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helping horticulture save energy

AHDB

# Energy management in protected cropping

# Contents

The original information was compiled by Steve Adams and Allen Langton (Warwick HRI) and Chris Plackett (NFU energy) in 2009, and has been updated to this version by Edward Hardy and Jon Swain (NFU energy).

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# Introduction

Energy costs in the protected edibles and protected ornamentals sectors as a proportion of business variable costs are dependent on their fuels, technology and the impact of incentives such as the RHI. However for a conventionally grown edibles crop with a gas boiler, representing the user with the largest energy costs, this can be as high as 30%. Defra and AHDB funded research projects in the 2000s helped change our thinking about glasshouse energy management. Based around science that demonstrated the capacity of crops to respond to average temperature this work identified new thinking in management of the whole climate control system, resulting in greater energy efficiency.

The outcomes of this work was summarised by Steve Adams and Allen Langton (Warwick HRI) and Chris Plackett (NFU energy) in 2009.

There have been significant developments relating to glasshouse energy management since 1990. These include, increasing fuels costs, government schemes incentivising the use of renewable energy, more stringent environmental legislation and new thinking on climate control strategies (New Generation Growing) emerging from The Netherlands. Factor in the increased use of supplementary lighting and other technologies, and it is easy to see why energy is an important consideration for growers.

While some growers may have gone down the route of renewable heating or self-generation of electricity, many others continue to rely on fossil fuel technologies. Most are at the mercy of the often volatile energy markets, and so would do well to optimise performance in terms of energy efficiency and tighten up on wasteful procedures.

This guide, which combines the updated factsheets, contains many useful facts, figures and tips for growers to better manage their energy use, which could lead to significant financial savings.

# Good housekeeping

This section highlights the benefits of good housekeeping, the first essential element in efficient energy management. The key is to appreciate where energy is being used (Figure 1) and to take steps to minimise waste.

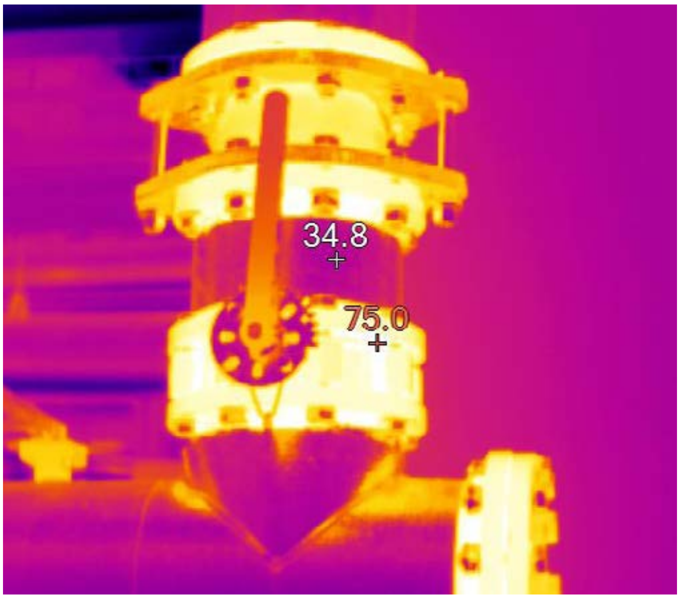


Figure 1. Thermal image of an uninsulated valve showing high heat loss

## Background

Despite the many sophisticated methods available for saving energy in horticultural production, the first and most cost-effective step is often good housekeeping. Good energy management requires an appropriate mindset, recognising that significant waste can arise from a lack of awareness, and in some cases, simple carelessness. Regular equipment maintenance and making essential repairs without delay can typically save up to 10% of energy for little or no capital outlay.

## Responsibilities

Someone in the organisation should have specific responsibility for energy issues, including the purchase of energy and related equipment, and efficient operation. Having a single person who is the energy champion gives the issue some consistent representation. Written energy policies are useful in setting down the aims and intentions of the business and are also a requirement of various crop assurance protocols. A policy should detail responsibilities and future plans pertaining to energy and be revised on a yearly basis. Training in energy matters is also useful; this can be as simple as awareness training on the importance of switching off basic pieces of equipment and extend to detailed technical training on the operation of heating and ventilation control systems. Feeding back information on energy performance to staff is important in engaging interest in energy efficiency. Using graphs and charts to compare energy use over different periods or between sites can be especially useful.

## Monitoring and benchmarking

It is impossible to determine whether an operation is energy-efficient and to make rational decisions on ways of reducing energy unless energy use is measured and recorded. It is not sufficient to rely on past energy bills, which may be estimated, infrequent and too general. Actual energy use data should be collected and assessed at least weekly. Include all fuels (gas, electricity, oil, etc.) and aim to take meter readings and/or storage tank levels at the same time each week. Compare energy use with similar periods in previous seasons. To be of most use, energy data should be compared alongside greenhouse climate data (temperature, humidity and $CO_2$ concentration), weather data (temperature, wind speed and solar radiation) and cropping information. The data will show where the energy is being used and the factors leading to changes in consumption. Increases in energy use that cannot be accounted for by changes in growing conditions indicate a possible problem with the heating equipment, requiring investigation. If possible, benchmark your performance against that of other growers. Energy use can vary greatly between growers of the same crop and informed comparisons can be very instructive.

Energy bills cover use at a site level and not at an equipment or operational level. Where a site has multiple boilers or greenhouse structures, utility meters and bills are unable to indicate energy-efficiency shortcomings associated with those specific areas of operation. It is recommended that submetering is installed for heat and electricity (Figure 2). Meters are cheap and easy to install and most can be connected to climate-control equipment, allowing data to be graphed in the usual way. The investment in meters will be recouped in the energy savings they help to identify. For more information, see GrowSave Technical Update: ***Measuring Energy***.

Figure 2. Meter used to monitor the heating energy used in a specific greenhouse area

## Degree day (DD) analysis

As weather conditions and temperatures change throughout the year, the amount of energy needed for heating changes. This makes comparing energy efficiency season to season difficult. Using degree days takes into account the weather when looking at energy use for heating or cooling.

A degree day is worked out by calculating the average outdoor temperature of a day and subtracting this from a base heating or cooling temperature inside the glasshouse. For example, if heating is set to 20°C and the outside temperature has averaged 5°C, then 15 degree days ([20–5°C] x 1 day) have been accumulated.

Temperature differences over time are calculated by multiplying the average daily difference by the number of days concerned. For example, the average temperature difference over a period of five days when the average outside temperatures are 10°C, 11°C, 15°C, 16°C and 13°C, and the inside is 20°C, is 35 DD – equation is (20°C – [(10°C + 11°C + 15°C + 16°C + 13°C) /5]) x 5 days = 35 DD. This data can be used to plot a graph of energy use compared with degree days over time (Figure 3).

DD data isolates the temperature effect so that better comparisons can be made for changes in equipment or settings. By analysing energy use during a particular period in terms of degree day values, a picture of how the temperatures and weather conditions may have had an impact can be seen. This also allows comparisons of different glasshouse units and with different growers, etc.

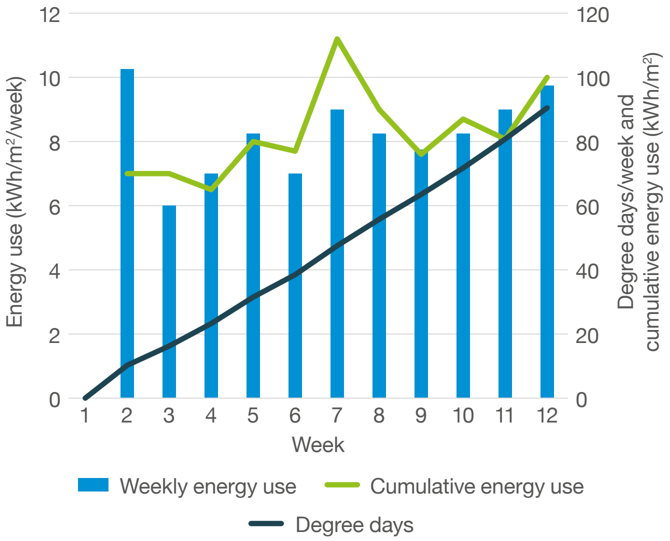


Figure 3. Energy use compared with degree days over the first twelve weeks of the season

The graph shows that degree days and energy use have closely followed each other (i.e. when the degree days value increases, the energy use increases accordingly). However, there have been two exceptions, in weeks two and 11. The energy use in week two was higher than expected because the greenhouse had to be heated up to its operating temperature from cold.

In week 11, the energy consumption was also higher than expected as wind speeds were exceptionally high. This caused the 'storm settings' to come into use, which meant that the thermal screen stayed open and therefore reduced the energy saving. If it was not possible to explain the exceptions, further investigation would be needed, for example:

- Is the measuring box correct, e.g. is the wick dry or has the fan failed?
- Is the heating system faulty, e.g. has a mixing valve stuck or is a temperature sensor faulty?
- Is the thermal screen operating correctly? Many systems do not measure the actual screen position, they calculate where the screen should be, so is the calculation correct and, is the screen really closing fully?
- Are the climate-control set-points correct?

## Maintaining control systems

The amount of capital tied up in the systems used to control the heating, ventilation and $CO_2$ supply is generally small compared with the value of the glasshouse, the crop and the energy used over a season. However, the effectiveness of these control systems is key to optimising the environment and minimising energy inputs. This can be illustrated by considering the effects on energy use of a measuring box that is inaccurate and reads 0.5°C below actual temperature. It is shown on page 34 (Manipulation of glasshouse temperature) that a 1°C change in temperature can alter energy use by 10–13%, so a 0.5°C measurement error could increase heating costs by at least 5%. For an annual energy use of 400 kWh/m², this increase could equate to an additional annual energy expenditure of £5,000/ha (gas priced at 2.5p/kWh). The desired greenhouse environment will not be achieved, and while there may be some compensatory increase in crop yield from the higher achieved temperatures, it is far from certain that this would be sufficient to cover the extra cost. The higher actual temperatures could also reduce product quality. As noted on page 19 ('Humidity control'), measuring boxes should be regularly maintained. In particular, the wet bulb sensor in a conventional box must always have a clean wick and a plentiful reservoir of clean, deionised water. The aspiration fan must be kept clean and the box itself must be suspended in a position within the glasshouse so that the measurements reflect the conditions experienced by the crop but where obstructions do not hinder the airflow.

Similarly, care needs to be taken to ensure that measurements made by the weather station are accurate. Measurements of outside radiation, temperature and wind speed are key variables used in the control of the glasshouse environment. If these are inaccurate, energy will probably be wasted. $CO_2$ analysers also need to be calibrated regularly and it is important to ensure that readings really do reflect $CO_2$ levels at the point of sampling when a single analyser is used to monitor $CO_2$ levels at multiple positions. Electronic sensors are now more widely used than ever and while they require significantly less maintenance, they do need to be calibrated and checked against each other on at least a bimonthly basis.

## Greenhouse heat loss

Some aspects of greenhouse heat loss can only sensibly be considered at the initial design stage, but others can be applied to structures that are already in existence.

### Greenhouse materials

Choice of glasshouse glazing material is a balance between light transmission, heat loss and cost. Average heat loss of a material can be represented as a ‘U’ value, allowing a comparison between materials. The lower the value, the better the material is at insulating. A single sheet of glass has an average U value of 8.8 W/m$^2$/°C. A double glass or twin-wall polycarbonate material may reduce this value to around 5.0 W/m$^2$/°C; however, direct and diffuse light transmission will be reduced and these materials will also have a higher cost. As a result, single glazing has remained the industry standard, but there is continued development of new materials on the market. Products such as Ethylene tetrafluoroethylene (ETFE) offer benefits of greater light transparency in a lightweight material, which requires less structural components and therefore reduces shading, has improved UV penetration and is non-stick and self-cleaning. Several formulations using ETFE are available and worth considering (Figure 4) as a primary cladding or as a retrofit screen.

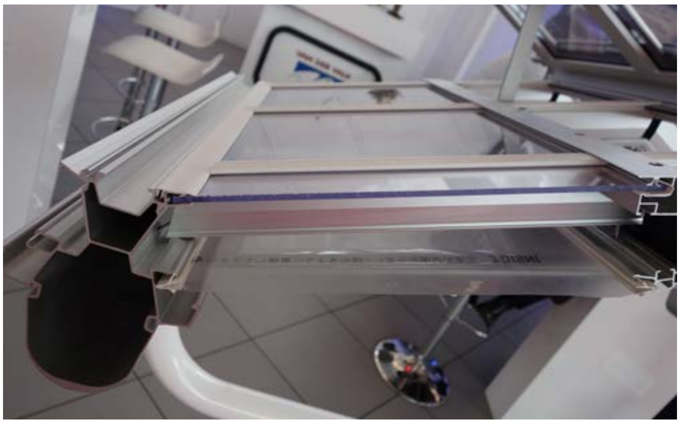


Figure 4. ETFE cladding

### Thermal screens

Retractable thermal screens will generally provide a better option for reducing heat loss than double glazing and this option applies equally to new and existing structures. The materials themselves give instant energy savings and a commercial trial of energy screens in tomato production (with conservative settings) gave annual energy savings of around 13% (PC 198/198a). Materials are constantly being developed that save more heat and allow greater light transmission, allowing use in the daytime and double screening. Screens have an important role to play in ‘Next Generation Growing’ (NGG) techniques. This Dutch initiative, with ambitious energy-saving targets, primarily aims for a homogenous greenhouse climate. Screens are opened later and closed earlier, sometimes resulting in higher temperatures and humidities. Screens with greater permeability can let water vapour through to be vented away without the need for heat. Keeping screens closed longer in the morning will allow the air above the screen to get closer to the glasshouse temperature prior to opening so that the temperature difference and therefore the requirement for heating are minimised. Thermal screens are considered in detail on page 24.

### Reducing air leakage

Between 5% and 30% of instantaneous greenhouse heating demand can be due to air leakage. A ‘leaky’ greenhouse structure may have two or more air changes per hour, whereas in a recently constructed greenhouse built to the highest standards this may be as low as 0.25 air changes per hour. Modern Venlo greenhouses are constructed so that the air loss through glass joins, closed ventilators and doors is minimised. In older structures, however, energy efficiency can be improved by using flexible sealant to seal the gaps between panes of glass and by fitting rubber or brush seals to greenhouse doors and ventilators to ensure that they close properly. No matter how old the greenhouse, gaps around pipe, cable or duct entry points need to be sealed. Broken or damaged panes of glass should also be replaced as rapidly as possible. A missing pane of glass has been calculated to increase the annual heat loss in high-input glasshouse production by around 1,200 kWh and, at 2.5p/kWh (current energy prices), this will cost nearly £40 per year, allowing for boiler efficiency.

The installation of windbreaks outside is worth considering, since these minimise the airspeed over the greenhouse surface and can greatly reduce heat loss, particularly under windy conditions and when internal energy screens are not in use. Plastic screen materials can be used, but banks of trees or shrubs can be equally effective (Figure 5). However, it is important to ensure that the siting of windbreaks does not result in crop shading since this can more than negate the benefits of energy saving.

Figure 5. Well-sited windbreak of alder

When air leakage has been minimised, it is important to promote good air movement within the glasshouse, otherwise temperature and humidity conditions can become localised, leading to poor crop performance, disease and high energy usage. Maintaining a minimum heat pipe temperature is an established method to move warm, dry air around, but this is an expensive solution. An energy-efficient method to produce a uniform greenhouse environment is the strategic use of fans. Air is heavy and difficult to get moving, so persistence of air movement, rather than speed, is the key. In general, the objective should be to install a system that is capable of circulating the entire air volume in the greenhouse once to twice per hour. Fans should be fitted with variable-speed motors, which can be modulated automatically and thereby save energy. For growers with climate computers, further energy saving is possible by controlling fans in conjunction with vent position so that the fans are switched off completely when the vents are open sufficiently to ensure good air movement. Care should be taken in this regard that any microclimatic effects around the plants and leaves are satisfactory; air movement with fans may still have purpose in these situations regardless of vent position. More information is available in GrowSave Technical Updates: ***Air Movement*** and ***Circulation Fans***.

Figure 6. Horizontal barrel fan

## Maximising light transmission

It is important to achieve maximum transmission of solar radiation into the glasshouse. This will maximise plant growth and will reduce energy use by lessening the need for heating to maintain glasshouse temperature. Clearly, geographical location, topography and glasshouse orientation affect the glasshouse light climate, along with glasshouse design, and these are all factors to be taken into account when a new glasshouse is being planned. Another important consideration at this stage is the glass. The transmission of horticultural glass is often reduced by 2–3% due to impurities, and selecting low-iron glass, for example, can improve the light transmission.

### Diffuse light

Greater improvements in light transmission can be obtained by the use of diffuse glass which has an etching or a structure that changes the properties of the surface. These surfaces cause a scattering (20–85%) of direct light. The light can penetrate deeper into the crop canopy, with a more even distribution and reduced shadow. The popularity of coverings which produce more diffuse light is being acknowledged for improved crop yield and quality.

Work at Wageningen University & Research has shown that, being grown under diffuse glass, the crop undergoes less stress because of a lower tissue temperature in the upper crop layers and a higher tissue temperature in the lower layers. The morphology and development of the crops also change. Tomatoes and cucumbers have been shown to be more generative and the fruits develop faster. The fruits are heavier and there are often more of them. Time to market has been reduced in ornamental crops and heavier weights on pot plants achieved with less risk of scorch.

Diffuse glass and related materials are more expensive than single-sheet glass, but with yield increases of 5–10% quoted for some crops, it makes alternatives worth considering (Marcelis et al., 2014). There is not enough evidence to say if energy savings can be made, but a more uniform temperature throughout the glasshouse helps energy management; for more information, see GrowSave Technical Updates – ***Diffuse glass for greenhouses*** and ***Enabling Diffuse Light***, ***CP 147*** and AHDB Event notes – ***Manipulating Light for Horticulture***.

### Cleaning

One of the most effective ways of maximising light is to keep the glass clean, inside and out. Work carried out by ADAS in the late 1980s showed that the light loss due to dirty glass averaged 18% for growers in the Lea Valley area of the UK. The move to cleaner-burning fuels will have improved the situation, but dirty glass can still be a problem, and cleaning is critical. Studies in the Netherlands indicate that a 10% increase in light transmission can result in a 2% reduction in energy use in tomato production and an 8% improvement in energy-use efficiency (Elings et al., 2005). Glass cleaning can be extremely labour-intensive and there are important safety issues to take into account. As a consequence, automatic roof-cleaning equipment can be an attractive option.

It is just as important to make sure thermal screens are kept clean, as algal build-up and dust will reduce their effectiveness and reduce overall light transmission. Regular cleaning regimes, such as chemical fogging or letting screens dry out before closing them, will help to maintain their light transmission.

# Heat generation and heat distribution

## Boiler efficiency

Boiler efficiency is influenced by three key factors:

- Good fuel combustion – this requires a well-designed burner which accurately controls the fuel/air mixture. The use of variable-speed drives on the boiler fan motor will ensure that the correct fuel/air mix is maintained in all operating conditions
- Good heat transfer to the piped water supply – this requires large heat exchangers that extract as much heat as possible from the flue gases
- Low-standing heat losses – boilers should be compact and have high levels of insulation

A flue gas condenser will ensure that the maximum amount of energy is extracted from the boiler flue gases. This uses a large heat exchanger that reduces the temperature of the flue gases to the point where the water vapour contained within them condenses out. Typically, this occurs at or below 60°C. At this point, the latent heat contained within the water vapour is released and the efficiency of the boiler is significantly increased.

The most efficient designs of boilers with condenser units can achieve seasonal efficiencies close to 90%. This compares to around 80% for modern boilers without a condenser and less than 70% for older boilers (20+ years old). Boiler upgrading clearly has considerable energy-saving potential. When a condenser is fitted, the temperature of the flue gases is closely related to the temperature of the water returning to the condenser. As a consequence, the returning water needs to be kept below 50°C so that the temperature of the flue gases can fall below 60°C and condensation can occur. In practice, this situation can only be reliably achieved when the heat recovered by the condenser is provided to a dedicated load because of its lower temperature. The lower-temperature hot water can be used for heating floors, benches or within the crops themselves (as in tomato and chrysanthemum production).

## Single or multiple boilers?

Heating in the protected crops sector is mainly by large, centralised boilers serving several individual growing areas. The boiler will have a heating capacity sufficient to meet the peak demand of the site, but this arrangement may not be the best solution from an energy-use perspective. This is because a boiler operates at its optimum efficiency only when its output is constant and close to its rated capacity. Once a boiler is required to 'modulate' its output to meet a fluctuating requirement for heat that is frequently well below its rated output, its efficiency will fall. This is why the seasonal efficiency that is achieved in practice is always below the maximum that is quoted by the manufacturer. Maximum heat output will only ever be needed for a few days (or even hours) per year, when it is particularly cold and when wind speeds are especially high. Figure 7 shows the relationship between heating demand and frequency for a typical greenhouse in the UK. This shows that for 90% of the time, the greenhouse heat demand is only a little over 70% of the maximum. Although not commonly practised, a more energy-efficient approach may be to use multiple boilers. This way, the base heating load can be satisfied by a very efficient lead boiler and peak loads can be met using subsidiary boilers. Another advantage of using several boilers is that they can be placed strategically around the site to reduce the length of the heat distribution pipework, consequently reducing energy-transmission losses. Systems should be engineered to ensure that boilers that are not operational are automatically isolated to prevent heat losses.

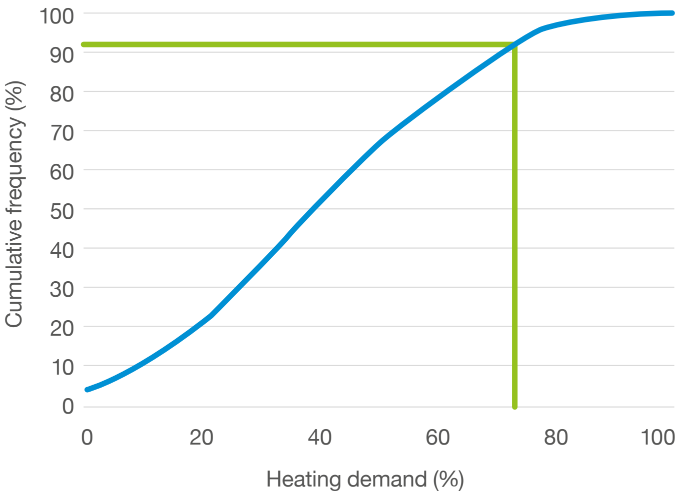


Figure 7. Simulated relationship between heat demand and frequency

## Air heaters

From the perspective of energy efficiency, the use of air heaters in greenhouses (Figure 8) offers some advantages over hot-water piped systems.

- Systems involving air heaters have a low thermal inertia and show rapid temperature response. This is in contrast to piped systems where heating response times of 20 minutes or more are normal. All of the products of combustion (including heat and $CO_2$) are delivered directly into the greenhouse atmosphere
- Positive air movement, associated with air heaters, can be helpful in combating diseases, and capital costs of heaters tend to be relatively low

On the other hand, air heating systems have a number of disadvantages:

- Temperature distribution tends to be uneven, especially when large temperature lifts are required in large greenhouses. Ducting systems are needed to ensure satisfactory air and temperature distribution, but light loss problems will be encountered unless the ducts can be accommodated at floor or bench-level, or under the gutters

- Without regular maintenance, fuel combustion can become inefficient and there can be a build-up of injurious aerial pollutants (see section on $CO_2$ burners, page 29). Water vapour is also produced during combustion and this can raise humidity levels and encourage disease spread
- Heating and $CO_2$ supply cannot be uncoupled (see section on $CO_2$ burners, page 29)
- There is no associated radiant heating

Figure 8. Air heater in use in a propagation house

## Lagging

As Figure 9 shows, uninsulated pipework can waste considerable energy. Insulation should be applied to all warm surfaces, including pipes, flanges and valves for hot water, the boiler casing and heat store. Depending on the type and thickness of insulation applied, heat loss is typically reduced by more than 90%, with payback periods typically being less than two years. As an example, the heat loss from 100 m of uninsulated 100 mm bore pipe, carrying hot water at 80°C, will be 260 W/m. Assuming year-round heat transmission and a gas boiler operating at 80% efficiency, this energy loss will equate to an annual cost (at 2.5p/kWh) of £7,115. However, by insulating the pipe with 63 mm of glass mineral fibre insulation, the heat loss will be reduced to 18 W/m and the annual cost will fall to £492. This represents an annual saving of £6,623 and, with installation costs of around £3,000, the payback period will be less than six months.

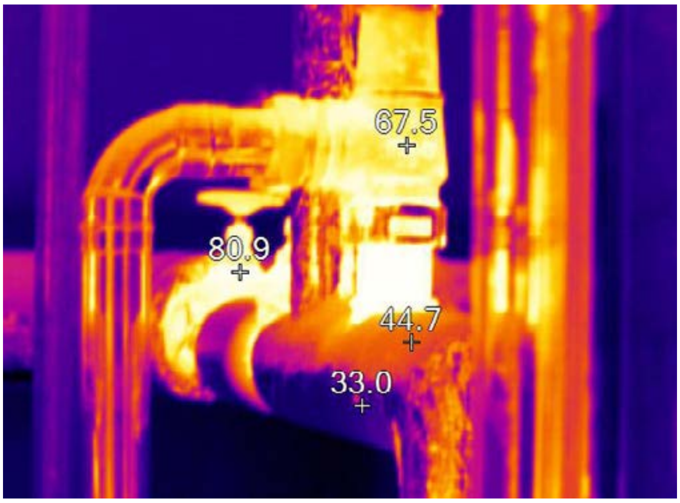


Figure 9. Thermal image of heat loss from uninsulated piping

All hot surfaces lose heat and attention must be paid to the valves and flanges that are often left uninsulated for maintenance reasons. An uninsulated valve (Figure 9) loses about the same amount of heat as a metre of uninsulated pipe of the same diameter. Uninsulated flanges, which have a smaller surface area, lose about half this amount. A variety of materials are available for insulating hot surfaces, as shown in Table 1. These should comply with the requirements of BS 5970. Straight pipework is normally insulated using preformed lengths of insulating material that are then secured in position by the use of metal bands or a suitable high-temperature tape. External pipework must be weatherproofed to prevent the insulation material absorbing moisture and losing its insulation properties. Valves are best insulated using flexible jackets, secured in position with quick-release fixings.

Table 1. Approved insulation materials and applications

| Insulation material | Maximum temperature (°C) | Application |
|---|---|---|
| Glass mineral fibre, aluminium foil faced, preformed | 230 | Internal pipework and surfaces |
| Glass mineral fibre, aluminium clad | 230 | Internal pipework and surfaces exposed to potential damage, or external pipework and surfaces open to the weather (with joints sealed) |
| Rock mineral fibre, aluminium foil faced, preformed | 830 | Internal pipework and surfaces |
| Rock mineral fibre, aluminium clad | 830 | Internal pipework and surfaces exposed to potential damage, or external pipework and surfaces open to the weather (with joints sealed) |

Figure 10 shows an example of the use of flexible insulation jackets. BS 5422 specifies the recommended thickness of insulation depending on the pipe size, service temperature and application and an example of the guidance given is shown in Table 2. It should not just be assumed that existing insulation is already providing optimal energy savings, since, in many cases, thicker insulation could be well justified. This is particularly the case when insulation has become damaged and/or wet.

Table 2. Recommended insulation thickness (based on the Carbon Trust Implementation Guide CTL038)

| Pipe diameter (mm) | Service temperature (ºC) | Recommended thickness (mm) |
|---|---|---|
| 32 | 75 | 38 |
| 32 | 100 | 54 |
| 100 | 75 | 46 |
| 100 | 100 | 64 |

Figure 10. A good example of how flexible jackets can be used to insulate pumps and valves

## Key points for good housekeeping

- Energy saving in protected cropping starts with good housekeeping. Regular equipment maintenance and making essential repairs without delay can reduce energy use by up to 10% for little or no capital outlay
- It is helpful to have someone in the organisation with specific responsibility for energy issues. Staff training in energy matters can be very beneficial
- Energy-use data, preferably using submetering, should be assessed at least once each week. This will give a detailed insight into factors affecting energy use. Ideally, energy data should be compared alongside greenhouse climate data, weather data and cropping information. If possible, benchmark performance against that of other growers
- Degree day analysis is a simple but effective technique that is useful in studying comparative energy use (between years, glasshouse units, growers, etc.)
- Control equipment, including measuring boxes, outside weather stations and $CO_2$ sensors, should be regularly maintained and calibrated. A measuring box giving a reading 0.5°C lower than it should can increase the annual greenhouse energy cost by around £5,000/ha
- Single glazing is still the industry standard for greenhouse cladding, and thermal screens generally provide a better option for reducing heat loss than double glazing. Double screens are now a commercially viable option and an important part of ‘Next Generation Growing’. The use of ETFE as a cladding material is being considered by some
- Diffuse glass can increase efficiency in transmission of solar radiation, producing better crop performance and yield
- Air leakage can account for 5–30% of instantaneous greenhouse heating demand, and energy efficiency can be improved in older structures by sealing the gaps between panes of glass and by fitting seals to greenhouse doors and ventilators. Once the glasshouse has been well insulated, air movement can be improved with the use of fans
- Windbreaks will reduce heat loss from the greenhouse, particularly under windy conditions
- The glazing and screens should be kept clean, inside and out. In tomato production, a 10% increase in light transmission has been predicted to result in a 2% reduction in energy use and an 8% improvement in energy-use efficiency
- Boiler upgrading has considerable energy-saving potential. The most efficient designs of boilers with condenser units can achieve seasonal efficiencies close to 90%. This compares to around 80% for modern boilers without a condenser and less than 70% for older boilers (20+ years old)
- It can be more energy-efficient to install a number of smaller, localised heating systems rather than a single, large central boiler. This will improve boiler-use efficiency and reduce energy-transmission losses
- Air heaters have some limited advantages over piped hot-water heating systems, such as speed of response and slight efficiency gains. However, heat distribution can be very uneven
- Insulation applied to pipes, flanges and hot-water valves, the boiler casing and the heat store will typically reduce heat losses by more than 90%, with a payback period that is typically less than two years

# Horticultural lighting

This section discusses the energy implications of using horticultural lighting and considers how energy inputs can be minimised while still maintaining plant yield and quality (Figure 11).

Figure 11. Horticultural lighting – minimising energy inputs while maintaining plant yield and quality

## Background

Artificial crop lighting is used in protected horticulture to supplement natural solar radiation (supplementary lighting) and to regulate the flowering of photoperiodic crops (photoperiod lighting).

Supplementary lighting is used mainly during the late autumn, winter and early spring when average solar radiation levels are low (Figure 12). It increases plant photosynthesis and, as a consequence, growth, yield and product quality. As a generalisation, 1% extra light gives around 1% extra crop dry weight.

Supplementary lighting can increase the speed of cropping and can help with crop scheduling. By enabling plants to be more closely spaced, it can further increase crop throughput. In the edibles ssector, supplementary lighting can be used to extend the production season.

Low-irradiance, photoperiod lighting is used to keep short-day plants (SDP) such as chrysanthemums and poinsettias vegetative and to promote the flowering of long-day plants (LDP). It can also be used to promote plant growth (weight increase), as reported in the Defra project HH3603SP.

Defra report AC0401 (2007) indicates that lighting in protected cropping accounts for around 122 GWh of energy use – only around 2.3% of the sector's total consumption. Nevertheless, for an individual grower, this usage can amount to 15% or more of their 'delivered' energy consumption. For such growers, reducing the energy input of lighting, while still maintaining yield and quality, is an important objective.

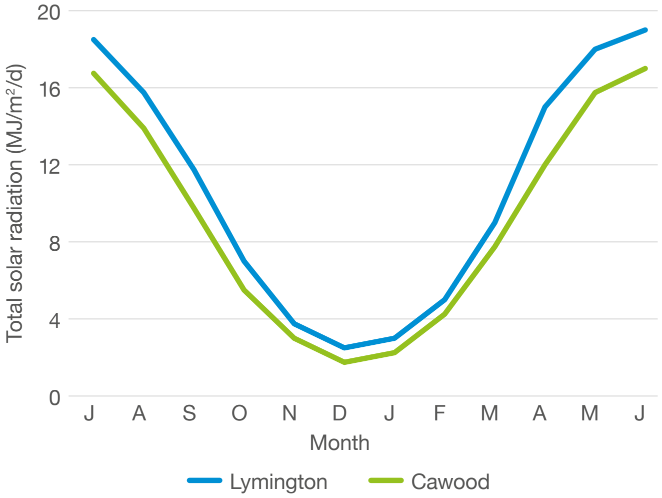


Figure 12. Average daily integrals of total solar radiation measured outdoors at a southerly (Lymington, Hampshire) and a northerly (Cawood, N. Yorkshire) UK location

## Units and measurement

### Solar radiation and PAR

It is the photosynthetically active radiation (PAR) component of solar radiation and lamp emissions that is important for plant growth, since this determines photosynthetic activity. PAR comprises radiation with wavelength between 400 and 700 nanometres (nm) and constitutes about 45% of total solar radiation (Figure 13). Highly efficient horticultural lamps will deliver a high proportion of their total light output as PAR.

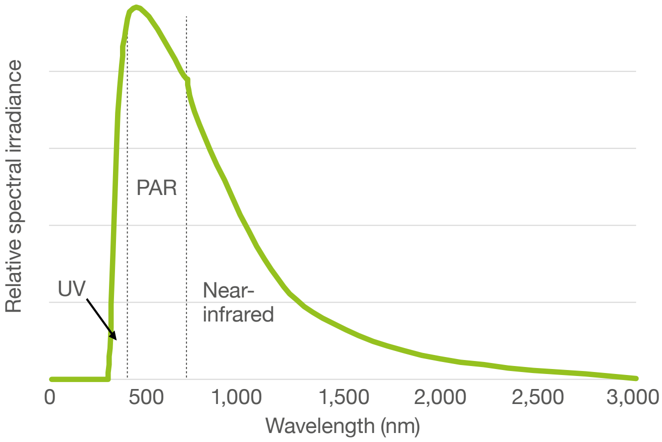


Figure 13. Irradiance spectrum of solar radiation as transmitted into the glasshouse

PAR can be measured directly in energy terms using a PAR energy sensor as watts per square metre ($W/m^2$ PAR). PAR can also be measured in photon terms using a quantum sensor as micromoles per square metre per second ($\mu mol/m^2/s$ or $\mu mol\ m^2\ s^{-1}$). This is called the photosynthetic photon flux density (PPFD) and is often preferred because plant photoreceptors are responsive to the number of photons/quanta, rather than their energy content. Since a quanta of blue light contains more energy than a quanta of red light, conversions between PAR $W/m^2$ and PPFD $\mu mol/m^2/s$ depend on the particular spectral emissions of the light source in question (see Table 3).

Both W/m$^2$ and μmol/m$^2$/s represent instantaneous PAR values, and both can be summed over time to give PAR integrals (e.g. MJ/m$^2$/d or mol/m$^2$/d). The solar radiation integral and the PAR radiation integral can also be expressed in kilowatt hours (e.g. kWh/m$^2$/d).

### Lux

Lux is a measure of how bright a light source appears to the human eye (illuminance) and is an inappropriate measure of lighting in commercial horticulture. Light sensors that measure in lux give much greater weight to green/yellow light than to PAR and give a misleading indication of the potential value of a light source for plant growth.

### Conversions

As shown in Table 3, conversions between W/m$^2$, μmol/m$^2$/s and lux depend on the particular spectral emissions of the light source in question. However, even these conversions must be treated with caution since there can be significant differences in the spectral output of lamps of a particular type (see later in relation to HPS lamps designed specifically for use in horticulture). The PAR (or PPFD) output of a lamp is now often quoted by manufacturers.

Table 3. Multiplication factors to convert from PAR W/m$^2$ to μmol/m$^2$/s PPFD and lux (Adapted from Thimijan and Heins, 1983, & Nelson and Bugbee, 2014)

| Light source | μmol/m$^2$/s per W/m$^2$ | lux per W/m$^2$ |
|---|---|---|
| Daylight | 4.57 | 249 |
| High-pressure sodium (HPS) | 4.98 | 408 |
| Metal halide (MH) | 4.59 | 328 |
| Warm-white fluorescent | 4.67 | 356 |
| Incandescent | 5.00 | 251 |
| LED – cool white | 1.52 | 111 |
| LED – red | 1.72 | 47 |
| LED – blue | 1.87 | 17 |

## Supplementary lighting

Supplementary lighting is, essentially, top-up lighting and it is important to ensure that natural, solar radiation levels in the glasshouse are as high as possible. Dirty cladding materials can reduce the light transmitted into the greenhouse by as much as, or more than, that provided by supplementary lighting (see page 7). It makes sense, therefore, to ensure that the glass is regularly cleaned, inside and out. Supplementary lighting installations will, themselves, have a shading effect on the crop and this needs to be taken into account at the system planning stage (see 'Minimising shading' overleaf). Information on lamps, luminaires (the lamp fittings), reflectors, etc. is provided in AHDB Horticulture project PC 176 and technical guide ***Supplementary lighting: Equipment selection, installation, operation and maintenance***.

### Lamps and ballasts

High-pressure sodium (HPS) lamps are still in common use (Figure 14); their popularity remains because they are relatively cheap to purchase and run, and specialised horticultural versions are available with excellent lamp efficiency (μmol/s per input watt or μmol/s/W).

Figure 14. High-pressure sodium (HPS) lamps – cheap to purchase and run

HPS works by generating an electrical arc between two electrodes that are mounted inside the glass envelope of the lamp. The colour of the light produced, and therefore its spectral distribution, is a function of the metallic compounds within the plasma of the arc.

In order to operate, HPS lamps need to be used in a fitting (known as a luminaire) that houses a number of electrical or electronic components. These components stabilise the electrical current passing into the arc. Collectively, these components are commonly called the ballast.

However, recent years have demonstrated that while HPS still has a place, LED lighting is becoming ever more popular. This could be because of its lower infrastructure requirement for new installations, its efficiency and its ability to be tailored to individual plant requirements. Not all LED lights are equal though. Studies conducted under AHDB Horticulture project CP 139 demonstrate that different LEDs have different efficiencies – some worse and some better than equivalent HPS lamps. The results of the tests are provided in Table 4 (overleaf), which presents the ranges of outputs and results for five LED lights and a plasma light against an HPS benchmark. Plasma lights have a whole-spectrum output closely matched to the solar spectrum, which may appeal to some growers.

Three of the tested LEDs are more efficient at producing PAR than the benchmark HPS, whereas two LEDs and the plasma are less efficient. However, and particularly in the case of the plasma, the spectral output of the lights must be taken into consideration.

Table 4. Typical lamp efficiencies based on test data (CP 139, appendix one)

| Lamp | PAR efficiency (µmol/J) | Power factor |
|---|---|---|
| HPS | 1.92 | 0.81 |
| LED 1 | 1.44 | 0.96 |
| LED 2 | 1.27 | 0.92 |
| LED 3 | 2.43 | 0.97 |
| LED 4 | 2.71 | 0.99 |
| LED 5 | 2.56 | 0.98 |
| Plasma | 1.16 | 0.98 |

For a more comprehensive understanding of LED lighting, it is advisable to read CP 139 available from **horticulture.ahdb.org.uk**.

## Lamp replacement policy

As the total operating time of a lamp increases, so its light output falls and the likelihood of failure increases. Typically, the output of a 600 W HPS lamp will fall by 6–10% after 10,000 hours of operation and by 18% or more after 20,000 hours. The decline might not be obvious to the human eye, but plant quality and yield will progressively suffer.

Lamps should be changed after around 10,000 hours of use and delaying the change cannot be justified on economic grounds. This optimum timing may vary slightly with different lamp types.

For a chrysanthemum grower, the 10,000 hours probably represents around 5–6 years of lamp use, and for a tomato grower, 3–4 years of use. For maximum efficiency, lamp running hours should be tracked and light fall-off should be monitored by taking spot readings under the lamps at plant height using a PAR meter. Light output is sensitive to voltage supply and a 1% voltage reduction can give a 2.5–3% reduction in PAR.

## Reflectors and uniformity of lighting

Efficient reflectors (Figure 15) are vital to direct light down from the lamps to the plants below. Light that fails to reach the plants is wasted lamp output. The light should also be uniformly distributed over the crop to avoid uneven growth and variable quality. High-wattage lamps typically need to be mounted higher above the crop in order to ensure uniformity of lighting. ‘Wide’ or ‘extra-wide’ beam reflectors (Figure 15) should be used when the mounting height is below 2.5 m to help prevent high irradiance ‘hot spots’ directly under the lamps and low irradiances between the lamps. Wide-beam reflectors should not be used with high-mounted installations since they will waste energy by giving too much light scatter.

With age, reflectors tend to become coated with spray deposits and dirt and surfaces become oxidised. This can be as detrimental to PAR reaching the crop as lamp ageing. To avoid this, reflectors and lamps should be regularly cleaned. As a rough estimate, a 2.5% reduction in light can be expected for each year that the lamps and reflectors are not cleaned. To help prevent dirt build-up, reflectors and lamps should be removed from the luminaires when the lighting is not in use.

Reflector replacement or re-anodising (as appropriate) should be considered every four to five years. Re-anodising currently costs around £10 per reflector and the payback period will be around 1.5–2.5 years. As an alternative, some manufacturers also offer replacement reflectors made from high-reflectivity materials and claim that these reduce light losses by up to 5% when compared with re-anodised reflectors.

Figure 15. Standard (left) and wide-beam (right) reflectors

## Electrical input – PAR output

Although HPS lamps designed for use in horticultural applications are more efficient than older designs in converting electrical energy to PAR, energy losses are still large. Overall, from an electrical consumption of 635 W, a 600 W lamp with an electronic ballast running on 400 V will give a PAR lighting efficiency of, at best, 36%. The remainder will be dissipated into the glasshouse as heat and this will offset heating costs.

## Minimising shading

The lamps and luminaires will, themselves, have a shading effect on the crop and this needs to be minimised. Older-style, iron-core ballasts are best located away from the lamps, at low level or under the gutter. Electronic ballasts are far more compact and cause much less shading. It is even possible with modern units to remove the lamps, reflectors and electronic ballasts in order to reduce shading when the lights are not in use (see Figure 16 overleaf). Care needs to be taken to avoid obstructions between the lamps and the plants since heating pipes, irrigation lines, screen mechanisms, etc. can easily result in 3–5% light losses.

Figure 16. If at all possible, remove the lamp, reflector and electronic luminaire in summer to reduce crop shading

## Lighting strategies

Care has to be taken to ensure that best use is made of supplementary lighting and that energy is not wasted. The study undertaken in AHDB Horticulture project PC 128 was conducted to explore the relative effects of different lighting strategies based in bedding plant plug production; the conclusions can be applied more generally.

Benefits of supplementary lighting were greatest when background light levels were low. Thus, lighting at 9.6 W/m$^2$ (48 µmol/s) PAR in November/December increased the average dry weight of four species by 54%. However, lighting in March and May increased dry weight by only 11–12% (Figure 17). Clearly, lighting should only be applied when commercial benefits exist.

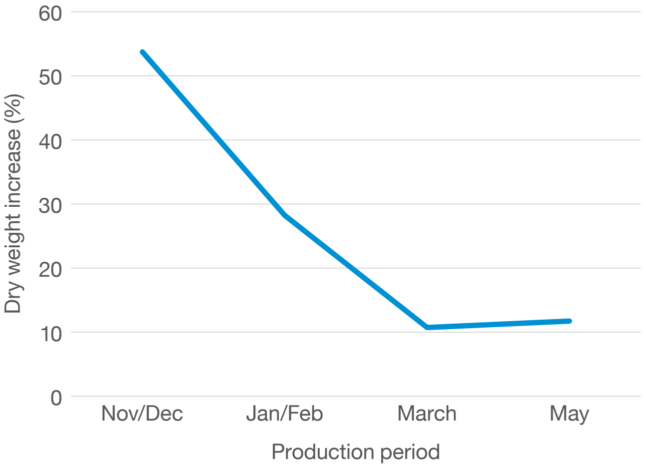


Figure 17. Effects of time of year on dry weight increase of plug plants of four bedding plant species (petunia, pansy, geranium and impatiens) lit at 9.6 W/m$^2$ (µmol/s) PAR (PC 128)

Lighting during the final phase of plug production had far more effect than lighting earlier. This was because the leaf area was larger during the final weeks and light interception was improved. Lighting during the final two weeks of production was more beneficial than lighting in the final week alone at twice the light level. This reflects the non-linear nature of the growth response as the light level is increased towards the light saturation point.

Supplementary lighting was particularly beneficial when applied so as to increase the daily photoperiod to 16 hours. When the natural day length was eight hours, supplementary lighting gave greatest benefits when given as a day extension (or immediately before daylight). However, an important point to bear in mind is that some species, such as tomato, react badly to being lit continuously. It is generally best to give several hours of darkness in each 24-hour cycle.

Supplementary lighting on plugs resulted in plants that flowered earlier after the plug was grown on.

A key decision relating to supplementary lighting, and the one with the biggest influence on energy use, is choice of lighting level. In AHDB Horticulture project PC 092d doubling the irradiance of supplementary lighting from 4.8 W/m$^2$ (24 µmol/s) to 9.6 W/m$^2$ (48 µmol/s) was shown to hasten marketing by two to three days and increased bud and flower numbers. Ornamental crops are frequently lit at around 10 W/m$^2$ (50 µmol/s) PAR, but levels for edible crops can be very much higher. In essence, this has to be decided by cost-benefit analysis, taking account of retail requirements and returns. The beneficial effects of supplementary lighting will decline as solar radiation levels increase. It is a good idea, therefore, to set an outside light level above which the supplementary lighting will no longer operate.

Plants respond to the total PAR integral to which they are exposed. It makes sense, therefore, to set supplementary lighting levels in relation to geographical location.

As noted in project AHDB Horticulture project PC 092e for pot chrysanthemums stuck in week 45, supplementary lighting needs to be given at 12.4 W/m$^2$ (62 µmol/s) PAR at Kirton (Lincolnshire) to give the same total PAR (and, presumably, quality) as that at Lymington (Hampshire) with supplementary lighting at 4.8 W/m$^2$ PAR.

## LED lighting

LED lamps work by passing electricity through a semiconductor, which releases energy in the form of photons. Originally invented in 1927, LEDs have only relatively recently received significant commercial interest. Like many electronic and semiconductor technologies, the recent rate of development of LEDs has been rapid. Efficiency and cost improvements have accelerated the commercial uptake of LED lighting.

Individual semiconductors emit monochromatic light. The wavelength emitted depends on the chemical composition of the semiconductor. To generate white light, various methods can be employed. Commonly, LEDs emitting certain wavelengths (red, green, blue, etc.) are mounted in an array; the light emitted by each blends together to generate white light. An alternative is to coat a short-wavelength-emitting LED in a particular chemical (phosphor). Some of the blue light is converted to yellow, which, when mixed with remaining blue light, produces white light. Commercially available horticultural LED lights could use either of these two approaches to produce a required spectrum.

A characteristic of LED lights is that they radiate little heat within the light beam. This allows them to be placed very close to leaves without causing scorching and this can be an advantage if used, for example, for inter-row lighting of high-wire edible crops. However, the process of electroluminescence is still relatively inefficient and wasted energy is converted into heat. This heat energy warms the semiconductor and reduces the efficiency of the light production.

LED light output decreases with operating temperature. Manufacturers typically quote efficiencies at 25°C, but the actual semiconductor temperature can warm to between 60 and 80°C. These higher temperatures can give losses of >10%. Large-scale LED arrays, as used for horticultural purposes, are therefore designed with large heat sinks to remove heat from the semiconductors. They may well have fan-assisted ventilation systems or even be water-cooled.

All LED lighting systems operate using DC current, but nearly all greenhouse electrical systems operate off AC-driven power systems. Within the luminaire, the electronics will therefore include an AC to DC rectifier. The power conversion process from AC to DC can lead to some energy losses of up to 7%, depending upon the system applied.

LEDs produce far less radiant heat than HPS, so care must be taken when using them as an HPS replacement. The radiant heat from HPS heats the crop, and studies have shown HPS lighting maintains a warmer crop leaf temperature than LED lighting with the same light output. Around 65–70% of the total electrical energy used to power HPS lamps is dissipated into the glasshouse as heat and this makes an important contribution in offsetting direct heating costs. It can be estimated, for example, that a correctly configured supplementary lighting installation over an ornamental crop will contribute the equivalent of around 60 kWh/m$^2$/year of heating.

In some Dutch studies, higher air temperatures have been used to compensate for the reduced radiant heating. This additional heating must be considered when examining the overall energy efficiency of an LED system compared to HPS, including the suitability of increased air temperature to substitute for the direct radiant heating effect of HPS lamps on plant tissues.

Also, consideration must be given to the heating arrangement used in the greenhouse to ensure that any additional heat can be effectively supplied to the crop. From a cost perspective, heating energy generated by boilers tends to be cheaper per kWh than electricity.

AHDB Horticulture project CP 139 compared seven different commercially available LED, plasma and HPS lighting systems. The project provided independent results on how performance varied between examples of current commercial horticultural lighting hardware.

Tailoring LED light to maximise growth, improve habit, change colour and flavour or control the flowering time of individual species is done to improve efficiency and make fittings cost-effective. These are often called ‘light recipes’ and are specific to plant types. It is also possible, by incorporating differently coloured LEDs on a single array, to change the light-quality environment over the course of a day. The amount of light released by individual LEDs can be adjusted to manipulate crop morphology at different stages of development or control the habits of different crops at different lighting requirements (Figure 18 and Figure 19). AHDB Horticulture projects CP 085 and CP 125 looked at plant responses to LEDs and the underlying biology that governs them.

Figure 18. LED lighting in edible crops

Figure 19. LED lighting in ornamental crops

# Photoperiod lighting

## Control of flowering

Day length is used by many plants to regulate flowering time, and photoperiod lighting can be used to promote flowering in long-day plants (LDP) and to delay or prevent flowering in short-day plants (SDP). It is the duration of darkness that is critical in determining the photoperiodic responses of many SDP. For these, therefore, breaking up a long night into two short dark periods using night-break (NB) lighting will cause the plants to respond as though they are growing in long days. NB lighting is often most effective when given around eight hours after the start of darkness.

Flowering in SDP can also be delayed or prevented by using day-extension (DE) lighting. However, NB lighting is usually more cost-effective than DE lighting. To give a long day (16 hours) in winter by DE lighting, for example, would mean lighting for up to an extra eight and a half hours, while as little as a few minutes of light are adequate as a NB for many SDP. Some SDP do need longer NB periods; the chrysanthemum, for example, requires several hours of light and, typically, NB periods of around four hours (at around 0.4–0.5 W/m$^2$ PAR using tungsten lamps) are the norm.

LDP similarly tend to require several hours of NB to promote flowering. In these cases, therefore, the benefits of NB lighting over DE lighting are not so clear-cut.

AHDB Horticulture project PC 296 assessed the suitability of alternative lamps to tungsten for photoperiod lighting in several ornamental crops. The project investigated the flowering responses to compact fluorescent (CF) light quality and quantity and examined the suitability of LEDs as an energy-saving alternative to tungsten in photoperiod manipulation. The study found that:

- Flowering and/or tuber formation in chrysanthemum, poinsettia, begonia and fuchsia was controlled as effectively by CF lighting as it was by tungsten lighting. However, for antirrhinum, Christmas cactus, lisianthus, pansy and petunia, the light spectrum from CF lamps did not match that from tungsten lamps well enough to control flowering successfully
- Deep red, white and far-red LED flowering lamps were able to control flowering and/or tuber formation as effectively as tungsten in chrysanthemum, poinsettia, begonia, antirrhinum, lisianthus, pansy and petunia. However, for Christmas cactus, none of the flowering lamps were able to control flowering to the same extent as tungsten lamps
- Although each species had a subtly different optimum, combinations of red and far-red LED modules were effective at controlling flowering and/or tuber formation for all of the species tested

## Enhancement of growth

DE lighting has been shown to promote dry weight increase (Defra project HH3603SPC). For example, Figure 20 shows average increases in fresh weight given by lighting plugs of six bedding plant species for 16 h/day using either compact fluorescent lamps (0.5 W/m$^2$ PAR) or HPS lamps (8.6 W/m$^2$ PAR). The fluorescent lighting enhanced growth by around 10% on average and this effect was principally due to increased photoperiod since there was little increase in daily light integral (DLI). The HPS lighting enhanced growth by around 30% and this was due to increases in both photoperiod and daily light integral. Thus, photoperiodic long-day lighting using compact fluorescent lamps gave around one-third of the benefit of supplementary lighting but with only a fraction of the energy use (1/20th under the particular conditions of this experiment). The benefits of long-day lighting were greatest early in the year when background solar radiation levels were low.

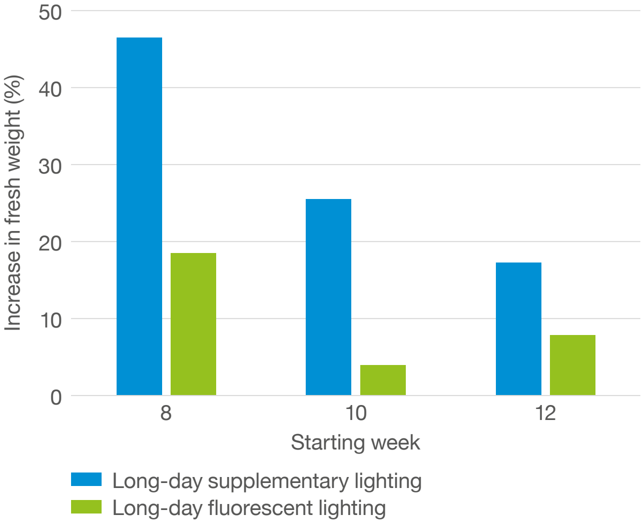


Figure 20. Average increases in fresh weight given by long-day lighting during plug production of six bedding plant species: supplementary lighting at 8.6 W/m$^2$ PAR and fluorescent lighting at 0.5 W/m$^2$ (HH3603SPC) lamps

## Lamps

Light levels for photoperiod lighting are typically much lower than for supplementary lighting. The most commonly used bulb has been the 100 W or 150 W tungsten (incandescent) bulb. This was because tungsten bulbs were effective and cheap, in spite of their tendency to cause plant stretching. However, European legislation has led to a gradual phase-out of tungsten bulbs due to their inefficient use of electricity. There are several alternative options, the most popular being compact fluorescent lamps (Figure 21) or LEDs (Figure 22). Ensuring the plants receive a similar level of PAR is the main criterion.

Because PAR levels have to be maintained, the replacement of tungsten bulbs by compact fluorescent lamps is not straightforward. Compact fluorescent lamps rated at 20 W may be equivalent to 100 W tungsten bulbs in terms of what the human eye perceives (lux), but they are not equivalent for plants.

To give a similar PAR output, a 100 W tungsten bulb would have to be replaced by two 15 W compact fluorescent bulbs. Furthermore, while tungsten lamps can be cycled for energy saving (often halving the number of hours that they are 'on'), this is discouraged when using fluorescent lamps. This means the hours of operation increase and, pro rata, increase the energy use. Overall, replacing tungsten bulbs with compact fluorescent lamps improves energy efficiency, but festoons need to be modified.

Chrysanthemum growers tend to use HPS lamps for supplementary lighting and it is more cost-effective to use these for photoperiod NB lighting rather than switch to compact fluorescent lamps. In the Netherlands, HPS lamps are frequently used for this purpose, with a third or a half of the lamps lit at any one time. Growers regularly rotate the groups of lamps used for lighting to ensure crop uniformity and to prevent uneven lamp ageing. In general, the duration of NB lighting that is needed to ensure effectiveness decreases as the intensity of lighting increases, and Dutch researchers have shown that periods as short as eight minutes can be effective if light levels are high enough. Nevertheless, most Dutch growers light with HPS lamps for four hours.

Red light is usually the most effective for the prevention of flowering in SDP. However, the situation appears more complex for LDP. Some species respond to green, yellow and red light, while others are sensitive to blue and far-red. It may be that for some species the optimal light quality for NB treatment is different from that for DE lighting. For a number of LDP (and a few SDP), a mixture of red and far-red light has been found to be more effective than red light alone. Tungsten lamps are rich in both red and far-red and work well because of this.

Alternative lamps with different spectral outputs may be less effective; fluorescent lamps, for example, have been shown to have only a limited effectiveness for some LDP. LED lighting arrays may provide a better alternative to fluorescent lamps.

Figure 21. Compact fluorescent lamps can be effective sources of photoperiod lighting for some species

Figure 22. LEDs can manipulate the light spectrum to control flowering time

## Key points for horticultural lighting

- Supplementary lighting for a lit crop can account for 15% or more of a grower's total 'delivered' energy
- Light measurements can be variously quoted as lux or PAR (photosynthetically active radiation) W/m$^2$ but could more accurately be given in terms of photosynthetic photon flux density (PPFD), which is more representative of plant response to light. The units of PPFD are μmol/m$^2$/s
- Until recently, the high-pressure sodium (HPS) lamp was the first choice for supplementary lighting. However, recent developments with light-emitting diodes (LEDs) are making the choice more difficult. HPS still retains the majority of the market, with some growers choosing a combination of HPS and LEDs
- HPS 600 W and 1000 W lamps are more energy-efficient than 400 W lamps but typically need to be mounted higher. Reflectors should be chosen in relation to lamp wattage and mounting height. Regular cleaning will optimise output. Lamps need to be replaced after about 10,000 hours of operation
- LEDs are highly electrically efficient and can produce light in defined spectral outputs. Growers must match lamps with their specific requirements and investigate the options available in a fast-moving marketplace
- Crop shading needs to be minimised. Electronic ballasts are more compact than switch-start ballasts, more efficient and create less heat than these conventional fixtures. If it is practical, remove lamps and reflectors in summer. Avoid obstructions between the lamps and the plants and regularly clean the greenhouse glass, inside and out
- Supplementary lighting is most beneficial when natural light levels are low. Operating times should, whenever possible, be chosen so as to give a long daily photoperiod. Settings should be used to turn the lighting off when outside light levels are high
- Photoperiod lighting to control flowering is usually most cost-effectively given as a night-break (NB) rather than as a day-extension (DE). However, photoperiod lighting can also enhance dry weight and, in this case, DE lighting is more beneficial
- Energy-intensive tungsten (incandescent) bulbs have been phased out from 2009. Replacement with energy-efficient light bulbs such as compact fluorescent (CF) lamps can be 80% more efficient than tungsten lamps. However, these need to deliver similar levels of PAR, and direct lamp replacement may not be possible. Fluorescent lamps have only a limited effectiveness in promoting flowering in some long-day plants

# Humidity control

Controlling humidity can be expensive in energy terms, yet it is essential for the control of fungal disease and to ensure active plant growth. Humidity control also needs to be carefully targeted so as not to negate the energy savings from measures such as temperature integration (TI) and thermal screens. This section focuses on the twin requirements of effective humidity control and energy saving.

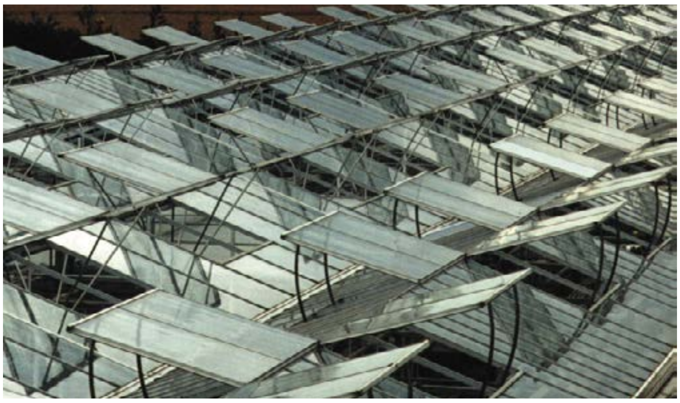


Figure 23. Venting results in energy loss but is an essential element in humidity control

## Background

The atmospheric humidity in the glasshouse is a measure of how much water vapour is contained within the air. When levels of water vapour are very low (low humidity), plants experience water stress, their stomata close and growth is reduced. However, much more frequently there is a high level of water vapour in the glasshouse air (high humidity). High humidity promotes fungal infection and this tends to increase the incidence of disease caused by pathogens such as *Botrytis* (*Botrytis cinerea*) and *Didymella*. High humidity also reduces plant transpiration and, if such conditions persist, calcium transport in the plant slows and growth may be depressed. Controlling humidity is, therefore, essential for active plant growth and to keep fungal disease in check. However, the control of humidity can be expensive in energy terms and an important element in good energy management is the adoption of measures that are effective in keeping humidity under control but which are, at the same time, energy-efficient. Humidity control also needs to be carefully targeted so as not to negate the energy savings from measures such as temperature integration (TI) and equipment such as thermal screens (see pages 37 and 24).

## Humidity measures

Air carries water vapour. How much water vapour the air can carry depends on its temperature, and the amount of water it actually contains is termed its humidity.

The two measures of humidity most commonly encountered in glasshouse production are ‘relative humidity’ and ‘humidity deficit’. There are pros and cons associated with both of these and the best option for humidity control may be to use a combination of the two. However, this is not always possible in practice. Other measures that are used and important to understand are absolute humidity (AH), vapour pressure deficit (VPD) and dew point.

### Relative humidity (RH)

This is a measure of the moisture content of air, relative to that of saturated air (i.e. air with the maximum amount of water it can hold) at the same temperature. If, for example, the air has an RH of 50%, it contains one half of the moisture content of saturated air of the same temperature (saturated air would have an RH of 100%). The water-vapour-holding capacity of the air is affected by temperature; while a cubic metre of air at 25°C is able to hold 23.9 g water vapour at saturation point (100% RH), it will only be able to hold 12.9 g at 15°C. Thus, if air at 25°C and 50% RH (holding 12 g water vapour) is reduced in temperature to 15°C, it will be close to saturation point. RH tends to be the humidity measure of choice for most growers of ornamental crops and is thought to be a good indicator of disease risk.

### Absolute humidity (AH)

Before considering humidity deficit (HD), it is important to understand the concept of absolute humidity.

Absolute humidity is a physical measure of how much water there is in a fixed volume of air in grams of moisture per kg or per $m^3$ of moist air. In the example given above, air at 25°C and 50% RH contains 12 $g/m^3$ of water; this value is its absolute humidity. As absolute humidity is given in these terms, it does not change with temperature, thus if air contains 12 g of water at 25°C and is warmed to 30°C it will still contain 12 g of water. Its relative humidity would have changed but its absolute humidity would not. Absolute humidity will change if water is removed from air (dehumidification) or added to air (humidification). Similarly, mixing two sources of air with different absolute humidities will result in mixed air with a different water quantity.

### Humidity deficit (HD)

This is a measure of ‘the drying power of the air’ and indicates how much more moisture a sample of air can hold before it becomes saturated. In mathematical terms, the humidity deficit is a calculated value given by the maximum water the air can contain at that temperature (saturation point) minus the air’s absolute humidity; i.e. HD ($g/m^3$) = water quantity at saturation point ($g/m^3$) – AH ($g/m^3$).

A HD of 2.6 $g/m^3$, for example, means that each cubic metre of glasshouse air can take up a further 2.6 g of water. HD can be a key determinant of transpiration and values of 2.25 $g/m^3$ and above are generally regarded as being ideal for the promotion of active plant transpiration. Given the importance of this to growth and yield, HD has become the humidity measure of choice for most growers of edible crops. However, HD may not be as good an indicator of disease risk as RH.

## Conversions between RH and HD

While a given HD will have much the same influence on transpiration regardless of temperature, this is not the case with RH. Air at 70% RH, for example, will be able to accept much more water vapour at 20°C than at 15°C. Thus the relationship between HD and RH is strongly influenced by temperature, as is evident in Tables 5a and 5b, which show conversions between the two measures.

## Vapour pressure deficit (VPD)

VPD is similar to HD in concept but its units are different. VPD is given in units of pressure – pascals and commonly kPa to make it more manageable. It can be useful to consider VPD because the transpiration of plants depends on their ability to release water, which is determined by the vapour pressure in the surrounding air. When the VPD is at zero, the air is considered fully saturated and unable to contain any more water. In plant terms, this means they are unable to transpire, and it is held that at a VPD value below 0.2 kPa, plants will be unable to transpire and there is a high risk of condensation. A high VPD (anything above 1 kPa) means that the air can potentially hold a lot more water, so the difference between the air and the plant (considered to be 100% saturated) is great, meaning the plant will be able to transpire and cool itself. Ideal VPD values differ with growth stage and crop, but safe values are between 0.2–1.5 kPa. If VPD is too high – greater than 2.0 kPa – the air is too dry. These conditions can cause plants to try to stop excessive water loss by curling leaves, closing stomata and reducing $CO_2$ uptake.

## Dew point

The dew point is not a humidity measure as such but, rather, the temperature at which air is saturated with water. At dew point, air can no longer hold the water vapour, so it condenses into liquid on solid surfaces or particles which are colder than the air. Air at dew point will have an RH measurement of 100%, HD value of 0 g/m$^3$ and a VPD of 0 kPa.

Table 5a. Values of HD (g/m$^3$) for various combinations of RH and air temperature

| RH (%) | Temperature (°C) | | | | |
|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 |
| 100 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 90 | 0.94 | 1.28 | 1.72 | 2.28 | 2.99 |
| 80 | 1.87 | 2.55 | 3.44 | 4.57 | 6.0 |
| 70 | 2.81 | 3.83 | 5.16 | 6.86 | 9.01 |
| 60 | 3.75 | 5.11 | 6.88 | 9.15 | 12.03 |
| 50 | 4.69 | 6.40 | 8.61 | 11.46 | 15.06 |

Table 5b. Values of RH (%) for various combinations of HD and air temperature

| HD (g/m$^3$) | Temperature (°C) | | | | |
|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 |
| 0 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| 1 | 89.32 | 92.16 | 94.17 | 95.61 | 96.66 |
| 2 | 78.66 | 84.33 | 88.35 | 91.23 | 93.32 |
| 3 | 68.00 | 76.51 | 82.54 | 86.85 | 89.98 |
| 4 | 57.35 | 68.70 | 76.73 | 82.48 | 86.65 |
| 5 | 46.75 | 60.90 | 70.92 | 78.11 | 83.32 |
| 10 | - | 21.98 | 41.99 | 56.33 | 66.72 |

## Measuring humidity

Traditionally, humidity (both RH and HD) has been measured using conventional measuring boxes (Figure 24). These have aspirated sensors that measure 'dry bulb' and 'wet bulb' temperatures and use standard relationships between these to determine the humidity. Such boxes work well and are accurate as long as they receive regular maintenance. In particular, the 'wet bulb' sensor must always have a clean wick and a plentiful reservoir of clean, deionised water. The aspiration fan must also be kept clean and the measuring box must be suspended in a position within the glasshouse so that obstructions do not hinder airflow. Some of these maintenance issues are avoided by the use of electronic humidity sensors (Figure 25). In these, the 'wet bulb' is replaced by an electronic sensor that measures humidity directly. It is also critical to calibrate the electronic sensors regularly, once or twice a year.

Figure 24. Conventional measuring box design with 'wet' and 'dry bulb' sensors

Figure 25. Measuring box incorporating an electronic humidity sensor

## Where to measure humidity

Measuring boxes need to be positioned as close to the crop as possible so that measurements reflect the conditions experienced by the crop. The ideal would be to position them directly within the crop canopy. However, free air movement is needed for effective operation, so normal commercial practice is to place boxes in the airspace just above the crop. It is inevitable, therefore, that measured humidities often reflect the conditions in the greenhouse airspace rather than those of the microclimate next to the plants.

For vine crops such as tomato, it can be a good idea to site measuring boxes in different locations. For example, a measuring box positioned between the rows at the base of the plants gives humidity measurements that reflect the conditions experienced by the stem bundles, and measurements made in this position can be useful for disease control. However, the traditional measuring position at the crop head still needs to be retained because measurements made there best indicate the potential for adequate crop transpiration.

An alternative approach to humidity measurement is to base the estimates on plant temperature rather than air temperature. This has particular value for the avoidance of condensation and is discussed later.

# Humidity conditions to be avoided

## Conditions favouring disease spread

It is generally agreed that glasshouse humidity control should aim to prevent the RH rising above 90%. This is because higher levels encourage the germination of spores of fungal pathogens such as *Botrytis* and *Didymella* (Figure 26) and promote disease spread. However, without plant damage, serious disease spread is unlikely to occur until the localised RH exceeds 95% since, as shown in Figure 27, levels of *Botrytis* spore germination are still relatively low at this humidity. There is also probably little risk of serious infection even at the highest levels of RH as long as the duration of exposure is relatively brief. This is because spores appear to germinate only after around three hours in conducive conditions (AHDB Horticulture project PC/HNS 121). It is clear from Figure 27 that air temperature (within the range likely to be encountered in glasshouse growing) is relatively unimportant for *Botrytis* spore germination when control is based on RH. While surface wetness is not essential for disease spread, moisture films provide ideal environments for the germination of spores of fungi such as *Botrytis* and are likely to increase levels of fungal infection and disease spread. For this reason, it is especially important to avoid conditions favouring the occurrence of condensation on plant surfaces (which can occur at RH levels below 90%).

Figure 26. Higher levels of humidity allow the germination and development of fungal diseases such as *Botrytis* (top) and *Didymella* (bottom)

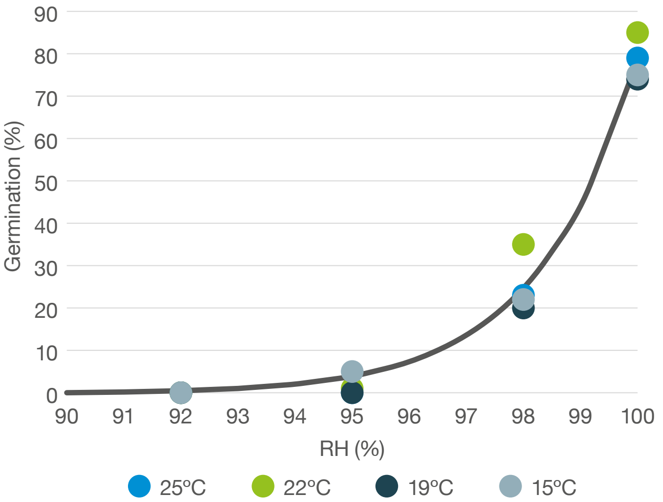


Figure 27. Effect of relative humidity (RH) at temperatures between 15°C and 25°C on the germination of spores of *Botrytis* after 24 hours (HH3611SPC)

## Conditions depressing growth

As a generality, HD levels between 2.0 g/m$^3$ and 7.5 g/m$^3$ are unlikely to have any noticeable effect on plant growth and yield. It is only levels outside of this band that can give potential problems. Studies have shown, for example, that the yield of tomatoes was reduced by 11% when grown continuously for 28 days at a HD averaging a little over 1.0 g/m$^3$. These are rather extreme conditions and they had to be sustained to have significant effect. It is the average HD that determines effects on crop physiology, and a low HD for a single night, for example, is likely to have negligible effect. In contrast, a very high RH for a single night could be highly detrimental for disease control. Thus, humidity-control regimes that are effective in protecting against fungal disease can be expected to protect equally against the high-humidity depression of growth.

## Avoiding condensation on plants

A key aim of humidity control must be to avoid condensation occurring on the plants since moisture films are ideal for fungal spore germination and promote disease spread. Condensation occurs when plant temperature falls below the dew point of the surrounding air (the temperature at which the air would become fully saturated) and water condenses out of the air on the cooler plant surfaces. This situation can occur at apparently safe RH/HD levels. Stems and fruits are at greatest risk of attracting condensation because these have high thermal inertia and are likely to be cooler than the moisture-laden air at key times of the day. It should be noted that it is not just edible crops that can be affected by condensation. Poinsettia crops, for example, are often grown with a temperature reduction at dawn and with a subsequent compensatory temperature lift to maintain the average temperature. However, plants do not warm up as rapidly as the surrounding air and, if unchecked, a marked differential in temperature can occur, providing ideal conditions for condensation.

This can, in turn, increase the incidence of *Botrytis*, which, for an ornamental crop, will greatly reduce its retail value. Figure 28 illustrates how circumstances favouring condensation can come about. The graph shows tomato stem temperature (monitored using an infrared sensor, see below), air temperature and dew point over a 24-hour period in late March and identifies two occasions when the stem temperature was very close to the dew point. The first was in mid-morning when air temperature was increasing more rapidly than stem temperature, and the second was early in the afternoon when clouds came over, the air temperature suddenly fell and the vents closed.

## Monitoring plant temperature

Obtaining data, as shown in Figure 28, requires the continuous monitoring of plant, or plant organ, temperature. This can be done by contact measurement or, more commonly, using infrared sensors.

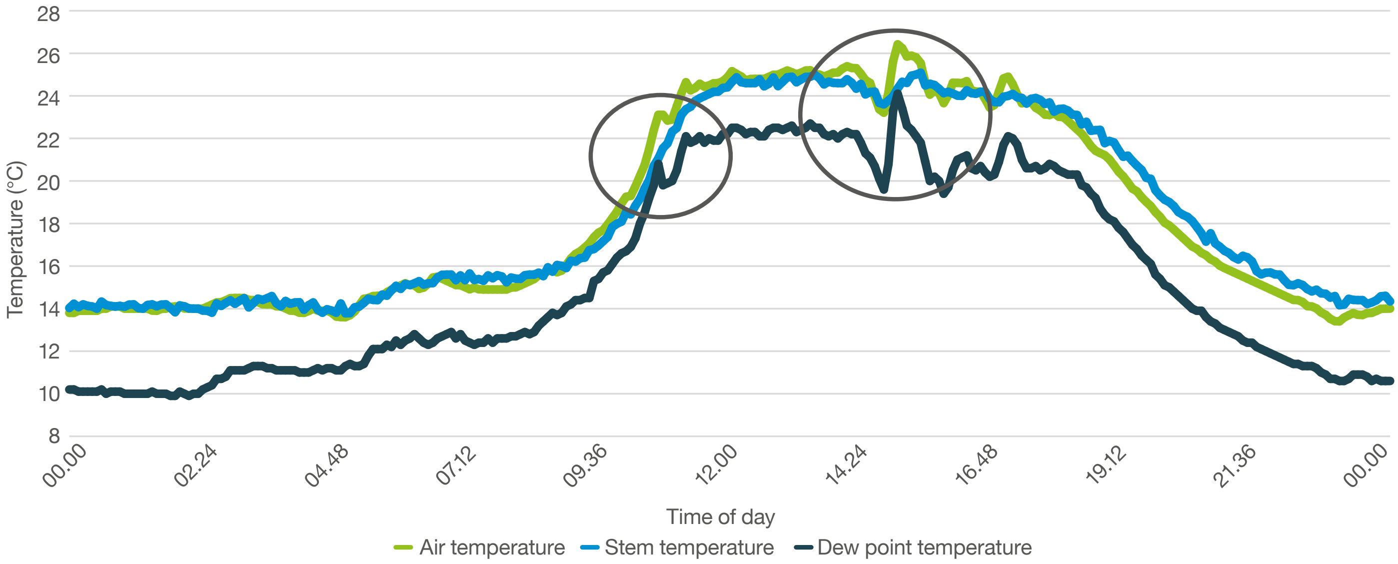


Figure 28. Temperature traces over a 24-hour period, showing two occasions when the tomato stem temperature and dew point were very similar and condensation became a serious risk (HH3611SPC)

Contact measurement is when temperature sensors are mounted directly on the plant surface of interest (e.g. stems). This is a procedure that is used routinely in plant research but which is not popular in commerce due to difficulties in fixing the sensors, the labour needed to mount and to move the sensors, and the fact that sensor cables can hinder efficient crop husbandry. The availability of wireless sensors could revolutionise the viability of contact measuring. While the labour involved with mounting and moving the sensors is unchanged, the lack of cables means sensors can be moved more easily from plant to plant.

Infrared sensors are non-contact and monitor infrared emissions from a distance (giving a temperature read-out). This method has advantages, but the sensors are more expensive and less accurate compared with those for contact measurement and they are not always easy to use in practice. Some current commercial designs are ‘wide-angle’ and give the average temperature of everything in their ‘field of view’. For an ornamental crop such as poinsettia, for example, this can include not only stems and leaves but also pots and compost (AHDB Horticulture project PC 207). This means that the sensor is failing to monitor those specific plant parts where condensation is thought most likely to occur. ‘Narrow-angle’ sensors (Figure 29) can be more easily ‘focused’ on specific target areas and may ultimately prove to be more useful. Use of IR sensors is becoming more commonplace as technology improves, with continuously calibrated sensors and products becoming cheaper.

Figure 29. Infrared sensor used to measure plant or plant organ temperature

## Using plant temperature and plant humidity estimates for the avoidance of condensation

Air and plant temperatures can differ markedly, as seen in Figure 28, and both can be used by modern environmental computers for the calculation and control of humidity. Using air temperature gives a humidity estimate representative of the air sampled in the measuring box (air humidity), but using plant temperature gives an estimate of humidity (plant humidity) close to the plants or the plant parts being monitored. A plant humidity estimate of 100% RH, for example, will indicate that condensation on the plant surface is a real risk.

Figure 30 shows that the conditions as measured by plant temperature sensors can be quite different to air temperature and hence how condensation events can occur.

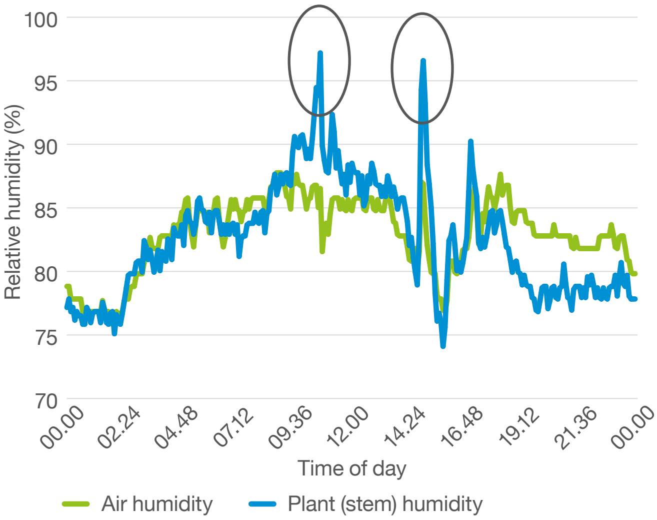


Figure 30. RH values calculated using the air temperatures (air humidity) and tomato stem temperatures (plant humidity) shown in Figure 28, with condensation risk periods indicated

Control based on the higher of either air humidity or plant (stem) humidity at any given time has been trialled with tomatoes at the University of Warwick (HH3611SPC). This combined strategy gives increased confidence that effective humidity control is being practised at the plant surface and enables a less aggressive approach than would otherwise be required for conventional control based on HD. The trials showed that in the trial block the RH was 5% higher than the control typically. This resulted in energy savings and even further savings when combining this technique with that of temperature integration (TI). In addition, through having improved humidity control at times of condensation risk, losses due to *Botrytis* were actually reduced.

# Humidity control

## Use of thermal screens

Screens can themselves be used as effective humidity control tools. This is because a screen in the closed position holds a significant amount of cold air above it and, like outside air, this 'sink' of cold air will have a lower moisture content than the air next to the crop. By allowing this drier air to mix with the moisture-laden air below it, effective humidity control can often be achieved. In practice, screen gapping is controlled in essentially the same way as minimum vent. Thus, a humidity influence is applied via the environmental computer so that the gap gradually increases to around 15% as humidity rises. Beyond this point, gapping has no further effect on humidity control and venting (with subsequent reheating) is brought into play. Screen gapping and venting can be used together (Figure 31), but it is common commercial practice to simply open the screen fully before moving on to venting and reheating.

Figure 31. Screen gapping and venting in operation

## Vent then reheat

In practice, it is often necessary to use a combination of heating and ventilation to control humidity and it is good energy-efficiency practice to use ventilation first. This is because ventilation removes moisture by exchanging a proportion of the moisture-laden glasshouse air with drier air from outside. Sometimes the ventilation reduces glasshouse temperature below set point and heating is then needed to restore the internal temperature. The alternative approach, to heat first, reduces RH but only by increasing the moisture-holding capacity of the air, not actually removing moisture. Ventilation will be needed eventually to remove moisture and reduce temperature, resulting in a loss of warm air and reducing energy efficiency.

Achieving stable humidity control for minimum energy use requires the use of settings that balance ventilation and heating. Good practice is to set a humidity influence on the vent set-point and/or introduce a minimum vent which is dependent on the humidity.

In this case, the degree of opening is increased as humidity conditions progressively worsen, with the advantage that venting can be imposed for humidity control irrespective of the internal temperature. Heating is then used to maintain the temperature at an acceptable level.

## Minimum pipe temperature

It was common practice in the past, when energy prices were lower, to achieve humidity control by setting a permanent, minimum pipe temperature. This, together with compensatory minimum vent position, maintained the glasshouse temperature at the desired level and reduced humidity by continuous air exchange. This approach works well but is wasteful in energy terms since much of the pipe heat introduced into the greenhouse has to be vented away. The effect of a permanent minimum pipe on energy use is simulated in Figure 32. This shows that for a tomato crop growing with a screen and with venting at 90% RH, the inclusion of a 40°C minimum pipe will increase energy use by around 31%. Using a higher pipe temperature will have an increasingly large effect on energy use. The additional energy expenditure will be mainly in the summer and this strategy should be avoided unless $CO_2$ is needed. However, in this case the $CO_2$ should not be considered as a free by-product and its cost should be apportioned appropriately and weighed against the likely yield benefit (see the 'Management of $CO_2$ enrichment' section). A more energy-efficient control strategy is to have a humidity influence on pipe temperature. In this case, a pipe temperature is introduced at an appropriate level and increased as humidity rises. This is a more energy-intensive strategy than relying solely on venting and reheating, as venting and heating are likely to operate in parallel. However, it could be useful at times of the year when the introduction of cold air into the glasshouse and a long lag time for the heating system to operate combine to give undesirable temperature fluctuations.

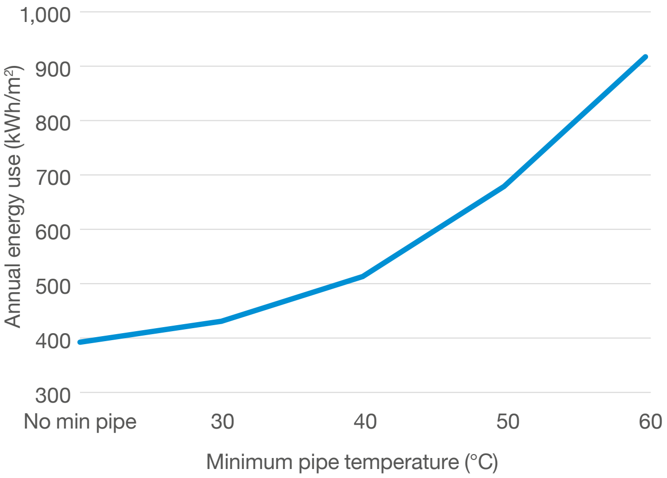


Figure 32. The influence of a permanent minimum pipe temperature on energy use in tomato production with a screen and with humidity controlled at 90% RH (simulated using a model developed in HH3611SPC)

## Reducing the leaf area

High leaf areas result in increased transpiration, giving more water in the greenhouse and consequent higher humidity. Energy is then used to control the increase in humidity, leading to higher overall energy use.

It follows, therefore, that deleafing of high-wire crops will result in energy savings. Simulations for tomato crops grown without humidity control show that taking off an additional six old leaves (to give a highly deleafed crop with a leaf area reduced by an extra 35%) will reduce the energy use by 3.2%. However, when grown with a humidity control set-point of 90% RH (vent then reheat), this saving rises to 5.8% (see Figure 33). The saving will be even greater when an even more aggressive deleafing strategy is applied to a particularly leafy crop. This degree of deleafing has been shown in trials at Wellesbourne to give no significant loss of yield, but it did show a slight increase in uneven fruit ripening. It can be expected that a more modest increase in the degree of deleafing of old leaves of tomato will avoid this potential problem and is worth trialling. It is probably also beneficial to leave more leaf on in summer to intercept the high light levels at this time of year. Furthermore, the additional transpiration will aid greenhouse cooling. Unreplicated AHDB Horticulture trials with pepper (project PC 285) indicated that leaf area can be reduced with no loss of yield and showed that deleafing saved approximately 5 kWh/m² of gas consumption over the year in 2009 and 3.6 kWh/m² when the trial was repeated in 2010. However, as the use of inter-row LED lighting becomes more commonplace, the trade-off between leaf removal and yield should be reconsidered.

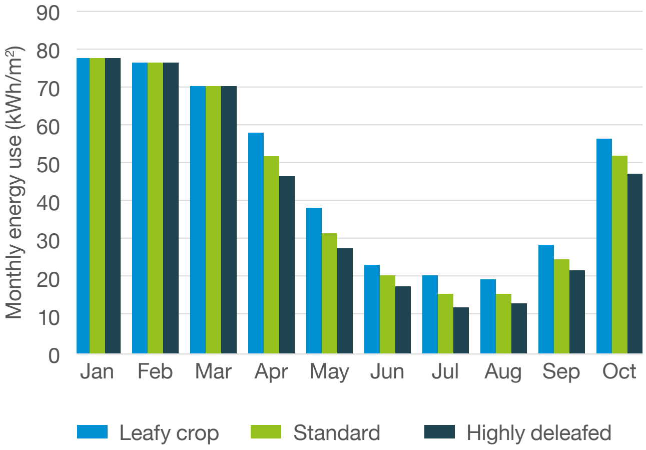


Figure 33. Effects of leaf area on monthly energy use in tomato (simulated using a model developed in HH3611SPC)

## Dehumidification

An alternative approach to control humidity is to directly remove water from the air using a dehumidifier. A refrigerant-based heat pump dehumidifier was trialled in a tomato crop in PE 013a, comparing a block with and without dehumidifiers. Four units were used with a combined water removal capacity of 180 L/hr in a 6,120 m² compartment. There was a net saving of energy usage of 102 kWh/m² but also 1.6 kg/m² of yield lost in comparison with a control block.

# Energy cost of humidity control

Aggressive humidity control increases energy use, as shown in Figure 34. This is derived by simulation using an energy model developed for tomato (HH3611SPC).

Humidity control is by a vent then reheat strategy, with the lee vent able to open fully for humidity control, and with no minimum pipe. Annual energy usage for a crop without screens or TI (see the 'Manipulation of glasshouse temperature' and 'The use of screens' sections), and with humidity control set at 85% RH, is estimated to be around 570 kWh/m$^2$. Of this, around 20% (118 kWh/m$^2$) is expended directly on humidity control. However, relaxing the RH control set-point from 85% to 90% RH reduces total energy use by around 12% (67 kWh/m$^2$), demonstrating that large energy savings can be made by adopting less aggressive humidity-control strategies. Humidity control also reduces the energy savings that can be made using TI and screens. Figure 34 indicates that without humidity control, TI and screens together reduce energy use by 39%. However, with an 85% RH set-point, the energy saving from these technologies is reduced to less than 30%. The savings from TI are especially sensitive to humidity-control strategy (see 'Temperature integration' on page 37). It is vital, therefore, to carefully target humidity control to ensure effectiveness and energy efficiency.

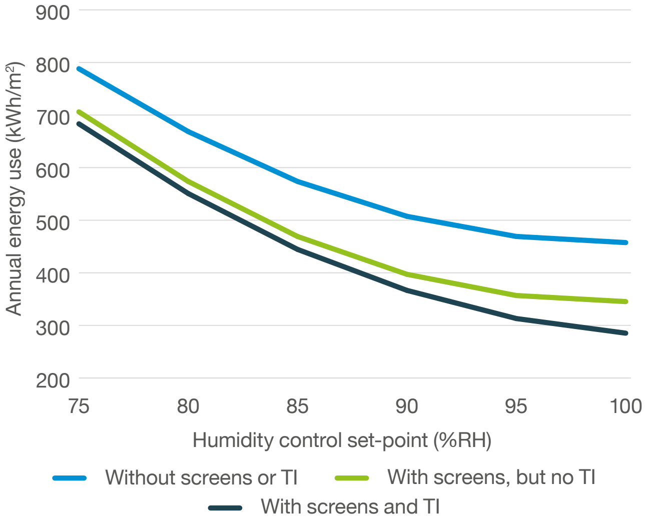


Figure 34. The effects of humidity control set-point on the annual energy expenditure in tomato production (simulated using a model developed in HH3611SPC)

The energy use for RH control will be less for many ornamental crops than that shown in Figure 34 (based on tomato) because ornamentals have smaller leaf areas and transpire less.

## Key points for humidity control

- Effective humidity control is essential to keep fungal disease in check and to promote active growth. Humidity deficit (HD) and relative humidity (RH) are both used routinely to monitor humidity, but RH may be the better indicator of disease risk
- An effective humidity control strategy is to prevent the relative humidity rising above 90% while, at the same time, preventing condensation occurring on the plants. Condensation poses a particularly serious disease risk and occurs when plant temperature is at or below the dew point temperature of the air
- Humidity control is expensive in heating energy terms and, in tomato production, can account for around 20% of energy usage when control is set at 85% RH. However, relaxing control from 85% to 90% RH can be expected to reduce overall energy use by around 12%, demonstrating that large energy savings can be made by adopting less aggressive (but effective) control strategies
- Air humidity can be accurately measured using a traditional wet/dry bulb measuring box, but regular maintenance is essential. Because of this, electronic sensors can be more reliable, as long as they are also regularly calibrated. Positioning of sensors relative to the crop is very important
- The most energy-efficient way of controlling humidity is to vent first, then reheat to maintain temperature. This can be done by having a humidity influence on the vent set-point and/or by introducing a minimum vent which is dependent on the humidity. Heating is then used to maintain temperature
- Setting a permanent minimum pipe temperature is wasteful in energy terms, since much of the pipe heat introduced into the greenhouse has to be vented away to avoid excess temperatures. However, the use of a minimum pipe operating with a humidity influence can be useful in preventing undesirable temperature fluctuations
- Plant temperature measurements (or estimates) will help identify condensation risk periods, and RH values based on plant temperature rather than air temperature (plant humidities) can be especially useful when introduced into the control strategy
- Thermal screens can make humidity control more problematic, but good operational practices can minimise their impact. For example, effective humidity control can often be achieved by controlled screen gapping to enable cold, drier air from above the screen to mix with the moisture-laden air beneath
- There is potential to reduce humidity levels and energy use associated with edible vine crops by reducing their leaf area and, within limits, this can be done without affecting yield. However, the introduction of inter-row LED lighting to high-wire crops is likely to alter this trade-off between leaf removal and yield

# *Management of $CO_2$ enrichment*

This section outlines why $CO_2$ enrichment is vital to the cost-effective production of many glasshouse crops. However, it can have a high energy cost and keeping this in check is the key focus.

## Background

Dry weight increase and yield are functions of crop canopy photosynthesis and this, in turn, is highly dependent on the $CO_2$ concentration in the air surrounding the plants. As Figure 35 shows, photosynthetic rate increases with rise in $CO_2$ concentration up to at least 1,200 ppm. However, the response is not linear and photosynthetic rate increase becomes progressively smaller as $CO_2$ concentration rises. The relationship shown is for tomato, but most other horticultural crops respond similarly. As a consequence, it is now common practice to raise the glasshouse daytime $CO_2$ concentration for many edible crops and some ornamental crops ($CO_2$ enrichment).

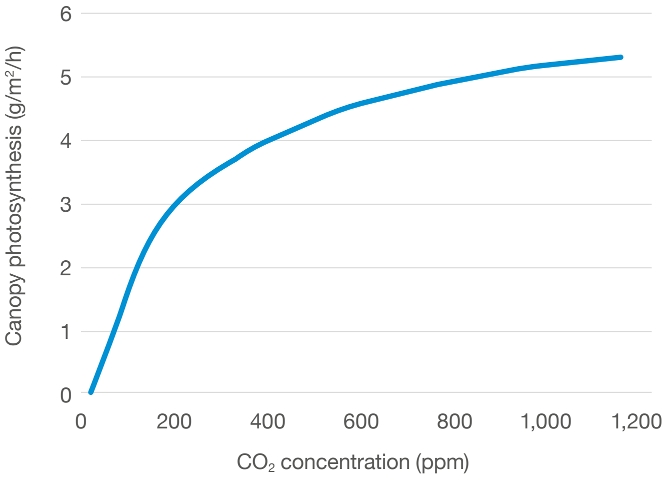


Figure 35. Relationship between tomato (cv. Blizzard) canopy photosynthesis and $CO_2$ concentration (simulated from a model developed by Nederhoff and Vegter)

Sources of $CO_2$ for enrichment include boiler, combined heat and power (CHP), burner exhaust gases and liquefied pure gas. At the very least, enrichment can be used to avoid $CO_2$ depletion, which occurs when its utilisation outpaces the rate of natural replacement from outside. Outside levels are now around 400 ppm, but, without enrichment, levels in the glasshouse can fall in summer to as low as 200 ppm, particularly when crops with a large leaf area are grown in tightly sealed glasshouses. As seen in Figure 35, this degree of depletion will reduce the rate of canopy photosynthesis by around 26%. However, depletion is not always as extreme as this and, in commercial tomato production, adding only sufficient $CO_2$ to prevent atmospheric depletion typically gives a 5–15% yield increase. For many crops, standard practice is to use $CO_2$ enrichment all year round and yields should be around 20–30% higher, depending on the degree of enrichment, species, crop density, etc.

Research has suggested a dosing capacity of 70–130 kg/ha/hr is needed to achieve 900 ppm when vents are closed and this rises to up to 580+ kg/ha/hr when vents start to open. A target $CO_2$ concentration of 800–1,000 ppm is recommended for raising seedlings (tomatoes, cucumbers and speppers), as well as for lettuce production. Lower levels (500–800 ppm) are recommended for some ornamental crops. Glasshouse design, age and crop density will all influence the capacity of a dosing system to achieve the desired $CO_2$ concentration.

## Energy cost of $CO_2$ enrichment

$CO_2$ enrichment increases crop yield and quality, but it also has an associated energy cost, depending on how it is accomplished and the extent to which it is practised.

When $CO_2$ is generated as a by-product of heating the glasshouse with natural gas, it is often considered as ‘free’ by some growers. However, as $CO_2$ requirements do not completely match the need for heat, it is often necessary to calculate its cost. For example, in the summer months when enrichment requirements are high, the need for heat is low and some, if not all, of the direct cost of running the boiler should be attributed to $CO_2$. If burning gas is only required to produce $CO_2$, then there are three options for the heat generated as a ‘by-product’: it can be diverted to insulated heat stores, destroyed by allowing it to dissipate into the glasshouse, or destroyed through dedicated equipment such as dry-air coolers. Costing can become quite complex if there are other reasons to run the boiler at this time, such as for humidity control and disease management. AHDB Horticulture project PC 227a ‘Optimising greenhouse environment and energy inputs for sweet pepper production in the UK’ showed additional energy use to deliver average (550 ppm) levels of $CO_2$ was 52 kWh/m$^2$ annually. In fact, as the heat destruction strategy was not as aggressive as possible, the energy use could have been higher still.

Assuming that burning gas is fully attributed to $CO_2$, then the cost to produce one tonne can be calculated from Table 6. Additional costs may be incurred for some boilers, if modification is required, and CHP plants will require gas cleaning and cooling.

Table 6. Cost of $CO_2$ from burning natural gas solely for $CO_2$

| Cost of natural gas | | Cost of $CO_2$ |
|---|---|---|
| Pence per therm | Pence per kWh | £ per tonne |
| 30 | 1.02 | 51 |
| 40 | 1.36 | 68 |
| 50 | 1.70 | 85 |
| 60 | 2.04 | 102 |
| 70 | 2.38 | 119 |
| 80 | 2.72 | 136 |
| 90 | 3.06 | 153 |

Pure $CO_2$ can cost £65–120/tonne delivered, depending on source, location and quantity being purchased. There is also the cost of storage-tank rental and maintenance (£2–3,000 per annum) and energy to both vaporise the liquid $CO_2$ (£2/t at 40p/therm) and keep the tank cool (£1,500 per annum).

The figures show that, at current gas prices (40p/therm), $CO_2$ from the back of the boiler is more cost-efficient than buying in pure $CO_2$. Furthermore, the cost of $CO_2$ from a modern, efficient CHP plant is estimated at £20/tonne, making it the cheapest source of $CO_2$ available. This is because many growers who have CHP will be generating heat, $CO_2$ and electric power at the same time. There will be times when the income from selling electricity is greater than operational costs and in those circumstances the $CO_2$ from CHP can be considered free.

$CO_2$ from other sources, such as biogas and biomass, is possible and a few commercial systems are in operation. An accurate estimate of cost for $CO_2$ production is complex but has been estimated at £20–50/tonne, although this does not make allowance for very high capital costs of the requisite equipment.

## Sources of $CO_2$

### Natural-gas boilers

Flue gases from natural-gas boilers are most commonly used in UK horticulture as a source of $CO_2$ for enrichment. They are initially very hot and have to be cooled before being introduced into the glasshouse by mixing the exhaust with fresh air or by passing it through a flue gas condenser. This latter method has the advantage of taking out most of the water vapour, which would otherwise tend to increase glasshouse humidity. Flue gas condensers also recover energy by ‘capturing’ the remaining heat in the flue gases, and warm water is used to support greenhouse heating demands. The burning of natural gas in a boiler provides $CO_2$ which is generally accepted as sufficiently ‘clean’ to require no further treatment. Several gas boilers of a mix of ages and types were monitored for flue gas contaminants in research project PC 287 ‘An investigation into the effects of flue gas quality on tomato plants’. The research confirmed that newer, well-maintained boilers provided good-quality $CO_2$, while growers with older gas boilers needed to be more vigilant, with increased monitoring and awareness of potential pollutants.

### CHP installations

The exhaust gases from CHP units can also be used to supply $CO_2$ for enrichment, together with heat and electricity (see Figure 36). They are highly efficient, typically converting over 90% of the input fuel into heat and electricity, and produce more $CO_2$ per unit of heat output than a glasshouse boiler. Most of the units installed on UK nurseries use natural gas-fuelled reciprocating engine generators with electrical outputs in the range of 1–3 MW and are fitted with catalytic converters to clean up the exhaust gases before being used in the glasshouse. Work in PC 287 showed that $NO_x$ levels must be closely monitored; both commercial nurseries with CHP tested showed levels of $NO_x$ exceeding the 250 ppb recommended levels during early-season conditions when $CO_2$ enrichment averaged 800 ppm. The installation of a CHP unit requires a large capital investment and detailed budgeting of the costs. However, with the right combination of energy prices and a realistic value of $CO_2$, this is certainly an option.

Microturbine CHP can also produce good-quality $CO_2$ from their flue gases and have the advantage of not requiring to be cleaned. Research in AHDB Horticulture project PC 287 showed them to have the cleanest exhaust gas of all sources tested. There are few units in operation because of historic issues with technological unreliability and support.

It is also possible to use biomass as fuel for a CHP system. Biomass CHP has been popularised by government support schemes for renewable technologies. Biomass combustion produces a very different flue gas composition to that of natural gas and is difficult to clean, but there have been recent advances in technology and new cleaning systems developed that enable a useable source of $CO_2$ (see 'Biomass boilers' (below) and 'Biogas' (opposite)).

### Biomass boilers

A range of contaminants in flue gases from biomass boilers have hampered the uptake of these systems for growers, who need a clean supply of $CO_2$. Over recent years, the theoretical systems for cleaning gases have been developed into practical systems and it is now possible to recover $CO_2$ from the flue gases of combusted biomass fuels (e.g. woodchip, straw, etc.). The basic process is quite simple (Figure 37): biomass flue gases are passed through a chemical solvent (an amine scrubber), which absorbs the $CO_2$ and rejects any pollutants. A $CO_2$-laden solvent is then stored in a tank, where it is kept until it is needed in the greenhouse. When $CO_2$ is required, the solvent is heated to release the gas.

Figure 36. Biomass boiler

There are several commercial systems installed in Canada and Europe, but the economic case for these is not yet attractive. Current calculations suggest that using gas-fired CHP with $CO_2$ recovery or a biomass boiler with a cleaning system would require a similar financial commitment, but CHP systems return investment faster because they can realise benefit from electricity sales to offset their cost.

A common solution is to use biomass fuels, such as woodchip, alongside natural gas. The low-carbon (and often lower cost) biomass fuel would deliver the baseload heating at times when $CO_2$ demands were low. The grower would switch to burning natural gas at times of high $CO_2$ demand (see AHDB Horticulture project PC 265 'An investigation into the technical and financial viability of biomass heating systems for greenhouse horticulture in the UK'). A credible alternative is to use pure $CO_2$ alongside a renewable fuel-fired boiler, but this relies on a good long-term contract price for pure $CO_2$.

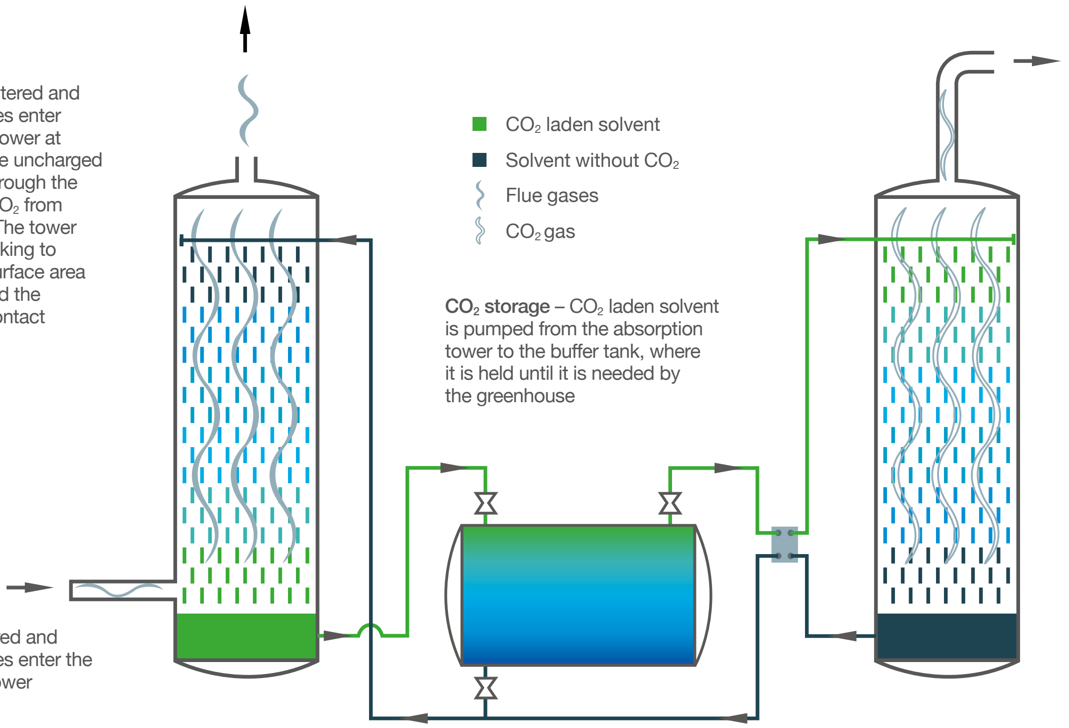
## Biogas

Some growers operate anaerobic digestion (AD) systems, which break down waste organic matter in an oxygen-excluded atmosphere, producing digestate, methane and $CO_2$ gas. The biogas (methane + $CO_2$) can then be used to power a CHP plant or just for heating alone. Some AD plants require the biogas to be cleaned up to leave purer methane; a by-product of this process is the $CO_2$. To extract useable $CO_2$ from biogas, a recovery system that also cleans the gas is required for contaminants such as hydrogen sulphide and hydrocarbons. An example of one such system is the Pentair Haffmans biogas refining system. In doing this on a large scale, AD businesses can now sell purified $CO_2$, which means growers may be able to purchase this slightly cheaper than from traditional sources depending on thier location.

## $CO_2$ burners

$CO_2$ burners (air heaters) differ from heating with boilers in that they are suspended within the glasshouse above the growing crops (Figure 38). They can burn liquefied petroleum gas (LPG) (propane), natural gas or sometimes kerosene. If LPG or kerosene is relied on, then this will be more costly than natural gas and therefore make $CO_2$ more expensive. As well as generating $CO_2$, burners produce heat, which will offset glasshouse heating costs, when required, but also produce water vapour, raising glasshouse humidity. Regular maintenance is essential to prevent incomplete combustion, since this results in the production of aerial pollutants 'Pollutants' on page 31). As glasshouses become better sealed, it may be necessary to provide the burners with their own outside air supply to ensure good, clean combustion. $CO_2$ burners tend to be either on or off, giving little or no control. Their disparate placement in the greenhouse can lead to uneven $CO_2$ and heat distribution.

Figure 38. $CO_2$ burner (air heater)



Flue gases will reduce $CO_2$ to the atmosphere

**Absorption** – Filtered and cooled flue gases enter the absorption tower at the bottom white uncharged solvent is fed through the top to absorb $CO_2$ from the flue gases. The tower is filled with packing to maximise the surface area where gases and the solvent are in contact

**Flue gas** – Filtered and cooled flue gases enter the bottom of the tower

**$CO_2$ storage** – $CO_2$ laden solvent is pumped from the absorption tower to the buffer tank, where it is held until it is needed by the greenhouse

**$CO_2$ supply** – A mix of $CO_2$ and water (as steam) is then cooled to give $CO_2$ for the greenhouse and condensed water

**Desorption** – When $CO_2$ is needed, the charged solvent is heated in the desorption tower. Heat is primarily provided by a boiler. However, heat is also recovered from returning heated solvent to minimise how much the boiler is needed

Once the $CO_2$ is released the uncharged solvent is recycled back to the absorption tower

Figure 37. An example cleaning system from ProSelect GC6. For more information, please see the GrowSave Technical Update: *$CO_2$ from biomass boilers for greenhouse enrichment – the ProSelect GC6 System*

### Pure $CO_2$

Pure, food-grade $CO_2$ can be obtained in liquefied form as a by-product of industrial processes and its use for $CO_2$ enrichment has little impact on the overall energy use of the glasshouse. This source of $CO_2$ has the advantage of being free from injurious pollutants. It can also be used independently of the need for glasshouse heating and is easily piped into the glasshouse. However, a certified bulk storage tank is required. Food-grade $CO_2$ can also be purchased from the renewable energy sector and, if available, may be a cheaper option.

### Alternative options

AHDB Horticulture project PE 003 highlighted that future sources of $CO_2$ may come from fresh air, carbon capture and storage and gasifiers. A watching brief will be kept on these technologies as their development in other industries may bring benefits to horticulture in the future. AHDB Horticulture project CP 143 'Increasing crop yield and resource use efficiency via root-zone $CO_2$ enrichment' is investigating the potential for using localised enrichment of the plant root-zone with low concentrations of $CO_2$ as an alternative to bulk $CO_2$ enrichment of the crop's aerial environment.

## Distribution systems and $CO_2$ measurement

### Distribution

It is necessary to distribute $CO_2$ around the glasshouse to achieve uniformity of supply. In the case of $CO_2$ burners, distribution is achieved by means of integral fans which blow the products of combustion around the glasshouse. However, as noted above, this inevitably results in the creation of both vertical and horizontal $CO_2$ gradients within the glasshouse. In the case of pure $CO_2$ and flue gases from natural-gas boilers and CHP units, a distribution system has to be installed. Usually, this comprises a central header, from which run small bore, perforated tubes, taking $CO_2$ to all areas of the glasshouse. $CO_2$ supply lines are best sited directly in the crop canopy where active photosynthesis takes place or, in the case of benched crops, on or under the benches.

### Measurement

It is important to measure $CO_2$ levels accurately in order to avoid wasteful generation, avoid adverse plant reactions and to optimise crop production. Two approaches are used to measure $CO_2$ concentration: the more traditional method of infrared gas analysers (IRGAs) and the modern system of electronic sensors.

IRGAs can be very accurate and reliable, but regular calibration is important. This can be done using calibration gases of known concentration. The zero value can also be tested by removing the $CO_2$ from the air with an appropriate absorbent such as soda lime. To reduce capital costs, a single analyser is often used to measure several glasshouse areas; consequently, sample pipes may be of considerable length. Air is drawn continuously from all of the pipes via a multiplexer, although only one will be measured at any given time. Even so, sufficient time needs to be allowed for the system to purge when switching between areas. If measurements are taken too soon, air from the first location may still be present in the analyser and the readings will be for a mixture of the two locations. It is good practice to sample at a height that will reflect the $CO_2$ concentration in the upper crop canopy, since this is where most photosynthesis takes place.

Electronic $CO_2$ sensors connected to the environment control computer have now become the industry standard. There is still a need to calibrate these regularly, but because each growing area can have its own sensor, they overcome some of the problems associated with long runs of pipework for IRGAs. Measuring a representative sample and accurate calibration is the key to managing $CO_2$ concentration and distribution.

## Optimising $CO_2$ availability

### Storing surplus heat

As noted on page 28, surplus heating energy is frequently generated in summer when using natural-gas boilers to provide $CO_2$. In this case, the surplus heat should be stored for later use as hot water in heat-storage tanks (Figure 36). Modern nursery installations can burn gas at rates in the region of 1.5–2 MW and a heat-storage capacity of around 150–200 $m^3$/ha is typically recommended. The heat store should be suitably insulated to ensure that heat is not wasted.

The quantity of $CO_2$ produced is directly related to the amount of gas burnt: the lower the burn level then the smaller amount of $CO_2$ that will be produced. When considering a heat store fill strategy, it is prudent to consider the benefit of $CO_2$ at different times of the day (see 'When to add $CO_2$', opposite) and how the distribution system responds to higher or lower gas volumes. For example, it may be better to dose with higher levels of $CO_2$ before noon rather than having a continuous, lower average level throughout the day.

### Minimum pipe temperature

A permanent minimum pipe temperature setting can be used to dissipate surplus heat if there is no heat store, or the heat store is full. However, this practice is not energy-efficient (Figure 39) and the cost of generating the $CO_2$ has to be balanced against the likely increase in crop yield. Increasing the minimum pipe temperature increases the supply of $CO_2$. However, it also increases the amount of heat dissipated into the glasshouse and this will increase ventilation and $CO_2$ losses. Previous work in AHDB Horticulture project PC 110a showed an economic benefit of using a minimum pipe strategy to optimise $CO_2$. The interaction between minimal pipe temperature and annual energy usage was investigated. It was concluded that minimum pipe temperatures greater than 40–45°C were unlikely to be economic for gas prices ranging from 0.5–1.5p/kWh. At high temperatures, high levels of $CO_2$ are lost through ventilation. The balance depends on the interaction between gas price, fruit yield and fruit price and this requires good modelling to state with any certainty.

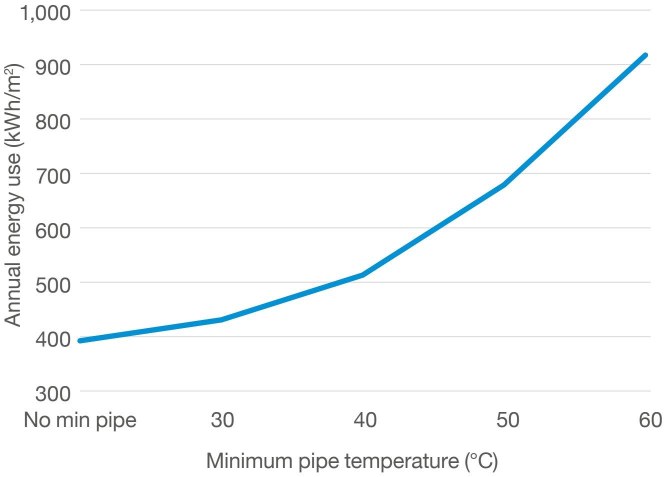


Figure 39. The influence of a permanent, minimum pipe temperature on energy use in tomato production with a screen and with humidity controlled at 90% RH (simulated using a model developed in HH3611SPC)

## Vent management

Although $CO_2$ is heavier than air, it is still rapidly lost from the glasshouse through the vents. Work in AHDB Horticulture project PE 021 suggests 70% may be lost to venting, and research from the Improvement Centre in Holland found it may be higher in the summer period. For this reason, $CO_2$ enrichment protocols (whatever the source) need to take account of vent operation. When vents are more than 10–15% open, it is not possible to maintain 1,000 ppm enrichment level. One strategy is to optimise $CO_2$ dosing according to ventilation rate (see 'When to add $CO_2$'), while a second is to manipulate ventilation set-points.

Trials HH1318SPC with spray chrysanthemums found that raising the vent set-point from 21°C to 27°C (with $CO_2$ supplemented to a maximum of 1,000 ppm, with vents <10% open in both cases) increased total plant fresh weight by 8.8% and dry weight by 15.7%. However, there was an increase in plant and pedicel height, which required PGR treatment. Overall, raising the vent temperature for the whole of the day increases the potential for enrichment and better $CO_2$ utilisation.

## When to add $CO_2$

It has been standard practice to enrich crops to the same target level throughout the day to avoid canopy depletion. $CO_2$ requirements of the crop change over the course of a day and a better understanding of crop physiology and knowledge of environmental conditions will enable a more accurate tailoring of $CO_2$ enrichment. The benefits of $CO_2$ enrichment increase at higher light levels, but the efficiency of enrichment decreases with higher ventilation rates. MAFF-funded work with four tomato cultivars grown in a multifactorial experimental glasshouse enriched with 425 ppm $CO_2$ in the morning, the afternoon, all day or no enrichment were compared. Yield was found to be related to the daily average $CO_2$ concentration; there was no observed significant difference, in these trials, of adding $CO_2$ in the morning or the afternoon.

Yet, recently, simulations carried out as part of AHDB Horticulture project PC 110a suggest that $CO_2$ levels should ideally be highest around noon in spring and autumn, but that in the summer they should be highest in the morning when ventilation rates tend to be lower.

An unreplicated trial, reported to the GrowSave Conference in 2016, carried out at the Improvement Centre, Holland, on tomatoes in 2011, compared constant $CO_2$ dosage rates of 200 kg/ha/hr (the control) with a trial block having minimum dosing of 75 kg/ha/hr, with occasional increased dosing at high light level, to achieve an annual total dose of half the control block. The results demonstrated that there was almost no difference in overall production, with both treatments achieving yields of 65 kg/m$^2$. Further analysis showed that the photosynthetic rate increased only marginally above 800 ppm and plants given the lower $CO_2$ rate appeared to adapt and develop more effective use of $CO_2$. A trial in the following year confirmed that dosing $CO_2$ at low light levels, i.e. below 100 W/m$^2$, is not effective, thus pointing the way to a future in which $CO_2$ dosing may be altered according to the amount of light available.

Results from commercial unreplicated monitoring in AHDB Horticulture project PE 021 suggest that there is a reduced photosynthetic response in the afternoon of a large vine (cv. Roterno) and cocktail cherry (Piccolo) tomato. The data suggests there may be merit in tailoring $CO_2$ enrichment to the morning and up to and including the brightest parts of the day; as the season progresses, this will move from around 15 hours back to 12–13 hours in September/October. The two varieties showed differing responses to $CO_2$ levels, which is another factor to consider in dosing strategies.

There is also potential to increase the effectiveness of $CO_2$ by ensuring that it is introduced at the ideal height (at the youngest fully expanded leaf) and by giving supplementary light to the shaded lower leaves. Further AHDB work to improve the lighting, timing and concentration of $CO_2$ enrichment is ongoing.

## Pollutants

As already noted, one of the disadvantages of burning a hydrocarbon fuel to produce $CO_2$ is that the combustion products can contain pollutants which are potentially harmful to plants and/or humans. It is possible to monitor the concentration of pollutants at the back of the boiler or, for a reciprocating CHP, after treatment. However, it is their concentration in the glasshouse that is more critical in determining effects on plants or workers and this requires very sensitive equipment able to detect concentrations as low as parts per billion (ppb). AHDB Horticulture project PC 287 concluded that $NO_x$ is the most likely to be an issue and the cause of poor plant performance (Figure 40).

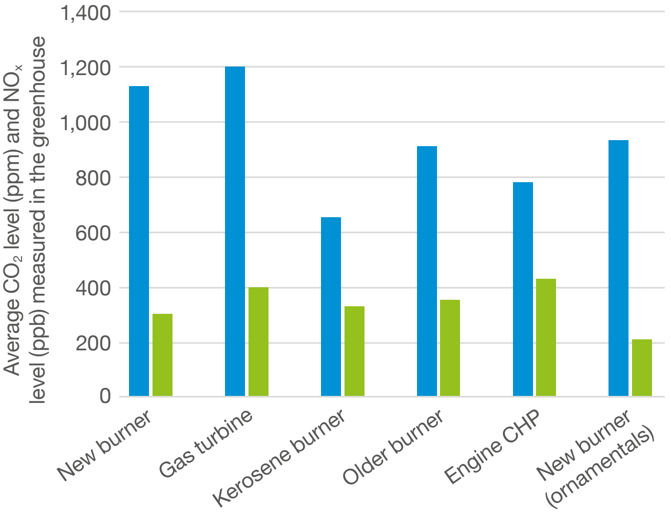


Figure 39. The influence of a permanent, minimum pipe temperature on energy use in tomato production with a screen and with humidity controlled at 90% RH (simulated using a model developed in HH3611SPC)

Direct measurement of pollutants in greenhouses is impractical for growers to carry out. Where a problem is suspected, it is recommended that growers measure the composition of flue gases and compare with guidelines in Table 7. To minimise the likelihood of pollutant-related problems, growers should ensure an effective maintenance programme is in place for all $CO_2$ related infrastructure, from burners through to $CO_2$ sensors.

Table 7. Safe pollutant concentration values

| Pollutant | Level harmful to tomato plants | Suggested 'safe' level |
|---|---|---|
| $NO_x$ (NO + $NO_2$) | Although it does not result in visible damage, 250 ppb may reduce growth and yield | Aim for less than 250 ppb |
| Ethylene ($C_2H_4$) | 50 ppb may reduce fruit set in some cultivars. Recommendations suggesting a 'safe' threshold of 10 ppb appear sensible | Aim for less than 10 ppb |
| Sulphur dioxide ($SO_2$) | Following the introduction of low-sulphur fuels, this is rarely a problem. The harmful levels suggested vary from 100 ppb to 500 ppb | Aim for less than 100 ppb |
| Carbon monoxide (CO) | Greater than human exposure limit (HEL) | HEL of 35 ppm – 8-hour working day |

## Oxides of Nitrogen ($NO_x$)

$NO_x$ is a generic term for mono-nitrogen oxides (NO and $NO_2$) which can be produced to harmful levels during combustion of hydrocarbons. Plants are damaged by $NO_x$ at levels below those judged to be harmful to human health, so it is plant response that determines acceptable levels in the glasshouse. Tomato leaves exposed to high $NO_x$ concentrations (2,000 ppb or more) for one or two hours can show water-soaked areas or 'windows' that later turn white or brown. Leaves may also develop damaged margins. Longer-term exposure to lower concentrations (500 ppb) can result in a temporary increase in leaf greenness, which is followed by chlorosis and premature leaf fall. The effects of lower concentrations can be more insidious; a concentration of 250 ppb can reduce tomato plant growth but without any visible leaf damage. Reductions in the growth of tomatoes, ranging from 22–32%, have been shown at $NO_x$ levels as low as 250 ppb. AHDB Horticulture project PC 287 found that typically this was exceeded in all the greenhouses monitored, especially when there was no venting and a $CO_2$ level of 1,000 ppm or more was achieved. Lettuce is also sensitive to $NO_x$ and a concentration of 500 ppb can inhibit growth.

Overall, it is difficult to be precise as to 'safe' levels of $NO_x$, given wide variation in response between species and cultivars. Plant sensitivity is also affected by the stage of development and environmental conditions, including $CO_2$ levels and the presence of other pollutants. A level below 250 ppb, though, is suggested (Table 7).

## Ethylene ($C_2H_4$)

Ethylene is a naturally occurring plant hormone but is also released into the glasshouse aerial environment as a result of incomplete combustion. Symptoms of ethylene injury include reduced growth, reduced apical dominance and shorter internodes, epinasty of leaves (downward bending due to greater growth on the upper side), premature senescence of leaves and flowers, delayed and malformed flowers and abscission of flower buds. Epinasty may be induced in tomatoes at 100 ppb, and 500 ppb for four days is sufficient to cause flowers to either abort or drop off (see Figure 46).

In chrysanthemums, 50 ppb ethylene was sufficient to cause a marked delay in bud formation. Under higher ethylene concentrations (1 to 4 ppm), chrysanthemums failed to initiate buds even when exposed to short days. The plants also had shorter internodes, thickening of stems, smaller leaves and loss of apical dominance. An ethylene concentration of 120 ppb has been shown to reduce the dry matter of lettuce by between 25% and 50%. Even 55 ppb was enough to cause a significant reduction in growth. AHDB Horticulture project PC 287 found that the concentration of ethylene in the samples from the turbine and new burner sites were too low to be detectable. However, samples from the reciprocating engine CHP sites showed a slight indication of ethylene, but the concentration was probably no more than 20 ppb (the limit of detection), even from the samples at the bottom of the crop close to the $CO_2$ enrichment pipe. Regardless, complacency is not advised, as there is considerable anecdotal evidence to suggest that a small number of nurseries are affected each year.

These nurseries almost exclusively have ageing reciprocating engine CHP and the problems normally occur early in the year when there is little venting.

Propylene pollution, which can be associated, for example, with leaky propane lines, causes symptoms similar to those of ethylene.

## Carbon monoxide (CO)

CO was not detected in any of the glasshouses monitored as part of AHDB Horticulture project PC 287 and plants are more tolerant to CO than humans, so it is the permissible levels for humans that needs to take priority.

The Health and Safety Executive (HSE) set the occupational health limits in the UK. The safe human exposure limit is 35 ppm for eight hours; this should be measured in the greenhouse. The presence of CO at levels above 50 ppm in flue gases is an indication of the likely presence of injurious levels of other pollutants.

## Sulphur dioxide ($SO_2$)

Kerosene is now rarely used for $CO_2$ generation and is now ‘low sulphur’, thus the risk of damage from $SO_2$ has become greatly reduced.

## $CO_2$

It must be noted that high levels of $CO_2$ itself can cause phytotoxic effects in crops. This has been seen in cucumbers, producing bleaching of leaves and reduction in yield. Recommendations from AHDB Horticulture project PC 159 were to only enrich to 1,000 ppm, especially in the early stages of the crop.

## Key points for $CO_2$ enrichment

- For some crops, $CO_2$ enrichment can greatly increase annual energy use. It is important to ensure that the benefits outweigh the costs
- Flue gases from natural-gas boilers and CHP units can be used for $CO_2$ enrichment. $CO_2$ from natural-gas boilers is essentially a by-product of glasshouse heating, but this doesn’t mean it is free, particularly if the boiler is being used solely for the purposes of $CO_2$ enrichment (see Table 6). CHP units (including microturbines) produce more $CO_2$ per unit of heat output than a boiler, but for reciprocating engines a catalytic converter is needed to remove harmful pollutants. The flue gases of combusted biomass have yet to be an economical source of $CO_2$ at greenhouse scale, although several commercial technologies are available to enable this and it is likely to become more cost-effective in the near future
- $CO_2$ enrichment using flue gases can generate surplus heat and this should be stored as hot water in well-insulated storage tanks for later use. The matching of $CO_2$ production to heat storage is critical to energy-efficient management. A heat storage capacity in the range of 150–200 $m^3$/ha is typically recommended
- There may be times when a permanent minimum pipe temperature setting is used to maintain greenhouse $CO_2$ levels in the absence of a heat store or if this is full. This practice is not energy-efficient and unnecessary heat use solely for $CO_2$ enrichment means the cost of this is entirely the value of the input fuel
- $CO_2$ can also be generated by LPG or kerosene burners within the glasshouse. $CO_2$ generated in this way can be expensive and dealing with the associated products of combustion (water vapour, heat and, possibly, aerial pollutants) can be problematic. Associated heat production in winter will offset glasshouse heating costs
- Enrichment can also be carried out using pure, liquefied $CO_2$. This is a by-product of industrial processes and its use for enrichment has minimal impact on overall energy use. It has the advantage over flue gases in that it can be used in summer without associated heat production. However, a certified bulk storage tank is required. Liquified $CO_2$ currently costs around 11p/kg. Depending on location, $CO_2$ may be available as a by-product of renewable technologies such as anaerobic digestion
- $CO_2$ needs to be distributed around the glasshouse to achieve uniformity of supply and this is achieved either by integral fans, in the case of burners, or by the use of lay flat ducts with perforated supply lines and an electrical fan. The supply lines are best sited within the crop canopy or, in the case of benched crops, on or under the benches. Accurate $CO_2$ measurement is important to optimise enrichment practices, and all $CO_2$ sensors should be regularly calibrated
- Raising the vent temperature for part or all of the day will reduce ventilation losses and increase the potential for $CO_2$ enrichment
- Standard practice has been to spread the use of available $CO_2$ over the whole course of the day to avoid canopy depletion. Recent research suggests tailoring release to be greater in the morning and during the brightest parts of the day

# Manipulation of glasshouse temperature

This section highlights the savings to be made by maintaining an effective glasshouse temperature (Figure 41).

Described herein is some of the latest thinking on temperature management, drawing on the techniques of 'Next Generation Growing' (NGG), an approach developed in the Netherlands. Traditional approaches to temperature management still form the basis of current practice, with lower set-point growing, temperature integration and DROP all explained.

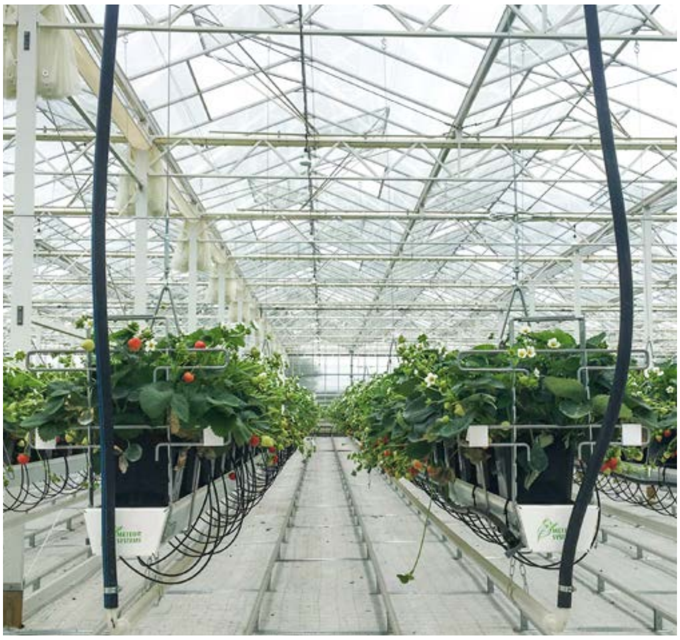


Figure 41. Temperature manipulation is an important element in reducing glasshouse energy use

## Next Generation Growing – keeping an even temperature

NGG focuses on optimising the glasshouse environment so that the plants are in perfect balance to maximise crop yield. It can be described by seven climate elements:

1. Homogenous temperature.
2. Improved humidity control.
3. Management of outgoing long-wave radiation.
4. Keeping an active climate.
5. Using leeside and windside vents.
6. Maximising photosynthesis.
7. Maintaining the right plant balance.

By keeping the conditions constant, the crop balance can be found and maintained. There can be considerable horizontal and vertical temperature variations within a glasshouse. AHDB Horticulture project PC 278 showed that there was a greater than 2°C variation in temperature between the central pathway and wall of a glasshouse compartment. Ideally, the variation should be no more than 2°C across the compartment and there are various methods to help with a more even climate.

## Using measuring boxes in multiple locations

The general philosophy is: the more you can measure, the better – ideally, using measurements to be predictive rather than corrective. In addition to the more standard measurements, it is also recommended to measure: temperature and absolute humidity above the screen using an aspirated measuring box (Figure 42), absolute humidity outside, plant temperature, net radiation and irradiation using a pyrgeometer. Wireless measurement units are available to buy or rent.

Additional sensors will give a fuller picture of the glasshouse environment. Temperature probes can be used to see what the crop is really 'feeling', while extra measuring boxes are useful in tall crops; infrared cameras will give the most accurate measurement. AHDB Horticulture project PC 301 has some practical advice on types and positioning of sensors in crops.

Figure 42. Aspirated measuring box

## Having a well-designed heating system

Having in place a well-designed heating system, delivering efficient combustion and good thermal and distribution efficiency, is the starting point to ensuring a homogenous climate throughout the glasshouse. Understanding the balance of heat delivery in your system (conduction, convection or radiation) will help when considering further modifications to make the greenhouse as energy-efficient as possible. Consider speaking to a specialist glasshouse-heating-system designer for advice on how to achieve this. Information can be found on the GrowSave website (**growsave.co.uk**).

## Using side screens

Irrespective of the heating system, it is likely that the maximum temperature variation in a glasshouse without side and gable screens will be greater than 2°C, because warm air in the greenhouse will inevitably be drawn to the colder sides, where the resulting higher relative humidity will significantly increase disease pressure.

Although gaining in popularity in newly built glasshouses, side and gable screens have not been as widely accepted in the UK as elsewhere, mainly due to their cost when compared with temporary plastic insulation. Side screens should always be used in combination with overhead screens. The amount of additional energy saving that a side screen will achieve is relative to the cumulative length of the sides and gables compared with the floor area.

### Installing apex seals

The movement of cold air along the bay above an energy screen is a major cause of uneven temperatures. The cold air above the screen is not static and will travel to the lowest point – or find a gap – and drop onto the crop, or simply create a cold spot below the screen. The installation of energy barriers (known as apex seals), consisting of transparent screen material at intervals of 30–40 metres along the bay above the screen, will typically reduce temperature variations by 50% (Figure 43).

Figure 43. Apex seal

### Stopping screen gapping

It has been standard practice to gap the overhead energy screen when humidity levels below the screen are higher than desirable. However, breathable screen materials make it possible to reduce humidity through the closed screen by venting above it. Keeping the screen closed not only saves energy but also prevents cold air dropping onto the crop, reducing local air movement and undesirable cold and warm spots in the process.

### Keeping screens in good condition

Energy screens have been in widespread use for a number of years. Existing screen systems which were installed more than a few years ago will not benefit from the energy-saving or light-transmission properties of the latest screen materials. The constant use of the screens over thousands of operational hours not only results in tears and gaps in the material, which reduces their energy-saving potential, but also the accumulation of dirt and grime, which makes daytime deployment inadvisable as light transmission is reduced. It is particularly important to let the screen dry out before retracting to prevent algal build-up on the moist surface. Regular cleaning regimes, such as fogging, will help to maintain light transmission. Screen suppliers claim that screens can lose 2–3% of their energy-saving and light-transmission properties annually due to wear and contamination (see page 43).

### Installing a double screen

The use of double screens is becoming more common. To extend the life of a single screen, a new, second screen can be added. Multiple horizontal screens provide the opportunity to benefit from greater energy saving by further reducing air leakage and their insulating effects. They also allow improved tailoring of the environment beneath the screens without compromising the uniformity.

### Using air-circulation fans

A well-designed fan installation will benefit the greenhouse climate by helping to maintain consistent temperature and humidity throughout the growing area. The gentle movement of air over the leaf surface is also an aid both to transpiration and the distribution and uptake of $CO_2$ (See GrowSave Technical Update: ***Circulation Fans***).

## Growing at lower set-points

In general, as temperature rises, plants respond with quicker growth, and, conversely, slow as temperature decreases. The 24-hour average temperature and the difference between night and day temperatures are key parameters for controlling plant growth. There will be an ideal growing temperature for each crop (and even variety) and the glasshouse must be managed to optimise conditions for maximising yield while minimising costs. The heating set-point temperature can be reduced, hence lower energy costs; however, potential savings have to be balanced against the effects of lower temperature on crop timing, yield and quality.

### Potential energy saving

Research funded by Defra and conducted at Warwick HRI in the mid-2000s modelled potential energy savings when set-point temperatures were reduced. Simulations were carried out for low-input ornamentals, pot chrysanthemums and tomatoes (Figure 46). The model was run with weather data for Bedfordshire and took account of such factors as inside and outside temperatures, solar radiation and wind speed, greenhouse design and condition. The following parameters were set:

### Ornamentals

Set-point heating temperatures from 14°C down to 8°C, with venting at 16°C, no humidity control, no minimum pipe temperature, no lights and no thermal screen.

### Pot chrysanthemums

Set-point heating temperatures from 18°C down to 12°C, with venting at 20°C, humidity control at 90% RH, no minimum pipe temperature, supplementary lighting at 9.6 W/m$^2$ and a blackout (thermal) screen.

### Tomatoes

Set-point heating temperatures from 18°C down to 12°C, with venting at 19°C, humidity control at 90% RH, no minimum pipe temperature, no lights but with an energy screen.

The simulations show glasshouse energy use decreases progressively with reduction in set-point temperature. A reduction of 1°C from the highest settings (in Figure 44) will give approximately a 13% reduction in energy use in ornamentals and pot chrysanthemum production and a 10% reduction in tomato production. On the basis of the parameters set, pot chrysanthemum production will consume less heating energy than tomato for a given heating set-point, because the supplementary lighting will, in part, substitute for pipe heating. In addition, blackout screens tend to have better insulation properties than energy screens, and lower rates of transpiration (because of smaller leaves) will reduce the energy expended on humidity control.

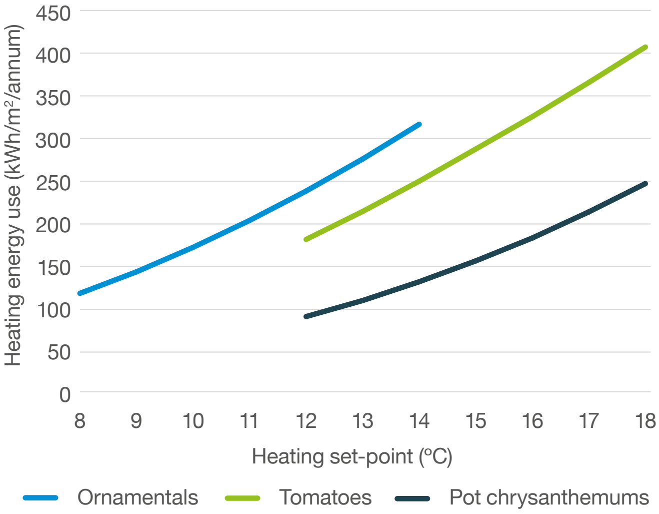


Figure 44. Relationships between heating set-point and glasshouse heating energy for ornamentals, pot chrysanthemums (excluding lighting energy) and tomatoes (simulated using a model developed in HH3611SPC)

## Effects on production

Lowering the heating set-point will, for most crops, give suboptimal growing temperatures and will increase production time and/or depress yield. Whether such effects are acceptable will depend on their magnitude and on market requirements, and the strategy of lower-temperature growing will be more suited to some crops than to others. Particular care will need to be taken to keep *Botrytis* in check, since lower-temperature growing will tend to increase glasshouse humidity (see page 21).

### Energy-intensive edible crops

The growth and development of edible crops such as tomato are adversely affected by reduction in growing temperature, as shown in Figure 45, and this will result in reduced yield. Trials at Littlehampton in the 1980s concluded that the financial cost of such yield losses was greater than the value of the energy savings and that this approach was not viable. Since then, however, energy costs have risen more than tomato prices and lower-temperature growing for tomatoes is now a more economical option.

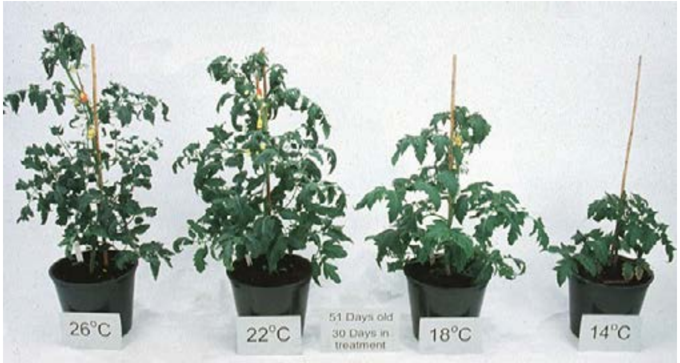


Figure 45. Effect of growing temperature on growth and development in tomatoes

### Energy-intensive ornamental crops

For ornamental crops, the biggest impact of lower-temperature growing is likely to be on throughput. Figure 46 illustrates this for pot chrysanthemums, using published relationships between achieved temperature and rate of flowering, and taking account of pot-spacing practices used in commerce. Based on this, and on simulated relationships between set-point temperature and achieved temperature given by the Hamer energy model (HH3611SPC), reducing the set point from 18°C to 16°C is not economic. Lower-temperature growing may, however, be better suited to ornamentals, such as poinsettias grown as Christmas spot crops. Trials with cultivars such as 'Freedom Red' have shown that lowering the set point at 'pinching' from 20°C to 15°C and retaining this through to marketing will give crops of sufficient size and quality, as long as potting is at least three weeks earlier than usual (see AHDB Horticulture projects PC 071c and PC 071d).

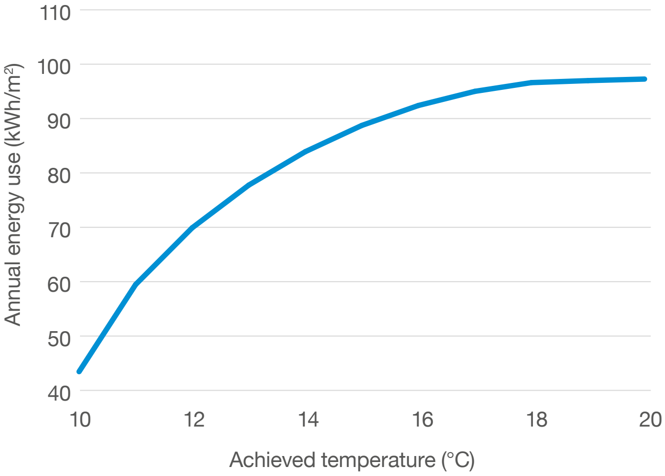


Figure 46. Relationship between set-point temperature and annual throughput of pot chrysanthemums

## Temperature integration

Glasshouse crops used to be grown with similar day/night set-point temperatures. However, plants are able to tolerate considerable temperature fluctuations (as happens in nature, for example) and growth and flowering generally reflects the average 24-hour temperature (see Figure 47). This ability of plants to respond to the average temperature, while tolerating considerable fluctuations around this average, led to the development of temperature integration (TI) as an energy-saving strategy.

Figure 47. Plants of impatiens growing at an average temperature of 18°C, showing that flowering is regulated by average 24-hour temperature rather than by day (D) or night (N) temperature (HH1330SPC)

### Basic TI – exploitation of solar gain

Basic TI is implemented by raising the glasshouse vent temperature setting and allowing solar gain to give higher than usual day temperatures. This enables ‘energy credits’ to be accumulated and these are then ‘spent’ by reducing the heating set-point to lower than usual at times when the heating demand would otherwise have been high, such as at night or on cloudy days.

The aim is to grow making use of the climate by keeping the crop warm when there are high light levels, low wind speeds or the screen is drawn over.

When it is wet, windy or light levels are low, the temperature can be kept low.

Figure 48 shows typical temperature profiles over a 24-hour period for conventional and Basic TI growing regimes. The gain in temperature during the middle of the day in the TI glasshouse (from solar gain) is compensated for by using a lower heating set-point temperature than normal at other times. Both profiles give the same average temperature, 20°C, and crop responses can be expected to be similar (other than for height). However, the TI regime requires a smaller heating input. In practice, a running average temperature is maintained over several days (the ‘integration period’) since it is not always possible to fully use energy credits within the 24-hour period in which they are generated. The integrating period will be specific to the crop and growers can build up the period while gaining confidence with the technique. Most computers allow for up to seven days. Any credits that remain at the end of the period are ‘discarded’. At times, the temperature will be above the optimum for cropping (supra-optimal), and at other times it will be below the optimum (suboptimal). Both of these are associated with slower development, but, in practice, a large degree of mutual compensation occurs and cropping delays tend to be minor. Plant growth regulating (PGR) treatments have frequently to be increased because the combination of high day temperatures and low night temperatures (‘positive DIF’) gives rise to taller plants.

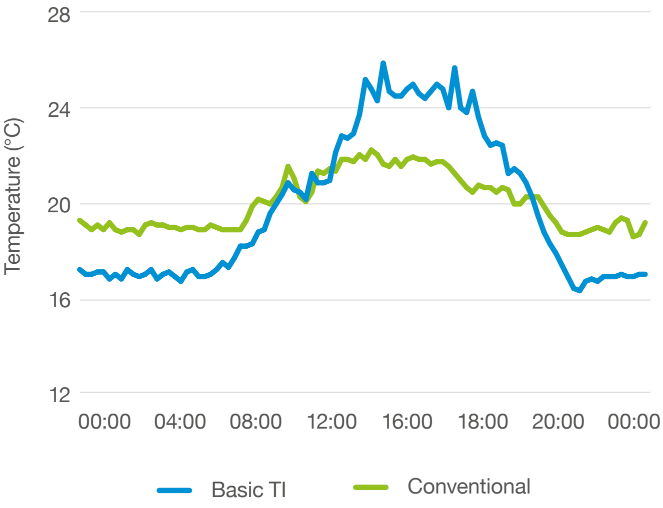


Figure 48. Typical daily temperature profiles for conventional and Basic TI crops

## Energy-saving aspects and humidity control

Three main elements can be manipulated in Basic TI to save energy – the length of the integration period, the vent temperature setting and the minimum permitted temperature.

Simulation studies (HH1330SPC and HH3611SPC) have shown that:

- Increasing the integration period up to around 10 days saves progressively more energy. Weather forecasting will indicate when energy credits are likely to accrue but will not increase the overall energy saving as long as the integration period is of reasonable duration
- Increasing the vent temperature setting from a conventional 19°C to 26°C by 1°C stages saves progressively more energy (Figure 49)
- Allowing a low minimum temperature setting (14°C rather than 16°C in Figure 51) will give more opportunity for using energy credits and will give greater energy savings. Best practice is to adjust the minimum temperature setting to more or less balance the accumulation and expenditure of credits
- Because of temperature fluctuations, humidity levels frequently tend to be higher in Basic TI than in conventional regimes and this needs to be countered in an effective but energy-efficient manner (see page 19). This is because humidity control incurs direct energy costs and also reduces the potential of Basic TI to save energy. In Figure 51, preventing the RH rising above 90% using a vent then heat strategy effectively halves the predicted savings

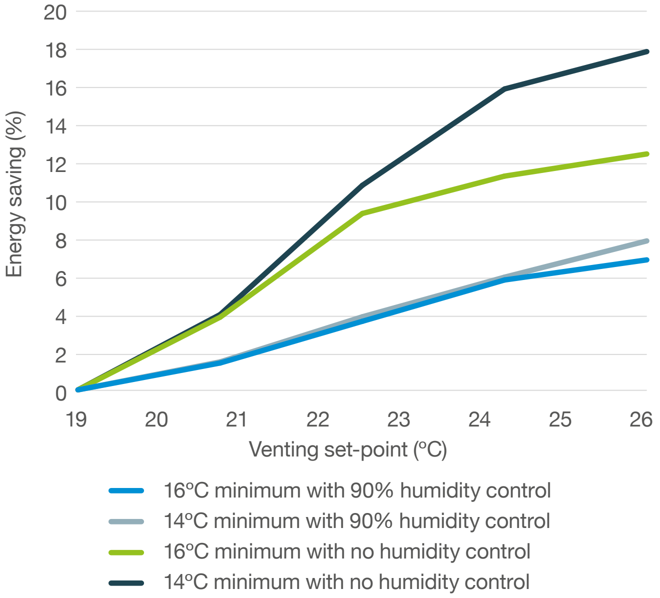


Figure 49. Effects on energy saving in Basic TI of varying the minimum heating and vent temperature settings (simulated using a model for tomato developed in HH3611SPC)

## Monthly energy savings

Potential energy savings from Basic TI will vary through the year. This is shown for an ornamental crop growing without lights, screens, minimum pipe or humidity control in Figure 50. The simulation assumes that the conventional crop has a heating set-point of 14°C and a vent temperature of 16°C. Two Basic TI regimes are shown: a 'modest' TI regime with venting at 18°C and a heating temperature that is allowed to fall to 12°C, and an 'aggressive' TI regime with venting at 20°C and a temperature that is allowed to fall to 10°C. Integration is over seven days. The simulations show:

- Energy savings are greatest in spring, summer and autumn when there are high levels of solar gain. Total energy use in summer is relatively small, but absolute savings given by TI at this time will be at least as high as at any other time (and are at their greatest in percentage terms). Savings are minimal in the winter months when there is little or no solar gain. A similar pattern of energy use is shown in Figure 51 (see opposite) for pot chrysanthemums
- On an annual basis, Basic TI gave annual energy savings of around 7% and 12% for modest and aggressive regimes respectively

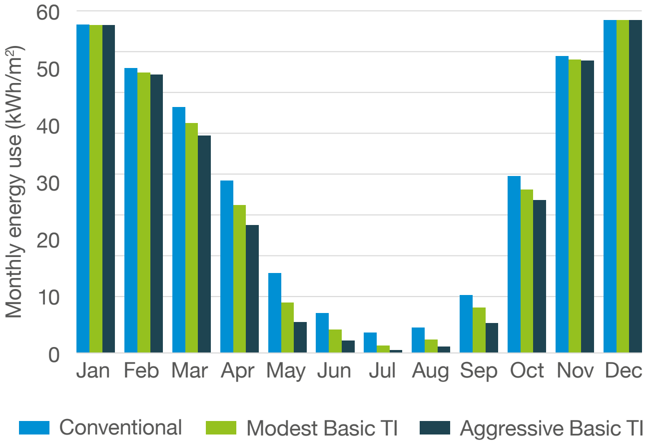


Figure 50. Monthly energy savings for an ornamental crop given by Basic TI – see text for details (simulated using a model developed in HH3611SPC)

## Running Basic TI

Basic TI is ideally run using a modern climate-control computer with inbuilt TI software. It can be applied without having TI software, but increased management time will be required to ensure that the correct conditions are maintained, and energy savings are likely to be less. Staff training to appreciate the dynamics of the greenhouse environment is likely to be beneficial.

## Getting started

Be conservative with the settings when using Basic TI for the first time. Energy savings will be relatively small, but so too the risks to crop yield and quality. Suggested starter limits are:

- Integration period – three days
- Minimum heating temperature – day and night the same at 1°C below normal night set-point
- Ventilation temperature – 1°C above normal set-point

More ambitious settings can be applied as confidence is gained.

## Seasonal changes

In practice, Basic TI set-points need to be modified throughout the year to take account of changing weather conditions:

Winter – raise the minimum heating set-point when solar radiation levels are low. This allows any accumulated energy credits to be used over several days. It also results in more stable temperature conditions in the glasshouse.

Spring – lower the minimum heating set-point to allow accumulated energy credits to be fully utilised.

Summer – reduce the ventilation set-point temperature to avoid accumulating credits that cannot be used.

When TI is working well and credits are being utilised (spring and autumn), the achieved average temperature will be close to the normal heating set-point temperature. However, this will be lower than the average temperature achieved in conventional regimes with the same heating set-point. This lower average can be avoided by raising the normal TI heating set-point.

## Crop trials of Basic TI

Commercial trials of Basic TI have been carried out on several high-input crops, incorporating best-practice humidity control. Heating temperatures have been set so as to prevent the day temperature falling below 18°C and the night temperature below 15°C. The day temperature has been allowed to rise to 26°C, but only when humidity conditions have allowed. The temperature integration period has been seven days.

## Pot chrysanthemum

Commercial trials in Hampshire in 2002/3 (AHDB Horticulture project PC 197) were followed up with semi-commercial trials in Warwickshire in 2004/5 (AHDB Horticulture project PC 206):

- Basic TI applied from final spacing to marketing gave a heating energy saving (weeks 43 to 21) of around 12% (65 $kWh/m^2$). Savings in individual weeks ranged from zero to 35% (see Figure 51)
- Humidity levels tended to rise especially high at night in late autumn and early spring. However, active humidity control ensured no detrimental effects on crop timing, growth, post-harvest quality or on the incidence of *Botrytis*
- Reduced boiler use during the day (and no heat store) in the TI regime meant there was less flue gas $CO_2$ available for enrichment. This decreased plant dry weight but had no obvious impact on perceived commercial quality or post-harvest longevity

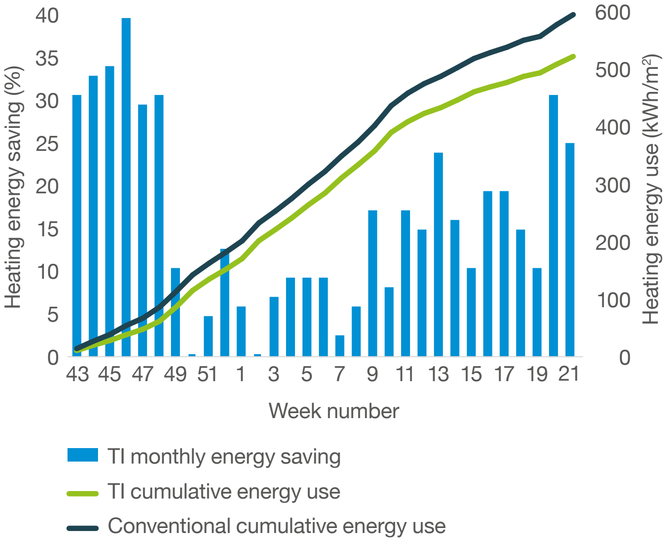


Figure 51. Cumulative heating energy use and weekly heating energy savings given by Basic TI on pot chrysanthemums (PC 197)

## Poinsettia

Trials of Basic TI were carried out on a commercial nursery in East Yorkshire in 2003–5 (AHDB Horticulture project PC 2017). TI was ended after week 45 when the potential for further savings was minimal.

- High-quality plants were produced, with no adverse effects on quality or post-harvest longevity. However, extra PGR applications were needed for height control
- Energy savings averaged around 15% during the first eight weeks when there were high levels of solar gain. However, savings declined greatly after this, especially as the need for active humidity control increased
- Overall, the energy saving was around 12%.
- Basic TI ought to work especially well with cool-temperature finishing to achieve a greater energy saving than by either method alone

## Other ornamental crops

Basic TI should work on most ornamental crops. Trials in AHDB Horticulture project PC 197 have shown, for example:

- Begonias can be grown successfully with Basic TI, giving energy savings (week 5 to week 21) of around 10% (15 $kWh/m^2$). Issues relating to humidity control, growth regulation, etc. are essentially the same as for pot chrysanthemums and poinsettias
- Lower-input crops such as pot bedding (including zonal pelargonium) can also be grown successfully with Basic TI. In this trial, TI was applied manually by adjusting the heating temperature to reflect the average temperature over the previous three days

## Tomato

Basic TI was tested on a commercial nursery in Lancashire growing classic rounds in 2002 and 2003 (AHDB Horticulture project PC 188a):

- Energy savings of 8.4% were given in year one and 5.9% in year two, with no loss of yield or quality (average annual saving of 39 kWh/m$^2$) (Figure 52). These savings were achieved without compromising humidity control (or increased *Botrytis*) since the TI settings were overridden whenever the humidity reached what was considered to be an unsafe level
- Reduced daytime ventilation in the Basic TI treatment in year one gave better $CO_2$ utilisation and an increased yield of 4.3%

Figure 52. High-quality tomatoes can be grown with Basic TI

## Other high-input edible crops

AHDB Horticulture project FV/PC 311 investigated whether TI during propagation subsequently increased the risk of bolting in endive, escarole, celery and Chinese cabbage in the field. Results suggest that this is not the case and that TI can be used safely; low night temperatures (10°C) during propagation did not increase the risk of field bolting, provided that a suitable mean temperature was maintained by high day temperatures. There are no reasons to believe that Basic TI cannot be adapted for use on any high-input edible crop. Peppers have been grown successfully with TI (AHDB Horticulture project PC 227a) with an integration period of three days and a minimum night temperature of 16°C.

## Extended TI – exploiting solar gain and screens

A limitation of Basic TI is that solar gain is a prerequisite and little energy is saved in the dull winter months when energy use is greatest (see Figure 52). However, as long as thermally efficient screens are fitted, energy savings can be made in winter by incorporating a routine low day set-point heating temperature into the Basic TI protocol (regardless of whether or not energy credits have been accumulated). By maintaining a high vent set-point, any solar gain is exploited under sunny conditions in the normal way, but any heating that is needed to maintain the average temperature on dull days is given preferentially at night when heat losses under the screen are reduced. Such Extended TI regimes can be implemented using conventional TI software.

## Monthly savings

Figure 53 shows the simulated monthly patterns of energy use for pot chrysanthemums growing in Extended TI, a conventional regime and in modest and aggressive Basic TI regimes.

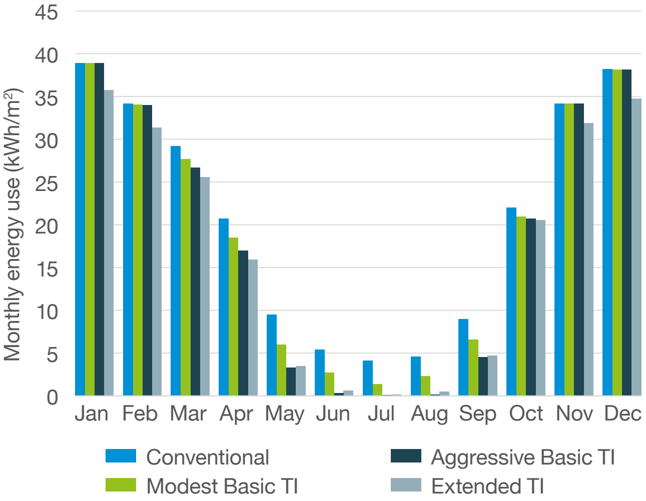


Figure 53. Monthly energy savings for pot chrysanthemums growing with Extended TI and other heating regimes (simulated using a model developed in HH3611SPC)

**Conventional** – set-point temperature of 18°C day and night, with 20°C venting.

**Modest Basic TI** – minimum heating temperature (when credits allow) of 16°C and venting at 23°C.

**Aggressive Basic TI** – minimum heating temperature (when credits allow) of 12°C and venting at 26°C.

**Extended TI** – minimum heating set-point (at all times) of 12°C and venting at 26°C.

Blackouts and supplementary lighting were assumed in all cases, together with humidity control at 90% RH. Integration was over seven days. The simulations show:

- Extended TI gives energy savings during the winter months when none are made using Basic TI. Extended TI also increases the energy savings in spring and autumn. Little or no heating energy is used with Extended TI (and Aggressive Basic TI) in June, July and August
- On an annual basis, Extended TI saved around 18% of the energy used in conventional growing. This contrasts with 8% and 13% for the modest and aggressive Basic TI regimes respectively

- Humidity control is particularly important in Extended TI regimes since humidity will tend to increase with fall in day temperature. Had humidity control not been factored into the simulation shown in Figure 53, the 18% saving would have risen to around 25%
- In general, energy savings given by Extended TI will be lower for crops grown with screens that are less thermally efficient than the blackouts used in pot chrysanthemum production. Energy savings will also tend to be lower for crops such as tomato with large leaf areas and which transpire more. This is because a greater heating input is required in such crops to counter the cooling effect of transpiration and the energy use for humidity control will be greater

Semi-commercial trials of Extended TI in Warwickshire (HH3611SPC) have shown that:

- Tomatoes can be grown successfully with a 14°C day temperature set-point and an elevated vent temperature, as long as the achieved average temperature is comparable to that of a conventional regime. Early yields were actually enhanced when a 24°C vent was set. In practice, the achieved day temperature was usually well in excess of the minimum heating set-point. However, to test the effects of a very cold winter/spring with little or no solar gain, a follow-up trial was done with active venting during the day at 15°C. This reduced early yields, but the cumulative yield over the year was unaffected. Extended TI increased fruit size, so care is needed to maintain plant balance
- Good-quality pot chrysanthemums can also be produced in Extended TI with the day heating set-point reduced from 18°C to 12°C and vent temperature raised to 26°C. Flowering was delayed by only 1–2 days and plants tended to be larger and heavier (Figure 54) as a consequence of the actual day temperature being frequently much higher than the set point. A follow-up trial tested the effects of Extended TI with achieved low day temperatures (average of 15–16°C) by setting the vent temperature to 14°C and using high night temperatures to maintain the overall average. In this case, delays of up to two weeks were experienced, indicating that Extended TI cannot be taken to extremes
- Pansies and petunias can also be grown successfully with Extended TI, both as plugs and after potting on, and a high vent set-point increased day temperature and hastened flowering. Plants grown in a trial with low achieved day temperatures were generally shorter and more compact than control plants and required less PGR treatment (Figure 55). This reflected ‘negative DIF’ conditions (day temperature lower than night temperature). Extended TI plants grown with low achieved day temperatures showed a flowering delay of up to one day in pansy and up to three days in petunia

Figure 54. Pot chrysanthemums (‘Covington’) grown conventionally (left pair) or with Extended TI (right pair). The left pot in each pair is without humidity control, while the right pot has been grown with active humidity control (HH3611SPC)

Figure 55. Pansies grown in Extended TI regimes with day heating set-points (left to right) of 8°C, 12°C, 16°C and 20°C. Active venting gave low achieved day temperatures, but all had the same average temperature (no PGR applications given after potting) (HH3611SPC)

## Wind speed

Wind increases glasshouse heat losses and commercial trials in the 1990s demonstrated the feasibility of growing tomatoes in a temperature-averaging regime where the set-point heating temperature was varied continuously to reflect wind speed (AHDB Horticulture project PC 049) (Figure 56). Energy was saved by lowering the heating set-point as the wind speed increased and raising it again as the wind speed dropped (wind-speed modulation). Wind-speed modulation is a form of TI and can be carried out manually or by climate-control computer if this feature is installed. Savings in older glasshouses will be around 5–10% but will be less in better sealed glasshouses or when screens are in use.

Figure 56. Weather station used to monitor conditions outside the glasshouse

## DROP

It can be expensive in energy terms to try to prevent the glasshouse air temperature falling when screens are removed in the morning and the warm air under the screen is replaced by unheated air from above. Best practice is to allow the glasshouse temperature to start falling around one hour before the screens are removed, allow it to remain low for a period, then to gradually increase it, making full use of solar gain, so that the average 24-hour temperature is maintained. This planned temperature reduction is known as DROP and its total daily duration (after screens are removed) is usually around three hours. It is a specialised form of TI and may save 1.5–2.0% of energy. In addition, by giving more compact plants, it reduces the need for PGR treatments. Its value in this latter regard is such that DROP is frequently used at dawn even in unscreened glasshouses. AHDB project trials of DROP have been carried out using poinsettias (PC 041, 155), pot chrysanthemums (PC 092/092a) and bedding plants (PC 041a).

**Poinsettias –** DROP reduced the need for PGR treatment and advanced marketing by around seven days. Paler green leaves resulted when DROP was given continuously, but leaves quickly regained colour once treatment ended around week 43–46 (to prevent undesirable reductions in the size of coloured leaves and bracts). There were no adverse effects of DROP on quality or post-harvest longevity.

**Pot chrysanthemums –** DROP reduced the height of winter-stuck pots lit continuously at 4.8 W/m$^2$ by around 11% and appeared not to interfere with speed of flowering.

**Bedding plants –** DROP reduced height in all four species tested: impatiens, geranium, petunia and salvia (Figure 57). The most effective treatment was a two-hour reduction in temperature starting at sunrise. There were no subsequent adverse effects when the young plants were grown-on.

### Key points for glasshouse temperature

- By keeping conditions as constant as possible, the crop balance can be found and maintained. Ideally, the variation in temperature should be no more than 2°C across the glasshouse compartment and various methods should be employed to maintain a more consistent climate
- Reducing the heating set-point by 1°C can typically save around 10–13% energy. However, account needs to be taken of the effects of lower temperature on crop timing, yield and quality
- Temperature integration (TI) saves energy, with little impact on yield and quality. In Basic TI, vent temperature is raised to gain energy ‘credits’ from solar gain and these are ‘spent’ by lowering heating set-points at other times when energy use would have been high. Trials incorporating best-practice humidity control have given energy savings of 6–12%
- Greater savings are provided by routinely incorporating a low day-heating set-point and preferentially heating the glasshouse at night under thermal screens (Extended TI). This gives savings in the winter months when there is little solar gain. Adverse effects on crop yield and quality can be overcome with good crop management
- Regulating temperature on the basis of wind speed can save 5–10% of energy in older glasshouses without screens
- Using DROP may save 1.5–2.0% of energy and reduce the need for PGR treatment. The temperature is allowed to fall at dawn or before screens are removed, but is increased again several hours later so as to maintain the average 24-hour temperature

Figure 57. Salvias growing at Efford with DROP (left) and without DROP (right). No PGRs were used (AHDB Horticulture project 041a)

# *The use of screens*

## Background

The first widespread use of internal screens in glasshouses in the UK was as blackout covers for the control of flowering in crops such as chrysanthemum. In the late 1970s, screens began to be installed specifically to save energy (thermal or energy screens). Depending on their construction, overhead and vertical screens can reduce heat losses from the greenhouse through leakage, infrared radiation and convection. Thermal screens reduce heat loss and their use is now commonplace in commercial glasshouses. The use of screens has been one of the biggest contributors to reducing the heat demand of glasshouses. Developments in materials, improving light and moisture transmission while retaining insulation properties and better operational and control systems have all increased the energy-saving potential. Energy saving and humidity control were considered to be the main functions of energy screens, but it is becoming increasingly clear that achieving a uniform environment is now equally important. Where a uniform environment can be achieved, growing at a higher relative humidity (RH) with less risk of condensation and, therefore, reduced energy consumption is possible.

## Energy screens

### Retractable screens

Most screens are now retractable (Figure 58) and are preferable to fixed screens, since they can be opened and closed as required. They are typically constructed of polyester strips mounted on a textile carrier and have a high light transmission (up to 89% direct and 92% diffuse, depending on conditions), a good insulating effect (instantaneous energy savings of around 40%), allow the transmission of water vapour, have anti-condensation properties and are virtually non-shrinkable. Most importantly, retractable screens are constructed to pack away tightly when not in use (frequently as a concertina package) and to have only a minimal shading effect.

Figure 58. Retractable screens

A range of folding, rolling and sliding systems have been devised to open, close and pack away the screens, but sliding systems are used most widely because of their easier and cheaper construction. Screen materials are durable, resistant to ageing from temperature, humidity, chemicals and ultraviolet radiation and have a high resistance to wear and tear. In practice, a working life of 8–10 years can be expected. With capital costs for a screen in the region of around £5/m$^2$, the payback period is typically around 24–30 months.

Modern screens have energy-saving properties which will benefit all high-temperature crops. However, the variations in light transmission and diffusivity need to be carefully considered against the crops and their response to these. Peppers, tomatoes and most ornamental crops respond very well to diffuse light, while latest research indicates strawberries receive a lesser benefit from diffuse light, so it is important to consider which screen material will provide the best combination of energy saving and light quality.

### Double screens

Multiple horizontal screens provide the opportunity to benefit from greater energy saving by further reducing air leakage and increasing insulation. They also allow improved tailoring of the conditions beneath the screens, while maintaining a homogenous environment. A double screen will not save twice as much energy as a single screen; this is because the second screen will be deployed less often than the first. A well-fitted single screen utilising new materials can reduce energy consumption by up to 47%. Fitting an additional screen will increase this energy saving to 63%. Screens only save energy when closed, so there will be no energy saving when the screen is fully open and reduced energy saving when the screen is gapped or if the material is suffering wear and tear.

Double screen use is becoming more common. To extend the life of a single screen, a new, second screen can be added so that the structural beam has a screen connected to the top and bottom edge. These are fitted so they retract from different sides to allow gapping, which minimises energy loss.

## Wear and tear

The constant use of the screens over thousands of operational hours not only results in tears and gaps in the material, which reduce their energy-saving potential, but also the accumulation of dirt and grime (which makes daytime deployment inadvisable, as light transmission is reduced). It is particularly important to let the screen dry out before retracting to prevent algal build-up on the moist surface. Regular cleaning regimes, such as fogging, will help to maintain light transmission. Screen suppliers claim that screens can lose 2–3% of their energy-saving and light-transmission properties annually due to wear and contamination.

In most cases, the existing mechanical parts of the screen system (motors, pulleys and wires) will be serviceable even after a number of years, so replacement of the old screen material will bring the whole system up to a modern standard. The cost of replacement will vary depending on the age and dimensions of the greenhouse but will typically be in the region of £2.50/m$^2$. Replacing screens is an ideal opportunity to make use of new screen materials on offer, such as materials that promote diffuse light or those with improved light transmission when wet.

## Commercial trials of energy screens

Commercial trials demonstrating the potential value of retractable screens have been carried out on tomatoes in East Yorkshire (AHDB Horticulture projects PC 198/198a) and sweet peppers in Essex (projects PC 227/227a).

### Tomato trial

Screens (Ludvig Svensson SLS10 Ultra Plus) were drawn over the crop when the light fell below 40 W/m$^2$ (total global radiation) and the difference between the inside and outside temperatures exceeded a preset value that varied with such factors as stage of crop growth and wind speed. The screen-use strategy was essentially conservative, but it was still found that:

- Thermal screens saved around 13% energy (Figure 59), with no reduction in yield. The saving was mainly made over winter, between weeks 41 and 17, and equated to an annual energy saving of about 100 kWh/m$^2$
- Screen gapping generally gave satisfactory humidity control and there was no increased incidence of *Botrytis*. However, some venting and reheating was also needed early in the season
- Irrigation regimes needed to be adjusted slightly to take account of reduced night-time water loss under the screens

### Sweet pepper trial

The energy-saving potential of a retractable screen (Ludvig Svensson SLS10 Ultra Plus) was compared with that of a temporary, fixed, plastic screen in place from planting in week 51 to week 5. The retractable screen was kept closed until week 3; thereafter, it was open as long as preset parameters were satisfied (see Deployment strategy below). Humidity control was achieved by gapping, then venting and reheating. High-quality peppers were produced and it was shown that:

- The retractable screen saved up to 15.5% more heating energy (90 kWh/m$^2$), with no reduction in total yield at the end of the season

## Screens and humidity

Closed screens can increase the glasshouse humidity. Venting above the screen and controlled gapping, possibly followed by reheating, is necessary to control this. Good operational practices can minimise the problem. Controlled gapping allows cold, dry air above the screen to mix with the moisture-laden air beneath and will frequently be sufficient to control humidity, without further recourse to venting and reheating. Screen gapping is generally set to operate on a humidity influence so that the screen gap gradually increases to around 15% as humidity rises. Beyond this point, gapping has no further effect and it is common commercial practice, if humidity is still not under control, to open the screen fully and to move on to the next steps of venting and reheating.

## Temperature stratification

Locating the measuring box just below the screen where warm air tends to collect can cause the pipe heating to turn off and vertical air-temperature stratification to occur. Under these circumstances, crops close to the floor can experience lower temperatures than those that have been set and this has in the past been the cause of significant flowering delays in chrysanthemum crops. The problem can be countered by locating temperature sensors closer to the crop and by the use of circulation fans.

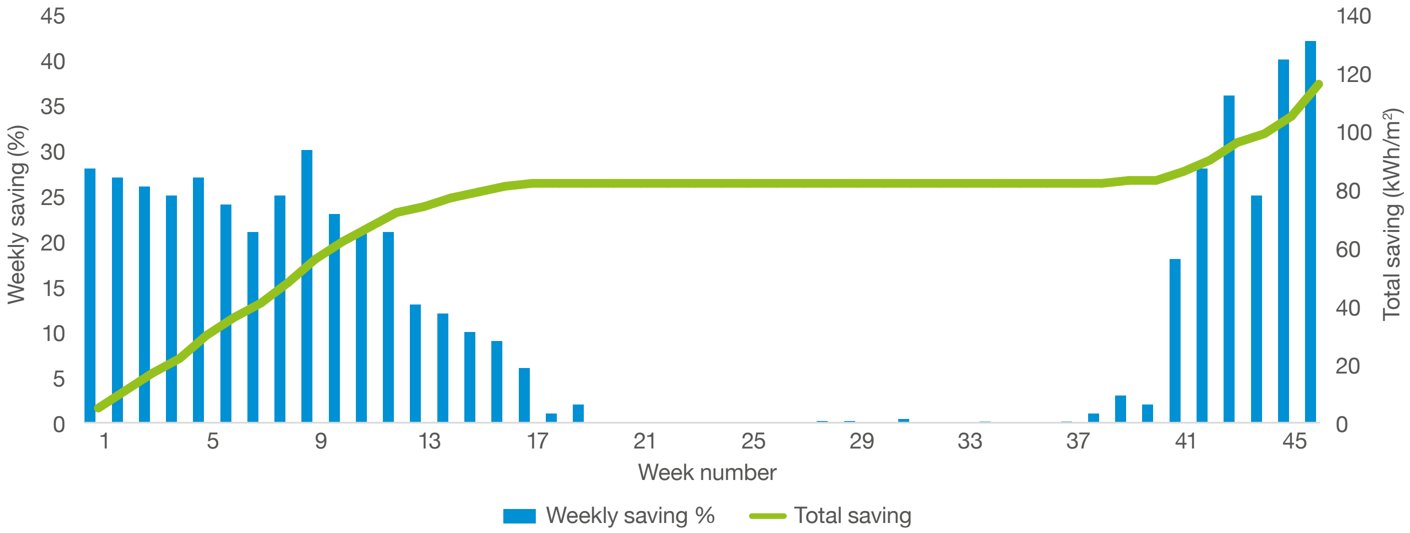


Figure 59. Average energy savings in tomato production provided by the use of a thermal screen (AHDB Horticulture projects PC 198/198a)

Horizontal air-temperature stratification can similarly develop when screens are used. This is because closed screens cause the heat loss from the greenhouse roof to be reduced but not that from the greenhouse side walls. As a consequence, greenhouse air temperatures will tend to be lower near the side walls. This can be overcome by the use of side screens (Figure 60), by the installation of additional side heating pipes or, as suggested above, by the use of circulation fans.

When screens are drawn closed, the air above them is isolated from the rest of the glasshouse and it becomes stagnant and colder. It does move slowly and, over the closed period, temperature differentials above the screens increase, with colder air slowly gathering round colder parts of the structure or where it is driven by external wind pressure. Also, with sloping sites, colder, heavier air gathers towards the lower end. One solution has been to reduce air movement above the screens, rather than promote it. Compartmentalising the area above the screen using what have become known as 'apex seals' can achieve this. The installation of apex seals, consisting of vertically orientated transparent screen material at 30–40-metre intervals along the bay above the screen, will typically reduce temperature variations by 50%.

An additional measuring box above the screen can be used to monitor temperature and humidity and to help determine the optimum moment to open the screen, when the conditions are right.

Figure 60. Side screens can reduce horizontal temperature stratification and save energy

## Deployment strategy

As an ideal to maximise energy saving, screens should be closed whenever humidity levels are acceptable and the value of the energy saved is greater than that of the yield lost due to reduced light. When light levels are low, the loss of yield will be small, especially when the screen has a high light transmission. It is better, therefore, to operate the screen on the basis of a light threshold rather than simply using dawn and dusk. Experiments on tomatoes in Holland have concluded that it is more cost-effective to open the energy screen at 50 W/m$^2$ than at 5 W/m$^2$ (total or global radiation). Even though the prolonged screening treatment received 0.34% less solar radiation, 3.5% extra energy was saved and growth and production were not affected. Theoretical calculations showed that screen opening at outside light levels of 50 W/m$^2$ was more or less optimal, although even at 150 W/m$^2$ the energy savings were greater than the production losses. This strategy of using a light threshold can be further improved by also taking into account outside temperature (or the difference between inside and outside temperature) as an indicator of energy use. This may mean that, over the winter months, the screen is closed for much of the time.

While energy savings can be maximised by increasing the number of hours that the screen is used, it is advisable initially to use conservative settings and then to become more ambitious as confidence is gained.

Screen opening tends to cause a temporary drop in greenhouse air temperature and, to minimise this, screens should be opened progressively at the start of the day. It is also important to gap screens for humidity control.

The initial settings used in the third year of the sweet pepper trials (AHDB Horticulture projects PC 227/227a) may provide a good starting point (Table 8). The screen was open whenever the light (outside) exceeded 175 W/m$^2$. Below this level, its operation depended on the difference between inside and outside temperature rather than just outside temperature alone. This gave more effective control, since the temperature difference automatically adjusted with change in heating strategy. When it was dark and the wind speed was 3 m/s or less, the screen was closed whenever the outside temperature was 7°C or more below the inside temperature (conditions giving a high potential energy loss from the glasshouse). This difference was progressively reduced with increase in wind speed to reach a value of 4°C at 6 m/s or higher. This was done to take account of the additional heat losses that occur with increase in wind speed. Conversely, the temperature difference was progressively increased by up to an extra 8°C with rise in outside light level from 0 to 175 W/m$^2$. For example, at 100 W/m$^2$ (and with a wind speed of 3 m/s or less) the screens were only used when the temperature difference (inside–outside) was greater than 11.5°C. The temperature difference from 10:30am to 02:00pm was set at a higher value than that between 02:00pm and 10:30am to reduce the midday use of the screens.

Table 8. Thermal screens control set-points used in pepper production (PC 227a)

| Factor | Time period | Value | Range |
|---|---|---|---|
| Radiation limit | All the time | 175 W/m$^2$ | N/A |
| Inside–outside temperature difference | 10:30–14:00 | 9°C | N/A |
| | 14:00–10:30 | 7°C | |
| Wind influence on temperature difference | All the time | Proportional decrease of up to 3°C | 3–6 m/s |
| Light influence on temperature difference | All the time | Proportional increase of up to 8°C | 0–175 W/m$^2$ |

## Next Generation Growing

The use of screens is an important part of ‘Next Generation Growing’, a Dutch initiative set to achieve ambitious energy savings in the greenhouse sector. It is focused on good plant ‘balance’, with close control of temperature and humidity, which produces an environment that the plant needs but with much reduced energy use.

As with most techniques in NGG, the effective use of screens relies on good information being available to advise on the conditions around them. It is highly recommended that a measuring box is fitted above the screens, in the apex of the greenhouse, to do this. As screens are kept shut for longer, growers must understand the potential for water exchange when their screen is closed. Manufacturers should be able to advise quantities of water that can be transferred by screen materials. By venting above a closed permeable screen, moisture in the air will be expelled without the need for heat.

On clear nights, the radiant cooling effect of the very cold night skies means that the effective temperature that plants ‘see’ can be as low as –60°C. Thus, the head of the plant cools, even though the glasshouse air temperature appears at set-point. Screens can be used to reduce this effect. Keeping screens closed for longer in the morning until the air temperature above them is within 5°C of the glasshouse air temperature, even when light levels are good, will reduce the amount of additional heat needed to warm up the glasshouse. While radiant cooling is not specific to NGG, the additional use of screens to mitigate its effects is one of the main considerations.

Another key technique of NGG is the use of windside vents in conjunction with the leeside. This has two benefits; the first is that it creates more air movement above a closed screen. The second benefit is the ability to use lower vent openings than with leeside ventilation alone, which helps to create more resistance between the glasshouse climate and the outside.

Under a closed screen, fans may be essential to maintain sufficient air movement in the crop, especially when little heating is required to maintain the desired glasshouse temperature. Using fans is one way to even out the climate by increasing air movement; it also has the effect of keeping an active climate, which improves plant conditions. However, more important is the screen strategy and not using gaps.

## Other screens

### Fixed screens

It has been shown in the past that fixed, unperforated polythene screens can reduce heat losses from the glasshouse by 40–60%, depending on whether they are single or double layered, and that energy savings increase with rise in outside wind speed (Figure 61). However, fixed screens in use today are most likely to be single layers of perforated polythene and energy savings will be slightly less. Perforated covers are chosen to reduce the build-up of humidity that can occur below fixed screens, but perforations will not completely overcome the problem. All fixed screens will also reduce light transmission to the crop below. Because of their potentially adverse effects on crop yield and quality, fixed screens are normally used only for relatively short periods during the winter months in years when energy prices are high. Adverse effects are not as great in the winter, because light loss is less of a consideration and plant transpiration is at its lowest. This practice does mean, however, that there are annual installation and removal costs and there can be problems of polythene disposal. On the positive side, though, material costs are relatively low.

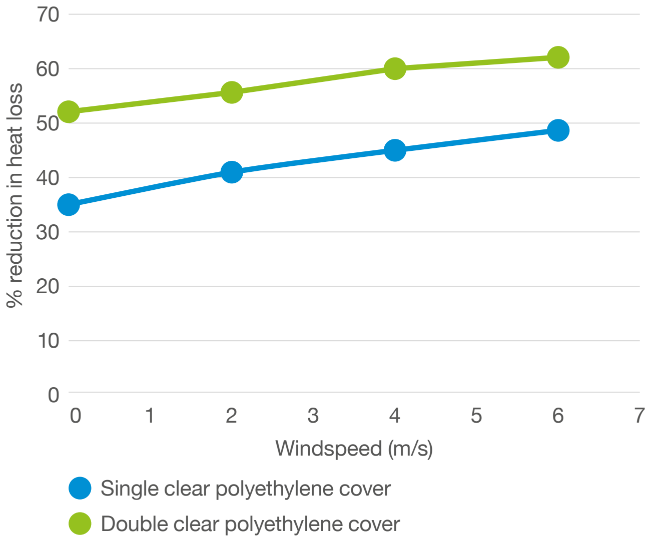


Figure 61. Reduction in instantaneous heat loss from the glasshouse due to single- and double-layer polythene covers for a range of wind speeds (after Bailey, 1979)

### Shade screens

Shade screens (Figure 62) are designed to be used in summer to provide protection to plants that are vulnerable to damage by high solar radiation. They are usually made up of strips of clear polyester and strips of foil-based materials to reflect incoming solar energy. They often also have 'open' strips to promote air movement across the screen. Shade screens can play a part in energy saving since, when drawn across, they give instantaneous energy savings of between 20% and 70%, depending on the proportions of polyester, aluminium and open strips used in their construction.

Shade screens may provide a good compromise in glasshouses where energy-intensive crops such as poinsettia are grown during the autumn/winter and others requiring solar protection are grown in the summer. As described earlier in 'Double screens', a multiple horizontal screen installation with a shade and energy screen would work best in this case.

## Blackout screens

Blackout screens (Figure 63) are impermeable to light and are principally used to regulate flowering in crops such as chrysanthemum. The materials used are generally of a heavy woven construction and, as a result, do not fold into such small packs as energy screens when retracted. However, the screens do give instantaneous energy savings of up to 75%. Care has to be taken with humidity control, however, since blackout screens generally have poor breathability. Like energy screens, blackout screens will usually be in place over the crop whenever it is dark outside. They are also frequently in place for some hours after sunrise and before sunset to satisfy photoperiod requirements. When photoperiod is not an issue, though, they tend to be opened at lower light levels than are typically used for energy screens to prevent excessive crop shading.

With greater production and increased use of LEDs, there has been an increased use of blackout screens to avoid light pollution and satisfy planning requirements.

Figure 63. Blackout screen gapped over spray chrysanthemums to improve the harvesting environment

Figure 62. Shade screen used in summer over pot chrysanthemums

## Key points for use of screens

- Fixed, perforated polythene screens reduce heat loss from the greenhouse but reduce crop yield and quality if kept in place for too long. Their use in the winter months is key, but they can be used well into the spring
- Retractable energy-saving screens (Figure 58) are preferable to fixed screens since they can be opened at times of high solar radiation and when humidity is becoming a problem. They typically have a high light transmission and diffusivity, a good insulating effect giving instantaneous energy savings of around 40%, allow the transmission of water vapour, have anti-condensation properties and are virtually non-shrinkable
- Annual energy savings of around 13% were achieved in a commercial tomato trial using a retractable screen (and conservative settings). Savings were mainly made over winter, between weeks 41 and 17, and there was no loss of yield
- In a sweet pepper trial, retractable screens saved up to 15.5% more heating energy (90 kWh/m$^2$) than a temporary screen. The extent of the savings depended on the screen deployment strategy and the control set-points used
- Screens tend to increase the glasshouse humidity and venting above the screen; controlled gapping and reheating may be necessary to control this
- The use of double screens can save even more energy and improve humidity control by allowing gapping of one or other of the screens
- Screens can cause vertical and horizontal air-temperature stratification and this may result in plants experiencing lower temperatures than those set. The problem can be countered by the use of circulation fans and, in the case of horizontal stratification, side screens and/or additional side heating pipes
- The installation of energy barriers (known as apex seals) consisting of vertical transparent screen material at 30–40-metre intervals along the bay above the screen will typically reduce temperature variations by 50%
- Shade screens and blackout screens can also contribute to energy saving by giving instantaneous energy savings of up to 75%, but use has to be counterbalanced by the reduction in light
- Using temperature integration (TI), and preferentially heating the glasshouse at night under thermal screens, gives energy savings in the winter months when there is little solar gain
- Allowing the temperature to fall around one hour before screens are opened, then increasing it again several hours later so as to maintain the average 24-hour temperature (DROP), can save up to 1.5–2.0% of energy and reduce the need for PGR treatment

# Further information

## AHDB publications

Factsheet 04/08 – Energy saving in tomato production

Technical guide (2015) – Lighting: The principles

Technical guide (2015) – Lighting: In practice

Technical guide (2015) – Lighting: The review

Technical guide (2015) – Supplementary lighting: Equipment selection, installation, operation and maintenance

## AHDB reports

PC 041 (1994) Pot and bedding plants: control of plant stature by manipulation of day and night temperatures (DIF regimes)

PC 041a (1991) Bedding plants: to assess the use of DIF during growing on and its influence on shelf life

PC 049 (1994) Optimal control of greenhouse climate

PC 071c (1997) Poinsettia: an investigation of the growth and shelf-life performance of new poinsettia cultivars at two different temperatures and an assessment of the costs of labour and energy in production

PC 071d (1998) Poinsettia: investigation of the impact of temperature and light during the phase of growth and an assessment of the interaction between marketing stage and shelf-life

PC 092 (1994) Chrysanthemums: the combined influence of supplementary lighting and difference in temperature (DIF) on winter quality of commercially grown varieties

PC 092a (1995) Chrysanthemums: the influence of combined supplementary lighting regimes and pot spacings on the quality and economics of the winter production of pot chrysanthemums

PC 092d (2002) Evaluation of the efficiency of production of winter pot chrysanthemums at 2000 lux and 4000 lux supplementary lighting

PC 110 (1996) The influence of $CO_2$ concentration and plant density on tomato yield and fruit quality

PC 110a Tomatoes (2002) Guidelines for $CO_2$ enrichment, Grower guide

PC/HNS 121 (2002) Integrated chemical and environmental control of grey mould (*Botrytis cinerea*) in protected container-grown ornamentals

PC 128 (2002) The efficient use of light during bedding plant production (LINK)

PC 155 (2001) Poinsettia: strategies for the reduction of plant growth regulator use

PC 159 (2001) Cucumbers: the role of environmental and agronomic factors in carbon dioxide toxicity

PC 176 (2001) Protected crops: improving the efficiency of supplementary lighting equipment and installations

PC 188a (2004) Enhancing the performance of temperature integrating climate control strategies – a commercial demonstration

PC 197 (2004) Protected ornamentals: a demonstration of the use of advanced greenhouse environmental controls for energy saving

PC 198 (2005) The use of thermal screens for energy saving and greenhouse climate management in protected edible crop production. Performance optimisation

PC 198a (2006) The use of thermal screens for energy saving and greenhouse climate management in protected edible crop production – performance optimisation

PC 206 (2005) Maximizing energy saving in the production of protected ornamentals using temperature integration: the conflict with humidity control and $CO_2$ enrichment

PC 207 (2005) Protected ornamentals: improved guidelines for humidity measurement and control when using advanced climate control strategies

PC 227 (2006) Optimising greenhouse environment and energy inputs for sweet pepper production in the UK – a commercial demonstration of the use of thermal screens and advanced climate control

PC 227a (2007) Extension to project PC 227: Optimising greenhouse environment and energy inputs for sweet pepper production in the UK – a commercial demonstration of the use of thermal screens and advanced climate control

PC 228 (2005) Tomatoes: an investigation into apparent yield improvements associated with the installation of a micro-gas-turbine CHP facility

PC 265 (2007) An investigation into the technical and financial viability of biomass heating systems for greenhouse horticulture in the UK

PC 269 (2008) Sweet peppers: The use of thermal screens for summer shading on plant growth and fruit quality

PC 278 (2011) The development and commercial demonstration of ducted air systems for glasshouse environmental control

PC 285 (2008) Assessing the benefits of deleafing in peppers

PC 285a (2011) Assessing the benefits of deleafing in peppers

PC 287 (2009) An investigation into the effects of flue gas quality on tomato plants

PC 296 (2012) Examining the lighting requirements for daylength control so as to assess the suitability of energy saving bulbs

PC 301 (2011) Targeting of humidity control, through the use of stem temperature measurements, to reduce stem botrytis and save energy in tomato production

FV/PC 311 (2009) Optimising the propagation environment for endive, escarole, celery and Chinese cabbage.

PO 010 (2012) LED Lighting for horticultural applications – establishing the economics of current hardware offerings

PE 003 (2011) $CO_2$ enrichment in the future: a technical and economic analysis of alternative $CO_2$ sources

PE 013a (2015) Refrigeration-based dehumidification: energy performance and cropping effect on commercial nurseries. 2nd year trials

PE 021 (2015) Targeted $CO_2$ enrichment management for modern varieties in long season tomato crop production in the UK

CP 085 (2017) Securing skills and expertise in crop light responses for UK protected horticulture, with specific reference to exploitation of LED technology

CP 125 (2017) Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs

CP 139 (2015) Knowledge Transfer: Commercial review of lighting systems for UK horticulture

CP 147 (2016) Optical coatings to increase the yield and quality of protected salads, fruit and ornamental crops

CP 164 – SPECTRA: Whole plant spectral response models

## Other information

AHDB Event (2016) Manipulating light for horticulture

Defra (2000) – Optimising the aerial environments for protected ornamental crops.

Defra (2003) HH3603SPC – Improving the efficiency of PC in winter through the use of low energy light intensity, long day lighting

Defra (2003) HH1330SPC – Energy efficient production of ornamental species

Defra (2007) – AC0401 Direct energy use in agriculture: opportunities for reducing fossil fuel inputs

Defra (2008) AC0407 – Reducing the carbon footprint of glasshouse production through the use of knowledge transfer and novel engineering solutions

Defra (2008) HH3611SPC – Energy saving through an improved understanding and control of humidity and temperature

### Growsave Technical Updates

LED lighting for horticultural applications (2011)

Air movement (2013)

CO2 – its current status in horticulture (2013)

CO2 from biomass boilers for greenhouse enrichment – the ProSelect GC6 System (2014)

Diffuse glass for greenhouses (2014)

Screens (2015)

Circulation fans (2015)

Enabling diffuse light (2016)

Measuring energy (2016)

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# Glossary

| | |
|---|---|
| AD | Anaerobic digestion |
| AH | Absolute humidity |
| CF | Compact fluorescent |
| CHP | Combined heat and power |
| DD | Day degrees |
| DE | Day-extension |
| ETFE | Ethylene tetrafluoroethylene |
| HD | Humidity deficit |
| HEL | Human exposure limit |
| HPS | High-pressure sodium |
| IRGAs | Infrared gas analysers |
| LDP | Long day plants |
| LED | Light-emitting diodes |
| LPG | Liquefied petroleum gas (propane) |
| NB | Night-break |
| NGG | Next Generation Growing |
| nm | Nanometres |
| PAR | Photosynthetically active radiation |
| PPFD | Photosynthetic photon flux density |
| RH | Relative humidity |
| SDP | Short day plants |
| TI | Temperature integration |
| VPD | Vapour pressure deficit |

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