72,65	188,86	255,38	292,83	252,78	167,28	128,86	95,10	0,00	0,00
8:00	73,32	111,78	219,13	367,13	442,29	479,93	439,12	349,39	299,94	228,63	116,61	53,06
9:00	199,72	262,21	392,63	531,34	615,18	651,59	618,76	533,76	482,77	357,70	252,48	169,42
10:00	322,95	402,73	543,63	663,86	727,94	784,64	764,12	687,53	631,58	481,06	381,28	284,41
11:00	402,85	489,98	641,86	742,27	785,57	863,60	857,02	783,49	719,93	557,99	436,30	357,43
12:00	441,55	523,19	672,51	789,57	814,94	891,78	887,96	825,48	745,76	573,11	471,86	388,50
13:00	414,55	491,93	653,50	764,75	789,00	861,81	873,41	802,96	715,98	527,97	442,53	363,22
14:00	345,53	430,21	579,24	674,24	725,11	774,90	804,78	727,28	639,43	449,12	359,50	288,76
15:00	238,88	307,78	457,30	540,29	615,57	644,10	685,64	606,77	501,94	320,36	234,47	181,99
16:00	108,54	173,02	297,05	364,69	449,68	484,91	519,13	455,57	331,06	175,78	102,74	70,01
17:00	46,03	58,30	127,22	185,10	269,90	297,04	330,02	260,22	157,57	75,44	44,11	0,00
18:00	0,00	26,28	29,13	51,33	108,79	127,37	151,87	90,94	41,11	37,36	0,00	0,00
19:00	0,00	0,00	0,00	37,87	40,59	26,41	39,96	57,08	0,00	0,00	0,00	0,00
20:00	0,00	0,00	0,00	0,00	0,00	0,00	32,67	0,00	0,00	0,00	0,00	0,00
21:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
22:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
23:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
suma	2593,93	3303,60	4685,83	5943,29	6733,02	7304,71	7354,62	6380,89	5395,93	3905,47	2841,90	2156,80

These radiation data are represent a typical average year because they include periods of sunshine and clouds. It provides precise information on the quantity of Energy available for a greenhouse and not so much on the theoretical solar radiation.

Colour code:

Rg
Rg<=200
Rg<=500
Rg<=800
Rg>800

3.2.2.2 Wind energy

SUMMARY

DATA PERIODS:

- 01/10/1996 - 18/02/1998
- 31/03/1998 – 14/04/1998
- 01/10/1998 – 30/09/2000

Number of measurements: 50696 (every 30 minutes) =25348 hours

AVERAGE VELOCITY [1](m/s)	2.49		
MAXIMUM VELOCITY (m/s)	18.3		
DIRECTION AND DATE OF MAXIMUM VELOCITY:		Southwest (207)	15 February 1998, 3:00

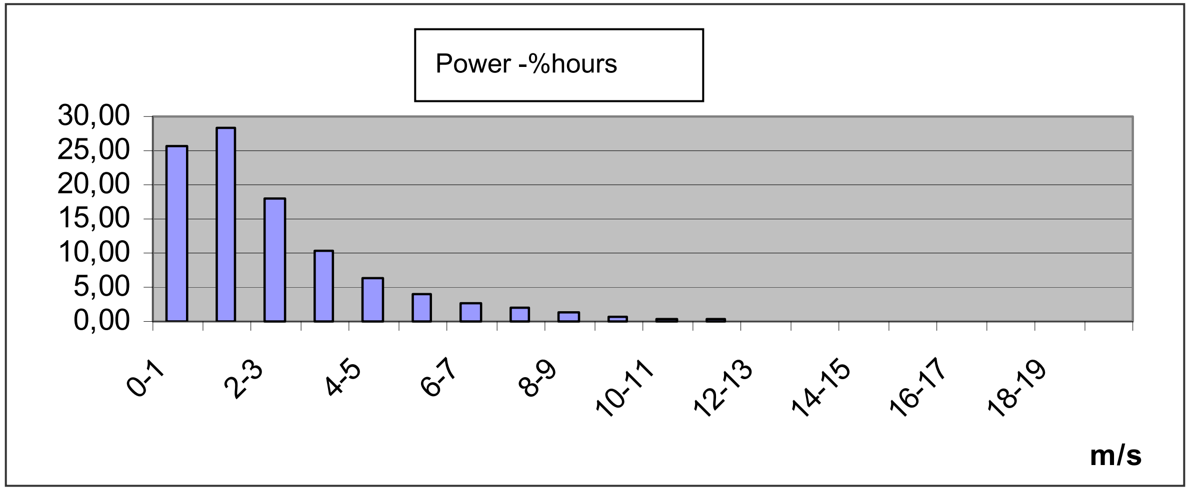
PREVAILING DIRECTIONS:

West-southwest	12.71%	3.67 (m/s)
Este	9.43%	2.7 (m/s)
Este- Noreste	8.81%	2.13(m/s)

Average power: 36.39 W/m^2

Velocity distribution:

VELOCITY (m/s)	FREQUENCY (%)
0-1	25,48
1-2	28,28
2-3	17,83
3-4	10,43
4-5	6,29
5-6	4,08
6-7	2,79
7-8	2,14
8-9	1,28
9-10	0,65
10-11	0,35
11-12	0,21
12-13	0,13
13-14	0,04
14-15	0,01
15-16	0,01
16-17	0,01
17-18	0,00
18-19	0,00
19-20	0,00



Power -%hours
30,00
25,00
20,00
15,00
10,00
5,00
0,00
0-1
2-3
4-5
6-7
8-9
10-11
12-13
14-15
16-17
18-19
m/s

The average power is calculated with: $P = \frac{1}{2}\rho v^3 A$ where: ρ=0,001225 kg/m^3, v is the wind velocity (m/s), and A the area over which the wind is impinging (m^2). For the calculation of the average power, the 30 minutes wind velocity value has been used to calculate the power, and then the average has been calculated.

Hourly average velocity per month:

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	1,68	1,70	1,59	2,17	1,73	1,78	1,48	2,38	1,68	1,48	1,73	2,06
1:00	1,69	1,80	1,84	2,00	1,76	1,92	1,33	2,29	1,78	1,50	1,76	1,99
2:00	1,76	1,74	1,69	1,91	1,74	1,89	1,26	2,18	1,70	1,50	1,87	1,94
3:00	1,82	2,14	1,54	1,99	1,65	1,79	1,36	2,06	1,67	1,53	1,82	1,86
4:00	1,73	1,98	1,66	2,01	1,52	1,76	1,43	1,87	1,71	1,57	1,84	1,86
5:00	1,64	1,96	1,70	1,88	1,49	1,73	1,45	1,60	1,70	1,48	1,87	1,94
6:00	1,71	1,93	1,76	1,68	1,45	1,99	1,35	1,56	1,63	1,46	1,86	1,87
7:00	1,72	2,02	1,62	1,83	1,69	2,43	1,72	1,75	1,73	1,51	1,87	1,89
8:00	1,72	1,78	1,67	2,24	2,23	2,90	2,28	2,30	2,16	1,76	1,92	1,90
9:00	1,68	1,74	2,42	2,56	2,79	3,65	2,95	2,71	2,80	2,28	2,27	2,02
10:00	2,01	2,24	2,62	3,24	3,33	4,29	3,54	3,06	3,29	2,79	2,79	2,51
11:00	2,38	2,51	3,05	3,76	3,98	4,58	3,78	3,27	3,83	3,22	3,15	2,78
12:00	2,68	2,80	3,31	4,45	4,23	4,85	4,04	3,41	4,07	3,47	3,42	2,97
13:00	2,87	2,85	3,62	4,95	4,39	5,02	4,21	3,48	4,28	3,57	3,59	3,09
14:00	2,93	3,07	3,74	5,16	4,45	5,06	4,24	3,40	4,35	3,47	3,67	3,22
15:00	2,87	2,84	3,62	5,35	4,41	4,90	4,13	3,26	4,20	3,26	3,47	2,95
16:00	2,60	2,66	3,34	4,79	4,33	4,66	3,89	3,07	3,83	2,87	2,96	2,43
17:00	2,19	2,14	3,08	4,05	4,03	4,31	3,55	2,99	3,41	2,42	2,35	1,96
18:00	1,76	1,82	2,70	3,75	3,51	3,66	3,01	2,63	2,72	1,94	2,11	1,90
19:00	1,69	1,54	2,30	2,74	2,63	2,85	2,33	2,36	2,25	1,61	1,98	1,86
20:00	1,72	1,52	1,95	2,24	1,99	2,23	1,82	2,27	2,06	1,52	1,86	2,03
21:00	1,75	1,69	1,84	2,81	1,71	2,00	1,64	2,23	2,03	1,50	1,86	1,94
22:00	1,68	1,80	1,77	2,62	1,75	1,95	1,55	2,33	1,87	1,45	1,89	1,86
23:00	1,73	1,90	1,72	2,59	1,80	1,84	1,36	2,38	1,69	1,46	1,86	1,95

Colour code: v<=2 (blue), v<=4 (green), v>4 (orange)

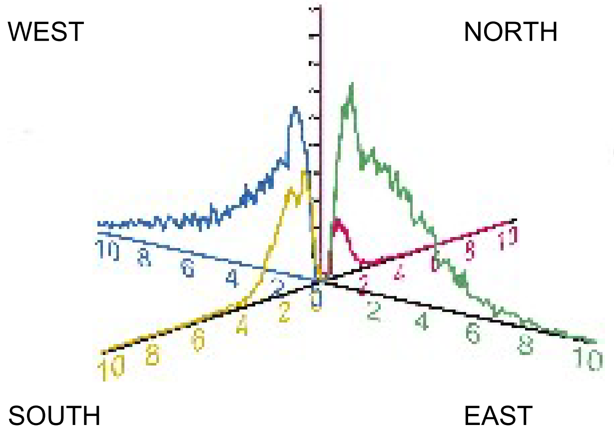
Hourly average power per month:

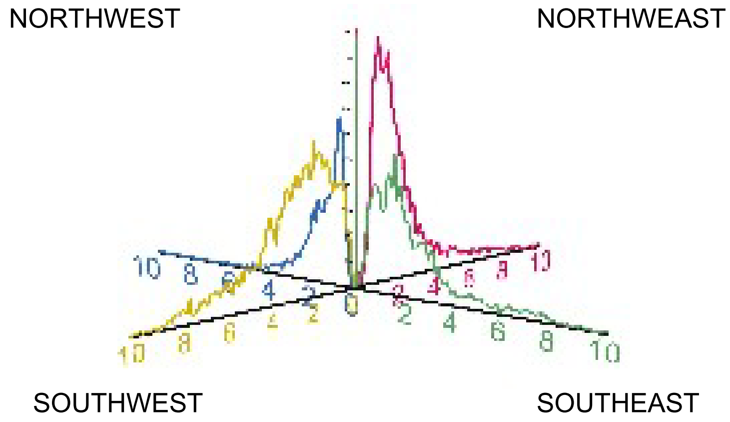
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	12,68	16,93	8,66	12,12	11,28	12,25	4,67	35,73	11,54	21,59	11,45	27,28
1:00	12,66	31,66	13,89	13,89	10,88	13,80	3,65	33,34	11,48	23,43	12,21	26,11
2:00	12,36	11,34	9,88	17,38	9,52	12,53	2,50	25,87	10,83	25,06	20,06	24,13
3:00	15,29	93,67	7,66	12,27	8,43	8,83	3,29	19,35	10,71	31,56	20,14	24,27
4:00	12,48	39,74	9,27	11,70	5,68	9,89	4,41	12,84	10,43	29,87	18,61	19,43
5:00	11,17	36,79	9,05	13,69	5,84	10,72	4,69	7,88	10,39	24,52	19,57	18,81
6:00	12,57	38,51	16,01	16,83	6,39	14,13	4,19	6,36	9,27	24,24	19,53	18,30
7:00	10,87	25,96	7,50	21,56	9,02	24,71	8,57	9,43	14,42	31,21	18,86	20,80
8:00	14,59	12,86	9,37	34,96	20,43	39,92	19,56	22,49	29,23	43,96	22,71	31,64
9:00	16,87	10,49	21,86	60,56	33,67	68,05	39,80	37,87	45,67	54,73	33,03	33,50
10:00	19,14	14,99	25,33	81,72	56,77	94,07	60,51	53,67	54,96	64,30	36,02	45,89
11:00	24,89	19,70	37,03	97,08	85,89	107,13	72,98	63,99	72,40	72,09	46,64	49,56
12:00	29,94	28,87	45,56	108,15	103,87	119,20	81,45	64,70	82,67	76,69	51,86	57,67
13:00	34,54	27,43	57,71	115,14	116,89	126,19	93,39	65,64	93,13	75,76	57,14	56,88
14:00	35,98	32,54	61,93	118,97	116,55	133,32	93,32	66,07	104,95	65,85	58,30	61,93
15:00	36,36	24,30	55,73	106,61	109,78	122,32	81,94	54,10	96,44	57,60	51,91	41,74
16:00	28,58	23,20	48,45	88,51	99,68	103,62	73,59	46,12	72,32	37,77	37,21	28,13
17:00	22,78	15,05	40,63	72,69	81,14	85,41	55,01	41,40	57,25	35,41	27,25	19,01
18:00	13,96	18,28	34,27	52,44	55,52	58,12	30,31	30,98	38,56	28,19	23,45	17,55
19:00	13,45	8,49	27,23	35,60	33,46	39,33	15,41	24,32	25,73	24,04	18,27	14,90
20:00	14,60	7,84	17,40	20,34	19,00	21,86	10,83	27,33	19,31	27,08	13,68	21,61
21:00	15,13	11,48	13,12	17,33	12,38	18,28	9,60	36,23	20,28	18,66	14,15	16,49
22:00	13,62	16,27	12,81	20,08	12,48	20,07	6,89	38,03	15,95	17,54	15,34	19,32
23:00	13,38	47,96	14,30	15,40	11,79	13,62	3,77	36,12	10,49	17,34	14,97	23,59

Colour code: P<=25 (blue), P<=80 (green), P>80 (yellow)

This distribution of wind velocities indicates a profile in which the breeze predominates. We can consider the wind in this area daytime resource, mainly during the central hours of the day and of low intensity.

Distribution of velocities along the prevailing wind directions





3.2.3 Heating and cooling requirements

Frequency of hours in which temperatures inside a reference greenhouse are above or below values considered as optimum limits: T<15ºC and T>25 ºC

T<15ºC

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	1,00	0,99	0,97	0,90	0,38	0,05	0,00	0,00	0,06	0,34	0,81	0,97
1:00	1,00	0,99	0,94	0,87	0,34	0,04	0,01	0,00	0,06	0,33	0,81	0,95
2:00	1,00	0,98	0,95	0,88	0,39	0,05	0,01	0,00	0,08	0,36	0,81	0,95
3:00	0,99	0,99	0,95	0,91	0,43	0,06	0,01	0,00	0,09	0,39	0,82	0,96
4:00	0,99	0,99	0,94	0,94	0,48	0,07	0,01	0,00	0,10	0,42	0,84	0,96
5:00	1,00	0,99	0,97	0,94	0,49	0,06	0,01	0,00	0,12	0,42	0,89	0,97
6:00	0,99	0,99	0,97	0,92	0,34	0,02	0,00	0,00	0,12	0,44	0,91	0,97
7:00	0,99	0,97	0,94	0,61	0,03	0,00	0,00	0,00	0,04	0,38	0,88	0,97
8:00	0,98	0,97	0,59	0,08	0,01	0,00	0,00	0,00	0,00	0,12	0,71	0,95
9:00	0,86	0,55	0,10	0,03	0,01	0,00	0,00	0,00	0,00	0,07	0,23	0,75
10:00	0,32	0,10	0,04	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,10	0,18
11:00	0,10	0,06	0,02	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,07
12:00	0,07	0,05	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,05
13:00	0,08	0,05	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,04
14:00	0,08	0,05	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,06
15:00	0,15	0,08	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,09	0,08
16:00	0,45	0,12	0,03	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,12	0,41
17:00	0,92	0,46	0,09	0,02	0,01	0,00	0,00	0,00	0,00	0,01	0,45	0,87
18:00	0,98	0,94	0,43	0,15	0,01	0,00	0,00	0,00	0,00	0,04	0,60	0,94
19:00	0,98	0,97	0,75	0,41	0,06	0,00	0,00	0,00	0,00	0,10	0,69	0,95
20:00	0,99	0,98	0,86	0,57	0,10	0,00	0,00	0,00	0,00	0,16	0,72	0,95
21:00	0,99	0,98	0,91	0,69	0,14	0,00	0,00	0,00	0,00	0,21	0,70	0,95
22:00	0,98	0,98	0,90	0,74	0,21	0,01	0,00	0,00	0,02	0,25	0,71	0,94
23:00	0,98	0,98	0,93	0,79	0,25	0,02	0,00	0,00	0,03	0,29	0,77	0,96

Colour code:

f>=0,66
f>=0,33
0<f<0,33
f=0

T>25ºC

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	0,00	0,00	0,00	0,00	0,00	0,03	0,06	0,16	0,01	0,00	0,00	0,00
1:00	0,00	0,00	0,00	0,00	0,00	0,02	0,04	0,10	0,01	0,00	0,00	0,00
2:00	0,00	0,00	0,00	0,00	0,00	0,02	0,05	0,09	0,03	0,01	0,00	0,00
3:00	0,00	0,00	0,00	0,00	0,00	0,02	0,03	0,11	0,01	0,01	0,00	0,00
4:00	0,00	0,00	0,00	0,00	0,00	0,02	0,02	0,09	0,02	0,00	0,00	0,00
5:00	0,00	0,00	0,00	0,00	0,00	0,02	0,03	0,07	0,00	0,00	0,00	0,00
6:00	0,00	0,00	0,00	0,00	0,00	0,04	0,10	0,14	0,01	0,00	0,00	0,00
7:00	0,00	0,00	0,00	0,00	0,03	0,27	0,64	0,73	0,18	0,00	0,00	0,00
8:00	0,00	0,00	0,00	0,03	0,19	0,65	0,91	0,96	0,56	0,06	0,00	0,00
9:00	0,00	0,01	0,04	0,14	0,54	0,87	0,96	1,00	0,87	0,26	0,00	0,00
10:00	0,01	0,03	0,14	0,30	0,74	0,94	0,98	1,00	0,94	0,48	0,03	0,00
11:00	0,02	0,05	0,26	0,44	0,80	0,95	0,99	1,00	0,97	0,61	0,06	0,01
12:00	0,02	0,06	0,34	0,48	0,82	0,97	1,00	1,00	0,97	0,72	0,09	0,02
13:00	0,03	0,07	0,35	0,52	0,82	0,97	1,00	1,00	0,97	0,72	0,11	0,02
14:00	0,01	0,09	0,31	0,46	0,81	0,97	1,00	1,00	0,96	0,69	0,08	0,01
15:00	0,01	0,06	0,20	0,35	0,76	0,96	1,00	1,00	0,93	0,55	0,05	0,01
16:00	0,00	0,02	0,10	0,21	0,61	0,93	1,00	1,00	0,87	0,33	0,04	0,00
17:00	0,00	0,00	0,01	0,11	0,40	0,83	1,00	0,98	0,68	0,11	0,02	0,00
18:00	0,00	0,00	0,00	0,02	0,16	0,63	0,94	0,94	0,39	0,01	0,00	0,00
19:00	0,00	0,00	0,00	0,00	0,03	0,24	0,71	0,67	0,11	0,01	0,00	0,00
20:00	0,00	0,00	0,00	0,00	0,01	0,03	0,26	0,36	0,04	0,01	0,00	0,00
21:00	0,00	0,00	0,00	0,00	0,01	0,02	0,12	0,24	0,03	0,01	0,00	0,00
22:00	0,00	0,00	0,00	0,00	0,01	0,02	0,08	0,17	0,02	0,00	0,00	0,00
23:00	0,00	0,00	0,00	0,00	0,01	0,02	0,05	0,15	0,01	0,01	0,00	0,00

Colour code:

f>=0,66
f>=0,33
0<f<0,33
f=0

Frequency of hours in which temperatures inside a reference greenhouse are above or below values considered as biological limits for most cultivated horticultural species: T<10ºC and T>30 ºC

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	0,78	0,59	0,20	0,05	0,00	0,00	0,00	0,00	0,00	0,01	0,14	0,54
1:00	0,71	0,57	0,21	0,08	0,00	0,00	0,00	0,00	0,00	0,00	0,14	0,50
2:00	0,71	0,63	0,27	0,09	0,00	0,00	0,00	0,00	0,00	0,00	0,16	0,53
3:00	0,74	0,66	0,31	0,12	0,00	0,00	0,00	0,00	0,00	0,00	0,18	0,55
4:00	0,76	0,66	0,36	0,14	0,00	0,00	0,00	0,00	0,00	0,00	0,21	0,56
5:00	0,76	0,71	0,43	0,18	0,01	0,00	0,00	0,00	0,00	0,00	0,24	0,59
6:00	0,78	0,74	0,43	0,14	0,00	0,00	0,00	0,00	0,00	0,00	0,24	0,58
7:00	0,77	0,72	0,30	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,23	0,60
8:00	0,63	0,43	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,45
9:00	0,11	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,02	0,04
10:00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,01
11:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,01
12:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,00
13:00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00
14:00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00
15:00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,00
16:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
17:00	0,11	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,05	0,07
18:00	0,37	0,10	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,07	0,20
19:00	0,48	0,21	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,09	0,25
20:00	0,56	0,30	0,05	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,09	0,32
21:00	0,60	0,36	0,06	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,39
22:00	0,64	0,42	0,07	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,43
23:00	0,66	0,47	0,11	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,08	0,45

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1:00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,00	0,00	0,00	0,00
2:00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00
3:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
6:00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00
7:00	0,00	0,00	0,00	0,00	0,00	0,02	0,04	0,03	0,00	0,00	0,00	0,00
8:00	0,00	0,00	0,00	0,00	0,00	0,18	0,20	0,23	0,04	0,00	0,00	0,00
9:00	0,00	0,00	0,00	0,02	0,04	0,47	0,53	0,66	0,23	0,01	0,00	0,00
10:00	0,00	0,01	0,01	0,05	0,09	0,72	0,75	0,85	0,44	0,04	0,00	0,00
11:00	0,00	0,02	0,04	0,06	0,14	0,87	0,85	0,93	0,59	0,07	0,00	0,00
12:00	0,01	0,03	0,04	0,08	0,20	0,98	0,86	0,94	0,71	0,09	0,00	0,00
13:00	0,01	0,03	0,04	0,08	0,21	0,97	0,89	0,94	0,66	0,07	0,00	0,00
14:00	0,01	0,03	0,04	0,07	0,20	0,92	0,89	0,94	0,61	0,05	0,00	0,00
15:00	0,00	0,02	0,04	0,05	0,13	0,84	0,88	0,89	0,56	0,01	0,00	0,00
16:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
17:00	0,00	0,00	0,00	0,01	0,02	0,41	0,63	0,60	0,07	0,00	0,00	0,00
18:00	0,00	0,00	0,00	0,00	0,00	0,17	0,24	0,26	0,00	0,00	0,00	0,00
19:00	0,00	0,00	0,00	0,00	0,00	0,02	0,03	0,04	0,00	0,00	0,00	0,00
20:00	0,00	0,00	0,00	0,00	0,00	0,01	0,02	0,01	0,00	0,00	0,00	0,00
21:00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00
22:00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00
23:00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Colour code:

f>=0,66
f>=0,33
0<f<0,33
f=0

Colour code:

f>=0,66
f>=0,33
0<f<0,33
f=0

The following tables have been calculated with the energy model described by González-Real and Baille (Polytechnical University of Cartagena, 2000), from yearly values of temperature, external global radiation and wind velocity measured in Las Palmerillas (10 years average)

The minimum and maximum temperatures established in the model for the greenhouse interior are 15 ºC and 25 ºC, respectively.

3.2.3.1 Cooling requirements of the closed greenhouse (without natural ventilation) (W/m^2):

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1												
2												
3												
4												
5						2,6						
6						39,5	14,1	14,8				
7				29,1	34,8	40,8	43,0	35,2	19,2			
8			37,2	48,5	67,9	90,9	97,7	88,1	58,0	31,6		
9	38,9	40,2	56,4	87,3	111,6	141,1	145,8	134,5	106,3	61,5	32,3	24,8
10	39,0	58,5	97,3	132,0	165,3	190,0	185,9	171,3	150,1	98,4	57,9	33,8
11	53,6	85,4	134,2	166,8	200,5	219,4	212,0	197,6	178,2	126,6	80,0	52,3
12	68,9	105,3	157,6	186,7	216,8	233,6	225,5	211,2	191,1	139,7	92,5	64,9
13	75,0	111,7	163,2	189,3	215,6	232,9	225,3	210,8	187,5	137,8	93,7	67,5
14	68,7	106,4	150,9	175,5	200,6	218,0	211,5	196,4	171,1	123,0	81,9	59,3
15	47,5	82,3	122,1	147,2	172,4	190,4	185,6	169,8	143,3	95,2	59,3	39,0
16	28,1	49,5	83,7	107,1	134,3	153,5	150,2	133,7	105,1	60,2	30,5	18,9
17	25,6	21,1	43,0	62,2	90,4	109,8	109,0	91,8	61,4	28,3	10,3	4,9
18	0,5	2,7	12,9	26,0	45,1	64,8	65,7	48,1	22,5	5,2		
19					16,4	23,9	23,4	9,7	1,0			
20						0,7	0,4					
21												
22												
23												

Colour code:

$0<W/m^2<50$

$50<=W/m^2<125$

$125<=W/m^2$

Difference between the power required for cooling and the power available by wind energy (W/m^2):

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0												
1												
2												
3												
4												
5						-3						
6						32	12	12				
7				18	30	28	39	31	12			
8			33	31	58	71	88	77	43	10		
9	30	35	45	57	95	107	126	116	83	34	16	8
10	29	51	85	91	137	143	156	144	123	66	40	11
11	41	76	116	118	158	166	175	166	142	91	57	28
12	54	91	135	133	165	174	185	179	150	101	67	36
13	58	98	134	132	157	170	179	178	141	100	65	39
14	51	90	120	116	142	151	165	163	119	90	53	28
15	29	70	94	94	117	129	145	143	95	66	33	18
16	14	38	59	63	84	102	113	111	69	41	12	5
17	14	14	23	26	50	67	82	71	33	11	-3	-5
18	-6	-6	-4	0	17	36	51	33	3	-9		
19					0	4	16	-2	-12			
20						-10	-5					
21												
22												
23												

Requirements covered:

Requirements not covered:

Percentage of energy required for cooling covered by wind energy (%)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0												
1												
2												
3												
4												
5						206						
6						18	15	21				
7				37	13	30	10	13	38			
8			13	36	15	22	10	13	25	69		
9	22	13	19	35	15	24	14	14	21	44	51	68
10	25	13	13	31	17	25	16	16	18	33	31	68
11	23	12	14	29	21	24	17	16	20	28	29	47
12	22	14	14	29	24	26	18	15	22	27	28	44
13	23	12	18	30	27	27	21	16	25	27	30	42
14	26	15	21	34	29	31	22	17	31	27	36	52
15	38	15	23	36	32	32	22	16	34	30	44	54
16	51	23	29	41	37	34	24	17	34	31	61	75
17	44	36	47	58	45	39	25	23	47	62	132	194
18	1396	338	133	101	62	45	23	32	86	273		
19					102	82	33	125	1306			
20						1507	1336					
21												
22												
23												

Colour code:

%<50

50<%<100

Surplus

Area (in m^2) of windmill required per m^2 of greenhouse to cover the greenhouse cooling requirements.

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1												
2												
3												
4												
5						0,49						
6						5,59	6,75	4,65				
7				2,70	7,71	3,30	10,04	7,47	2,66			
8			7,95	2,78	6,65	4,55	9,99	7,84	3,97	1,44		
9	4,61	7,67	5,15	2,88	6,63	4,15	7,33	7,10	4,65	2,25	1,96	1,48
10	4,08	7,80	7,68	3,23	5,82	4,04	6,14	6,38	5,46	3,06	3,22	1,47
11	4,31	8,67	7,25	3,44	4,67	4,10	5,81	6,18	4,92	3,51	3,43	2,11
12	4,60	7,29	6,92	3,45	4,17	3,92	5,54	6,53	4,62	3,64	3,57	2,25
13	4,34	8,15	5,66	3,29	3,69	3,69	4,83	6,42	4,03	3,64	3,28	2,37
14	3,82	6,54	4,87	2,95	3,44	3,27	4,53	5,95	3,26	3,74	2,81	1,91
15	2,61	6,77	4,38	2,76	3,14	3,11	4,53	6,28	2,97	3,31	2,29	1,87
16	1,97	4,27	3,45	2,42	2,69	2,96	4,08	5,80	2,91	3,19	1,64	1,34
17	2,25	2,80	2,12	1,71	2,23	2,57	3,96	4,44	2,15	1,60	0,76	0,52
18	0,07	0,30	0,75	0,99	1,62	2,23	4,33	3,11	1,17	0,37		
19					0,98	1,22	3,03	0,80	0,08			
20						0,07	0,07					
21												
22												
23												

Colour mode:

0<A<=2

2<A

Difference between the energy required for cooling and the energy available from PV (W/m^2):

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0												
1												
2												
3												
4												
5						3						
6						27	4	11				
7				10	9	12	18	19	6			
8			15	12	24	43	54	53	28	9		
9	19	14	17	34	50	76	84	81	58	26	7	8
10	7	18	43	66	93	112	109	103	87	50	20	5
11	13	36	70	93	122	133	126	119	106	71	36	17
12	25	53	90	108	135	144	137	129	116	82	45	26
13	34	63	98	113	137	147	138	130	116	85	49	31
14	34	63	93	108	128	140	131	124	107	78	46	30
15	24	52	76	93	111	126	117	109	93	63	36	21
16	17	32	54	71	89	105	98	88	72	43	20	12
17	21	15	30	44	63	80	76	66	46	21	6	5
18	1	0	10	21	34	52	50	39	18	1		
19					12	21	19	4	1			
20						1	-3					
21												
22												
23												

Requirements covered:
Requirements not covered:

Percentage of energy required for cooling covered with PV(%)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0												
1												
2												
3												
4												
5						0						
6						31	69	22				
7				65	73	72	59	47	67			
8			59	76	65	53	45	40	52	72		
9	51	65	70	61	55	46	42	40	45	58	78	68
10	83	69	56	50	44	41	41	40	42	49	66	84
11	75	57	48	44	39	39	40	40	40	44	55	68
12	64	50	43	42	38	38	39	39	39	41	51	60
13	55	44	40	40	37	37	39	38	38	38	47	54
14	50	40	38	38	36	36	38	37	37	37	44	49
15	50	37	37	37	36	34	37	36	35	34	40	47
16	39	35	35	34	33	32	35	34	32	29	34	37
17	18	28	30	30	30	27	30	28	26	27	43	0
18	0	97	23	20	24	20	23	19	18	72		
19					25	11	17	59	0			
20						0	806					
21												
22												
23												

Colour code:

%<50
50<%<100
Surplus

Square meters of PV panels required per m^2 of greenhouse to cover cooling requirements:

Only values in which energy for cooling is required are shown.

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0												
1												
2												
3												
4												
5						no						
6						3,19	1,45	4,47				
7				1,54	1,36	1,39	1,70	2,11	1,49			
8			1,70	1,32	1,54	1,89	2,22	2,52	1,93	1,38		
9	1,95	1,53	1,44	1,64	1,81	2,17	2,36	2,52	2,20	1,72	1,28	1,46
10	1,21	1,45	1,79	1,99	2,27	2,42	2,43	2,49	2,38	2,05	1,52	1,19
11	1,33	1,74	2,09	2,25	2,55	2,54	2,47	2,52	2,47	2,27	1,83	1,46
12	1,56	2,01	2,34	2,36	2,66	2,62	2,54	2,56	2,56	2,44	1,96	1,67
13	1,81	2,27	2,50	2,48	2,73	2,70	2,58	2,62	2,62	2,61	2,12	1,86
14	1,99	2,47	2,61	2,60	2,77	2,81	2,63	2,70	2,68	2,74	2,28	2,05
15	1,99	2,67	2,67	2,73	2,80	2,96	2,71	2,80	2,86	2,97	2,53	2,14
16	2,59	2,86	2,82	2,94	2,99	3,16	2,89	2,94	3,17	3,42	2,97	2,69
17	5,56	3,62	3,38	3,36	3,35	3,70	3,30	3,53	3,90	3,76	2,34	no
18	no	1,03	4,41	5,07	4,14	5,09	4,32	5,29	5,47	1,38		
19					4,04	9,07	5,85	1,70	no			
20						no	0,12					
21												
22												
23												

Not available: no
A<2
A<2

Cooling requirements (W/m^2) covered with a typical plant of 200 m^2 of PV panels:

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
5						2,60 / 0,01						
6						39,50 / 0,01	14,14 / 0,00	14,80 / 0,00				
7				29,13 / 0,02	34,76 / 0,01	40,79 / 0,02	43,04 / 0,01	35,25 / 0,01	19,22 / 0,01			
8			37,24 / 0,01	48,55 / 0,03	67,93 / 0,02	90,89 / 0,03	97,66 / 0,01	88,13 / 0,02	57,96 / 0,02	31,64 / 0,03		
9	38,85 / 0,01	40,23 / 0,01	56,36 / 0,02	87,31 / 0,05	111,65 / 0,03	141,08 / 0,05	145,80 / 0,03	134,48 / 0,03	106,27 / 0,03	61,51 / 0,04	32,29 / 0,02	24,80 / 0,03
10	39,03 / 0,01	58,48 / 0,01	97,26 / 0,02	132,00 / 0,06	165,30 / 0,04	189,99 / 0,07	185,87 / 0,05	171,31 / 0,04	150,15 / 0,04	98,39 / 0,05	57,94 / 0,03	33,77 / 0,03
11	53,58 / 0,02	85,36 / 0,01	134,17 / 0,03	166,83 / 0,07	200,54 / 0,06	219,39 / 0,08	211,97 / 0,05	197,58 / 0,05	178,17 / 0,05	126,63 / 0,05	80,00 / 0,03	52,34 / 0,04
12	68,89 / 0,02	105,27 / 0,02	157,58 / 0,03	186,65 / 0,08	216,80 / 0,08	233,56 / 0,09	225,49 / 0,06	211,21 / 0,05	191,07 / 0,06	139,66 / 0,06	92,51 / 0,04	64,86 / 0,04
13	75,03 / 0,03	111,72 / 0,02	163,24 / 0,04	189,32 / 0,09	215,60 / 0,09	232,89 / 0,09	225,34 / 0,07	210,77 / 0,05	187,54 / 0,07	137,77 / 0,06	93,72 / 0,04	67,48 / 0,04
14	68,66 / 0,03	106,41 / 0,02	150,92 / 0,05	175,48 / 0,09	200,60 / 0,09	217,98 / 0,10	211,53 / 0,07	196,41 / 0,05	171,06 / 0,08	123,02 / 0,05	81,91 / 0,04	59,26 / 0,05
15	47,49 / 0,03	82,30 / 0,02	122,14 / 0,04	147,24 / 0,08	172,38 / 0,08	190,37 / 0,09	185,57 / 0,06	169,76 / 0,04	143,31 / 0,07	95,24 / 0,04	59,34 / 0,04	38,96 / 0,03
16	28,10 / 0,02	49,49 / 0,02	83,68 / 0,04	107,14 / 0,07	134,30 / 0,07	153,46 / 0,08	150,22 / 0,06	133,72 / 0,03	105,08 / 0,05	60,19 / 0,03	30,53 / 0,03	18,86 / 0,02
17	25,60 / 0,02	21,10 / 0,01	42,97 / 0,03	62,21 / 0,05	90,40 / 0,06	109,84 / 0,06	109,01 / 0,04	91,84 / 0,03	61,42 / 0,04	28,34 / 0,03	10,32 / 0,02	4,90 / 0,01
18	0,50 / 0,01	2,70 / 0,01	12,85 / 0,03	26,02 / 0,04	45,08 / 0,04	64,84 / 0,04	65,66 / 0,02	48,14 / 0,02	22,49 / 0,03	5,17 / 0,02		
19					16,40 / 0,03	23,95 / 0,03	23,37 / 0,01	9,71 / 0,02	0,99 / 0,02			
20						0,73 / 0,02	0,41 / 0,01					

Require / Available

3.2.3.2. Heating requirements of the greenhouse (W/m^2):

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	37,45	33,06	23,39	17,68	10,45				3,75	7,10	18,61	27,82
1	40,26	36,42	27,51	19,84	12,00	1,20			6,78	9,19	20,92	30,31
2	43,38	39,74	30,56	23,17	14,19	4,44			7,27	9,42	22,55	32,82
3	46,66	43,70	33,29	26,89	14,09	7,11		3,63	7,02	8,40	24,47	35,88
4	49,67	47,32	36,36	29,71	14,59	8,16	1,44	8,00	7,82	9,70	26,99	38,69
5	52,45	50,45	38,56	32,19	16,82	10,00	4,02	6,75	9,56	11,46	29,07	40,86
6	53,75	51,98	40,28	28,62	12,74	6,76		5,42	10,31	11,72	29,84	42,06
7	55,28	53,60	26,05	15,51	23,09					6,86	30,18	43,14
8	37,24	29,48	14,74	13,23	5,19						13,33	25,32
9	15,89	28,53	24,03	9,84	8,14						19,00	16,16
10	17,26	27,31	44,34	4,67	5,42						17,35	19,42
11	15,50	22,47	38,13	1,18	3,62						17,70	19,85
12	22,46	21,83	32,66		2,25						5,91	18,42
13	20,16	27,44	28,75		1,24							14,49
14	15,82	29,75	26,95		0,55							11,17
15	16,50	18,14	27,77		0,95							10,32
16	11,39	19,42	29,74		1,14						4,47	10,82
17	11,93	23,38	11,61		2,06						4,81	9,16
18	13,61	12,89	11,42	3,96	2,98						6,40	12,42
19	17,44	14,40	10,38	8,29	2,82					0,84	8,83	14,15
20	22,22	18,23	10,19	11,79	8,45					2,01	11,42	17,07
21	26,23	21,68	13,38	12,54	6,32					3,95	12,51	19,13
22	30,19	25,30	16,63	13,63	8,27					3,45	15,30	21,89
23	33,70	28,59	20,10	15,66	9,40				1,03	5,64	16,10	24,79

Colour code:

0<W/m^2<50

50<W/m^2

Difference between the energy required for cooling and that available from wind energy (W/m^2):

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0	31	25	19	12	5				-2	-4	13	14
1	34	21	21	13	7	-6			1	-3	15	17
2	37	34	26	14	9	-2			2	-3	13	21
3	39	-3	29	21	10	3		-6	2	-7	14	24
4	43	27	32	24	12	3	-1	2	3	-5	18	29
5	47	32	34	25	14	5	2	3	4	-1	19	31
6	47	33	32	20	10	0		2	6	0	20	33
7	50	41	22	5	19					-9	21	33
8	30	23	10	-4	-5						2	9
9	7	23	13	-20	-9						2	-1
10	8	20	32	-36	-23						-1	-4
11	3	13	20	-47	-39						-6	-5
12	7	7	10		-50						-20	-10
13	3	14	0		-57							-14
14	-2	13	-4		-58							-20
15	-2	6	0		-54							-11
16	-3	8	6		-49						-14	-3
17	1	16	-9		-39						-9	0
18	7	4	-6	-22	-25						-5	4
19	11	10	-3	-10	-14					-11	0	7
20	15	14	1	2	-1					-12	5	6
21	19	16	7	4	0					-5	5	11
22	23	17	10	4	2					-5	8	12
23	27	5	13	8	4				-4	-3	9	13

Requirements covered:
Requirements not covered:

Percentage of energy required for heating by means of wind energy (%)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0	17	26	19	34	54				154	152	31	49
1	16	43	25	35	45	574			85	128	29	43
2	14	14	16	38	34	141			74	133	44	37
3	16	107	12	23	30	62		267	76	188	41	34
4	13	42	13	20	19	61	153	80	67	154	34	25
5	11	36	12	21	17	54	58	58	54	107	34	23
6	12	37	20	29	25	104		59	45	103	33	22
7	10	24	14	70	20					227	31	24
8	20	22	32	132	197						85	62
9	53	18	45	308	207						87	104
10	55	27	29	875	524						104	118
11	80	44	49	4114	1186						132	125
12	67	66	70		2308						439	157
13	86	50	100		4713							196
14	114	55	115		10595							277
15	110	67	100		5778							202
16	125	60	81		4372						416	130
17	95	32	175		1970						283	104
18	51	71	150	662	932						183	71
19	39	29	131	215	593					1431	103	53
20	33	22	85	86	112					675	60	63
21	29	26	49	69	98					236	57	43
22	23	32	39	74	75					254	50	44
23	20	84	36	49	63				509	154	46	48

Colour code:

%<50
50<%<100
Surplus

Square meters of windmill required per m^2 of greenhouse to cover the heating requirements.

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	5,91	3,91	5,40	2,92	1,85				0,65	0,66	3,25	2,04
1	6,36	2,30	3,96	2,86	2,21	0,17			1,18	0,78	3,43	2,32
2	7,02	7,01	6,19	2,67	2,98	0,71		0,00	1,34	0,75	2,25	2,72
3	6,10	0,93	8,69	4,38	3,34	1,61	0,00	0,38	1,31	0,53	2,43	2,96
4	7,96	2,38	7,85	5,08	5,14	1,65	0,65	1,25	1,50	0,65	2,90	3,98
5	9,40	2,74	8,53	4,70	5,76	1,87	1,71	1,71	1,84	0,93	2,97	4,34
6	8,55	2,70	5,03	3,40	3,99	0,96		1,70	2,23	0,97	3,06	4,60
7	10,17	4,13	6,95	1,44	5,12					0,44	3,20	4,15
8	5,10	4,59	3,15	0,76	0,51						1,17	1,60
9	1,88	5,44	2,20	0,32	0,48						1,15	0,96
10	1,80	3,64	3,50	0,11	0,19						0,96	0,85
11	1,25	2,28	2,06	0,02	0,08						0,76	0,80
12	1,50	1,51	1,43		0,04						0,23	0,64
13	1,17	2,00	1,00		0,02							0,51
14	0,88	1,83	0,87		0,01							0,36
15	0,91	1,49	1,00		0,02							0,49
16	0,80	1,67	1,23		0,02						0,24	0,77
17	1,05	3,11	0,57		0,05						0,35	0,96
18	1,95	1,41	0,67	0,15	0,11					0,00	0,55	1,42
19	2,59	3,39	0,76	0,47	0,17					0,07	0,97	1,90
20	3,04	4,65	1,17	1,16	0,89					0,15	1,67	1,58
21	3,47	3,78	2,04	1,45	1,02					0,42	1,77	2,32
22	4,43	3,11	2,60	1,36	1,32				0,00	0,39	2,00	2,27
23	5,04	1,19	2,81	2,03	1,59				0,20	0,65	2,15	2,10

Colour mode:

$0 < A \le 2$ (light orange)
$2 < A$ (orange)

3.2.3.3 Energy requirements to manage the vents in the greenhouse(W/m^2):

Estimation based on data registered for the roof vents of three experimental greenhouses during the growing season 1999-2000 from November to May for a bean crop.

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	0,002	0,007	0,005	0,002	0,005						0,002	0,001
1	0,002	0,007	0,002	0,002	0,002						0,002	0,002
2	0,002	0,007	0,002	0,002	0,002						0,002	0,002
3	0,002	0,007	0,002	0,002	0,002						0,002	0,002
4	0,002	0,007	0,002	0,002	0,002						0,002	0,002
5	0,002	0,006	0,002	0,002	0,002						0,002	0,002
6	0,002	0,008	0,002	0,002	0,002						0,002	0,002
7	0,003	0,009	0,003	0,003	0,003						0,003	0,003
8	0,005	0,007	0,005	0,005	0,005						0,005	0,005
9	0,007	0,017	0,007	0,007	0,007						0,007	0,007
10	0,014	0,014	0,014	0,014	0,014						0,014	0,014
11	0,018	0,016	0,018	0,018	0,018						0,018	0,018
12	0,022	0,015	0,022	0,022	0,022						0,022	0,022
13	0,023	0,015	0,023	0,023	0,023						0,023	0,023
14	0,021	0,013	0,021	0,021	0,021						0,021	0,021
15	0,014	0,013	0,014	0,014	0,014						0,014	0,014
16	0,010	0,012	0,010	0,010	0,010						0,010	0,010
17	0,009	0,013	0,009	0,009	0,009						0,009	0,009
18	0,006	0,005	0,006	0,006	0,006						0,006	0,006
19	0,004	0,006	0,004	0,004	0,004						0,004	0,004
20	0,004	0,006	0,004	0,004	0,004						0,004	0,004
21	0,003	0,006	0,003	0,003	0,003						0,003	0,003
22	0,002	0,006	0,002	0,002	0,002						0,002	0,002
23	0,002	0,006	0,002	0,002	0,002						0,002	0,002

Technical characteristics of the windmill with which calculations have been made:

Diameter of the rotor: 15.35 m
Swept area: 185 m^2
Height of the tower: 18 m
Asynchronous windmill:
Rated power: 55kW
Minimum wind velocity (for starting) 3.5 m/s
Nominal wind velocity 13.5 m/s
Stop velocity 24 m/s

Characteristics of the PV cell:
Monocrystalline silicon cells
Intensity at the point of maximum power (Imp): 0.12 A.
Open circuit voltage (Voc): 0.47V

Square meters of PV panels (per square meter of ground covered greenhouse area) to supply the energy required to open/close the greenhouse vents:

PV

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	no	no	no	no	no						no	no
1	no	no	no	no	no						no	no
2	no	no	no	no	no						no	no
3	no	no	no	no	no						no	no
4	no	no	no	no	no						no	no
5	no	no	no	no	no						no	no
6	no	no	no	no	no						no	no
7	no	no	no	0,0007	0,0003						no	no
8	no	0,0027	0,0007	0,0003	0,0002						no	no
9	0,0010	0,0015	0,0003	0,0002	0,0002						0,0006	0,0013
10	0,0007	0,0005	0,0004	0,0003	0,0002						0,0006	0,0008
11	0,0006	0,0004	0,0003	0,0003	0,0002						0,0005	0,0006
12	0,0005	0,0003	0,0003	0,0003	0,0003						0,0005	0,0006
13	0,0005	0,0003	0,0003	0,0003	0,0003						0,0005	0,0006
14	0,0005	0,0003	0,0003	0,0003	0,0003						0,0005	0,0006
15	0,0004	0,0003	0,0002	0,0002	0,0002						0,0004	0,0005
16	0,0004	0,0004	0,0002	0,0002	0,0002						0,0004	0,0005
17	0,0008	0,0008	0,0003	0,0003	0,0002						0,0009	0,0013
18	0,0012	0,0009	0,0004	0,0003	0,0002						0,0013	no
19	no	0,0023	0,0015	0,0008	0,0004						no	no
20	no	no	no	0,0011	0,0011						no	no
21	no	no	no	no	no						no	no
22	no	no	no	no	no						no	no
23	no	no	no	no	no						no	no

Not available
A<0.0005 m^2
A>0.0005 m^2

Square meters of PV panels (per square meter of ground covered greenhouse area) to supply the energy required to open/close the greenhouse vents:

Windmill

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
0	0,0003	0,0003	0,0007	0,0003	0,0009						0,0002	0,0001
1	0,0003	0,0008	0,0004	0,0003	0,0003						0,0003	0,0001
2	0,0003	0,0004	0,0002	0,0002	0,0003						0,0003	0,0001
3	0,0003	0,0012	0,0003	0,0002	0,0004						0,0002	0,0001
4	0,0002	0,0001	0,0005	0,0003	0,0004						0,0002	0,0002
5	0,0003	0,0003	0,0004	0,0003	0,0007						0,0002	0,0002
6	0,0004	0,0004	0,0005	0,0003	0,0008						0,0002	0,0003
7	0,0005	0,0005	0,0004	0,0004	0,0009						0,0003	0,0003
8	0,0009	0,0005	0,0013	0,0004	0,0010						0,0005	0,0005
9	0,0010	0,0026	0,0015	0,0004	0,0007						0,0006	0,0004
10	0,0017	0,0027	0,0013	0,0005	0,0008						0,0008	0,0008
11	0,0019	0,0022	0,0014	0,0004	0,0006						0,0010	0,0008
12	0,0017	0,0015	0,0012	0,0004	0,0005						0,0009	0,0009
13	0,0015	0,0010	0,0010	0,0004	0,0004						0,0009	0,0008
14	0,0012	0,0010	0,0007	0,0004	0,0004						0,0007	0,0007
15	0,0008	0,0008	0,0005	0,0002	0,0002						0,0005	0,0005
16	0,0005	0,0010	0,0004	0,0002	0,0002						0,0004	0,0005
17	0,0006	0,0012	0,0004	0,0002	0,0002						0,0005	0,0006
18	0,0005	0,0007	0,0003	0,0002	0,0001						0,0004	0,0006
19	0,0006	0,0007	0,0003	0,0002	0,0002						0,0004	0,0005
20	0,0006	0,0013	0,0003	0,0002	0,0003						0,0005	0,0006
21	0,0004	0,0016	0,0004	0,0003	0,0003						0,0004	0,0003
22	0,0003	0,0011	0,0004	0,0003	0,0004						0,0003	0,0003
23	0,0003	0,0008	0,0004	0,0002	0,0004						0,0003	0,0002

$A<0.0005\ m^2$

$A>0.0005\ m^2$

3.2.4. PV and wind energy combined with thermal storage.

On a parallel approach, the HortiAlmería module has also been used with climate data from Almería and The Netherlands to make some estimations of possible use of renewable energies to cover greenhouse heating and cooling requirements. All calculations, both for Almería and The Netherlands have been performed for a 15 spans greenhouse with the following dimensions and cover properties:

Dimensions

Span width	7.0	m	Length	100.0	m	Wall height	3.5 m
Roof angle	11.0	deg	Number of spans		15		

Solar radiation transmission

Cover (Total)	0.90	Cover (PAR)	0.90	
Shade (Total)		1.00	Cover (net)	0.90
House (net)	0.65	Emissivity of cover		0.90

The settings used for the simulation were:

Control settings

Heating temp	12	C	
Vent/Cooling temp		27	C
Evap. cool efficiency		0	
Mech. cooling rate		200	W/m2
Cooler temp	10ºC		

Wind energy

The wind energy module determines the energy that could be obtained from the wind. The power flux density P was calculated from:

$P = 0.5\,\rho\,w^3$

where ρ is the air density and w the wind speed. As an example of how this might be used it was applied to a windmill that generates heat by friction with a fluid in a heat churn and the heated fluid transfers the energy to a heat exchanger in the greenhouse.

Table 21. Parameters for wind energy simulations

Parameters for wind energy	
Ghouse area / windmill area	**5.00**
Heat conversion efficiency	**0.7**

The size of the area swept by the windmill is expressed as the ratio of greenhouse area / swept area, as this avoids the need to use the dimensions of a specific windmill and to consider the number of windmills. The Heat conversion efficiency includes the efficiency by which wind energy is converted into heat by the windmill and the heat is conveyed to the greenhouse.

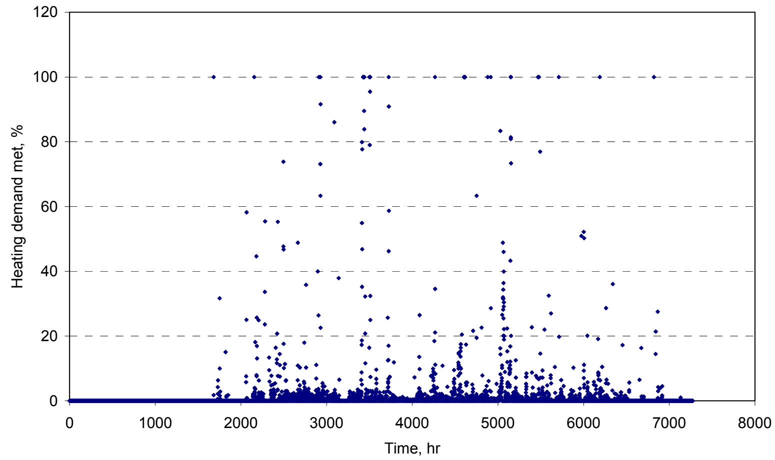


Fig. 51. Proportion of heating energy met by heat generated by a windmill – no storage

Using the parameters shown above, the energy produced by the windmill in Almería (year 2007) and The Netherlands (reference year) were 157 MJ/m^2 and 167.4 MJ/m^2, while the heat requirement of the greenhouse were 84.7 MJ/m^2 and 746.2 MJ/m^{-2} respectively However, there was poor correlation between when the windmill produced energy and the greenhouse need (see Fig.51 for the Almería case) and only 5.7% and 9.9% of the energy produced by the windmill was used for Almería and The Netherlands respectively. The use of heat storage enabled this miss-match between the availability and demand for heat to be reduced. Using a heat store of 5 MJ/m^2 enabled wind energy to meet 53.7% of the total greenhouse requirement for Almería and 21 % for The Netherlands. The behaviour of the heat store for the Almería case is shown in Fig. 52.

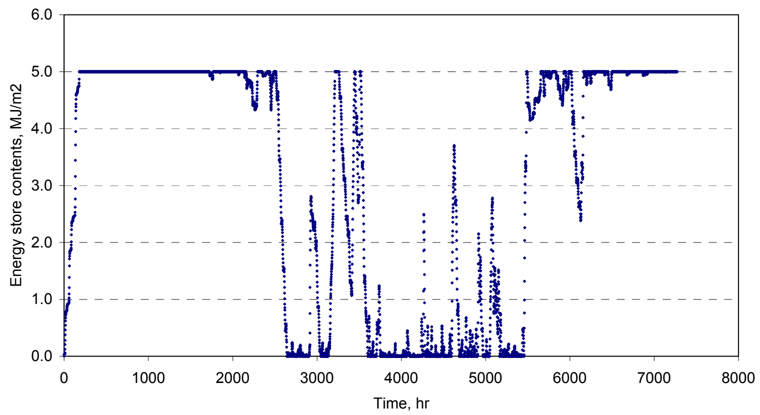


Fig. 52. Energy store for output from windmill.

Photovoltaic electricity

Another possibility is to use electricity generated by photovoltaic cells. This could be used to power greenhouse systems in conjunction with battery storage. Another possibility is to use the electricity to drive a vapour compression heat pump.

Table 22. Parameters for photovoltaic electricity simulations

Parameters for photovoltaic electricity				
Ghouse area / Photocell area				20.00
Photocell conversion efficiency				0.08
Heat pump CoP cooling				4.80

Using the parameters shown, the electricity produced was calculated and used to drive a vapour compression heat pump. The coefficient of performance (CoP) of the heat pump was taken as the average of the measured values (US Federal Government Procurement Office) for vapour compression heat pumps used for cooling with air as the heat sink. Over the total period this provided 96 MJ/m^2 of cooling while the greenhouse requirement was 1966 MJ/m^2 for Almería and, thus using the photovoltaic electricity in this way could meet only 6% of the cooling requirement (see Fig. 53).

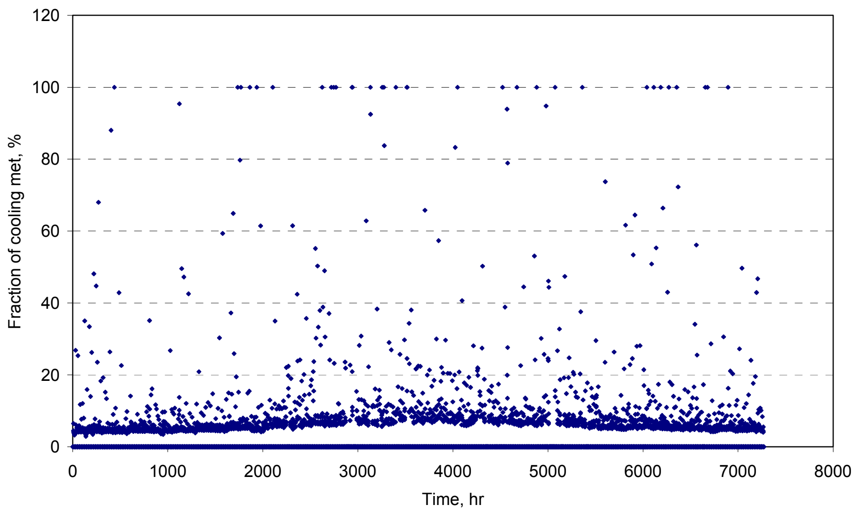


Fig. 53. Proportion of cooling met by electrically driven heat pump

3.2.5 Conclusions of the analysis

The studied resources (solar radiation and wind energy) show a certain similarity in their distribution. Obviously, there is much more energy during the daytime hours than during the nighttime hours and in the months around the summer than during the winter.

There is a concordance with the time of the year in which the conditions inside the greenhouse are such that the temperatures are above the optimum and limit temperatures, but not during the moments in which temperatures are below the limits (winter.)

According to the different tables, we can clearly say that neither PV nor wind energy can be used economically to cover heating or cooling requirements of the greenhouses in Almería. The only possibility with some interest would be to use the wind energy to produce heat (using a heat churn) and heat storage, but that would only meet part of the demand.

Another possibility is to cover the electricity use associated to the motors that open and close the greenhouse vents and other electricity consumptions (irrigation pumps, screens, etc.), which have not been included in this study. In any case, a study would be required to study the pattern of electricity consumption of the greenhouse (specially the peaks) because in many cases there would be no concordance between the moments in which the energy is generated and when it is required. For this, accumulation would solve the problem but would increase the costs. In the following section an example on how to build a profile for energy use in a reference greenhouse is provided.

Another example on how PV panels can cover small electricity consumptions in a greenhouse was provided by Al-Shamiri et al. (2007), who tested a hybrid photovoltaic system consisting of two photovoltaic sub-systems were connected to each other (48 photovoltaic solar Panels with 18.75 watt each, one inverter, 1 charge controller and a battery bank, including 12 batteries). The PV system is located at University Putra Malaysia (UPM) Research Park. The national electricity grid was used as a backup unit. The load consisted of two misting fans for cooling greenhouse (during test period time) with 400 Watt electric power and five hours (11:00 am to 16:00 pm) daily operation. The results obtained showed that the maximum current drawn from the array was found to be 14.9 ampere at 13:00 pm (with load). The voltage of array was found to be 26.9 volt while the voltage and current of battery bank were found to be 26.2 volt and 23.0 ampere respectively. In conclusion, this study highlights the primary study of PV hybrid energy systems for tropical greenhouse cooling as an application of renewable energy in Selangor, Malaysia. The results showed that PV system would be suitable to supply electricity to cover the loads requirement demands without using energy from the grid. However, no economic study was shown.

In any case, the growers which would decide to use PV or wind energy would normally sell the energy because in most countries, selling this energy is subsided by the government, so the growers would rather sell it than use the electricity directly in the greenhouse, except for extremely isolated greenhouses. One of the advantages of the PV solar plants in Spain, with the existent subsides, nowadays, is that they have a very short period of depreciation, of approximately 8 years. Recently there has been an enormous interest in some countries (mainly Mediterranean) in the installation of PV panels directly over the roof of the greenhouses. Since semi-transparent PV panels are still under development, the need to use opaque PV panels, involves in the case of installing them over the greenhouse roof, a decrease in transmissivity that will involve on its turn in a decrease in the yield, which is obviously compensated by the income obtained from selling the electricity. Italy is probably the country in which more projects of this type have been executed, in many cases growing inside the greenhouse species of low light requirements (some ornamentals, mushrooms, etc.). In the case of Spain, a regulation recently approved on Solar Energy has excluded the greenhouse and water basin roofs from the possibility of installing PV panels.

For those countries in which regulation allows for installing PV solar panels in the roof, combined with horticultural production inside the greenhouse, the main question to solve is how to balance the electricity production (area of PV panels and distribution of the panels over the roof) and the shade generated over the crop (potential production loss caused by the shadows). In this sense, information available is scarce. Some researcher studied the use of PV systems to operate greenhouses, including energy to operate fans, water pumping and heaters (Oheimb et al., 1994; Parker, 1991; Reuss and Muller, 1994; Koazu et al., 1999). Koazi et al. (1999) simulated the solar radiation transmission to a greenhouse having photovoltaic cells on the roof. The study included the effects of roof area coverage of photovoltaic cells, greenhouse orientation, northern latitude, and season on the diurnal time courses of averaged transmissivity for direct solar radiation on the floor surface, and the crosssectional distributions of transmissivity for daily integrated global solar radiation on the floor surface. They concluded that significant amounts of electricity could be generated using photovoltaic cells without significant reduction in solar radiation transmission, if the roof coverage with photovoltaic cells and greenhouse orientation are chosen properly for the latitude (geographical location) and time of year. In their study, Reuss and Muller (1994) discussed the suitability of solar PV power supplies for greenhouse ventilation and irrigation systems. The PV system developed for greenhouse application was described and its efficiency and operating costs were compared with those of conventional grid and battery installations.

A recent study by Yano et al. (2010) assessed the spatial distribution of sunlight energy in an east–west oriented single-span greenhouse equipped with a PV array (12.9% of the roof area) inside a Gothic-arch style roof. Two geometrical arrangements of the PV array were tested—straight-line (PVs array) and checkerboard (PVc array)—each of which comprised 30 PV modules facing the southern sky. The study showed that the PVs array casts a shadow on the same position in the greenhouse continuously for 4 months. In contrast, the PVc array casts a shadow intermittently on the same position during a single day, providing a more uniform spatial distribution of long-term irradiation in the greenhouse than that provided by the PVs array. However, a wider area in the greenhouse can be partially obscured by the PVc array's intermittent shadows. Under a cloudless sky assumption, the PVs and PVc arrays are respectively estimated to generate 4.08 GJ y^{-1} and 4.06 GJ y^{-1} electricity. The calculated annual values of sunlight energy received in the greenhouse equipped with the PVs and PVc arrays are, respectively, 5.31 GJ m^{-2} and 5.03 GJ m^{-2}. These results demonstrate that the checkerboard arrangement improves the unbalanced spatial distribution of received sunlight energy in the greenhouse, with only slightly reduced amounts of received sunlight energy and generated electrical energy.

According to Campiotti et al. (2010) the PV capacity installed in the European Union during 2007 and 2008 reached up to 9,533.3 MWp (PV barometer 2009). Photovoltaics can power greenhouse electricity costs for actuators (opening and closing of windows, fertigation, …) and cooling operation in summer and supply water pumps, lights, electric fences Since the associated goal is mainly to implementing solar PV systems into the greenhouse agriculture, the following criteria should be met: being simple, easy to manage and repair, and with the possibility of being manufactured locally. Previous experimental evaluations made in southern areas of Italy (36°50' latitude, 14°31'longitude, 87 m of altitude), showed that a 1 kWp m-PV arrays generated 333.6 kWhel during the period 10 September-23 December 2008. However, it should be outlined that the recorded energy production was mainly referred to the energy delivered to both the battery storage and the greenhouse electric applied loads as inside light, various LEDs, dataloggers and pumps (Campiotti et al., 2008). Research is still in progress. Recently, on the market are being commercialized crystalline silicon modules coming from China, with relative low price (between 1,500 to 2,000 €/kWp). The promotion of PV modules integration in greenhouse agriculture have also a significant importance for reducing the environmental impact associated with the fossil energy (for each kWhel it is reported till to 700 g of CO2 emissions) since the photovoltaic solar installations produce a corresponding GHG emissions between 21-45g of CO2-eq.kWh-1 (Fthenakis and Alsema, 2006).

Therefore we can conclude that for areas in which solar radiation is abundant (i.e. desert areas) in which greenhouses are built in remote locations, without access to the network, PV panel systems, if properly designed and provided that a good study of the electricity consumption patterns along the year is made, are a reliable source to cover small electricity consumptions of the greenhouse operation (motors opening and closing vents, pumps for irrigation or fogging, etc.).

3.3 Biomass heat

The possibility of growing plants for energy production is a reality nowadays, for example energy cereals, quick growing wood from plantations or Miscanthus sinensis. Earlier the combustion of wood and straw for greenhouse heating has been discussed (v. Zabeltitz et al., 1982). According to Campiotti et al. (2010) solid biomass should exceed 75 Mtoe in 2010, including 1.6 Mtoe net imports from outside the EU, and thus contributing to reach the 2005 European Plan of action’s for biomass which aimed for 149 Mtoe of consumption (55 Mtoe for electricity, 75 Mtoe for heat and 19 Mtoe for transport at the end of 2010) for all bioenergies (solid and liquid biomass, biogas and municipal wastes) (Solid biomass barometer, 2009). However, the agricultural and forestry biomass resources should be considered as the most promising renewable energy sources from the agriculture sector. More than 300 million tons crop residues and over 230 million tons green residues and animal wastes are produced in Europe as unutilized by-products. Among the crop residues (biomass residues as organic by-products of food, fibre, and forest production), straw is the most important resource with not less than 21 million TOE, of which nearly 0.3 million TOE are utilized for agricultural heat supply, mostly in Austria, Denmark, Germany, and The biomass energy sources are decentralized energies suitable for heat supply of greenhouses, individual farms or rural districts. The calorific values of absolutely dry biomaterials makes them are excellent and clean energy carriers for direct combustion. Some 20% of biomass potential for combustion may cover the total heat demand of primary food production (agriculture and greenhouse districts) and a further 30% of it the heat requirement of rural communities.

Wood biomass can be considered as greenhouse gas (GHG) neutral when converted to heat energy if we exclude some greenhouse gas generation during harvesting, transportation, pre-processing. Fields of biomass application for heat generation are:

- low temperature heat and hot water preparation for single houses;
- district heat (with and without cogeneration);

 industry process.

The wide-scale practical distribution in greenhouse agriculture of this technology now depends on the national and European energy price policy and the introduction of subsidiary systems which are still necessary to make these technologies more attractive for the farmers (Project Accent, 2006). At present, the wood industry is addressed to introduce adapted cost-effective technologies and suitable supply chains for using pellets (15-60kW as biomass burners), briquettes (15-100kW as biomass burners) and chips (200-300 kW).

Biomass consumption as fuel for greenhouse heating is related to both the greenhouse surface and the specific energy needs of crops. Considering a thermal power of the greenhouse surface to be heated equivalent to 100 W/m2, a conversion yield of 85%, biomass producing 3.9 kWh/kg, the annual average biomass consumption is about 45 kg/m2 with 1.500 running hours, 90 kg/m2, 3,000 running hours.

Von Zabeltitz (1994) calculated the necessary agricultural area of biomass production with the assumption of the following conditions in Germany, Table 1. The average calculated energy requirement for greenhouse heating under German climate conditions is given by:

Vegetables:

Single glazing without thermal screen; Inside temperature ti = 8°C; Mean energy requirement E = 16.2 1 oilequivalent (oe) per m^2 and year

Cutflowers:

Single glazing without thermal screen; ti = 12°C; E 35.2 1 oe/(m^2*a)

Potplants:

Single glazing with thermal screen; ti = 16°C;E 45 1 oe/(m^2*a)

The oil equivalent (oe) per ha of different plants for energy production is (Schön et al, 1992):

Residues:

Straw 2000 1 oe/(ha*a)

Energy plantations:

Wood from plantation, including drying 4500 1 oe/(ha*a)

Energy cereals 5000 1 oe/(ha*a)

Miscanthus sinensis, including drying 7000 1 oe/(ha*a)

Table 4. Agricultural area (ha) necessary for heating 1000 m^2 of greenhouse area

	Residues: Straw	Energy plantation: Wood	Cereals	Miscanthus
Vegetables	8.1	3.6	3.2	2.3
Cutflowers	17.6	7.8	7.0	5.0
Potplants	22.5	10.0	9.0	6.4

As we can see, large cultivation areas are required if enough supply for greenhouse clusters wants to be covered in cold climate areas. For Mediterranean areas, since the heat requirements are much lower (i.e. In Almería, between8-10 less energy is required) the energy crops areas required are much lower.

McKenney et al. (2011) performed a study to explore the economic feasibility of fossil fuel substitution with biomass from short-rotation willow plantations as an option for greenhouse heating in southern Ontario, Canada. They assessed the net displacement value of fossil fuel biomass combustion systems with an integrated purpose-grown biomass production enterprise. Key project parameters included greenhouse size, heating requirements, boiler capital costs and biomass establishment and management costs. Several metrics were used to examine feasibility including net present value, internal rate of return, payback period, and the minimum or break-even prices for natural gas and heating oil for which the biomass substitution operations become financially attractive. Depending on certain key assumptions, internal rates of return ranged from 11–14% for displacing heating oil to 0–4% for displacing natural gas with woody biomass. The biomass heating projects have payback periods of 10 to >22 years for substituting heating oil and 18 to >22 years for replacing a natural gas. Sensitivity analyses indicated that fossil fuel price and efficiency of the boiler heating system are critical elements in the analyses and research on methods to improve growth and yield and reduce silviculture costs could have a large beneficial impact on the feasibility of this type of bioenergy enterprise.

Chau et al. (2009) performed a techno-economic analysis and determined that the installation of a wood pellet or a wood residue boiler to generate 40% of the greenhouse heat demand is more economical than using a natural gas boiler alone to generate all the heat for an average-sized greenhouse in British Columbia. The techno-economic analysis contained forecasted parameters and a therefore a thorough sensitivity analysis was done, assessing the effect of fuel price, wood biomass energy contribution, and greenhouse size changes on the net present value (NPV) when using a wood pellet or wood residue boiler with or without an electrostatic precipitator (ESP). The results indicated that the attractiveness of using wood biomass would increase if the price of fossil fuels increased more than 3% per year or carbon taxes and regulations were applied. Increasing the biomass energy contribution by 20% (to provide 60% of the total heat demand) would still be economical. The installation of a wood pellet boiler or a wood residue boiler is economical for average (7.5 ha) or large (15 ha) greenhouses.

It is obvious, that taxes and regulations (i.e. subsides for buying biomass boilers) of each country may have big effect in pushing growers to use these systems. In Mediterranean greenhouses, where heating is scarcely applied in the greenhouses, there is a big opportunity of biomass heating, to become a system used by the growers to increase the quantity and quality of their yields during the winter, especially where cheap biomass is available and subsides are available for the growers (i.e. In Spain up to 40% of the investment on the biomass heating system can be subsided by the government).

In any case the following section deals with another possibility that has not been studied in detail: the use of greenhouse vegetal waste as a source of biomass for heating.

3.4.1 Potentialities for the use of greenhouse vegetal waste as biomass source for greenhouse heating

One of the biggest problems of greenhouse cultivation is the large volume of vegetal waste generated. In countries like The Netherlands or in areas like Almería (only during the recent years) composting this waste has been the technology used to provide an added value to these residues. In the case of The Netherlands, the relatively low calorific value of the majority of horticultural crops and the high energy requirements for heating are possible causes for not having considered this waste as a possible source of energy for the greenhouse itself. In the case of Mediterranean greenhouses, Almería could provide an example of the problem associated to these residues. In the past the growers left the vegetal waste near the greenhouses and burned them or used them as food for the animals, mainly cattle (Escobar, 1998). These practices, had terrible consequences, such as creating spots for dissemination of pests and diseases, which affected the surrounding greenhouse crops, could derive in putrefaction matter with the subsequent bad smell and pollution of the aquifers, as well as the negative visual impact (Parra, 2004).

The management of residues is complex, among other reasons because:

Heterogeneity of the residues which come from different crops and that include other materials as the polypropylene threads used to train the plants.

Great dispersion of the vegetal waste which makes transport and storage operations more expensive

Generation of vegetal waste during the whole year.

a) Characterization of the greenhouse vegetal waste.

<u>Dry and fresh matter</u>

The fresh and dry weight data shown in the Figure for the different horticultural crops grown in greenhouses in Almería have been obtained at the Experimental Station of the Cajamar Foundation during 10 years. Only vegetative organs have been considered (leaves and stems) and non-commercialized fruits. The fresh weight of the products is determined by the moisture content, being influenced by the ambient temperature, the days passed since the crop cycle ended, as well as the time interval between the last time the crop was irrigated and the moment the plant was detached from the roots. The vegetal waste should not remain in the greenhouse more than a week (disease propagation).

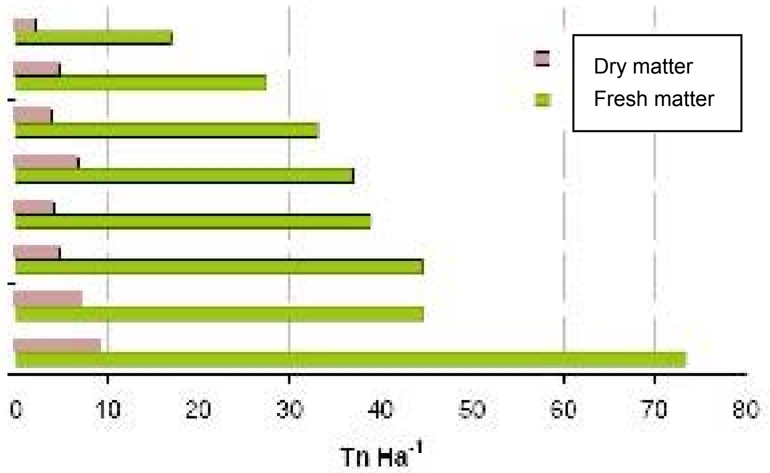


Figure 54. Vegetal waste of the main horticultural crops of Almería greenhouses, in the moment of cutting the plant (fresh weight) and dry, in a store at 65ºC. Source:Estación Experimental de la Fundación Cajamar.

The province of Almería, with a greenhouse area of 26.000 Ha, produces an estimation of 1.751.373 Tn. The two main crops of the province (tomato and pepper) generate 60% of the total fresh weight of vegetal waste.

Characterización of the biomass

The following table shows the results of the elemental composition of some vegetal waste

		RVI1	RVI2	RVI3
Carbon	%	36,60	37,70	38,30
Hydrogen	%	4,88	4,83	4,93
Nitrogen	%	3,23	3,77	2,88
Sulphur	%	0,12	0,21	0,16
	%	36,00	36,60	38,40

Table 5 .-Elementary composition of several greenhouse vegetal wastes determined on 10/11/2008.

It is important also to determine the content in Sulphur and Chloride. Chloride content should be low because a high content is harmful for the combustion process because it causes sticking of the material in the heat exchangers, decreasing the efficiency of the combustion and causing blockings in the gas circulation. Sulphur is environmentally harmful for obvious reasons (acid rain, …)

It is important also to characterize the density, moisture content, texture, … of the waste. These determinations have been done but have not been included in this report, for the sake of brevity.

We will focus then, on showing some data on the heating power contained in the greenhouse vegetal waste (a heterogeneous mix coming from different greenhouses). Results showed that the gross fraction has a good heating power, with a value of 2,375 cal/g. The thicker particles, which are the most ligneous ones, reached a value of 3,200cal/g. The presence of smaller, more humid particles and with more ashes decreases the total heating power. However, the value is coherent with the literature, in between impregnate sawdust (3,200 cal/g) or lignite (2,000- 4,000 cal/g), although lower than soft coal (3,000-5,000 cal/g) or carbon coke (7,000 cal/g).

Resides, specific biomass from a greenhouse tomato and pepper crop has been analyzed to determine the heat power. Results show as the heat power from both dry crops is similar, and around 15 MJ/kg, a value almost constant during the drying period in both cases, although a certain loss of heat power occurs with time due to the decomposition of some degradable materials.

Definition of the previous treatments.

The physical transformation of the greenhouse vegetal waste biomass, for their use as fuel requires the following processes, with the aim of obtaining agri-pellets.

1. Drying: it is necessary to dry the vegetal waste so the particles generated in the process of grinding, can self-agglomerate during the compression process.

   Humidity must range between 8-15 %. The drying can be done using natural means, but if there is no time available to eliminate the vegetal wastes forced drying can be used. In this last case, the increase in price in the process of obtaining the pellets or briquettes, as it requires higher energy.

2. Conditioning: in this stage it would be desirable to eliminate the polypropylene threads twisted around the stems. This operation can be complicated. There aren't specific machines for this task. An "idea" could be to use tromer cylinders with fix elements capable of generating frictions that break the vegetal mass but not the threads and specifically located exits for the vegetal pieces (it must be experimented).

   Depending on the conditioning type the crushing stage may be avoided. Another alternative, although probably very expensive, can the pre-treatment system developed by López et al. (2001)

3. Grinding (milling): it must provide a homogeneous texture with sizes oscillating between 6-8 mm, for the fabrication of pellets of 0.5-1 cm for the briquettes (hammer mill with sifters of proper size).

4. Compacting: presses of different sizes are used with the aim of increasing the specific weight of the biomass. In this way the transport and storage costs decrease. The heating power also increases. Once the pellets have been generated they must be cooled to avoid their disintegration.

b). Steps to be followed in the design of a biomass greenhouse heating system

Once the grower knows in detail, what type of biomass or biomasses he is going to use (the most important parameters are their heating power, their price, their availability, and their quality) the next step is to calculate the heating requirements of the greenhouse. The energy demand of a greenhouse depends on the relation between the external climate and the environmental requirements of the crop inside the greenhouse. Heating systemas are used to control the greenhouse internal temperature improving the conditions trying to reach temperatures as close as possible to the production optimum set points.

Calculation of the energy requirements

i. **Location and greenhouse type to be heated**

ii. **Meteorological conditions that affect the energy requirements**

The following parameters must be available from the closest meteorological station to the farm.

- *Global solar radiation*
- *Maximum radiation intensity*
- *Sunshine hours*
- *Dominant wind directions*

The main parameter in the energy balance of a greenhouse is the external temperature, which determines directly the cooling and heating requirements. The main values to be used in the design of a heating system are:

- Maximum absolute monthly temperatures
- Average of the monthly maximum temperatures
- Average of the average monthly temperatures
- Average of the minimum monthly temperatures

– Absolute minimum monthly temperature

iii. Favourable climate conditions for the greenhouse crops.

The ambient temperature that must be kept inside the greenhouse depends on the crop, the desired level of comfort and its development stage. These values can be found easily in the scientific literature. Such values serve as a basis to establish the heating systems set points, as well as to calculate the power of the system by means of an energy balance.

In the design the most restrictive conditions for the crop must be considered, so the heating will be designe to satisfy the heating requirements during the winter nights.

iv. Calculation of the energy balance of a greenhouse

A simple energy balance can be used to calculate the energy required, and from there, the required power of the heating system. An example of energy balance to be applied is:

$$R_n + Q_{cli} = Q_{cc} + Q_{ren} + Q_{evp} + Q_{sue}$$

Donde:

Rn: net radiation

Qcli: heating energy that must be supplied (Qcal) or eliminated (Qref) from the greenhouse

Qcc: Heat lost by conduction-convection

Qren: Sensible and latent heat lost by internal air renewable

Qevp: Latent heat consumed through evapotranspiration from the plants and the soil

Qsue: Heat flux lost by conduction from the soil

Once Qcli has been calculated, the grower must choose among the different technical options available in the market the best boiler to suit his energy requirements. It is important, in the case of biomass heating, if the grower is planning to use more than one type of biomass, to choose a multi-residues boiler, although they are a bit more expensive, but provide flexibility to the grower, if a certain biomass becomes scarce, or the price becomes to high.

From an environmental and productive point of view, it would be advisable to adapt a sytem to the biomass heating system capable of adsorbing the CO_2 from the combustion gases, store it and use during the daytime inside the greenhouse (CO_2) enrichment. Different materials, such as certain types of active carbon, are capable of doing almost infinite cycles of adsorption-desorption of CO_2. An example of such a system is being tested at the moment, linked to the biomass boiler at the Experimental Station of the Cajamar Foundation.

3.4 Geothermal energy

According to von Zabeltitz (1994), the use of geothermal energy for greenhouse heating is a very good solution, if the geothermal water is available not too deep in the subsoil and if the water temperature is suitable. Main problems are the economy of the drillings, the salinity of the geothermal water and the discharge of the cooled saline water. In many cases heat exchanger have to be used in greenhouses (Popovski et al., 1988; v. Zabeltitz et al, 1988). Advantegeous is the applicability of low enthalpy energy for greenhouse heating. Low temperature heating systems are available for less than 35°C today. In some southern countries like Greece, Turkey, Israel and mainly in Tunisia there are remarkable areas of greenhouses in practice heated by geothermal energy.

The geothermal energy resources have irregular distribution over Europe, Fig. 2. Mainly low enthalpy sources are characteristic, except the area of southwestern Italy, eastern Greece and Turkey where also high enthalpy sources can be found. It is possible to determine the location, temperature characteristics and heat energy potential of most geothermal fields in Europe (Haenel et al., 1988)

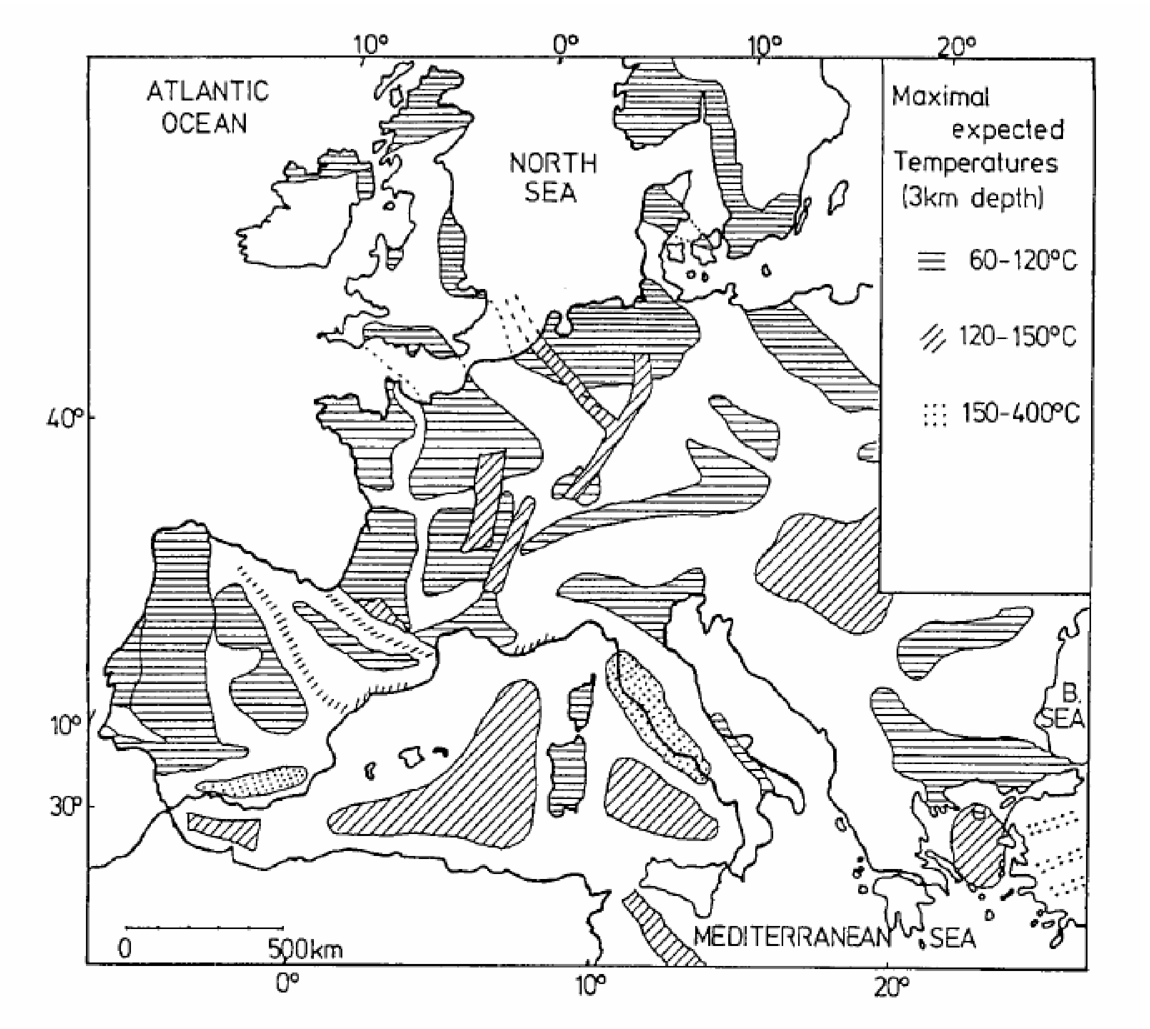


Figure 55. Geothermal energy resources in Europe.

Brackish water desalination is one of the most promising fields for the application of geothermal energy. When using geothermal energy to power desalination plants, thermal storage problems are avoided, also the energy output of this resource is generally stable compared to other renewable resources such as solar and wind energy (see Mahmoudi et al., 2010).