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[The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.]

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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GROWER SUMMARY

Headlines

Protected edible crops

- A final year heat saving of 118kWh/m² (32%) was achieved with a refrigerant based dehumidifier trialled in a commercial tomato crop.
- This was offset by electricity use of 16 kWh/m² and an average yield reduction of 1.6 kg/m². The cause of the yield reduction remains unproven.

Protected ornamental crops

- Extrapolation of data from the tomato trial to high energy ornamental crops grown at 16°C or higher indicates potential for use and should payback on capital of around six years.
- Nurseries using gas oil for heating may get a faster payback as oil is a more expensive fuel than gas.

Background

Controlling humidity is a vital part of growing high-yielding, quality crops, whilst also minimising the use of crop protection chemicals. Normally humidity is controlled by venting warm, humid air from the greenhouse and replacing this with colder, air from outside. This air carries less moisture and is warmed to restore the correct growing temperature. We estimate that 20% to 40% of a nursery's annual energy consumption is used in humidity control.

An alternative approach to reduce humidity is to directly remove water from the air using a dehumidifier. There are a number of basic designs of dehumidifier; the most common being the refrigerant-based heat pump which has been used in this project. The heat pump design is well proven and has found many applications, e.g. grain drying and wood kilning. It has in the past been trialled in greenhouses e.g. by ADAS at Stockbridge House (Bartlett, 1991). Early investigation of the technique failed to show significant commercial advantage and subsequent uptake was low. Improvements in the technology and increased energy costs have led to this reinvestigation of the technique.

Summary

Edible crop trials

Trial set up

Four dehumidifiers (supplied by DryGair Ltd), with a combined water removal capacity of 180 litres/hour were installed in a 6,120m² greenhouse at Red Roofs Nursery Ltd in East Yorkshire. Energy and crop performance were compared to an adjacent, conventionally heated and ventilated greenhouse compartment over two growing seasons.

The dehumidifiers were positioned half-way along the crop rows and straddled the rows as shown in Figure 1 below.

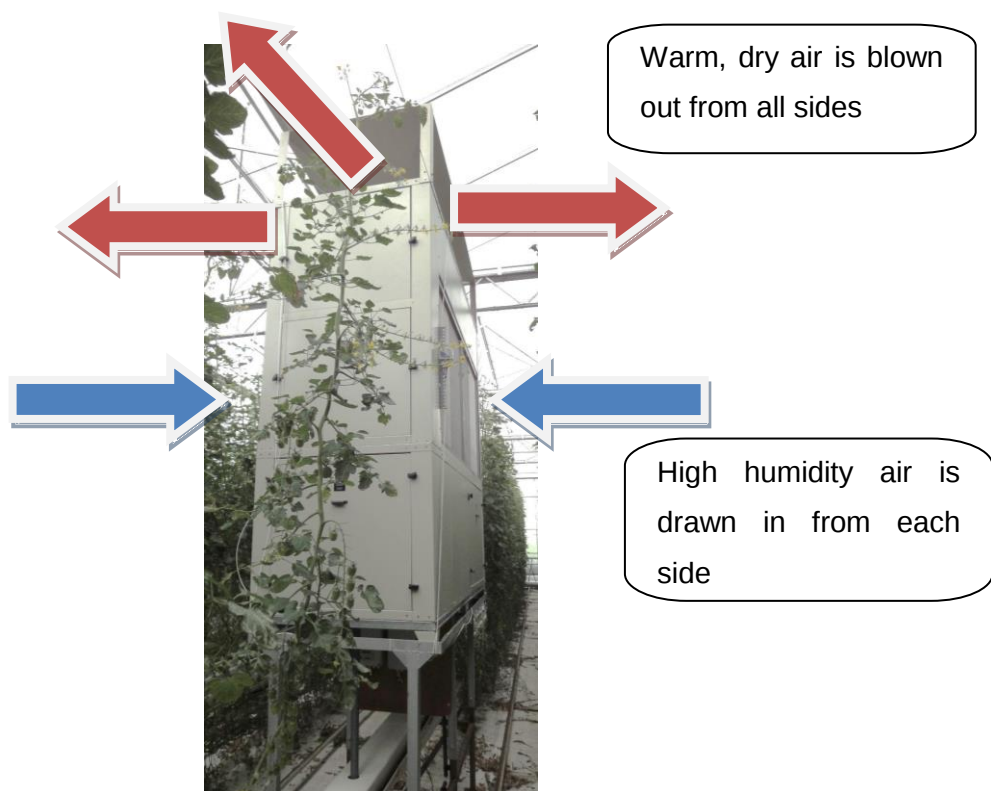


Figure 1. Dehumidifier in situ at Red Roofs Nursery

Results

After some initial problems with the dehumidifiers were resolved, they successfully performed close to specification, extracting approximately 45 litres/hour of water for an energy input of 10kW of electricity i.e. 4.5 litres of water removed per kWh of electricity used. This figure is termed the Specific Moisture Extraction Rate (SMER) and is a key figure when comparing different manufacturer's equipment.

Although the original expectation was that they would only be used when the humidity was at its highest, it was soon evident that savings were possible in all but the lowest humidity conditions (<65%). Therefore as long as the RH was >65% and there was a heat demand in the greenhouse, the dehumidifiers were operational. The exception to this was when the heat produced as a by-product of CO₂ enrichment met all of the greenhouse heat demand. As a result, the dehumidifiers were not used during the summer and early autumn.

Figure 2 below shows the heat saving achieved in each of the 2 years.

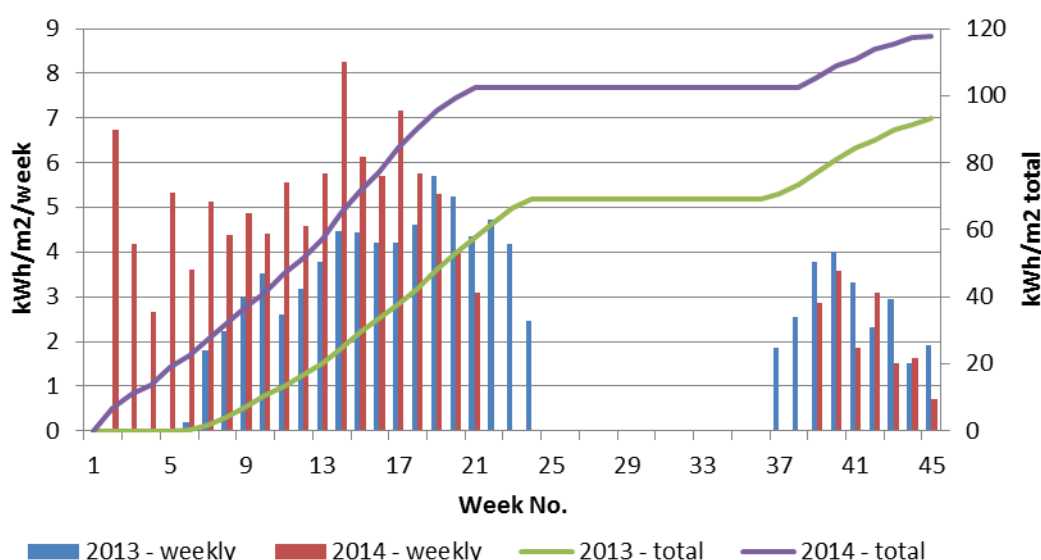


Figure 2. Weekly % and cumulative heat energy savings in 2014

Better performance in 2014 was achieved through a combination of improved dehumidifier efficiency, (a fault was identified in 2013), better control strategies and an earlier start in the season. This was offset to some extent by a longer off period during the summer.

2014 provided representative data for the likely savings going forwards. The greenhouse compartment with a conventional heating system used 367kWh/m² of heat whereas the compartment with dehumidifiers used 249kWh/m²; a saving of 118kWh/m² (32%). This saving was of course offset by electricity used by the dehumidifiers (16kWh/m²).

One area of possible concern was temperature uniformity. With the four dehumidifiers being, in effect, point heat sources compared to the distributed pipe heating source, one might have expected some degradation in uniformity. However, measurements showed there was actually a slight improvement in temperature uniformity, possibly as a result of the fact that dehumidifiers have internal fans to provide heat delivery and air mixing.

In both years, the crop in the dehumidifier compartment yielded fewer tomatoes than the control (average 1.6kg/m² less), and was as a result of the plants becoming too vegetative around week 11. Although this was pre-empted in the 2014 growing season where the crop was steered more generatively from the start in a bid to prevent it, the affect was still noticeable and the yield was still less. Whether the yield reduction was wholly due to the dehumidifiers remains uncertain as anecdotal evidence from other trials suggests that this problem is not endemic.

Ornamental crop modelling

Data on environmental conditions and energy use was collected from the pot chrysanthemum greenhouse at Double H Nurseries, Hampshire in 2013 to allow the probable impact of dehumidifiers to be derived theoretically. We measured the amount of time that heat was being used whilst the humidity was greater than 65%. Using this with the data recorded in the tomato trial we could determine the likely performance for ornamental crop.

Figure 3 below shows the amount of heat used (no dehumidifiers) and the likely heat saving if they had been used. The key figures are:

- Original heat use – 261kWh/m²
- Heat saving – 97kWh/m²
- Electricity used – 19.5kWh/m²

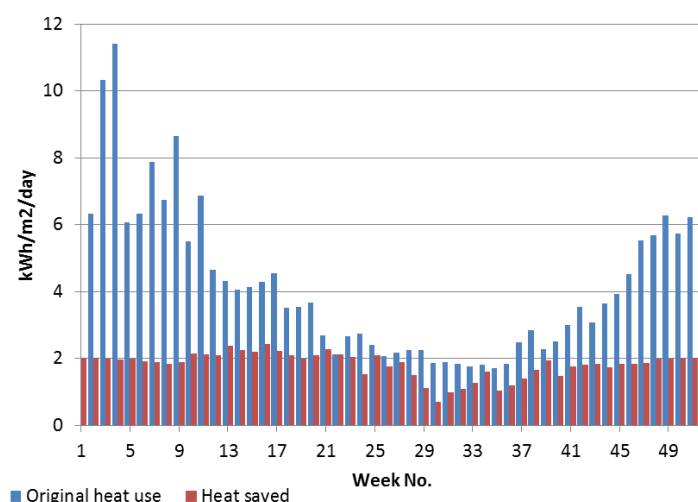


Figure 3. Ornamental crop: predicted heat saving

Consultation with ornamental plant growers suggests that a negative impact on plant growth / yield from the use of a dehumidifier system would be unlikely but this has not been tested.

Financial Benefits

Tomato trials

Focussing on energy saving alone, Figure 4 below shows the net energy saving based on the assumption that all heat saved would have been produced by a natural gas boiler.

As performance in the second year of operation was more representative of what could be achieved in practice (the equipment and control having been refined) second year figures are used in energy saving projections. Savings are illustrated in a family of curves representing a range of electricity and gas costs. Current gas costs are in the order of 60p per therm and electricity is around 8p per kWh (assuming a high proportion of cheap night rate use).

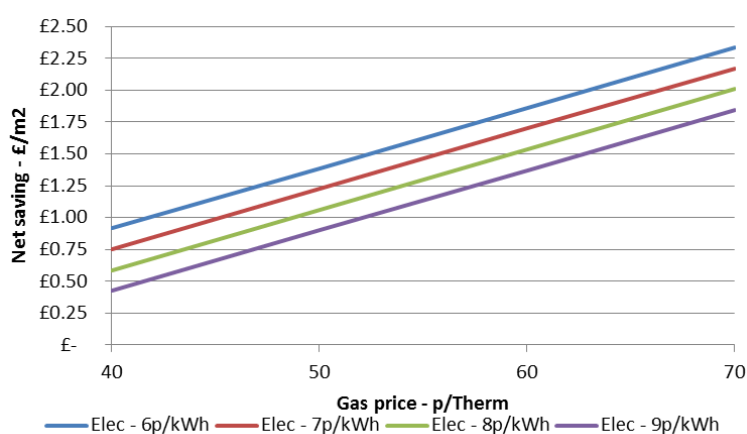


Figure 4. Energy cost savings from dehumidification at different gas and electricity rates

Nurseries that have CHP benefit from lower electricity costs than those using grid electricity so savings would be higher. The capital cost of an installation for an edible crop is in the order of £10/m² so a payback of between six and seven years is likely with current energy prices.

Ornamental crop modelling

Advice suggests that no impact on crop yield or quality is likely with ornamental crops as such crops are somewhat less sensitive to humidity conditions. Figures 5 and 6 below present the expected result for nurseries using natural gas and gas oil for heating.

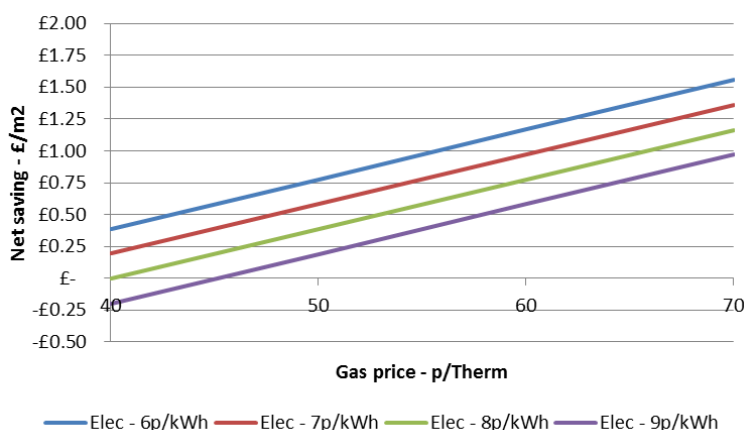


Figure 5. High energy ornamentals: net value of energy saving (natural gas)

Although net heating use and therefore saving is less for ornamentals, the capital cost of an installation for an ornamental crop is also lower (circa £5.50/m²), as the transpiration and moisture load is reduced and less dehumidification equipment is needed per unit area. Also, with no availability of ‘free’ heat from a boiler which is being used to produce CO₂, the dehumidifier heat can be useful all year round. Taking these issues into account a return on investment similar to edible crops (six to seven years) is possible.

We must also consider nurseries using gas oil as their heating fuel; as this is more expensive than gas the payback on dehumidifiers looks even better.

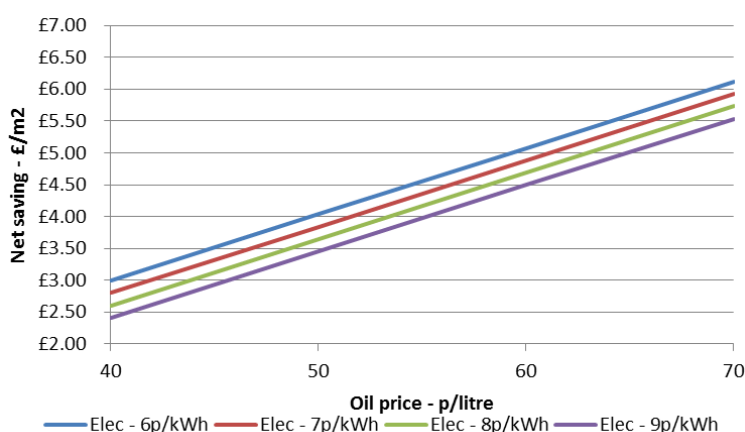


Figure 6. High energy ornamentals: net value of energy saving (gas oil)

Figure 6 assumes the same energy use as a 'high energy' natural gas fuelled ornamental crop. However it's important to realise that growers who use gas oil are likely to be the ones growing lower temperature crops with lower net energy consumption; offsetting the greater 'per kWh saving' that displacing gas oil brings. Taking the example of a grower who is using a 1/3 of the energy shown in the figure below, the return on investment might still be economically justifiable (four to five years). The only proviso to this is that our modelling has been done on a dehumidifier running in a higher temperature environment ($>16^{\circ}\text{C}$), and one would expect the dehumidifier to perform less efficiently at lower temperatures.

Capital cost is clearly a key element in the economics of a dehumidification system. As well as the hardware itself, the cost of providing sufficient electrical power to the greenhouse is often a significant issue. This is site specific so hard to factor into a general economic model.

Action Points

Edible crops

- The energy economics of dehumidifiers are promising. However some doubt still exists over their ability to deliver the highest crop output. There should be no show-stopping technical reason to prevent this being overcome.
- The mechanism by which crop output is being held back needs to be identified and solved.

Ornamental crops

- Dehumidifiers represent a viable energy saving option in specific circumstances.
- Any growers using gas oil to grow crops at 16°C or above should compare their energy use to that of the ornamental crop nursery monitored. Even if using 1/3 of the heat the return on investment is under five years.
- Growers using natural gas should investigate the capital cost, especially if a bigger electricity supply is required. Only those where the installation is relatively straightforward and therefore cheapest are likely to be a financially viable investment.

SCIENCE SECTION

Introduction

Controlling humidity in greenhouses is a vital part of growing high-yielding, quality crops as it helps optimise growth, minimise disease and the consequent use of crop protection chemicals. The normal method of controlling humidity in a greenhouse involves venting warm, humid air whilst replacing this with colder, outside air which holds less moisture. Heat is then required to maintain the glasshouse temperature. We estimate that 20% to 40% of a nursery's annual energy consumption is for humidity control.

An alternative approach is to remove the water vapour using a dehumidifier. There are a number of basic designs of dehumidifier the most common being the refrigerant-based heat pump which has been trialled in this project. The heat pump design is well proven and has found many applications (e.g. grain drying and wood kilning) Trials have also been carried out in greenhouses, for example Stockbridge House, North Yorkshire (Bartlett, 1991). Early investigation of the technique failed to reveal significant commercial advantages and subsequent industry adoption. However since then, there have been advances in the technology and energy costs are now more significant. So a renewed investigation was sought by growers.

Some international commercial trials and applications by Israeli dehumidifier manufacturer DryGair Ltd and an offer of equipment for AHDB Horticulture trials in the UK have helped to stimulate interest in this project area.

Potential benefits of dehumidification are:

- A reduction in energy use and cost for growing
- Improved yield due to reduced venting and therefore higher CO₂ levels
- Reduced fungal disease due to better humidity control

The trial objectives were to evaluate these whilst identifying any downsides of the technology.

Materials and methods

Trial Site and Description

Tomato - commercial trial

The project was carried out on a commercial tomato nursery - Red Roofs Nursery's North Moor Lane in Cottingham, East Yorkshire. The test compartments used were Compartment 3 (CMP3) where the dehumidifiers were situated and Compartment 4 (CMP4) which was used as a control. Each greenhouse was a typical double Venlo glass greenhouse structure with thermal screens and hanging gutters. CMP3 had a growing area of 6,120m², CMP4 was 9,432m²; all the data presented in this report is expressed per unit area to allow for this difference. The most fundamental difference between the compartments was that CMP3 had a voided thermal screen (1 in 10 strips missing) whereas CMP4 had a thermal screen with no strips missing.

The crop grown in both compartments in 2013 and 2014 was the mini plum tomato variety cv. *Gurrincha*. Young plants arrived on the nursery in week 1 and cropping continued through to week 45 (Table 1).

Table 1. Key dates / changes

Week No.	2013	2014
1 - 2	Young plants arrived from the propagator	Young plants arrived from the propagator Dehumidifiers also ran from the very start
5	Commissioning/testing of equipment	Not applicable
6	Dehumidifiers turned off to benchmark greenhouse compartment energy use	
7	Dehumidifiers turned on again	
15	Compressor replaced on a single dehumidifier due to poor performance	
24	Dehumidifiers turned off due to combination of low heat demand and high CO ₂ demand.	Dehumidifiers turned off in week 20.
37	Dehumidifiers turned on again due to	Dehumidifiers turned on in week

	increasing heat demand and reducing CO ₂ demand.	39. Later than in 2013 due to better weather and continued CO ₂ demand.
45	End of cropping	End of cropping

Ornamentals - data collection and modelling

Rather than carry out additional commercial trials, performance data collected from the tomato trial was used, with energy and climate data from an ornamentals nursery, to derive likely performance figures; allowing the impact of dehumidifiers on energy use to be estimated. The primary objective was to provide a strategic steer on whether ornamental specific trials might be financially viable.

Data was collected from Double H's nursery in New Milton, Hampshire. The monitored compartment was approximately 18,000 m² and is a modern all year round pot chrysanthemum greenhouse.

Dehumidifier Equipment

The dehumidifier units used in the trial were refrigeration-based heat pump dehumidifiers. With these, air is drawn over the cooling (evaporator) coil of a refrigeration unit and its temperature is reduced to below dew-point. At this temperature water vapour condenses from the air. The cooled air is then passed over the hot (condenser) coil picking up the latent energy given up in the cooling/condensing process. The air is now lower in humidity and its temperature is typically 6-8°C warmer than when it entered the unit.

Figure 7 below a simplified schematic showing the operation of the units with the key indicative performance figures:

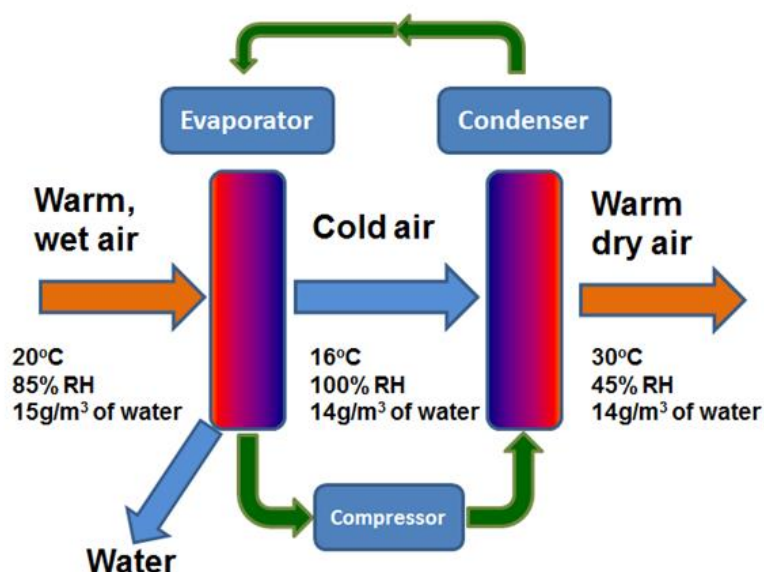


Figure 7. Refrigerant dehumidifier schematic

This technology is widely used in the heating, ventilation and air-conditioning industry.

An AFRC Institute of Engineering Research project (Bailey & Chalabi, 1989) and further work carried out by ADAS at Stockbridge House (Bartlett, 1991) confirmed that the technology could be applied to greenhouses. However, at the time when energy costs were relatively low, the savings did not justify the investment required.

Although applied in a different way, the principle of condensing water on a cold surface to deliver humidity control was used most recently in closed greenhouse projects in the Netherlands. This was reviewed in HDC project PC 256 (Pratt CT, 2007).

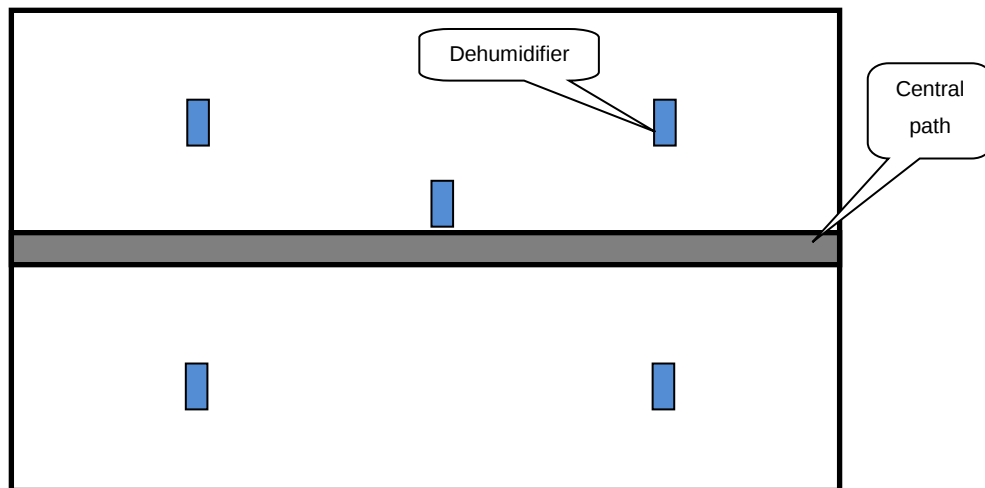
The supplier of the equipment for this project, DryGair, has carried out trials at the Volcani Institute of Agricultural Research in Israel. Although published reports are not available, a specific energy reduction ratio (SERR) of 8.0 has been quoted (ratio of heat saved to electrical energy used). If this could be replicated in UK conditions, the heat equivalent costs would be around 0.78p/kWh (23p/Therm); compared to gas prices during 2013 of 2.22p/kWh (65p/Therm). The key specifications of each dehumidifier were:

- Energy input – 10kW of electricity
- Water removal rate – 45 litres per hour
- Airflow – 2 fans with a combined capacity of 40,000 m³/hr

According to the manufacturer a single dehumidifier is suitable for 1,400m² of tomatoes. With CMP3 being 6,120m² in area, DryGair chose to supply five dehumidifiers with a view to only running four if they proved to be adequate. The dehumidifiers were installed in a

'domino' pattern as shown in Figure 8 below. As it turned out four units proved to be adequate for the trial, so the central unit was not used.

Figure 8. Dehumidifier layout



The dehumidifier's design was such that they could straddle a row of tomatoes whilst still allowing the crop work platform to pass.

With ornamental crops being less leafy / transpiring less than salads, the recommended installation density falls to one dehumidifier for 3,500m².

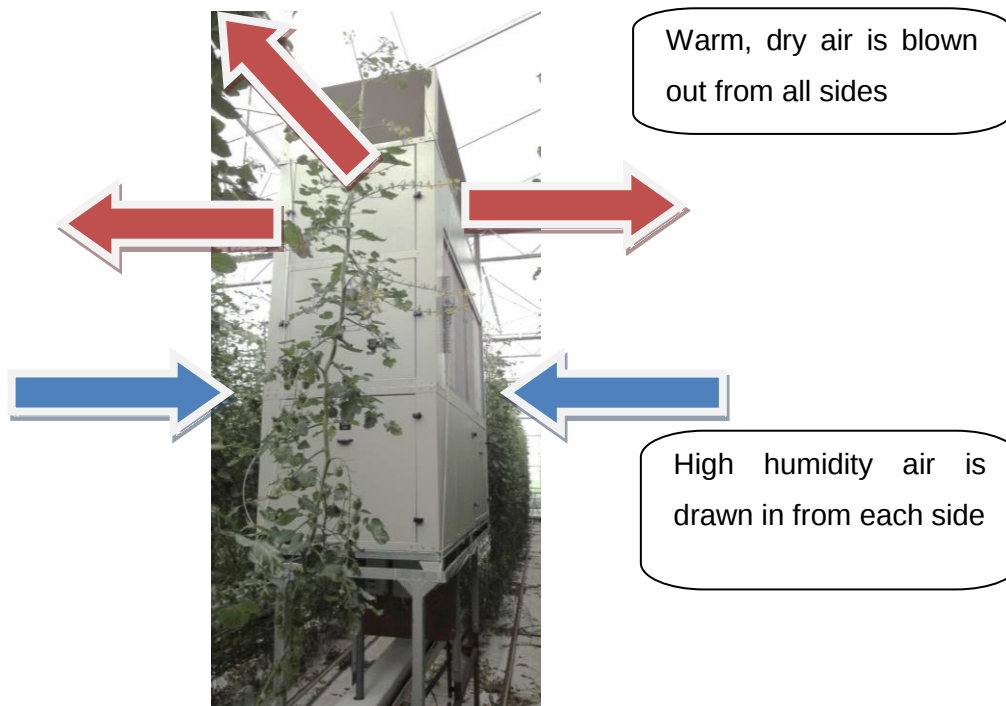


Figure 9. Dehumidifier in situ at Red Roofs Nursery

Monitoring and Data Collection

The main objective of the trial was to derive two primary metrics which are required to enable UK growers to make well-informed investment decisions about this technology. They were:

- The value of the net reduction in energy cost (heat saved minus electricity used)
- Effect on crop yield

To this end the following data was collected at the Red Roofs Nursery trial.

Energy and dehumidifier performance

Heat used by each greenhouse compartment

This was monitored using non-invasive flow meters and heat meter integrators fitted to the hot water supplies to each compartment.

Electricity used by the dehumidifiers

An electricity meter was connected to one of the dehumidifiers and linked to the heat meter data logger. As all the dehumidifiers were turned on and off together by the same control equipment the recorded energy was multiplied by the number of dehumidifiers to give total dehumidifier consumed energy for the compartment.

Dehumidifier performance

The key efficiency performance indicator for a dehumidifier is the amount of water removed from the air for each kWh of energy used. This is known as the Specific Moisture Extraction Rate (SMER). It can be assessed by measuring both electricity input and the water condensed from the cold 'evaporator' coil.

In the trial, the water recovered by a one of the dehumidifiers (the one with the electricity meter fitted) was drained into a sump. The volume of water was measured using a calibrated pump that transferred the water into the irrigation drain water collection system.

Another useful performance measure is the ratio of useful heat produced compared to electricity used. This is often referred to as Coefficient of Performance (CoP). However, a better practical performance measure is the amount of heat saved per unit of electricity used; for the purposes of this report we have referred to this as the Specific Energy Reduction Ratio (SERR).

All the energy and dehumidifier data was recorded every five minutes by a data logger which included a modem allowing remote access to the data recorded. This enabled regular

analysis and feedback in response to changes in the control / operation of the dehumidifier and the greenhouse climate.

Greenhouse climate

The greenhouse climate was controlled by a Brinkman climate control computer. This enabled all the normal greenhouse climate and equipment status to be recorded in five minute intervals. Remote access to the Brinkman computer facilitated 'live' climate analysis and set point adjustments and downloading of the data for further investigation.

The following data were captured for each greenhouse compartment:

- Aerial environment
 - Temperature
 - Humidity – RH and HD
 - CO₂ concentration
- Equipment status
 - Heating pipe temperature
 - Vent and thermal screen position
 - Dehumidifiers on/off (CMP3 only)
- Weather data
 - Light level
 - Outside temperature

Simple battery powered temperature monitoring data loggers were also laid out in a grid pattern in each greenhouse compartment to determine the effect of the dehumidifiers on temperature uniformity.

Crop data

Crop registration data was collected by the nursery every week, under the guidance of their advisor (Ronald Duyvesteijn). The data collected was:

- Fruit set – per m²
- Crop balance
 - Fruit size (visual)

- Leaf length
- Truss length
- Truss height
- Yield
 - kg/m²

Formal disease monitoring was not carried out. Feedback from the grower (Chris Durnford) and visiting tomato study groups was however noted.

Ornamental nursery data collection

The following data (recorded every 5 minutes) were exported from the nursery's climate control computer:

- Heating pipe temperature
- Vent and shade screen position
- Greenhouse temperature and relative humidity

Energy data collected included:

- Gas used by the boiler – weekly meter readings
- Heat used – heat meter connected to a GSM enabled data logger

Results

Tomato – commercial trials

Dehumidifier performance

Specific Moisture Extraction Rate (Litres of water removed per kWh of electricity used)

Figure 10 shows the SMER through each year of the project.

2013

Early season performance was lower than predicted and some diagnostic analysis showed the cause to be a problem with the compressor. This was replaced in week 15. The impact of this is demonstrated by the step improvement in performance in week 16. Following this, the dehumidifier performed just below its expected level (4.5 litres/kWh) throughout the project.

The dehumidifier was turned off during the summer; hence no data for this period is shown.

2014

Performance at the very start of the year was better than in 2013. This was expected due to the compressor fault identified in 2013. Performance continued to improve and reached an unlikely high level. During this period the monitoring equipment was found to be faulty and was repaired in week 18. The trend, prior to turning the dehumidifiers off for summer was as expected. The black dotted line is a reasonable assessment of performance during this period. Further problems with data capture in the latter part of 2014, meant dehumidifier performance data is missing during this period. However enough information was gathered to extrapolate long term running performance.

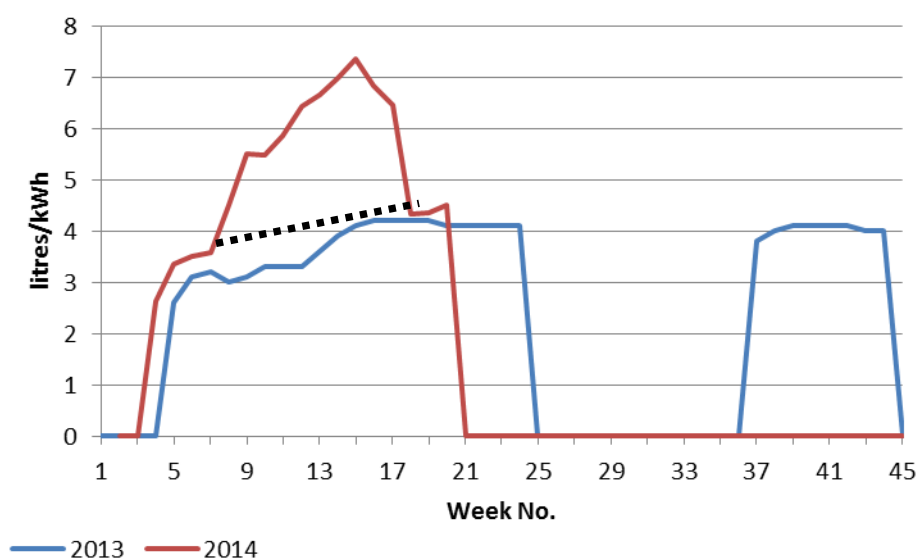


Figure 10. Dehumidifier performance - litres of water extracted per kWh of electricity

Dehumidifier System

Specific Energy Reduction Ratio (This is the ratio of heat saved to electricity used)

Figure 11 shows the SERR through each year of the project.

2013

The relatively poor performance during the early weeks of 2013 were due in part to low greenhouse humidity (small plants, low outside temperature) and the compressor problem previously discussed. The impact of the former was exaggerated by the unseasonably cold weather during weeks 10 – 16 in particular.

The SERR from week 37 onwards appears abnormally low especially when the litres/kWh data for the same period were similar to the weeks leading up to the summer shutdown. Late in the cropping year there were differences in the crop that may have contributed to this apparent poor performance but this was not proven. A SERR of 5.0, reducing to 4.0 by week 45 was expected rather than the achieved average of 3.0.

2014

The combination of better dehumidifier efficiency (compressor problem in 2013) and a better understanding of optimum operating conditions meant that the SERR was consistently higher throughout 2014. The SERR reduces to zero earlier due to the fact that the dehumidifiers were turned off earlier.

The manufacturer's claim of a SERR of 8.0 at the outset of this project was confirmed during ideal operating conditions (higher temperatures and humidity) in weeks 15-19.

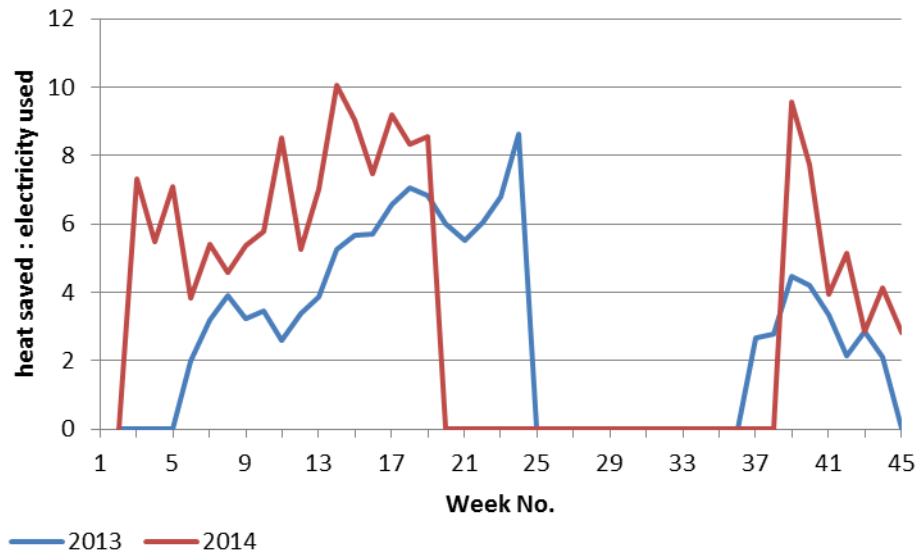


Figure 11. Dehumidifier SERR

Dehumidifier running hours

The dehumidifiers ran for a total of 3,411 hours in 2013 but only 2,857 hours in 2014. The average hours/day were higher in early 2014 because at that early stage we took a cautious / progressive approach (Figure 12). During weeks 9 to 17 the hours run were slightly lower in 2014 due in part to better weather but also to a more optimal running strategy that avoided running them when savings were marginal. This ultimately delivered a better overall performance (SERR and energy saving).

In 2013 the dehumidifiers were run for longer into the summer than was truly beneficial to maximise our experience with them. They were turned off almost 5 weeks earlier in 2014. Better weather and crop condition towards the end of 2014 meant that they were turned on again 3 weeks later than in 2013.

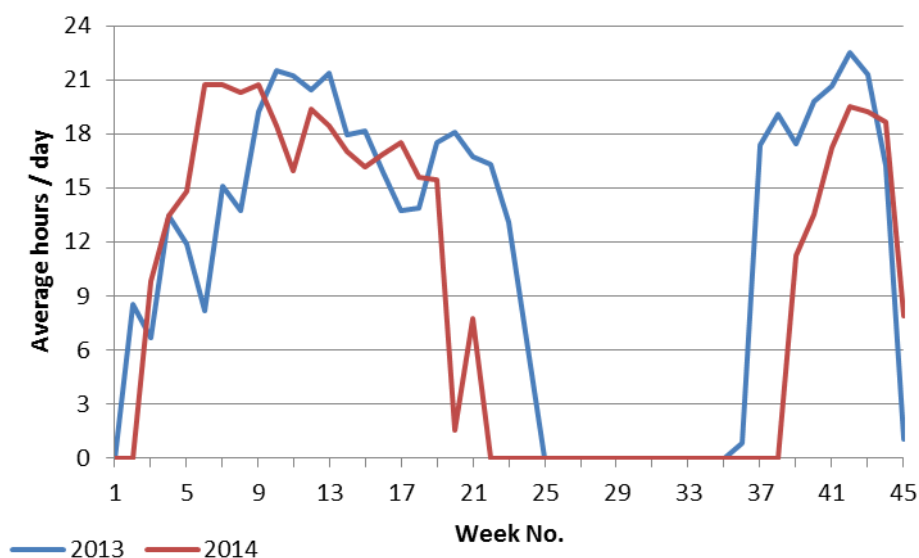


Figure 12. Dehumidifier running hours

Energy data

The trial and control greenhouse compartments were not identical and would normally be expected to use different amounts of heat even when operated in the same way, without dehumidifiers. To assess the underlying difference the compartments were operated with heat only in week 6 (2013) and the heat used by each compartment compared. CMP3, the trial compartment, had a 6% greater underlying energy demand than CMP4 (control). All the data that follows was corrected to take account of this difference.

Prior to the trial, we postulated that the dehumidifiers would only deliver savings when the humidity was high. In such instances they would be used as the first line of 'action' to lower humidity i.e. before gapping the screen, opening the vents or increasing the minimum heating pipe temperature. During the early weeks of the trial in 2013 the dehumidifiers were, in effect run on a timed basis (19:00-16:00). The 'off' period coincided with both high electricity prices and when a rapid drop in greenhouse temperature was required for the pre-night temperature strategy. The reason for running them such long hours when there was potentially no benefit was to produce data so their performance characteristics could be evaluated across a wide range of conditions.

We relied on the underlying physics of the process to provide immediate feedback on total heat output and the associated energy input under different conditions. This was derived from:

- Heat recovered = the energy released by condensing the amount of water produced in 1 hour
- Electrical energy input via the compressor and fans

Costing the heat produced at 'boiler equivalent', minus the electrical running cost gave a simple 'is it worth running' answer.

Prior to the faulty compressor being identified, our assumption on economic operation gave a slightly pessimistic view of how the units could be operated economically. However, once the compressor was repaired the data suggested that running the dehumidifiers at lower humidity's could also deliver savings.

Experience with this project has led us to conclude that dehumidifiers could be run economically:

- Whenever there is a heat demand (whether for temperature or humidity control)

But NOT

- When the greenhouse humidity (RH) is especially low as the ability to remove water is restricted and the efficiency of the dehumidifier is poor
 - The cut-off humidity below which the dehumidifier should be turned off depends on many factors but as a guide an RH of 65% or less seems sensible

Figures 13 and 14 below detail the weekly heat use and saving for each compartment over the two years.

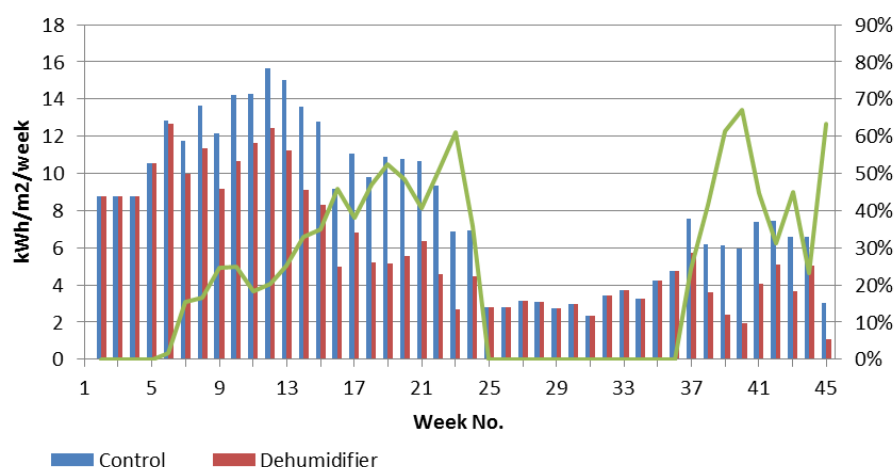


Figure 13. Weekly energy use 2013

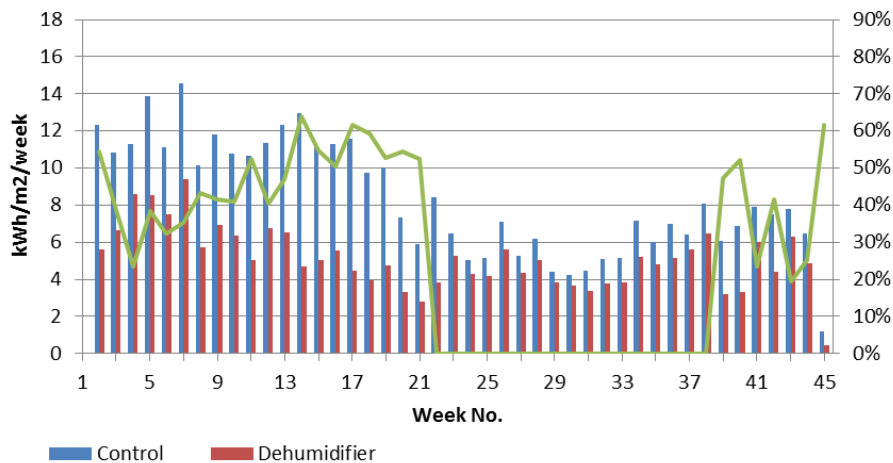


Figure 14. Weekly energy use 2014

Comparing weekly energy use across the two years of the trial, the increase in energy saving as a result of using the dehumidifiers in the second year is visually evident (Figure 15). At first the higher savings in 2014 might seem disproportionate considering the much reduced running hours. However, these were offset by improved dehumidifier efficiency and more optimal control. An additional factor was the consistently higher thermal screen closed hours between weeks 7 to 21. Whereas the additional hours around weeks 17 to 25 in 2013 delivered little benefit.

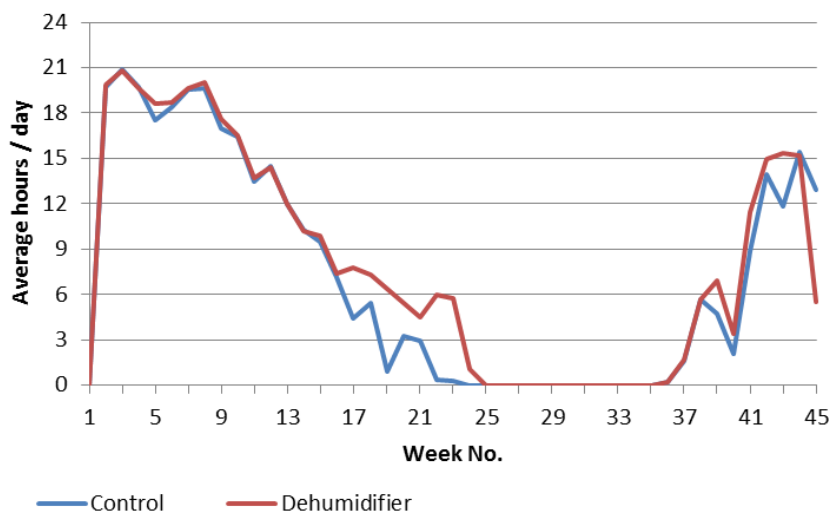


Figure 15. Thermal screen hours 2013

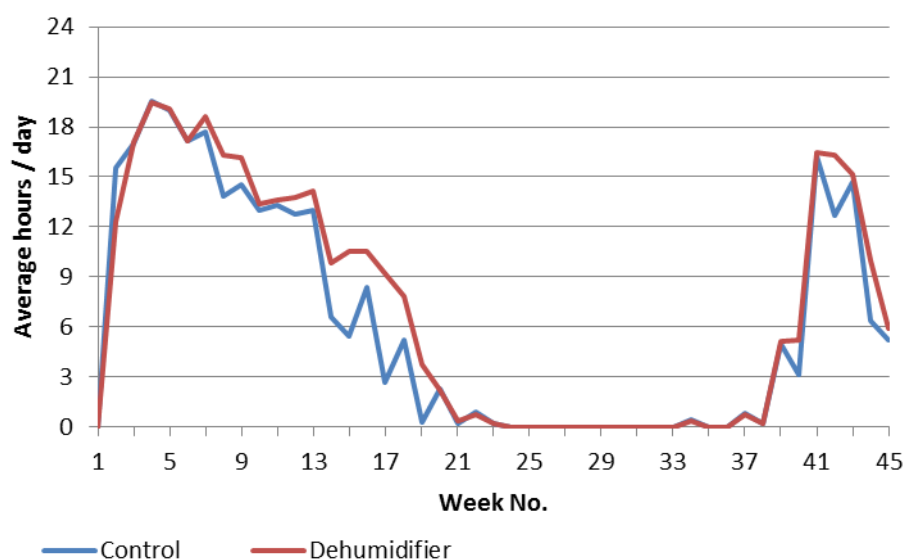


Figure 16. Thermal screen hours 2014

One unexplained issue was a notable difference between energy use in the compartments during the summer period in 2014 when the dehumidifiers were off (Figure 14), when one would have expected to see them being much closer. The modelling correction which seems to have worked well in the first year has not been quite as effective in the second year. We suspect some seasonal operational issue caused this, but there was no single definitive reason identified. For the purposes of assessing the heat saving (Figure 17), we assumed zero savings during this period.

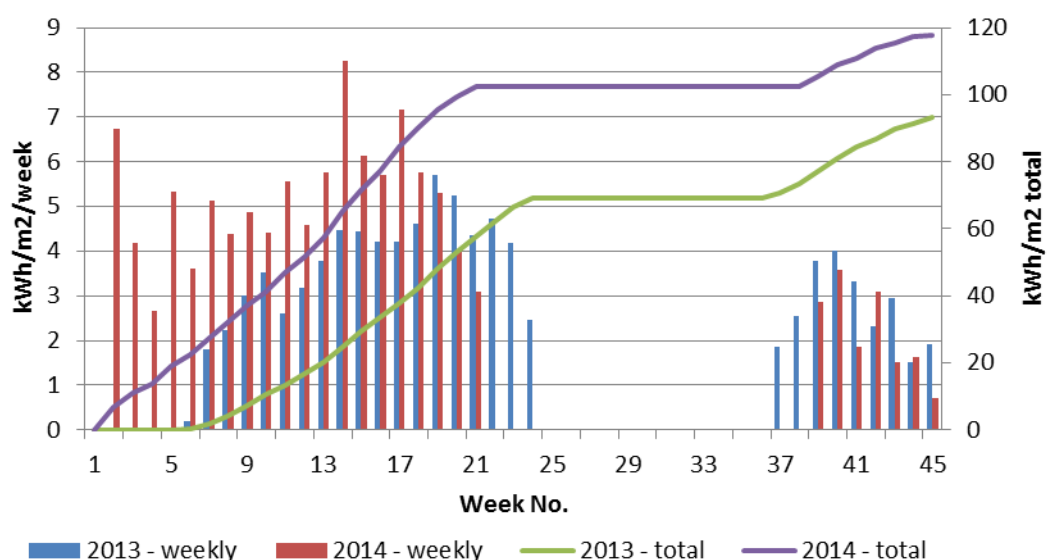


Figure 17. 2013 and 2014 energy savings compared

Figure 17 shows the comparable energy savings attributable to the dehumidifiers for the two years of operation. Clearly the second year was much more successful due to more reliable

operation and refinement of control set points. The initial 2 month bedding-in period in 2013 clearly did not have to be replicated in 2014, giving the system a head start in year 2.

For the purposes of system evaluation year 2 energy performance data was used as it represents a year's true operational trial without the early period of system testing (Table 2).

Table 2. Total energy use

	Heat used (kWh/m ²)	Electricity used by dehumidifiers (kWh/m ²)
CMP3 (dehumidifiers) Corrected for summer difference	249	16
CMP4 (control)	367	-
Difference	118 (32%)	16

This gives a whole of season dehumidifier SERR of 7.4.

It is worth noting that CMP4 used the equivalent of 432 kWh/m² of gas (assumed boiler efficiency of 85%). This is already a low figure compared to most tomato nurseries making a further reduction of 139kWh (gas equivalent) even more significant.

Greenhouse climate

Humidity

As energy savings were possible in all but the highest HD conditions (low RH), the dehumidifiers were used if RH levels was above 65%. This meant running the dehumidifiers even when the humidity itself did not need to be 'controlled' for crop growth/disease reasons.

As a result lower average humidity conditions (higher HD) were achieved in the compartment with the dehumidifiers.

For the daytime operation, the average figures don't reflect a consistently higher HD in the dehumidified compartment. Other effects – ventilation, high crop transpiration and solar influence probably overshadow the dehumidification influence.

With the crop transpiring much less overnight the dehumidifiers had a bigger impact on the night time HD achieved. Data from 2014 when dehumidifier operation was most consistent, demonstrates this difference most clearly between weeks 1 to 13 and again towards the end of the year (Figure 18).

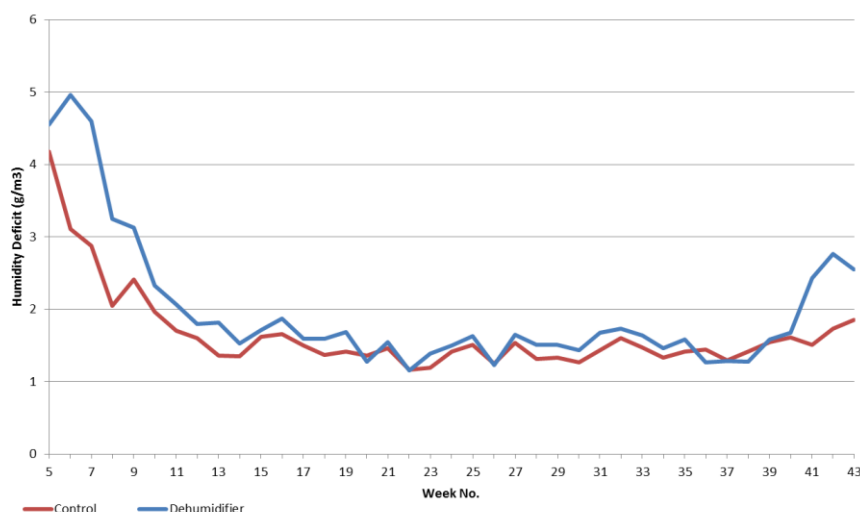


Figure 18. Average night time humidity deficit 2014

CO₂

With the dehumidifier compartment achieving a slightly better HD during the daytime in CMP3 and with less venting, we might have expected higher CO₂ levels. However, their impact on daytime CO₂ levels and therefore venting was relatively small. Part of the reason for this was that during periods of high heating requirement although the dehumidifiers were actively contributing to limiting the need for ventilation; the injection of CO₂ from the boiler/CHP was also at its highest for both compartments and in fact could cope with the additional CO₂ demand without leading to any significant depletion through ventilation.

The dehumidifiers did however have a notable impact on the night time CO₂ level. This ties in with the fact that, with the dehumidifiers it was possible to achieve more screening hours and less gapping / venting overnight. Perversely, the night time CO₂ level has no direct consequence / impact on yield, and there was thought to be a potentially negative impact through the greater retention of flue gas pollutants such as NO_x and ethylene.

Temperature uniformity

An area of concern with the dehumidifiers was their possible adverse impact on temperature uniformity. We considered that, as a less distributed form of heat, regional areas of higher temperature might be evident. Figure 19 below shows the average temperature achieved on a grid of 15 data loggers over a 3 day period in February 2013 when the dehumidifiers were turned off. Figure 20 shows data from the same loggers under comparable conditions one week later when the dehumidifiers were turned on.

With the dehumidifiers off, the highest temperature was 1.9°C above the average and the lowest was 2.0°C below the average. With the dehumidifiers on, the highest temperature was 0.4°C above the average and the lowest was 1.7°C below the average. This result was

validated / confirmed by comments from the grower pertaining to the comparative evenness of the crop compared with previous years.

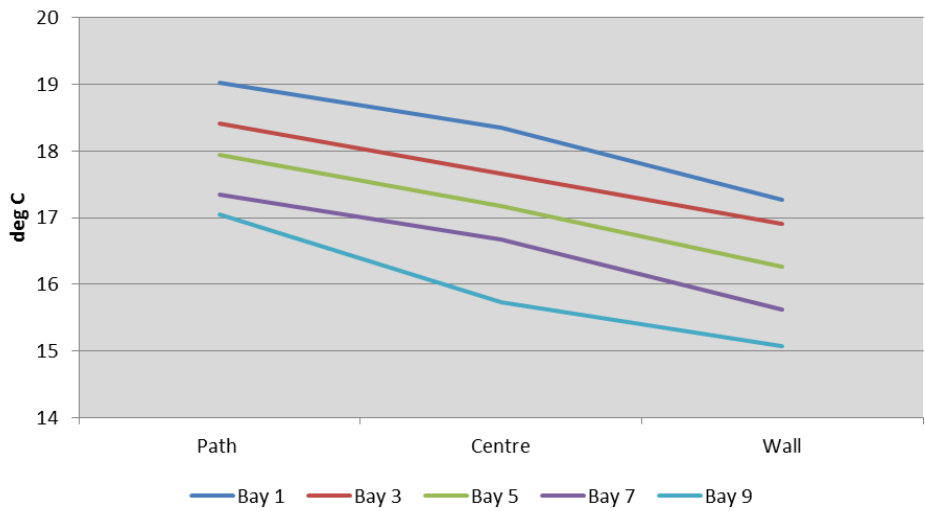


Figure 19. Temperature uniformity: dehumidifiers off

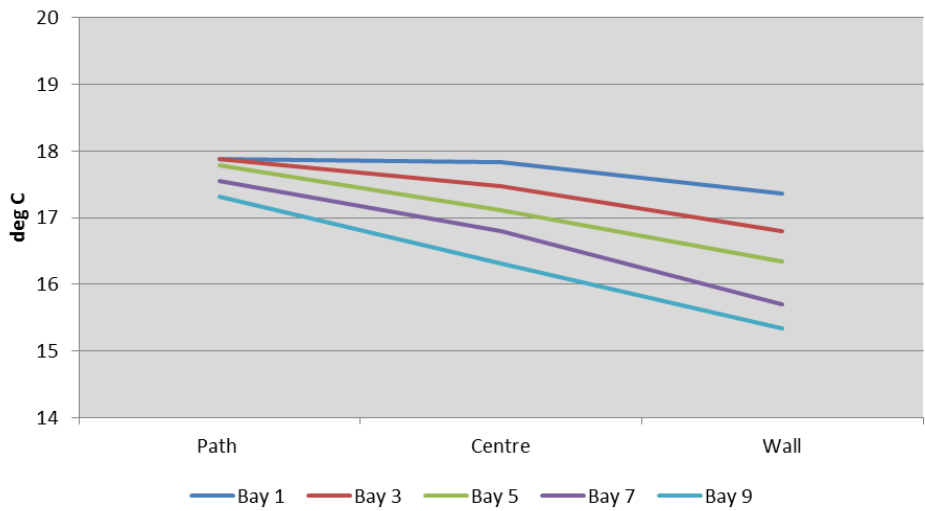


Figure 20. Temperature uniformity: dehumidifiers on

Crop data

All data was compiled by the nursery's crop advisor Ronald Duyvestijn and was used to aid crop management decisions in both greenhouse compartments.

2013

The data focusses on the period up to week 28 only. After this date other factors, principally pests and flue gas pollutants, affected crop performance and made any potential comparison invalid.

Fruit set

At the start of the season fruit set was similar in both compartments each year (Figures 21 and 22). In 2013 the total number of fruit set up to week 29 was higher in the dehumidifier treatment (1,936 vs. 1,886); although the quality of fruit was poor in dehumidifier treatment. In 2014 the total fruit set was only marginally more in the dehumidifier treatment (2,033 vs. 2,009); the quality / evenness were also similar.

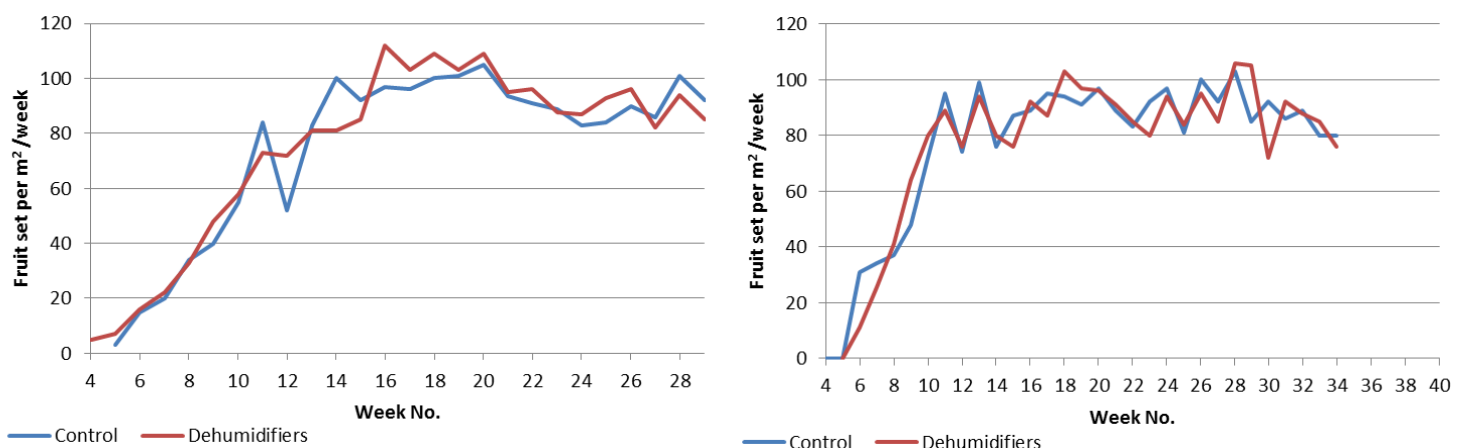


Figure 21. Fruit set per week (2013 LHS, 2014 RHS)

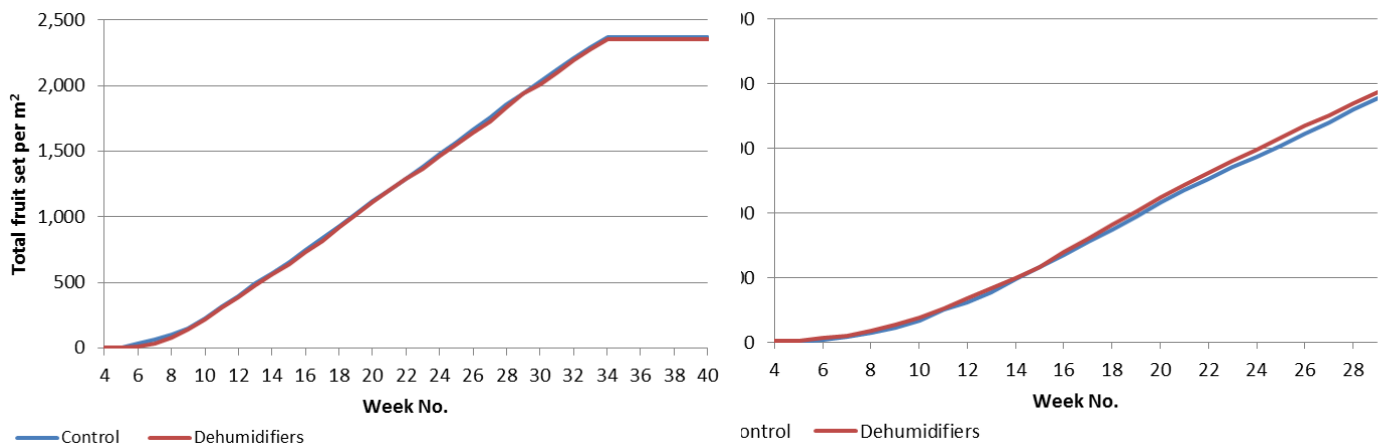


Figure 22. Total fruit set (2013 LHS, 2014 RHS)

Fruit size

2013. Although not measured specifically for this trial, measurements in the control treatment gave an average fruit weight of 12g. The fruit size in the dehumidifier treatment was often visibly smaller. Although the fruit set was higher, the quality of fruit set in the dehumidifier treatment was inferior.

2014. Although the fruit set in the dehumidifier compartment was more uniform and better quality they were again visually smaller.

Leaf length

2013. Between weeks 7 to 10 the leaf length in the dehumidifier treatment was shorter, possibly caused by the lower humidity in that compartment (Figure 23). Around week 11 this pattern reversed and although the trend was for shorter leaves, the leaf length in the dehumidifier treatment was longer until the dehumidifiers were turned off (week 25). Longer leaves suggest a more vegetative growth.

2014. Expecting a similar vegetative shift to that seen in 2013 the crop in the dehumidifier compartment was steered more generatively from the start. This is reflected in the consistently shorter leaves up to week 11. However, once again in week 12 the leaf length in dehumidifier crop increased at the same time as it decreased in the control crop. Unlike 2013, the difference in leaf length remained even when the dehumidifiers were turned off (week 21).

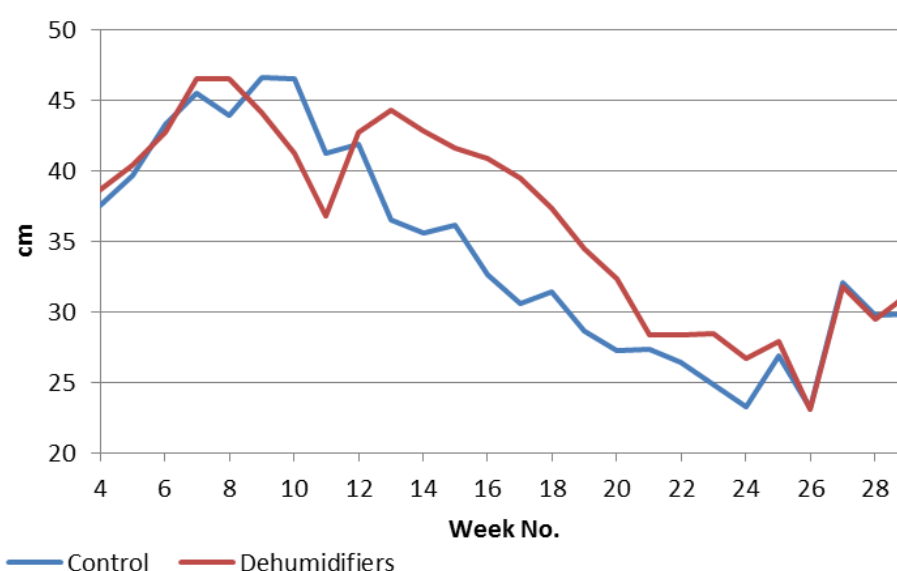


Figure 23. Leaf length (2013 LHS, 2014 RHS)

Truss length

This is the distance between the stem and the first set fruit. Short truss length indicates larger fruit and a more generative growth habit.

2013. The trend was similar to the leaf length with a notable change in week 11 (Figure 24). The longer truss length was in line with the visually smaller fruit size seen at the same time.

2014. Albeit less marked a similar pattern to 2013 was observed.

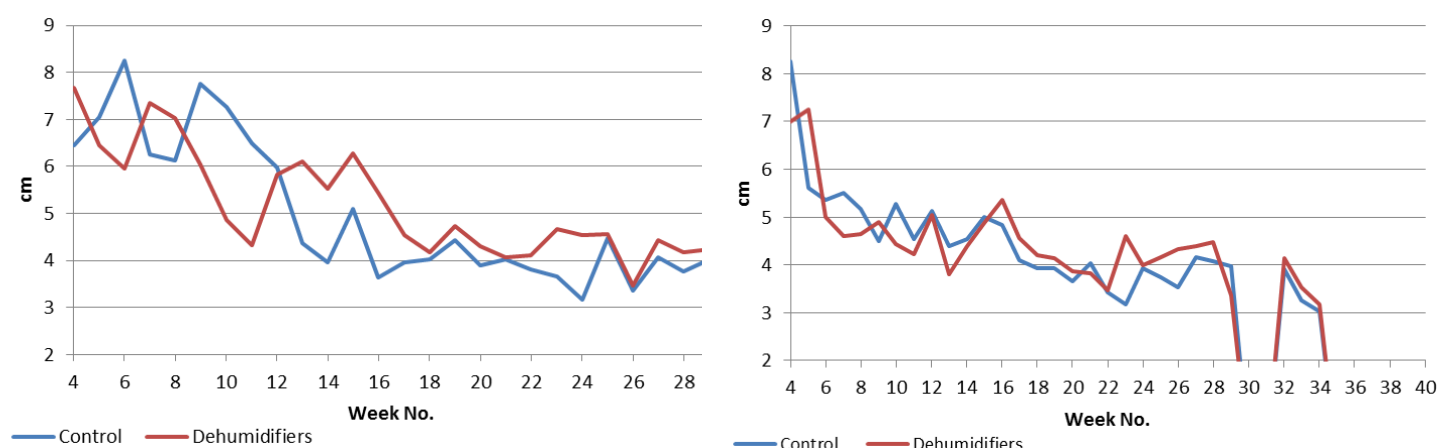


Figure 24. Truss length (2013 LHS, 2014 RHS)

Truss height

This is the distance between the top of the plant and the first flowering truss. The pattern across both years was similar to the truss length (Figure 25).

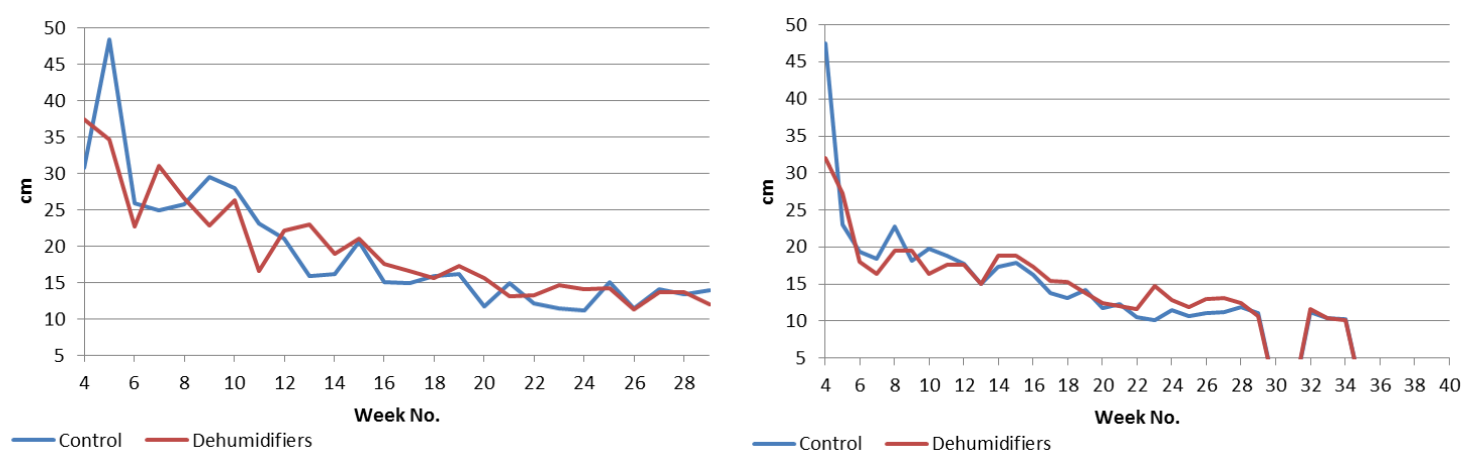


Figure 25. Truss height (2013 LHS, 2014 RHS)

Yield

2013. The total yield up to week 30 was 17.2kg/m² in the dehumidifier treatment and 18.2kg/m² in the control (Figure 26). This difference occurred mainly between weeks 17 and 20. These fruit were set between weeks 10 to 14 which coincides with the more vegetative trend in the crop noted in the leaf length and truss length at the same time. Looking more closely at the yield between weeks 21 to 30, the total was 11.68kg/m² (dehumidifier) and 11.66kg/m² (control). The fruit harvested in this period were set when the plants were equally in balance in both compartments and dehumidifiers had a rapidly diminishing impact on the greenhouse climate.

2014. The total yield up to week 30 was 16.4kg/m² in the dehumidifier treatment and 18.0kg/m² in the control, a bigger difference than in 2013 (Figure 27). However, unlike 2013, the difference increased through the remainder of the year to final yields of 27.2kg/m² and 29.3kg/m² in the dehumidifier and control compartments respectively.

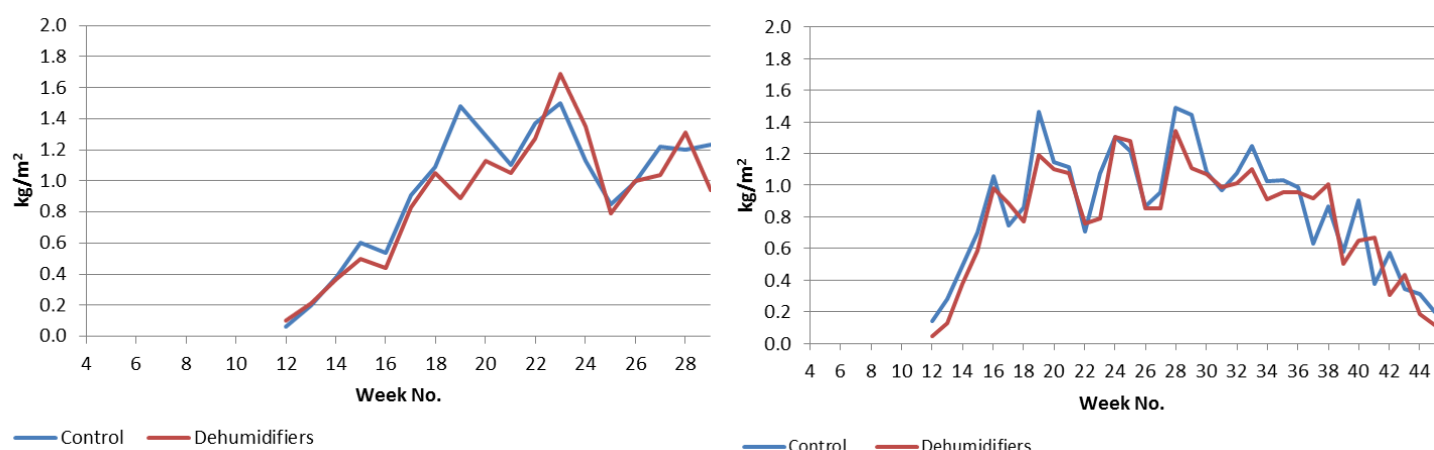


Figure 26. Yield – weekly (2013 LHS, 2014 RHS)

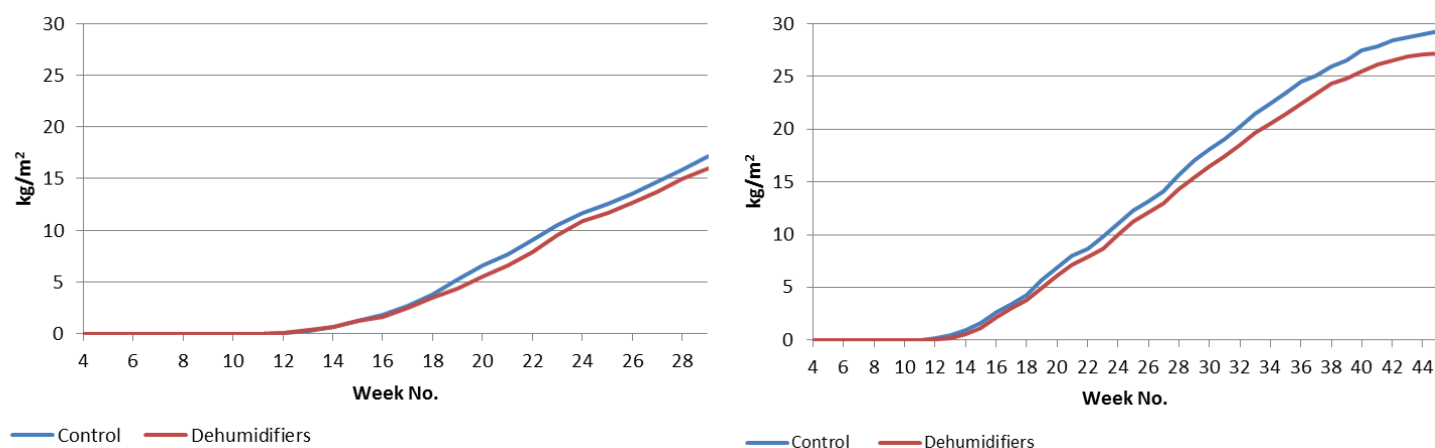


Figure 27. Yield – total (2013 LHS, 2014 RHS)

Disease

Formal disease monitoring was not carried out. However, the clearest indication of the impact of dehumidifiers on fungal disease such as *Botrytis* was the nursery's spray records.

2013. The control compartment received two fungicide applications; one in early May and one in early October. The dehumidifier compartment received no fungicides at all.

2014. Albeit slightly different timing, both compartments received the same number of fungicide treatments.

Summary of crop data / effects:

- The dehumidifiers had a more vegetative effect on the plants.
- There was no effect on the ripening speed; as the production started in both compartments at the same time.
- The fruit size was smaller.
- The total fruit set was less in 2013 but the growing strategy in 2014 corrected this.
- The total production was less in both years. The cause remains unknown.

Ornamentals crop – data collection and modelling

This part of the project was completed in 2013. However, for completeness it is included in this final project report.

Analysis of data collected

Energy

Figure 28 shows the amount heat used each week by the ornamentals greenhouse. This served as the benchmark against which savings have been calculated. The total amount of heat used p.a. was 261 kWh/m².

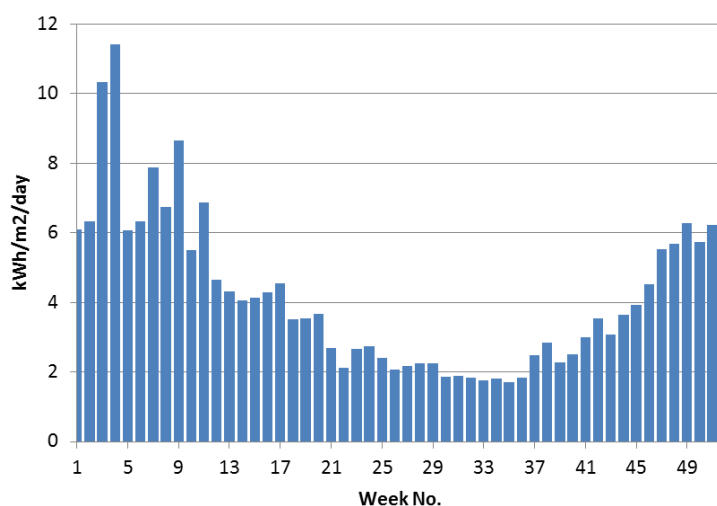


Figure 28. Ornamental crop heat use

Greenhouse climate – prediction of dehumidifiers operation

As mentioned previously, energy savings are possible even when the humidity is deemed to be acceptable. The degree of saving achieved is however linked to the amount of water in the air, a lower RH resulting in a lower saving. In addition, a lower air temperature at a given RH will also result in a lower saving as the amount of water held in the air (absolute humidity) is less, limiting the latent energy that can be recovered. Fortunately, the temperature in both the ornamental and tomato greenhouses were broadly similar leaving the humidity as the key difference.

To determine the dehumidifier running hours with the ornamental crop the following control strategy was applied. The dehumidifier was deemed to have been running if:

- The heating pipe temperature was above a set threshold
 - Ensuring that it only runs when a heat saving would have been achieved
- The RH was above a set threshold
 - Ensuring that it only runs when it's efficiency is acceptable

Figure 29 shows the predicted daily length of dehumidifier operation time for RH and pipe temperature thresholds of 65% and 30°C respectively. In this situation the dehumidifiers would run for 6,491 hours p.a.

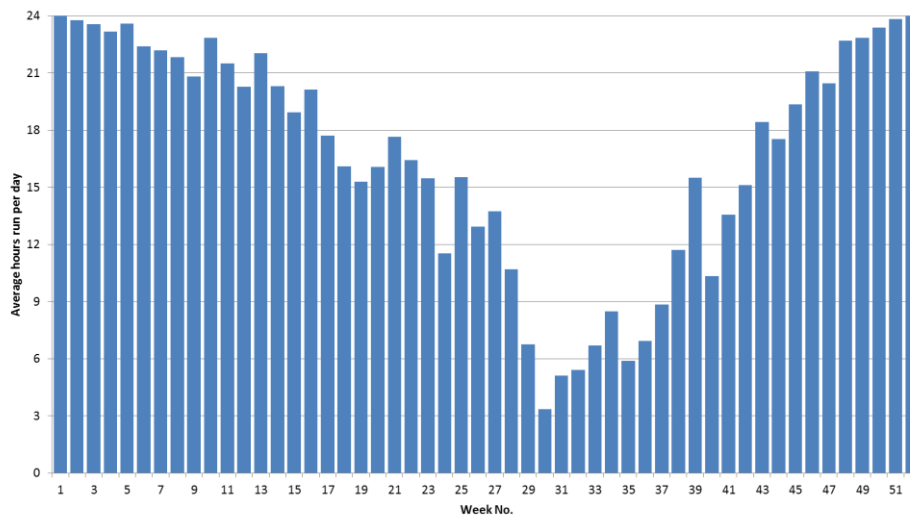


Figure 29. Ornamental crop run regime model

The modelled impact of increasing the RH threshold to 70% (the main driving factor) was relatively small, reducing the total hours to 6,401 hours p.a. (1.4% less).

Dehumidifier SERR

Multiplying the dehumidifier running hours by power rating (kW) gives the total kWh of electricity used. Multiplying this by the dehumidifier SERR gives the amount of heat saved. SERR data from the 2014 tomato trial has been used in the comparison work. Figure 30 shows the SERR trend used to calculate the potential savings.

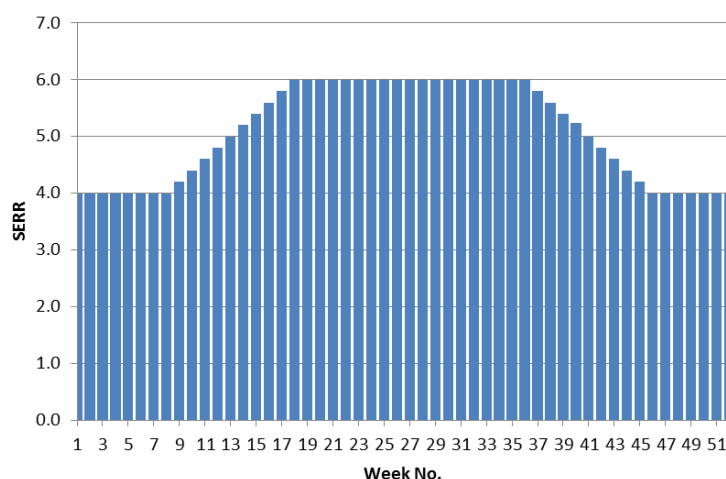


Figure 30. Ornamental crop: SERR expected

Energy saving

Combining all the information above produces the data forming Figure 31 below. The model produces an anomaly around week 30 in particular; the impact of the dehumidifier seems disproportionately low. However with energy used in this period being small and considering the limitations of the model, the effect on indicated annual performance is not significant. The projected annual energy data were:

- Heat saved 97kWh/m² (37%)
- Electricity used 19.5kWh/m²

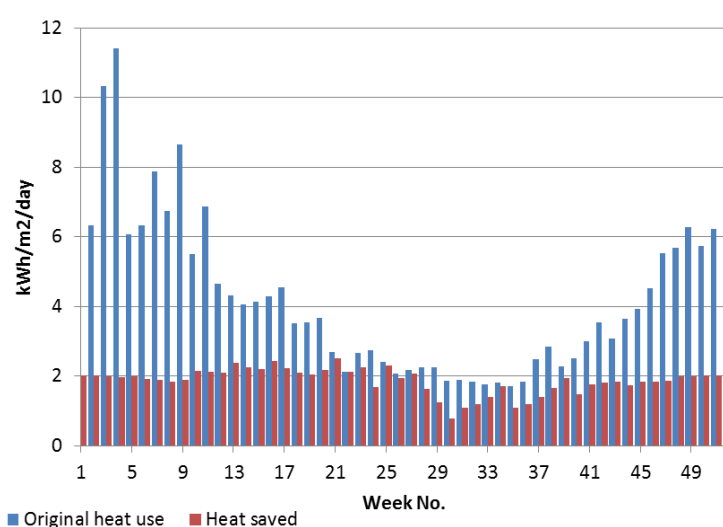


Figure 31. Ornamental crop: calculated heat saving relating to use of dehumidifiers

Financial impact

Crop effect

A lower yield was recorded in the tomato trial in in both years despite considerable effort in trying to improve things in the second year. Anecdotal evidence from other trials, and the continued development of fan and duct technology would tend to lead to the conclusions that given some considered work and development, the yield difference could be solved.

For the purposes of this report we are concentrating on the potential energy saving benefits as these are tangible and should be the initial driving force for longer term development and adoption. It could be argued that, even if there is no long-term yield reduction, lower yields in the early years of a nursery adopting this technology should be built in to the investment appraisal.

A quality/yield effect is not expected on ornamental crops.

The figures that follow assume no crop related benefit or loss.

Capital cost

The current list price of the dehumidification equipment supplied by Drygair is £17,000 per unit. Normal purchasing discounts plus the possibility of competition in the market could reduce the price down to around £14,000 per unit.

The cost to install the dehumidifiers can be significant. One area that needs to be considered is the cost of providing electricity to each unit. This comprises both cabling within the nursery plus the possible need to reinforce the grid connection to a nursery. Both costs are site related.

For the purposes of the following calculations we have assumed:

- Tomato crop (broadly applicable to all high temperature edible crops)
 - 6 dehumidifiers per Ha – total cost £84,000
 - Electrical installation including controls - £15,000
 - Total installed cost £99,000/Ha (£9.90/m²)
- Ornamental crop
 - 3 dehumidifiers per Ha – total cost £42,000
 - Electrical installation including controls - £10,000
 - Total installed cost £52,000/Ha (£5.20/m²)

Energy saving

Cost of electricity used

Red Roofs Nursery benefit from having CHP, the cost of electricity used whilst the CHP is running is somewhat less than if it was imported from the grid. However, with dehumidifier operation being weighted towards the night, when the CHP does not run, electricity from the grid was still required; albeit during cheaper times of day.

Nurseries that do not have CHP are clearly 100% reliant on grid electricity.

Value of the heat saved

With Red Roofs having CHP it could be argued that the heat saved is worth less than if it had been produced by a boiler. However, the CHP rarely satisfied all of the heat demand so the heat saved by the dehumidifiers would have been used to offset boiler operation in most

instances. For the purposes of this assessment we have assumed a boiler efficiency of 85%.

With energy prices being so variable and even site specific Figures 32-34 detail the net financial saving for the likely range of gas, oil and electricity costs.

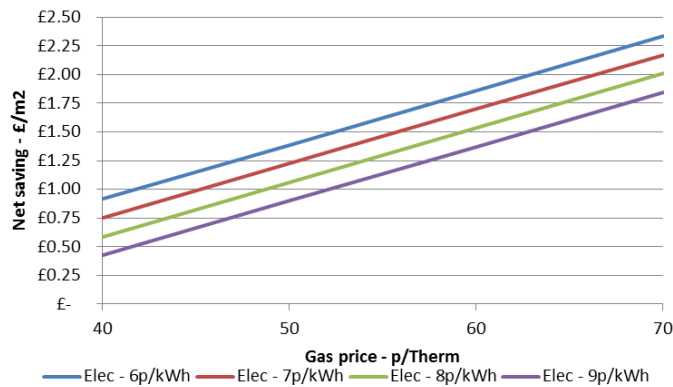


Figure 32. Tomato: net value of energy saving

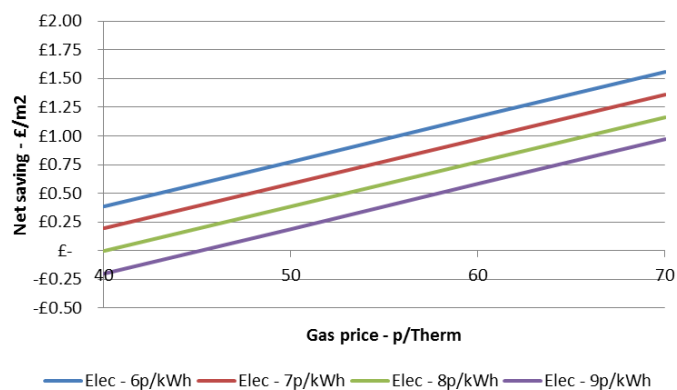


Figure 33. Ornamentals: net value of energy saving (natural gas)

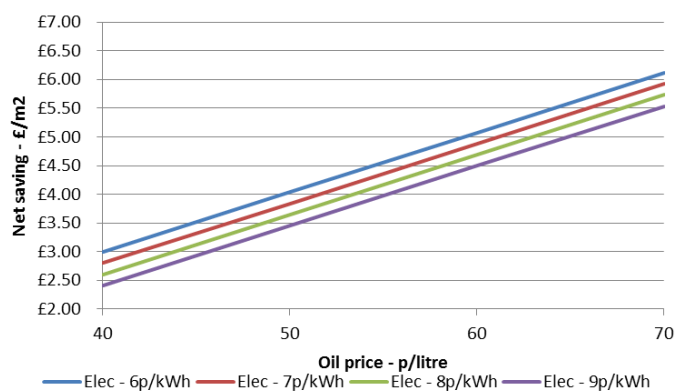


Figure 34. Ornamentals: net value of energy saving (gas oil)

Edible crops

In practice most nurseries have natural gas. At current energy costs (gas 60p/Therm, electricity 8p/kWh) a saving of £1.53/m² is expected. This would give a payback on investment in 6.5 years. A nursery with CHP (electricity perhaps 7p/kWh) would recoup their investment within 6 years.

Ornamental crops

Very few (if any) ornamental nurseries in the UK have CHP i.e. all electricity used would be imported from the grid. Furthermore high energy ornamental crops tend to use natural gas. Therefore a saving of £0.78/m² is most likely to apply to high energy ornamentals nurseries. This being the case, a payback on investment in 6.5 years is expected.

As a consequence of the higher cost of gas oil, ornamental nurseries that use it tend to grow crops with lower energy requirement. Therefore the potential energy saving (kWh) are less; and the example in the graph above is unlikely to occur in practice. In this situation, a simple pro-rata apportionment of the savings based on total current heat use compared with the data from Double H Nurseries is applicable. For example, if a nursery used 1/3 of the heat p.a. the savings would be in the order of 1/3 (£1.50/m²). Note however that dehumidifiers are less efficient at lower temperatures so actual savings are likely to be less.

Discussion

Tomato trial

Energy

For edibles, taking 2014 figures as representative of what could be achieved with dehumidification, heating fuel savings of 32% are possible. Clearly there are electrical running costs and capital repayments to offset this, but at current costs, a payback related to energy saving alone might be around 6.5 years. This leaves the big issue of crop performance which, if substandard, can be enough to offset any savings in energy.

Ornamentals would seem to benefit from similar energy related paybacks, but crop performance has not been monitored.

It is felt there is enough potential benefit for dehumidification technology to be explored further. Such work should be aimed at refining control, reducing capital and optimising crop performance.

It is curious that heat-pump technology which uses similar components to dehumidifiers is supported by subsidy payments through the Renewable Heat Incentive scheme but

dehumidifiers to not attract it. This is certainly an area for political lobbying as essentially the environmental benefits are comparable.

Beyond the direct impact of the dehumidifiers on energy use, they offer interesting potential opportunities to change other aspects of greenhouse construction/equipment. The most obvious is with thermal screens where there is often a compromise between energy saving and humidity control. Thermal screen manufacturers presently develop materials that are well sealed with regard to air exchange and which have an inbuilt 'wicking' action to allow moisture to pass through them. This latter characteristic leads to energy loss through the loss of latent energy in the water vapour. Dehumidifiers both remove the need to allow moisture to pass through screens, thereby allowing higher energy saving materials to be used, and recover the energy contained in the water vapour. This provides the opportunity for a second tier of energy saving through the use of different thermal screen materials and/or the addition of a second thermal screen (whether moveable or temporary) designed to work in conjunction with dehumidification. We believe that there is the potential to save a further 20-40kWh/m² if this was done. This would bring the total annual energy use of a modern, but far from state of the art greenhouse, down to the same levels as those being achieved at the Improvement Centre (NL) using the 'New way of Growing'.

As with many energy saving technologies and/or alternative heat sources, the financial benefit of the technology is compromised if it is necessary to burn gas to produce CO₂ and produce what is effectively 'free' heat. If free heat is available, then why spend money to save it?

Greenhouse climate

One major concern about the dehumidifiers was their potential heat distribution characteristic and its possible effect on the uniformity of the climate achieved.

Warm air discharge was delivered over the top of the crop rather than being delivered at low level from heating pipes as is the case with a conventional hot water system. One impact of this could have been slower ripening of the fruit, although this was not evident in the crop data. Clearly, this radically different distribution system and the modified micro-climate that it will have produced may have impacted on fruit production. What is still in question is the mechanism by which this effect occurred.

It would appear that we can discount temperature uniformity as results from the network of temperature loggers showed that, if anything, there was a slight improvement in this when the dehumidifiers were used.

Crop

Crop yield was down for the dehumidified crop for both years. There was only one year preceding the trial when the same varieties were grown in each greenhouse and there was negligible difference in yields. The crop registration data clearly shows a shift in plant balance around week 11 in both trial years.

On the other hand anecdotal evidence from other dehumidifier trials gave a higher yield one year and lower yield the next. Also, trials with the closed greenhouse and similar techniques took at least three years of experience to optimise yields.

The impact on yield needs to be more clearly proven / understood. With the payback on investment currently being borderline for many businesses a yield reduction, even in the first year alone (whilst growing experience is gained), would extend the simple payback on investment to more than 7 years.

Further work is required to understand the cause of the yield reduction and identify solutions.

Ornamental crop modelling

The lower dehumidification load per hectare makes the installation cheaper compared with an edible crop. The fact that a system can be operated year round (not restricted due to the need for CO₂) also improves equipment utilisation. This is however offset by the fact that even 'high energy' ornamental crops use less heat than a tomato crop; so the potential for savings is less. Modelling suggests that these factors cancel each other out and that a similar payback on investment (6 years) to a tomato crop is likely.

Lower energy use ornamental nurseries that use gas oil for heating have less to save in energy (kWh) terms. However, the substantially higher unit cost of gas oil means that dehumidifiers can still represent a good investment. It should be noted though that dehumidifier performance with lower temperature crops (less than 16°C) will be worse than shown in this report. The effect of this has not been quantified.

Conclusions

Edible crop trial

- Heat savings in the final trial year of 118 kWh/m² p.a. (32%) were achieved.
- Dehumidifier electricity use was 16kWh/m²

- In 2013 no fungicides were applied to the dehumidifier crop compared with two applications to the control crop. In 2014 the same fungicide applications were made to each crop.
- Yield in the dehumidifier crop was less in both years
 - The underlying cause remains unproven.
- Return on investment
 - 6.5 years (excluding yield reduction)
- The need for CO₂ (from burning natural gas) during the summer significantly limits the savings that are possible.

Ornamental crop modelling

- Savings of 97kWh/m² (37%) were calculated vs. electricity use of 19.5kWh/m²
- The need for less dehumidifiers means that a return on investment within 6.5 years appears possible.
- Nurseries that use gas oil for heating tend to be lower energy users. However, the high cost of gas oil offsets the lower kWh saving and could deliver a return on investment within 6.5 years.

Knowledge and Technology Transfer

- Tomato Working Party – nursery visit, April 2013
- HDC Energy News – July 2013
- Tomato Growers Association – Technical Committee meeting, September 2013
- Tomato Growers Association – Annual Conference, September 2013
- British Protected Ornamentals Association – Technical Committee meeting, October 2013
- Nursery Open Day – July 2014
- HDC Energy News – December 2014
- HDC News – March 2015

Glossary

CHP	Combined Heat and Power
CO ₂	Carbon dioxide
CoP	Coefficient of Performance
Ha	Hectare
HD	Humidity deficit
KPI	Key performance indicator
kWh	Kilowatt hour
NO _x	Nitrogen oxides
RH	Relative humidity
SERR	Specific energy reduction ratio
SMER	Specific moisture extraction rate

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Pratt C.T. (2007). An initial investigation into the potential for using sealed greenhouse technologies in the UK. Horticultural Development Company Final report for project PC 256.