Project Title: A technical & economic appraisal of technologies & practices to improve the energy efficiency of protected salad crop production in the UK.

Project Number: PC 188 Experimental work ‘A demonstration of advanced environmental control strategies’.

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Grower Summary

Headline

The benefits of applying temperature integration (TI) to the production of a commercial crop of classic round tomatoes over the 2002 season were found to be:

- An energy saving of 8.4%
- A yield increase of 4.3%

Using current energy prices and crop values this represents an increased margin of £17,950/ha.

Background & Expected Deliverables

Recent increases in the cost of energy and the introduction of the Climate Change Levy (CCL) have focused the attention of growers on ways of improving energy efficiency. For salad crop production in the UK, energy can account for up to 40% of the total cost of production. Further increases in the cost of energy are seen to pose a serious threat to the future profitability of this sector. Consequently, many growers are looking for practical methods to help them reduce their energy use.

Over recent years a considerable amount of R&D has been carried out on temperature integration (TI). TI takes advantage of the fact that crops will thrive just as effectively when grown in an 'average' environmental temperature over a given period as they would under a single 'fixed' temperature. This principle offers significant potential for energy saving, as it allows the lowering of the temperature in the greenhouse during periods when the external conditions would tend to lead to high heating costs (e.g. during a cold, windy night). This is compensated for by allowing the greenhouse temperature to rise at times when conditions are more favourable (e.g. on a bright sunny day) to maintain the correct average temperature.

Most previous R&D in this area has concentrated on crop response to TI, and has shown that considerable temperature swings can be accommodated over periods of up to 14 days without loss of yield or quality. However, despite these findings, commercial uptake of TI has been minimal. Growers have been reluctant to abandon the environmental control strategies and set points they have traditionally used.

Concerns over humidity control, disease control and crop balance & regularity have been sited as the main obstacles to change. With these issues in mind the objectives of this work were to:

- Demonstrate the level of energy saving that can be achieved by applying TI on a commercial nursery
- Quantify any crop related effects (disease, yield etc.)
- Determine the overall economic impact of TI strategies on the production of a commercial tomato crop
- Give guidelines on the application of TI for a commercially grown crop of tomatoes

Summary of Results and Main Conclusions

Research method

Over the 2002 production season, a crop of ‘Encore’ classic round tomatoes was grown in two separate greenhouse compartments on a commercial nursery in the North West of England. The size of each compartment was approximately 3,600m^2. Each compartment had a separate heating circuit and hot water heat meters were installed to record energy use throughout the trial. Nursery staff kept ongoing yield and disease records and a detailed disease assessment (particularly of Botrytis) was carried out at the end of the season.

A Priva Integro v720 environmental control system with TI software was used. This equipment and the associated software have been commercially available for several years. One compartment was grown using the nursery’s ‘conventional’ control strategy whilst the other was grown using the same basic set points, but with the addition of TI.

Environmental control strategies & energy saving

During the early part of the season (weeks 5 to 11), simply ‘turning on’ TI gave average energy savings of 5%. This was achieved by increasing the temperature setting at which ventilation was introduced and allowing the night temperature to be reduced to compensate. These settings allowed the TI compartment to:

- Run at a higher temperature than the conventional one during the day period
- Automatically reduce the heating temperature during the night period. This compensated for any accumulated ‘energy credits’ and allowed the same average temperature to be achieved in both compartments.

Over the period from weeks 12-17, the predominant energy requirement of the greenhouse became driven by the need to control humidity rather than temperature and savings reduced to almost zero despite the fact that the original TI settings were retained. To accommodate the changing requirement for energy, a radical approach to humidity control was adopted. This involved relaxing the basic humidity control strategy and introducing a ‘heat boost’ triggered by consistently high humidity levels. Whilst this gave energy savings as high as 30%, a prolonged period of poor weather conditions revealed the limitations of this approach. The result was unacceptable levels of Botrytis on leaf debris in the TI compartment. This required a clean up period where TI was turned off and a single application of the fungicide Scala was given to the crops in both the TI and control compartments.

The use of TI was reinstated in week 21. The environmental control settings were refined to fully integrate the needs of TI alongside the requirements to control humidity. A successful humidity control strategy based on a ‘ventilate then heat’ approach was devised which gave consistent energy savings averaging 11%. This method of humidity control contrasted with the control treatment where the commonly used ‘heat then ventilate’ approach was retained.

As weather conditions deteriorated towards the end of the season (from week 38 onwards) a more conventional ‘heat then ventilate’ approach to humidity control was gradually introduced. Over this period energy savings averaged 7%.

During the last few weeks of the season (weeks 43-44) TI was turned off as crop requirements and the prevailing weather conditions gave little opportunity for energy savings.

Overall Energy Savings & CO_2 Concentration

Over the whole season, the corrected specific energy consumption for the two individual compartments was as follows:

Block	**Specific Energy Consumption (kWh/m^2)**
Conventional	418 (100%)
TI	383 (91.6%)
Difference	35 (8.4%)

Note that these figures relate to the heat energy delivered by the piped hot water system to each compartment. To determine the quantity of gas saved, the efficiency of the boiler and the distribution network also have to be taken into consideration. Assuming a combined seasonal efficiency of 80%, **the gas saving is 44kWh/m^2**.

Both of the trial blocks were supplied by a common CO_2 system, with the control set point being determined by the CO_2 concentration in the conventional block. When viewed over the complete season, the effect of using TI was to reduce the level of venting. This led to daytime CO_2 levels in the TI compartment that averaged 11% higher than the conventional treatment.

Crop Yield & Disease Levels

The yield results from the trial were as follows

Block	**Yield – (kg/m^2)**
Conventional	53.42 (100%)
TI	55.73 (104.3%)
Difference	+2.31 (+4.3%)

Although this was not a fully replicated trial, confidence in this result is increased as historical yield data from the nursery showed little difference in yield between the two blocks.

With regard to disease, an end of season assessment was carried out in week 41. The results were as follows:

Block	**Mean % non-wilting heads**	**Mean number of Botrytis lesions / 100 stems**
Conventional	82.2	11.8
TI	81.6	9.4

This analysis shows that, even with the high level of Botrytis that was evident on leaf debris in the TI block in week 17, the overall levels of disease in the TI block was slightly lower by the end of the season.

Conclusions

Key conclusions from this work are:

- TI can be successfully applied to a commercially produced crop of heated tomatoes. Even by applying the technique in its simplest form, energy savings of the order of 8% can be expected.
- Better CO_2 utilisation may result from using TI. This is because TI leads to less greenhouse ventilation and hence better retention of CO_2 within the greenhouse. Response is likely to be very site-specific however.
- TI settings need to work in harmony with other greenhouse environmental control settings. This is particularly important where humidity control is concerned. To this end a framework of settings needs to be used that takes into account the different production phases and weather influences that are experienced throughout the season.
- When successfully applied, TI does not have a detrimental effect on crop yield or quality.
- To get the most out of TI without risking crop quality or yield requires a detailed understanding of both the fundamentals of environmental control in a greenhouse and

how to implement it using the grower's own specific climate control computer. Investment in appropriate training will be required in many cases and almost without exception will benefit the business even if TI is not used.

- Bearing in mind the lessons learnt during the 2002 cropping season, the project is being repeated during 2003 to ensure the validity of the results. These results will be available in due course.

Financial Benefits

Energy cost

Assuming a mains gas price of 0.85 p/kWh plus climate change levy of 0.07 p/kWh (i.e. 50% rebate applied) the value of saving 44kWh/m^2 is £4,050 /ha.

Increased yield

Assuming an average net price for classic round tomatoes of £0.60 /kg, the additional 2.31 kg/m^2 of tomatoes produced are worth £1.39/m^2 or £13,900/ha.

Cost of implementation

Growers with relatively modern climate control computers may already have TI software installed. In these circumstances no additional capital investment is required to use TI and apply the recommendations from this project.

For other growers, software or hardware upgrades may be required, depending on the age and capabilities of the existing system. The costs of these upgrades will range from approximately £5,000/ha for an upgrade to £15,000/ha for a new system. Based on a gross benefit of £17,950/ ha, payback times of less than one year can be expected even if a complete new system is required.

It is possible to apply the principles of TI to climate control computers that do not have TI built in. However this requires increased management time to ensure that the correct conditions are maintained for the crop. Energy savings are also likely to be less. In the long term, upgrading the climate control computer will enable a grower to take full advantage of developments in climate control systems yielding improvements in energy efficiency, crop management and therefore profitability.

Action Points for Growers

- Growers should investigate how the principles of the temperature integration (TI) technique can be applied on their nursery and establish the capabilities of their current control system. They should determine what upgrades and capital investments, if any, are required to enable TI to be used.

- It is recommended that growers consider specific training in the fundamentals of environmental control and the detailed operation of climate control computers for key staff. Energy savings and crop performance can only be optimised through a full understanding of the greenhouse environment and the ways that it can be optimised.

- The following settings framework is recommended for the application of TI (see table). These settings should only be considered as guidelines as in some cases they will need to be adapted to meet a grower's own specific needs and the characteristics of their facilities. Growers may also initially consider that some of the changes recommended are too big a step from their normal growing practice. With this in mind those considering using the strategies suggested in this report would be well advised to introduce the changes in small increments in order that confidence with the system can be built up.

Stage 1 - Winter Period

Control Variable	Day Setting	Night Setting	Notes
Heating Temp (ºC)	18	16	
Ventilation Temp (ºC)	26	26	Set as high as the crop allows
Minimum Pipe Temperature (ºC)	45	45	+20ºC on low HD. High heat demand for temperature control means this is rarely reached
Negative Compensation (ºC)	0	1	Few degree-hours will be accumulated so low NC should be adequate
Integration Period (days)	7		

Stage 2 - Spring Period

Control Variable	Day Setting	Night Setting	Notes
Heating Temp (ºC)	18	16	
Ventilation Temp (ºC)	20	18	-1ºC on low HD, +6ºC when HD high to give max VT of 26ºC
Minimum Pipe Temperature (ºC)	35	35	-5ºC on high HD, +25ºC on low HD
Negative / Positive Compensation (ºC)		2	Increase gradually if degree-hours accumulated are not all used
Integration Period (days)	7		

Stage 3 - Summer Period

	Day Setting	Night Setting	Notes
Heating Temp (ºC)	18	16	
Ventilation Temp (ºC)	19	17	Set close to HT to keep avg. temperature down. –1ºC on low HD
Minimum Pipe Temperature (ºC)	30	30	Day, -5ºC at high HD, +20ºC at low HD. Night, +30ºC at low HD
Negative / Positive Compensation (ºC)	0	2	Allow the temperature to go as low as possible during the night
Integration Period (days)	7		

Stage 4 – Season Remainder

Gradually reverse the settings as:

1. Weather conditions deteriorate
2. The degree-hours accumulated reduce
3. Humidity control becomes easier

HT – heating temperature, VT – ventilation temperature, MP – minimum pipe temperature, NC – negative compensation, HD – humidity deficit

Science Section

1. Introduction

1.1 Background

Recent increases in the cost of energy have heightened the interest of many growers in reducing energy consumption. The Climate Change Levy (CCL), which was introduced in April 2001, has further inflated the cost of energy for growers. With energy representing up to 40% of crop production costs, such changes have a significant effect on the profitability of the protected cropping sector. Therefore to remain competitive with overseas competition, ways must be found to cut specific energy use (KWh/unit of production).

Political pressure also means that growers need to improve energy efficiency. Although horticulture has been granted a 50% rebate on CCL, it is the intention of the UK Government that this will only initially be available for up to 5 years. To strengthen the case for continuation of this rebate, and to comply with requirements of EU State Aid, a voluntary energy efficiency agreement between the horticultural industry and the Government has been established. This agreement requires a 15% reduction in the specific primary energy consumption to be achieved over the 10-year period beginning in October 2000.

1.2 Temperature integration

Temperature integration (TI) is one technique that has been proven at a scientific level to offer the potential to save energy without apparent loss of yield or quality in a range of crops. However the principle has not yet been widely exploited commercially. Up to now, the main reasons for this lack of uptake seem to be that growers lack confidence in the technique and are unsure of the financial benefits.

Most of the relevant earlier experiments on TI concentrated on the physical performance of the crop and did not involve the complexities of greenhouse systems or energy costs. The aerial environments in these experiments were simply set to test the plant response to varying temperature regimes. The experiments gave no regard to practical greenhouse systems, the effect of prevailing weather conditions or the issues pertaining to energy use. This failure to address the wider issues is apparent when growers attitudes to TI are considered. They are concerned about losing the ability to control humidity and other aspects of the environment if they abdicate some measure of environmental control to a temperature integration control algorithm. Prior to this project, the only work carried out on a commercial crop of tomatoes gave small energy savings due to the grower’s reluctance to relax temperature set points because of crop steering concerns (van den Berg, et al., 2001).

1.3 Objectives

The objectives of the project were designed to address the issues highlighted in section 1.2:

- To demonstrate the level of energy saving that can be achieved by applying the principles of temperature integration on a commercial nursery
- To quantify any crop related effects (disease, yield)
- To determine the overall economic impact of temperature integration strategies on the production of tomatoes

Combined, these will give growers the confidence to apply TI on their own nurseries safe in the knowledge that crop yield and quality will not be compromised.

2. What is temperature integration?

It has been shown that many plants can be grown successfully at temperatures both above and below the optimum target without detrimental effect as long as the average temperature remains at the required level. There are clearly limits to these extremes of temperature and the time period over which the average is measured. However as long as these limits are adhered to it is possible to grow a plant at a higher temperature than is considered optimum as long as it is compensated for by a period of lower temperature.

For a tomato plant, the ability to apply this concept to it’s full extent is limited by the need to ‘steer’ the crop by increasing or decreasing the difference between day and night temperatures.

The interim report for this project (PC 188, literature review) (Plackett, Adams, Cockshull 2002) reviews work previously carried out in this area.

2.1 Basic concept

To understand how TI reduces the energy required for heating we must first look at the conventional approach to temperature control:

- During the daytime when solar gain on a greenhouse is high and the temperature rises above the heating set point (18-20°C), the air vents in the roof open to help control the temperature.
- During the night-time the optimum temperature is lower (16°C) and heat is required to maintain this temperature.
- In both cases the temperature at which the vents start to open (ventilation temperature) is typically 1-2°C higher than the temperature at which the heating is turned on (heating temperature). This helps to give accurate, responsive control of both temperature and humidity.

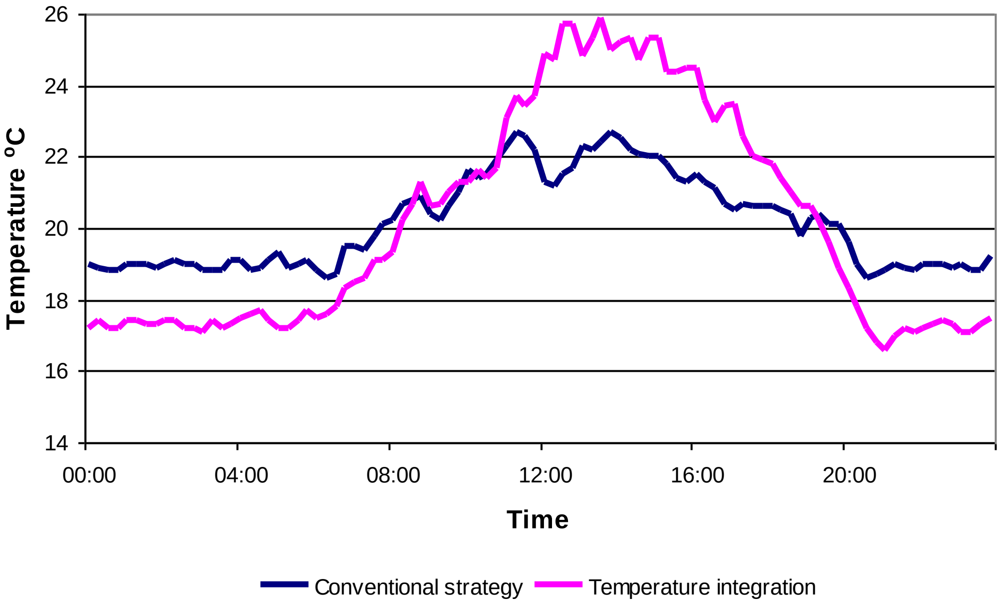
In contrast the approach taken with TI is as follows:

- The ventilation temperature is set several degrees higher than the heating temperature.
- During the daytime, the vents are not opened until the temperature rises significantly above the heating temperature. Any increase above the heating temperature is the result of solar radiation and is effectively free energy.
- The difference between the heating set point and the actual temperature is integrated over time and a running total of degree-hours is accumulated. This is referred to as the temperature sum (T-sum).
- During the night-time, assuming that sufficient degree-hours have been accumulated, the actual heating temperature applied is reduced. Therefore reducing

the energy requirement to heat the glasshouse. The net effect is that the average temperature remains the same.

Figure 1 below shows a classic temperature profile for both a conventionally operated and TI operated greenhouse. The area between the lines during the middle of the day when the TI greenhouse is warmer than the conventional one is balanced by the area between the lines during the night when the TI greenhouse is cooler. The average temperature in both cases is 20°C.

Figure 1 - A comparison between conventional and TI greenhouse temperatures



2.2 How does TI save energy?

The principles of TI can be applied in two fundamentally different ways.

2.2.1 Simple TI

As described in section 0, it can be used to accumulate ‘free’ degree-hours during the daytime when weather conditions are favourable. These can then be used the following night, or even several days later, by applying a lower heating temperature when heat is required within the greenhouse. When weather conditions are poor and few ‘free’ degree-hours are accumulated, the heating temperature reverts to its normal setting and little or no energy is saved.

2.2.1 Optimised TI

This involves two additional refinements. The first uses a thermodynamic model and weather forecast data to predict when heat loss from the greenhouse is likely to be greatest. During periods when few degree-hours are accumulated, they are used to reduce the heating temperature when heat loss from the greenhouse is greatest and therefore optimise the amount of energy saved.

The second refinement allows energy saving even when no ‘free’ degree-hours are available. It does this by using heat to raise the temperature within the greenhouse when heat loss is low, for example when external temperatures are higher, to accumulate degree-hours that can be used during periods of higher heat loss.

This project used Simple TI. It was chosen because, at the start of this project, TI in any form was still viewed with scepticism by many growers. Optimised TI was considered to be a step too far at this stage.

3. Practical application of simple TI

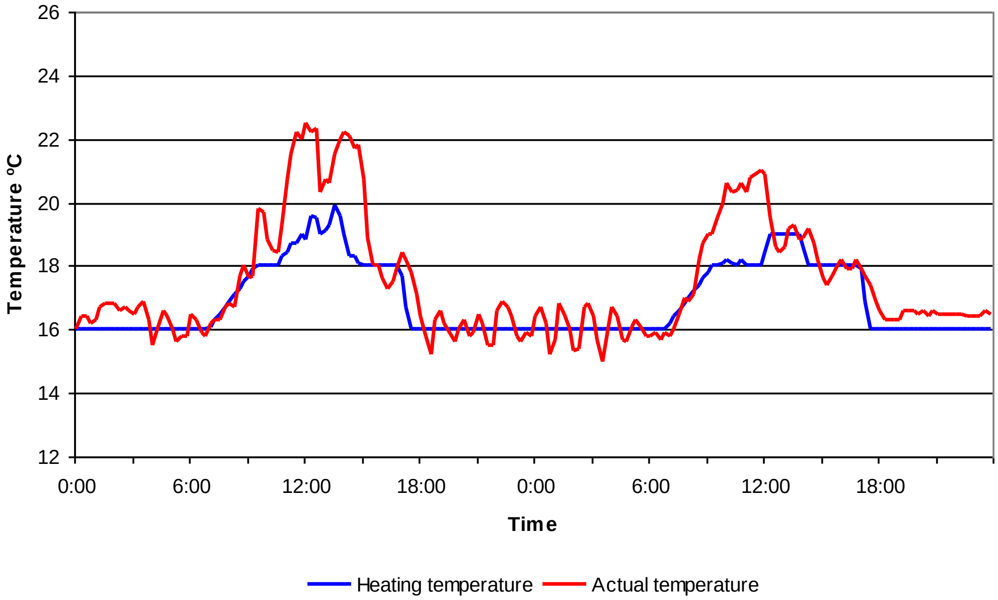
The nursery where this project was carried out had a Priva Integro version 720 climate computer which has TI software (simple TI) as a standard feature. The following section describes how TI is applied using this system.

3.1 Conventional settings

Figure 2 overleaf illustrates a 48-hour period and shows the calculated heating temperature and actual measured temperature using conventional control techniques. The calculated heating temperature is the result of the basic set point for the time period in question plus any influences. The 24-hour day is divided up into individual time periods during which almost any combination of basic heating temperature set point and influences can be applied. The influences most commonly applied to the heating temperature are instantaneous solar radiation and radiation sum.

In this example there is a basic 18°C daytime set temperature with a 19°C mid-day peak and an additional 1°C radiation influence. The night time temperature is 16°C with no influences. During the first 24-hour period solar radiation levels were good resulting in a high measured air temperature (24.8°C max) and peak heating set temperature of almost 20°C. During the second 24-hour period solar radiation is relatively poor and the heating temperature curve is only slightly affected by the radiation influences.

Figure 2 – Conventional control



The average heating temperature during successive 24-hour periods was 16.9°C and 16.8°C. This compares to an average measured temperature of 17.6°C and 17.3°C respectively. Growers aim for a specific 24-hour average temperature depending on the status of the crop and light levels. The heating set points are adjusted accordingly if this is not achieved. A grower will only set a heating temperature with an average equal to the target average during periods of low solar gain in the midst of winter. During all other periods growers rely on the fact that the temperature within the greenhouse will exceed the heating set point for some part of the day, thus achieving the final required average. Therefore even using what are considered to be conventional control strategies, growers are, to some extent, already using TI.

3.2 TI settings

3.2.1 Negative compensation

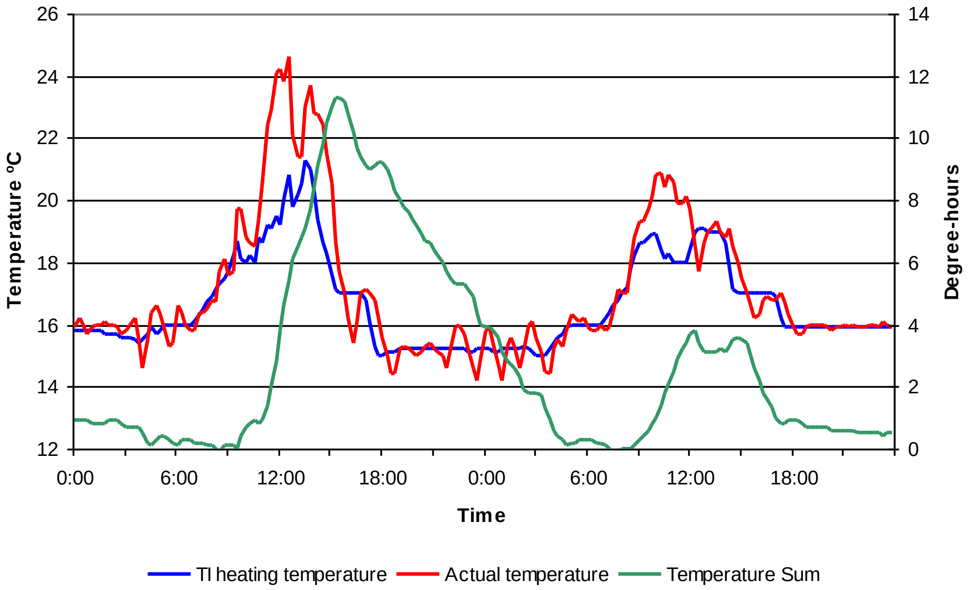
This is the amount by which the basic heating temperature is allowed to be reduced by TI. The grower can choose what time of day negative compensation is allowed and even vary the amount allowed at different times of day. This can vary through the season depending on the variety, time of year, disease pressure etc.

During extended periods of poor weather conditions when few degree-hours are accumulated negative compensation of 1^{O}C will probably be adequate. However, as weather conditions improve it should be raised to increase the ‘window’ within which TI can operate. Similarly, the number of hours within a day when negative compensation is allowed also affects the number of degree-hours that can be ‘burnt off’. Therefore to save the most energy when sufficient degree-hours are available, the negative compensation allowed should be as high as possible for as many hours as possible.

When negative compensation due to TI is allowed, the computer looks at how many degree-hours are in the ‘bank’ and how many hours over which they can be spread in the following 24-hours. This ensures that a relatively stable heating temperature is applied. If all the degree-hours accumulated cannot be burnt off in the immediate 24-hour period, they will be carried forward to the next period.

Compare Figure 2 to Figure 3 below, which shows the same basic settings with TI added. In this case negative compensation of 1^{o}C was allowed between the hours of 15:00 and 05:00. To ensure that the crop was not too cold at sunrise and therefore prone to condensation on the fruit, negative compensation was turned off and the heating temperature gradually raised back to conventional settings prior to sunrise.

Figure 3 – TI control



3.2.2 Integrating period

If, in the example in Figure 3, more degree-hours had been accumulated or the level of negative compensation allowed had been smaller there would have been spare degree-hours to carry forward to the next day. Degree-hours accumulated during a succession of good days can then be used at some point in the future when weather conditions are less favourable. From an energy saving point of view this is advantageous, however if the degree-hours are carried forward indefinitely this can have a detrimental effect on the plant.

During the summer period excess degree-hours will always be accumulated. If they are retained indefinitely a time will be reached, in late summer / early autumn, when the heating temperature is consistently reduced and higher daytime temperatures are not achieved. The result will be prolonged periods of high average temperatures during the summer followed by a prolonged period of low average temperatures. There is clearly a limit to the time period over which plants can integrate temperature. This is referred to as the integrating period.

The integrating period used must balance energy savings with the needs of the crop. Work carried out at HRI Stockbridge House in the 1996/97 growing season (Cockshull, Adams, & Plackett, 2002) showed that a program of 8 cold nights followed by 8 warm nights, effectively an integrating period of 16 days, had no detrimental effect on quality or yield.

The Priva Integro 720 allows a maximum integrating period of 7 days which allows a reasonable margin of safety compared to the figures above. The project therefore used an integrating period of 7 days thought the whole cropping season.

3.2.3 Radiation influence

The TI software continuously records the difference between the calculated heating temperature and actual temperature achieved to produce a running total of the degree-hours accumulated (T-sum). However, if all other settings remained the same (as with conventional control), TI would simply integrate away all the degree-hours accumulated, and the average temperature achieved would be the same as the average heating temperature. During this project, to ensure that both the conventional and TI compartments achieved similar 24-hour average temperatures, a greater radiation influence was added to the TI controlled compartment. In the case of the example in Figure 3, a +3^{o}C solar radiation influence was used compared to +1^{o}C in the conventional control in Figure 2.

The temperature sum line in Figure 3 shows that between 00:00 and 06:00 on the first day, few degree-hours are in the bank. Therefore the heating temperature is almost unaffected by TI. However during the following daytime period solar gain is high, the actual temperature achieved is much higher than the heating temperature and degree-hours are accumulated. The effect is that from 15:00 to 05:00 on the 24-hour period, the actual heating temperature applied was reduced by 0.8^{o}C. Once solar gain reduces and the glasshouse temperature falls below the basic 18/16^{o}C heating temperature, the T-sum starts to drop. In this case all the degree-hours accumulated during the day were burnt off during the following night.

During the second daytime period few degree-hours were accumulated and therefore the effect of TI on the applied heating temperature was minimal.

3.2.4 Ventilation temperature

Simple TI relies on the fact that ‘free’ degree-hours are accumulated during periods of good weather. As explained in section 0 growers already integrate temperature to some extent when using conventional control strategies. The only way to accumulate additional degree-hours for TI to burn off, is to raise the ventilation temperature further. As with other set points, the setting applied depends on many factors including the tolerance of the crop to higher temperatures, humidity, disease and even the effect on people in the glasshouse who also have to tolerate the conditions produced.

The simple solution is to raise the basic ventilation temperature so that the heat – vent differential is much greater. However as soon as humidity control becomes a dominating factor in the glasshouse this policy can create poor humidity conditions. A major obstacle this project had to overcome was to optimise the degree-hour accumulation without creating unacceptable humidity levels. The approaches tested and conclusions reached are discussed in section 5.

3.2.5 Minimum pipe temperature

The minimum pipe temperature is the minimum allowable water temperature within the heating pipes regardless of the temperature within the glasshouse. There are three primary reasons for using minimum pipe temperature:

- Improved speed of response - even if the boiler plant and distribution main are continuously running, raising the temperature of the heating loop within the glasshouse itself from cold to say 40°C can take over half an hour. The conditions within a glasshouse can vary quickly especially on a cold, sunny day with broken cloud. The temperature can drop rapidly if the sun disappears behind a cloud resulting in a heat demand. Similarly the humidity can also quickly reach unacceptable levels. Operating a minimum pipe temperature ensures the heating system is ‘up and running’.
- Air movement - convection currents rising from the heating pipes laid on the floor help to ensure uniform conditions within the glasshouse and avoid ‘cold pockets’ or still, high humidity air within the crop canopy.
- Humidity control – the air temperature within the glasshouse may be acceptable however the humidity may not. Adding heat regardless of the temperature is one way of controlling humidity.

The minimum pipe setting in use at any point in time is a combination of the basic minimum pipe set point and the influences applied. The most common influences applied to minimum pipe are:

- Humidity – used to increase the minimum pipe setting
- Solar radiation – used to decrease the minimum pipe setting during good weather conditions.

From late spring through to early autumn humidity control is the main environmental issue so the minimum pipe set point is the main influence on energy use. Glasshouse temperature control essentially happens by default. Effective, efficient use of energy during this period relies on the careful use and control of minimum pipe temperature.

If minimum pipe settings are too high the temperature may be held high by default, reducing the ability of TI to save energy. Optimising minimum pipe settings and humidity control to work in harmony with TI is a major challenge and formed a significant part of this project.

4. Research Method

4.1 Overview of location, facilities and cropping

The project was carried out at Lansdale Nurseries in the North West of England using equipment and technology widely available to any grower.

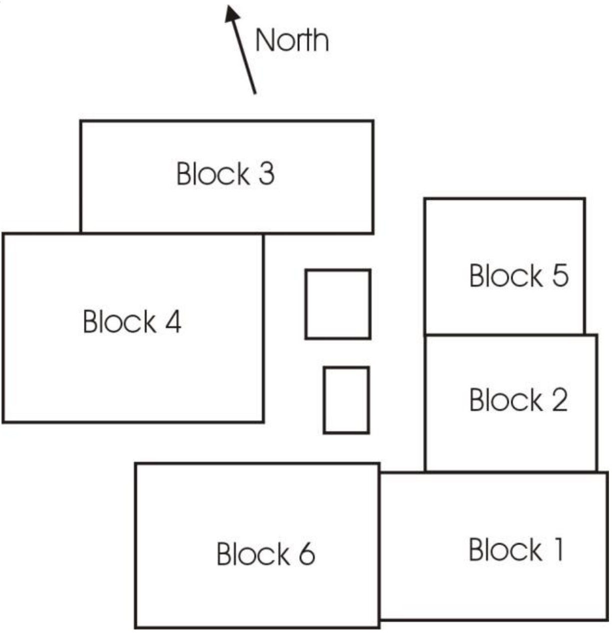
4.1.1 Glasshouse facilities

A plan view of the nursery is shown in Figure 4 overleaf. To obtain the best possible comparison, blocks 2 & 5 were chosen for the project. Both are of a modern Venlo type construction with 4.0m gutter height and 4.5m bays. Each block had independent heating and ventilation controls but a single CO_2 enrichment system controlled by the CO_2 level in block 2.

Conventional control settings were applied to block 2 which had a total area of 3,937m^2. TI was applied to block 5 which had an area of 3,472m^2. All the results have been presented on a per m^2 basis to eliminate this difference.

The whole nursery was controlled by a Priva Integro version 720 climate control computer which had TI software built in as standard.

Figure 4 – site plan



4.1.2 Cropping

The crop grown in both compartments was the classic round tomato variety Encore. Young plants were brought in from a plant raiser in week 1 and planted into rock wool blocks during week 3 of year 2002. The crop was grown on the floor.

4.2 Data collection

All the glasshouse environmental and energy data was recorded by the Priva computer and downloaded via modem connection by FEC at weekly intervals throughout the project.

Glasshouse data collected and analysed included

- Set points – heating & ventilation temperature
- Heating system – measured heating pipe temperature
- Ventilation system – measured vent position
- Glasshouse environment – temperature, humidity deficit, CO_2 concentration

Energy use

- Hot water heat meters were installed in each heating circuit.

Note - all energy use figures are quoted as kWh of hot water and not kWh of gas.

Crop data collected

Site staff carried out weekly crop recording including:

- Crop registration data
- Yield, recorded daily as the fruit was picked
- Disease incidence, primarily plant death and removal due to botrytis infection

A mid season site visit followed by a detailed end-of-season assessment of botrytis infection was carried out by Dr Tim O’Neill of ADAS Consulting.

5. Results & discussion

As a commercial demonstration project, the overriding objective was to ensure that a successful crop was grown. Therefore great care was taken to modify the TI control strategy to take account of crop status, disease pressure and the prevailing external circumstances such as weather conditions.

As a rule, the basic heating temperature settings applied in the conventional block were also applied in the TI block. TI was effectively superimposed on top of these. Minimum pipe and ventilation temperature settings tended to be different in the TI block compared to the non-TI block.

The following sections summarise the fundamental approaches taken as the project progressed.

5.1 Benchmarking

In order to allow an accurate comparison of energy use to be made between the two blocks a benchmarking exercise was carried out on several occasions during the project. This involved applying identical settings (conventional strategy) to both blocks and comparing the energy use on a per m^2 basis.

On average, block 5, where TI was applied, used 13% more energy than block 2. This was as expected and was predominantly due to the fact that block 5 has an additional external wall compared to block 2. All the energy use data that follows has been corrected to take account of this difference.

5.2 Week 1 to week 4

Both compartments were controlled using conventional strategies whilst the crop became established. A typical 18^{o}C day, 16^{o}C night temperature regime was adopted following a short period at a continuous 20^{o}C. This served as a benchmarking period. Little was lost in terms of energy saving opportunities during this period as the seasonal weather conditions only present limited periods when 'free' heat is available.

Due to the high heat demand during this time of year and the low moisture output of the crop humidity control was not an issue and the heating pipe temperature required never reached the minimum pipe setting.

Table 1 below details the control settings in use at the end of this period.

Table 1 – Settings weeks 1 to 4

	Conventional		**TI**		
Control setting	**Day**	**Night**	**Day**	**Night**	**Notes**
Heating temperature	18	16	18	16	+2°C on radiation
Ventilation temperature	24	24	24	24	Ventilation for HD control not required. A high setting stops cold air falling on the crop and helps to maintain CO_2 levels
Target HD	3.5	3.0	3.5	3.0	Effectively irrelevant at this stage due to high heat demand and small crop ensuring high HD consistently maintained
Minimum pipe	45	45	45	45	-10°C on radiation, -10°C at high HD
Integrating period					TI not turned on
Negative compensation					TI not turned on

5.3 Week 5 to week 11

5.3.1 Settings

Table 2 – settings weeks 5 to 11

	Conventional		**TI**		**Notes**
Control setting	**Day**	**Night**	**Day**	**Night**	
Heating temperature	18	16	18	16	Conv. +2°C on radiation TI +4°C on radiation
Ventilation temperature	20	18	26	26	Conv. +4 on radiation Both -1°C on low HD
Target HD	3.5	3.0	3.5	3.0	
Minimum pipe	45	45	30	30	Conv. -10°C on radiation, -10°C at high HD, + 20°C at low HD TI –10°C on radiation, +35°C at low HD
Integrating period			7		
Negative compensation			2		Effective between 15:00 and 1 hour before dawn

The basic ventilation temperature in the TI block was initially set at a constant 26°C. However as the requirement for humidity control increased it was reduced to 24°C. The basic minimum pipe set point was reduced in the TI block as the heat output of the pipes was such that it was invariably greater than that needed to maintain the glasshouse temperature above the required heating temperature. This was predominantly the case when the full 2°C negative compensation was used and mild night time temperatures prevailed.

An additional component of the general growing strategy not shown in the table was an increase in the minimum pipe set point during the dawn period to stimulate plant activity at the start of the day.

During this period basic heating temperatures increased to 20°C day, 18°C night in response to crop requirements.

5.3.2 Energy use

During the first few weeks of this period average weekly energy savings varied between 5% and 12% depending on weather conditions. Savings as high as 20% were achieved on certain days. However as the requirements for humidity control increased energy savings fell. By week 11 energy savings were minimal.

5.3.3 Summary

When temperature control rather than humidity control dominated, TI was shown to save energy. It should be noted that the TI block was a naturally colder block and therefore less able to accumulate degree hours compared to the conventional block. There is no doubt that this will have limited the ability of TI to save energy during this period.

5.4 Week 12 to week 17

5.4.1 Settings

In the early part of this period little energy was being saved and a scheduled visit by Carl Otto Ottosen from the Department of Horticulture, Aarslev Research Centre, Denmark took place. In combination with preliminary results from project PC/HNS121 (O'Neill, Pettitt, McQuicken, Shaw, Barnes 2002) which was studying the benefits of heat boosts in controlling botrytis in ornamental crops, the strategy detailed in Table 3 overleaf was adopted.

Table 3 – settings weeks 12 to 17

	Conventional		**TI**		**Notes**
Control setting	**Day**	**Night**	**Day**	**Night**	
Heating temperature	20	18	20	18	Conv. +2°C on radiation TI +4°C on radiation
Ventilation temperature	21	19	21	19	Conv. +4°C on radiation,-1°C at low HD TI +5°C on radiation, no HD influence
Target HD	3.5	3.0	n.a.	n.a.	
Minimum pipe	45	45	30	30	Conv. -10°C on radiation, -20°C at high HD, + 20°C at low HD TI –10°C on radiation, +10°C at low HD during the night only
Heat boost	n.a.		3 hours at 65°C		Triggered by relative humidity exceeding 85% for over 2 hours
Integrating period			7		
Negative compensation			2		Effective between 15:00 and 1 hour before dawn

The rationale underpinning this approach was:

- Retain the early morning plant activation period in both blocks. This ensured that the risk of condensation on the crop was controlled during the period of highest risk
- Rely on solar gain to control humidity during the daytime
- Humidity during the night would be adequately controlled by a minimum pipe temperature of 40°C
- An ‘insurance policy’ based around a heat boost triggered by periods of relative humidity above 85% for more than 2 hours was used

5.4.2 Energy use

During this period energy savings in the TI block averaged 15% and were as high as 30% on some days.

5.4.2 Summary

Although significant energy savings were made during this period, humidity control proved to be inadequate. During week 17 dull, warm, humid weather conditions dominated. Night time humidity control in the TI block was in the main acceptable. However significant swings in humidity during the daytime and a 10 day period when the average daytime humidity deficit was consistently below 3.0g/m^3 resulted in some sporing botrytis on leaf debris as shown in Figure 5 below. There was also an infection of Botrytis in the conventional block, during this period, but it was not as severe.

Figure 5 – botrytis on leaf debris

Fortunately there was no Botrytis infection evident on the tomato plants. In response to this disease incidence, TI was turned off and an aggressive humidity control strategy was adopted in both blocks. Both blocks also received a single application of the fungicide Scala.

This should not be taken as an indication of the poor performance of any single part of the strategy employed in the TI block, or of the heat boost strategy which has been shown to give a significant improvement in botrytis control in cyclamen. The main factor leading to the development of the problem was the weather during this period. With hindsight, had this been counteracted by the inclusion of more responsive humidity control until the weather improved, the degree of botrytis encountered may have been avoided.
No additional fungicide treatments were applied in either block during the remainder of the season.

5.5 Week 18 to week 20

Conventional settings as detailed in Table 3 were applied in both compartments. The differential between the heating and ventilation temperatures was reduced to 0.5°C. Combined with the application of Scala this cleared all the botrytis infection and no infection on living plant material was evident in either block.

5.6 Week 21 to week 25

5.6.1 Settings

Initially, the settings used during weeks 12 to 17 (Table 3) were reinstated. The aim during this period was to refine these settings to improve the effectiveness of the heat boost in reducing humidity and generate a more consistent ‘drying period’. This goal was achieved. However, it was found that the high energy cost of the improved heat boost strategy cancelled out the saving achieved through TI and the net energy saving was minimal. Consequently, the final goal during this period was to achieve humidity control in the TI block that was as good as in the conventional block without the use of a heat boost.

At this time of year keeping the 24-hour average temperature low enough (typically below 20°C) is a dominating requirement. Good weather conditions also mean that more degree-hours are accumulated than can be burnt off during the night. In both the conventional and TI blocks, the ventilation temperature was reduced compared to earlier in the season to help keep the average temperature within the required limits.

Table 4– settings week 25

	Conventional		**TI**		**Notes**
Control setting	**Day**	**Night**	**Day**	**Night**	
Heating temperature	18	16	18	16	
Ventilation temperature	19	17	22	17	Conv. –1^{o}C on low HD TI –4^{o}C on low HD (daytime), -1^{o}C on HD (night time). Tracking negative compensation on heating temperature
Target HD	3.5	2.5	3.5	2.5	
Minimum pipe	45	45	30	30	Conv. -10^{o}C on radiation, -20^{o}C on high HD, + 20^{o}C at low HD TI –10^{o}C on radiation, -10^{o}C on high HD, +35^{o}C at low HD during the night
Integrating period			7		
Negative compensation			2		Effective between 15:00 and 1 hour before dawn

Several important points about the control strategy employed in the TI block need to be explained:

- It is common practice to heat then vent to control humidity, especially during the winter months. Venting followed by heat would seem be a more logical and energy efficient way to control humidity but the former method is preferred as it avoids cold air dropping onto the head of the crop. As chilling is not such a risk during warmer periods the ventilation temperature was reduced using a humidity influence before increasing the minimum pipe temperature. However, careful tuning of settings was required to ensure the correct balance was achieved and significant dips in glasshouse temperature did not occur.

- When the heating temperature is reduced by TI (negative compensation) the ventilation setting must be reduced by the same amount to maintain the correct differential. The Priva Integro has facilities to allow this to happen automatically.

5.7 Week 26 to week 33

5.7.1 Settings

The settings shown in Table 4 were applied throughout this period. Slight changes were made to the basic day / night temperatures as required by the crop. These changes were applied to both the conventional and TI blocks. The overall basis of the strategy in the TI block remained the same.

5.7.2 Energy use

During this period energy saving in the TI block averaged 11% and was as high as 17% on one particular day.

5.7.3 Summary

In general, temperature and humidity control in both blocks was good. On most nights the lower set temperature in the TI block, meant that humidity could be controlled by venting for much longer than in the conventional block before the minimum pipe had to be increased. However on rare nights when the outside temperature was close to the heating temperature, it was more difficult to control humidity in the TI block because of the small temperature rise required. On these occasions the TI block actually used more energy.

5.8 Week 34 to week 35

Both compartments were run using identical conventional settings to compare energy use.

5.9 Week 36 to week 42

5.9.1 Settings

At this point in the season 24-hour average temperatures started to fall. As a result the heating / ventilation temperature differential was increased in both blocks and the TI block reverted to the heat then vent approach for humidity control.

Table 5– settings week 36-42

	Conventional		**TI**		**Notes**
Control setting	**Day**	**Night**	**Day**	**Night**	
Heating temperature	20	17	20	17	
Ventilation temperature	22	19	25	20	Conv. +2°C on high HD, no reduction on low HD TI –3°C on low HD (daytime), -1°C on low HD (night time). Tracking negative compensation on heating temperature
Target HD	3.5	2.5	3.5	2.5	
Minimum pipe	45	45	40	40	Conv. -10°C on radiation, -20°C on high HD, + 25°C at low HD TI –10°C on radiation, -15°C on high HD, +30°C at low HD during the night
Integrating period			7		
Negative compensation			2		Effective between 15:00 and 1 hour before dawn

5.9.2 Energy use

During this period energy savings in the TI block averaged 12%, reducing to 7% at the end of the period as weather conditions deteriorated further.

5.9.3 Summary

The increasing need for heat to maintain temperature within both blocks meant that humidity control became less demanding. As such humidity control was equally effective in both blocks.

5.10 Week 43 to week 44

The overriding need during this period was to maintain a high 24-hour average temperature to ripen the remaining fruit. Gradual senescence of the crop and almost constant heat demand to maintain the glasshouse temperature meant that humidity levels were always acceptable. The ventilation temperature in both blocks was set 4°C above the heating temperature. The result was almost no venting in either block and there was therefore little opportunity to accumulate degree-hours in the TI block. TI was therefore turned off during this period.

5.11 Review of whole season data

The following figures show how the weekly average temperature, humidity and energy use varied through the whole cropping season. In most cases significant changes can be related to the different control strategies employed, a summary of the changes is given in

Table 6 below. Vertical lines on the graphs help to identify the start and end of each period.

Table 6 – diary of events

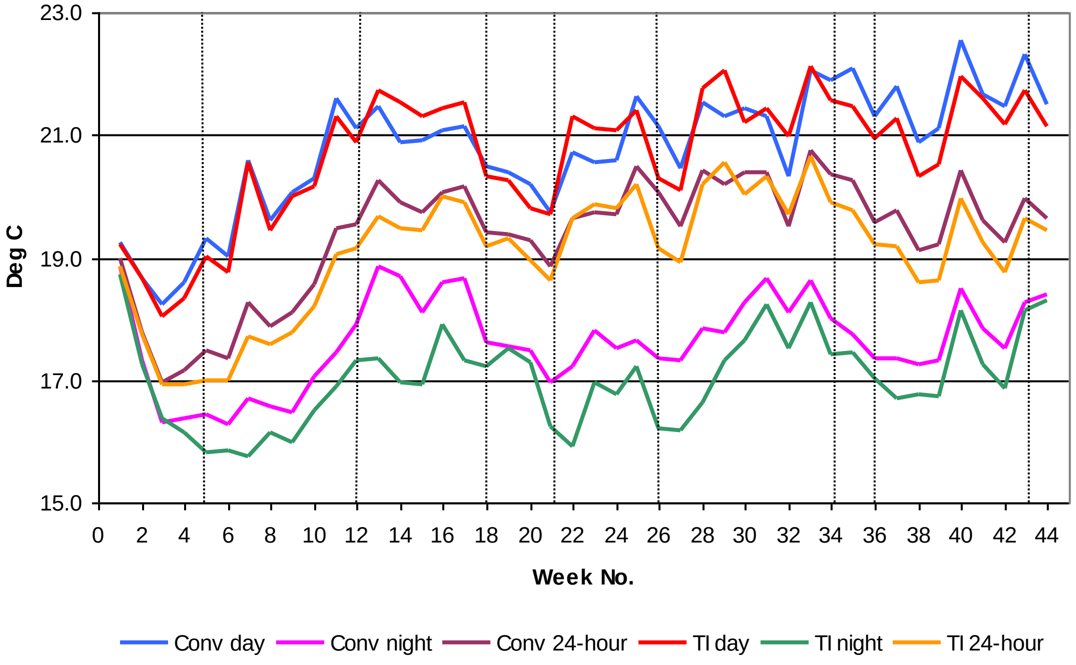
Weeks	**Notes**
1 to 4	TI off, high heat demand to maintain temperature
5 to 11	TI on, heat demand for temperature control gradually replaced by heat demand for humidity control.
12 to 17	TI on, strategy designed to accumulate degree-hours. Humidity control suffered as a result
18 to 20	TI turned off due to disease pressure
21 to 25	TI on, evolution of settings to improve humidity control
26 to 33	TI on with refined settings
34 to 35	TI off, benchmarking carried out
36 to 42	TI on
43 to 44	TI off, higher average temperature required, ventilation temperature raised in both blocks, few degree-hours accumulated.

5.11.1 Temperature

The natural tendency of the TI block to be colder than the conventional one even when operating with identical settings is consistently shown during all the periods when TI was turned off. This no doubt had an impact on the number of degree-hours that could be accumulated in the TI block at each end of the season during periods when similar average 24-hour temperatures were being maintained. As a result the energy savings achieved through the use of TI will have been lower than might be expected with identical glasshouse blocks. In spite of this the average temperatures for the whole season only differed slightly, 19.1°C for the TI block compared with 19.4°C in the conventional block.

One of the most notable periods was between weeks 12 to 17 where the strategy was designed to accumulate as many degree-hours as possible. This is reflected in the consistently higher daytime temperature in the TI block. This was compensated for by TI and resulted in significantly lower night time temperatures during the same period. However the average temperatures remained very similar, the difference was only 0.3°C.

Figure 6 – average weekly temperatures



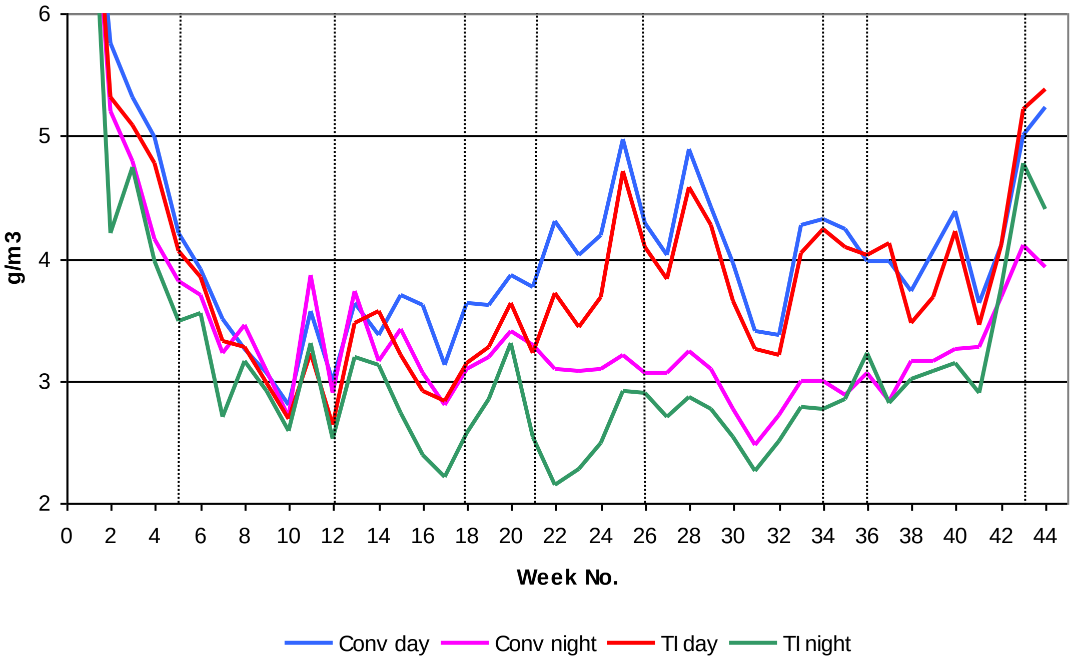
5.11.2 Humidity

Like temperature, the humidity deficit in the TI block always tended to be slightly lower even when the same conventional control strategy was applied in both blocks.

There were three notable dips in night time humidity levels. The first was between weeks 12 to 17 with week 17 being especially low. The same trend occurred in the conventional block albeit less pronounced. The difference between compartments was no doubt as a result of the difference in control strategies. It would be reasonable to assume that this caused the higher level of botrytis on leaf debris in the TI block.

The second period (week 22) of poor night time humidity occurred shortly after the reintroduction of TI but was resolved as the control strategy in the TI block was refined. The third period (week 31) was equally poor in both blocks and was caused by warm humid nights when adequate humidity control was difficult to achieve.

Figure 7 – average weekly humidity



5.11.3 Carbon dioxide levels

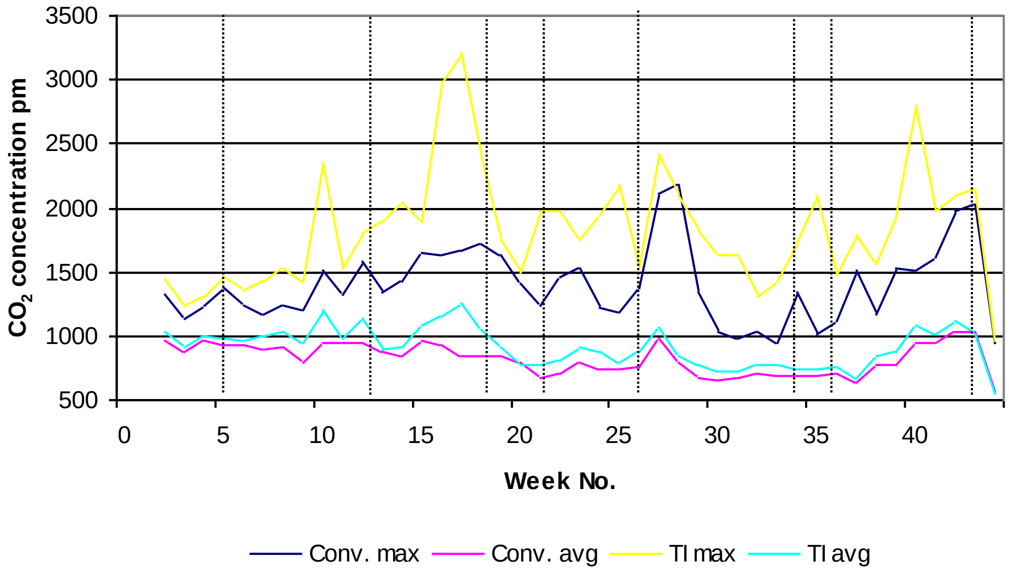
Figure 8 overleaf shows the weekly daytime average and maximum CO_2 levels achieved in each block. It should be noted that both blocks were supplied by a single CO_2 enrichment system controlled according to the CO_2 level in the conventional block.

Comparing the CO_2 level during periods when TI was turned off, the TI block had consistently higher levels. As the TI block was generally colder than the non TI block it required less venting and hence retained more CO_2. The difference was only 5% in the early weeks (no venting in either block), rising to 7% in the summer months.

The application of TI based control strategies required even less venting. This had the effect of increasing CO_2 levels even further in the TI block. The long term average CO_2 level in the TI block was 924ppm compared to 829ppm in the conventional block, a difference of 11%.

The maximum CO_2 level recorded was also of interest. The levels reached within the TI block regularly reached concentrations at which it could have had a negative effect on the plants. Some minor leaf damage was noted in the TI block although it was not possible to determine whether or not it was caused by high CO_2 levels.

Figure 8 – carbon dioxide levels



5.11.4 Energy use

Figure 9 overleaf shows energy use in the TI block expressed as a percentage of the conventional block. All data has been adjusted to allow for the difference in size of each block and corrected for the different heat loss characteristics. Figures below 100% indicate the TI block using less energy than the conventional block.

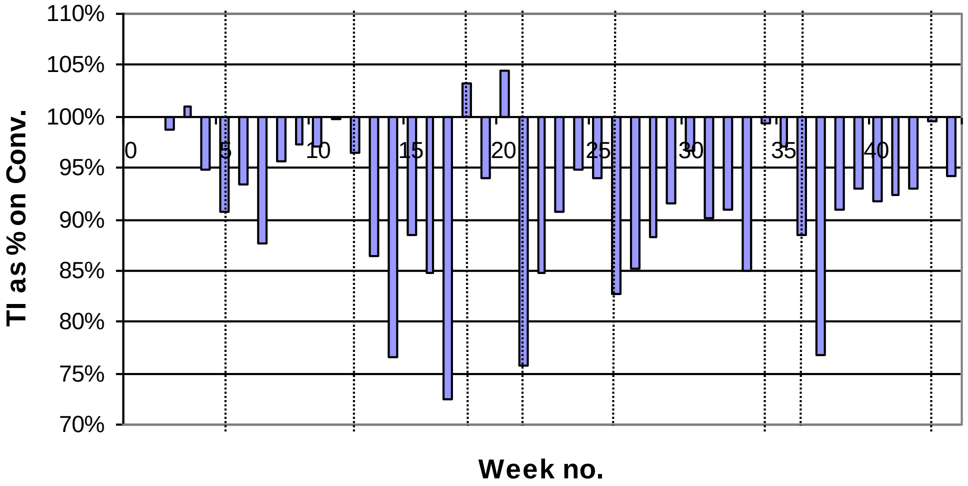
Once TI was turned on (week 5) savings of over 10% were achieved, however they gradually fell as humidity control started to dominate energy use.

Some of the biggest energy savings were made between weeks 12 to 17. However the strategy applied in the TI block gave poor humidity control and was modified in response to the disease threat created.

From week 26 onwards the TI control strategy remained fundamentally unchanged and consistent energy savings averaging 11% were achieved. To attribute all these savings to TI would be incorrect. More efficient control of humidity through the adoption of a greater emphasis on ventilation prior to heating during the summer months doubtless saved energy. TI definitely played an important role by applying a lower heating temperature and therefore a lower ventilation temperature during the night. This meant that venting could continue for longer in the TI block.

At the end of the season, total energy use in the TI block was 383 kWh/m^2 compared to 418 kWh/m^2 in the conventional block. This represents a saving of 8.4%. These figures are slightly distorted due to the periods when TI was turned off and poor strategies were adopted. A conservative assessment suggests that energy savings of 10% could be achieved if the experience gained during this project were applied consistently through a complete season.

Figure 9 – comparison of energy use



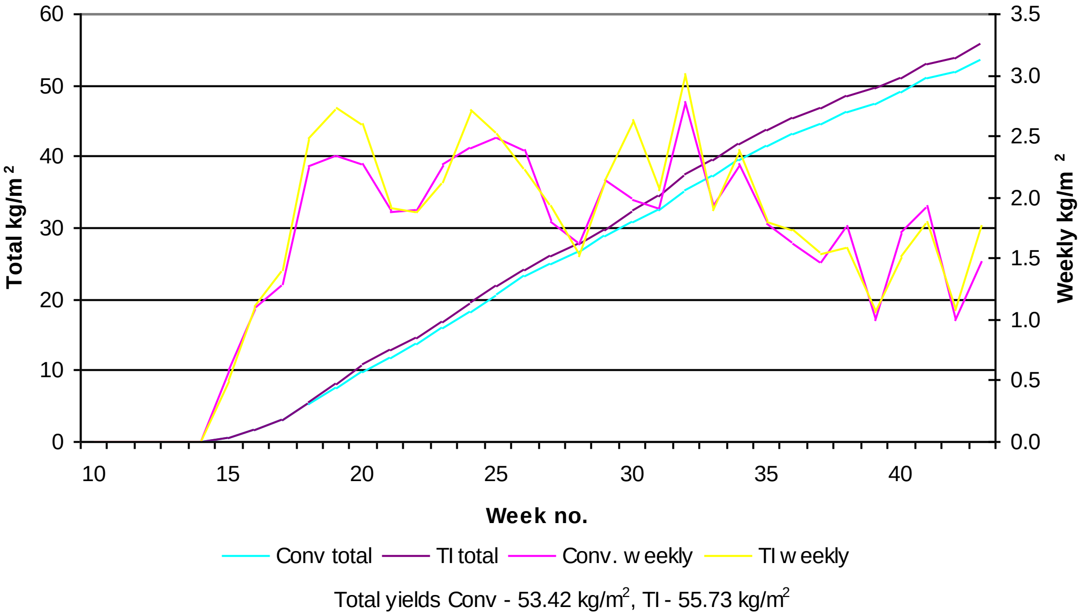
5.12 Crop data

5.12.1 Yield

Total fruit weight was recorded as standard nursery practice. Nursery management commented that fruit size appeared to be slightly greater in the TI block compared to the conventional block, however no structured assessment of fruit size or number was carried out. Figure 10 overleaf shows the weekly and cumulative yield in each block through the cropping season. There was no significant difference in the date of first pick or yield pattern throughout the cropping season.

Overall the TI block yielded 55.73 kg/m^2 compared to 53.42 kg/m^2 in the conventional block, this represents an increase of 4.3%. Although it is difficult to draw firm conclusions when comparing non-replicated yields on a commercial nursery, historically the two blocks have consistently given very similar yields. If anything, the TI block (run conventionally) has tended to yield slightly less. This gives added confidence in the validity of the 4.3% yield increase obtained.

Figure 10 – yield data



5.12.2 Disease

5.12.2.1 Assessment method

In April ten pathways were selected and marked in each block and a record of wilting or dead plant heads that were removed was kept. The total number of heads monitored in each block was in excess of 2,000. On 30th September, 7th and 21st October the number of non-wilting heads in each pathway was assessed. In addition, on 7th October, assessments were made to determine the incidence of stem lesions, infection routes and the position of the infection. Green and part-brown spent fruit trusses, 30 from each block, were also collected on the 7th October and tested for B*otrytis cinerea*.

5.12.2.2 Results

Overall the incidence of botrytis in each of the blocks was very similar (see Table 7 below). In spite of the high levels of botrytis noted on leaf debris in the TI block in week 17, the records and measurements taken show the TI block was marginally better than the conventional block.

Table 7 – disease assessment, 7th October 2002

Block	Mean % non-wilting heads	Mean number of botrytis lesions / 100 stems
Conventional	82.2	11.8
Temperature integration	81.6	9.4

Examination of the crop on 7th October showed that the majority of stem lesions present at that time arose from fruit truss die-back (88%). A smaller percentage arose at a stem split where the second head was taken, or at de-leafing wounds (4%). The majority of the stem lesions resulting from truss die-back arose on the lower third of the plants (trusses 1-8).

6. Discussion

Control strategy

The fundamentals of TI are relatively simple to understand and implement especially on a climate control computer equipped with the appropriate software such as the Priva Integro 720. What has become clear as a result of this project is that simply turning TI on will at best give minimal energy savings and at worst give poor humidity control and the potential for increased levels of disease.

Early in the season (up to week 7) whilst the crop was small and heat demand for temperature control dominated, TI could be applied in a relatively simple way to save energy. During this period energy savings averaged 5 – 12%. However as weather conditions improved, reducing the need for heat to control temperature, and the crop reached full density, increasing the heat demand to control humidity, energy savings were minimal.

Following a site visit in week 11, a somewhat radical approach to humidity control was taken. It was designed to increase the number of degree-hours accumulated during the daytime by relaxing conventional means of humidity control. A heat boost strategy triggered by an extended period of high relative humidity was implemented as a form of insurance. For several weeks this strategy provided adequate control of humidity and energy savings of 15% were achieved. However a 10 day period (week 17) of particularly poor weather conditions resulted in a high level of botrytis on leaf debris in the TI block. The response was to turn TI off for 3 weeks and give a single application of the fungicide Scala to both blocks. With hindsight, the humidity control strategy should have been modified in response to the poor weather conditions and the high levels of botrytis may have been avoided. This should not be taken as an indication that heat boost strategies as an aid to disease control are not effective. More likely that the conditions within which they were applied were too harsh and their implementation was not optimised.

Between weeks 21 – 25 the heat boost strategy in combination with TI was refined and adequate humidity control was achieved. However the high energy use of the heat boost strategy meant that the energy saved by TI was effectively cancelled out. By the end of this period a heat boost was not being used and TI had been fully integrated with more conventional means of humidity control. Adopting a ventilate-then-heat approach to humidity control was possible at this time of year as outside temperatures were much higher and excessive dips in glasshouse temperature were unlikely. Towards the end of this period and through the remainder of the summer this strategy remained and energy savings averaged 11%. However to attribute all of these savings to TI would be inaccurate. Adopting the vent-then-heat approach to humidity control clearly helped TI to work better but it also saved energy in it’s own right.

Finally as weather conditions deteriorated towards the end of the cropping season (week 43) the point was reached at which few degree-hours were being accumulated and TI was therefore turned off.

Energy savings

Energy savings varied significantly through the cropping season as weather conditions, crop demands and control strategies changed. Overall a net energy saving of 8.4% was achieved. It is believed that this could have been over 10% if optimised strategies had been applied through the whole season. There is also no doubt that energy savings have been reduced by the fact that the TI block was ‘colder’ and therefore less likely to accumulate degree-hours during the daytime. It is however difficult to assess the impact of this.

CO_2 levels

CO_2 levels were naturally higher in the TI block even when operated using conventional settings. This was due to it’s tendency to be colder, therefore requiring less venting. TI increased this effect by reducing venting even further. As both compartments were supplied by a single CO_2 enrichment system the result was consistently higher CO_2 levels in the TI block. The long term average daytime CO_2 level in the TI block was 11% higher than in the conventional block. It would be reasonable to assume that this was responsible for at least some of the increased yield in the TI block.

Crop yield and disease

In spite of poor humidity control for a short period early in the season and the resulting high disease pressure, there was virtually no difference in the incidence of botrytis at the end of the season.

The TI block yielded 4.3% more than the conventional block. An obvious explanation for this is the higher average CO_2 level achieved in the TI block. However it has been suggested that the reduced amount of venting especially during the early morning period, avoiding cold air dropping on the head of the crop was also a factor influencing the increased crop yield.

7. Conclusions

The results of this project clearly demonstrate the potential of TI in achieve energy efficiency improvements when growing a commercial tomato crop. Total energy savings of 8.4% were achieved in addition to a recorded yield increase of 4.3%.

The trial served to illustrate the following key points:

- Temperature integration works in saving energy in tomato production. In combination with a different approach to humidity control annual energy savings of 10% have been shown to be possible under the conditions tested. A yield increase of 4.3% has also been recorded. This is expected to vary depending on the specific crop being grown, target temperatures, location etc.

- Simply turning TI on will save little energy. To benefit fully from TI, settings must work in harmony with other environmental set-points. This is particularly important when considering humidity control

- Growers are right to be wary of TI. However all the points of concern can be easily overcome with the careful selection of environmental settings.
- There is no single approach that can be applied for the whole of the year and a gradual change in emphasis is required as the season progresses.

- Reliance on the use of minimum pipe temperature as a primary means of humidity control throughout the whole season will restrict the ability of temperature integration to save energy.

- Growers require a full understanding of environmental control & the processes employed to save energy whilst providing the best possible climate for the crop.

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