Factsheet 09/09

Protected crops

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Horticultural Development Company

Stoneleigh Park
Kenilworth
Warwickshire CV8 2TL
T: 0247 669 2051
E: hdc@hdc.org.uk

Energy management in protected cropping: Horticultural lighting

Steve Adams and Allen Langton, Warwick HRI, and Chris Plackett, FEC Services Ltd

This factsheet in a series on energy management discusses the energy implications of using horticultural lighting, and considers how energy inputs can be minimised whilst still maintaining plant yield and quality (Figure 1).

Summary points

- Supplementary lighting can account for 15% or more of a grower's total 'delivered' energy. PAR (photosynthetically active radiation) determines growth and yield and this should be measured as W/m² or µmol/m²/s.

- The high pressure sodium (HPS) lamp is still first choice for supplementary lighting. 600 W and 1000 W lamps are more energy-efficient than 400 W lamps, but typically need to be mounted higher. Routinely replace lamps after about 10,000 hours of operation. Reflectors should be chosen in relation to lamp wattage and mounting height, and should be regularly cleaned.

- Crop shading needs to be minimised. Electronic ballasts are more compact than older types and cause less shading. 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.

1 Horticultural lighting improves plant yield and quality but increases energy use

- Tungsten lamps can, in some cases, be replaced by compact fluorescent lamps for photoperiodic lighting. However, these need to deliver similar levels of PAR, and direct lamp replacement may not be possible. Fluorescent lamps may also have only a limited effectiveness in promoting flowering in some long-day plants.
- LED lights have significant future potential for use in horticultural applications since it should be possible to design these to provide precisely specified spectral outputs. However, significant advances are still needed before they can be used widely for supplementary and photoperiod lighting.
- Currently, Combined Heat and Power (CHP) is economically viable for the generation of electricity for supplementary lighting only when there is an insufficient mains supply (and upgrade costs are very high) or when alternative uses can be found for the electricity during periods when lighting is not needed.
- The heat from supplementary lighting will offset glasshouse heating costs. For example, a typical supplementary lighting installation over an ornamental crop will provide heating of around 60 kWh/m^2/year.

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).

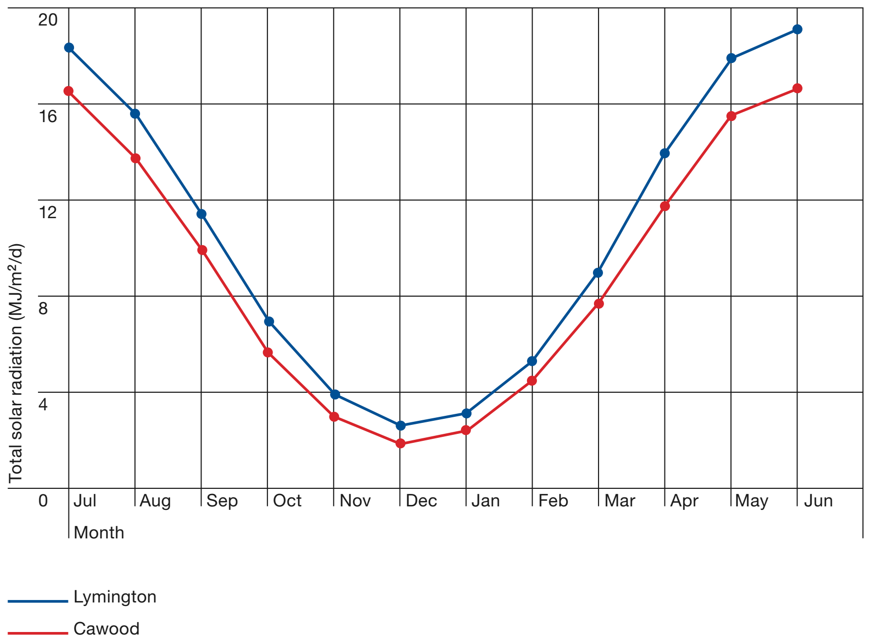
Supplementary lighting is used mainly during the late autumn, winter and early spring when average solar radiation levels are low (Graph 1). It increases plant photosynthesis and, as a consequence, growth, yield and product quality. As a generalisation, 1% extra light gives around 1% extra crop dry weight.

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 sector, 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 HH3603SPC.

A recent Defra report (AC0401) indicates that lighting in protected cropping accounts for around 122 GWh of energy use, only around 2.3% of the total in the sector. Nevertheless, for an individual grower, this usage can amount to 15% or more of the total on the basis of 'delivered' energy, or 28% or more of the total when energy used or lost in the manufacture of electricity and its transmission is added in. For such growers, reducing the energy input of lighting whilst still maintaining yield and quality, is an important objective.

Graph 1 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 PAR (photosynthetically active radiation) component of solar radiation and lamp emissions that is important for plant growth, since this determines photosynthetic activity. PAR comprises radiation between 400 and 700 nanometres (nm), and constitutes about 45% of total solar radiation (Graph 2). Efficient lamps for supplementary lighting will have a high proportion of their output as PAR.

PAR can be measured directly in energy terms using a PAR energy sensor as Watts per square meter (W/m^2 PAR). PAR can also be measured in photon terms using a quantum sensor as micro moles per square meter per second (μmol/m^2/s). 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 W/m^2 and μmol/m^2/s depend on the particular spectral emissions of the light source in question (see Table 1).

Both W/m^2 and μmol/m^2/s represent instantaneous PAR values, and both can be summed over time to give PAR integrals (eg 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 (eg 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 1, 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.

Graph 2 Components of solar radiation transmitted into the glasshouse

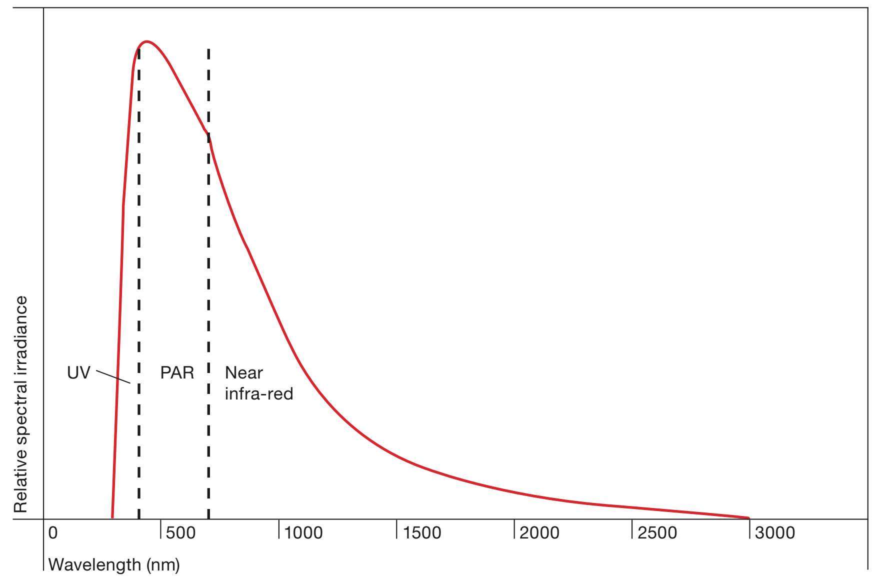


Table 1 Multiplication factors to convert from W/m^2 PAR to μmol/m^2/s PPFD and lux (Thimijan and Heins, 1983)

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

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 or more as that provided by supplementary lighting (see Factsheet 05/09). 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' below). Information on lamps, luminaires (into which the lamps fit), reflectors etc is provided in project report PC 176 and Grower Guide 'Supplementary lighting – equipment selection, installation, operation and maintenance'.

Lamps and ballasts

Currently, the lamp of choice for supplementary lighting is the high pressure sodium (HPS) (Figure 2). This is relatively cheap to purchase and run, and specialised horticultural versions are now available with excellent lamp efficiency (μmol/s/input W). Table 2 shows, for example, that current 400 W horticultural HPS lamps are around 15% more efficient than standard 400 W HPS lamps designed to aid human vision. HPS lamps have typically been rated at 400 W, but 600 W and 1,000 W lamps are also available and these tend to be somewhat more efficient. The 230 V, 600 W lamp in Table 2, for example, has an efficiency of 1.64 μmol/s/input W (17% more energy efficient than the HPS standard). Operating on a 400 V electrical supply increases energy efficiency and Table 2 shows that the 400 V, 600 W horticultural lamp has an efficiency of 1.72 μmol/s/input W (23% more energy efficient than the HPS standard).

The metal halide (MH) lamp is typically 14% less efficient than the standard HPS lamp, and 25% less efficient than a modern horticultural HPS lamp (Table 2). It also tends to have a higher capital cost and, for these reasons, its use in commercial horticulture is currently restricted.

Electronic ballasts are now beginning to replace traditional electro-magnetic types. These are about 5% more energy efficient (Table 2), and are more compact and lighter. In theory, electronic fittings can be used to dim the output of the lamps, allowing the user to tailor lamp output to the needs of the crop. However, this currently causes the energy efficiency of the lamp to fall off quite significantly, and for this reason, the feature is rarely used.

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 400 W HPS lamp will have fallen 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. This fall-off in light output can be expressed as a direct energy cost by calculating the additional lighting hours required to maintain the light sum given by a new lamp. This energy cost is not always fully taken into account in determining the frequency of lamp change, but it is an important element, together with the actual cost of new lamps.

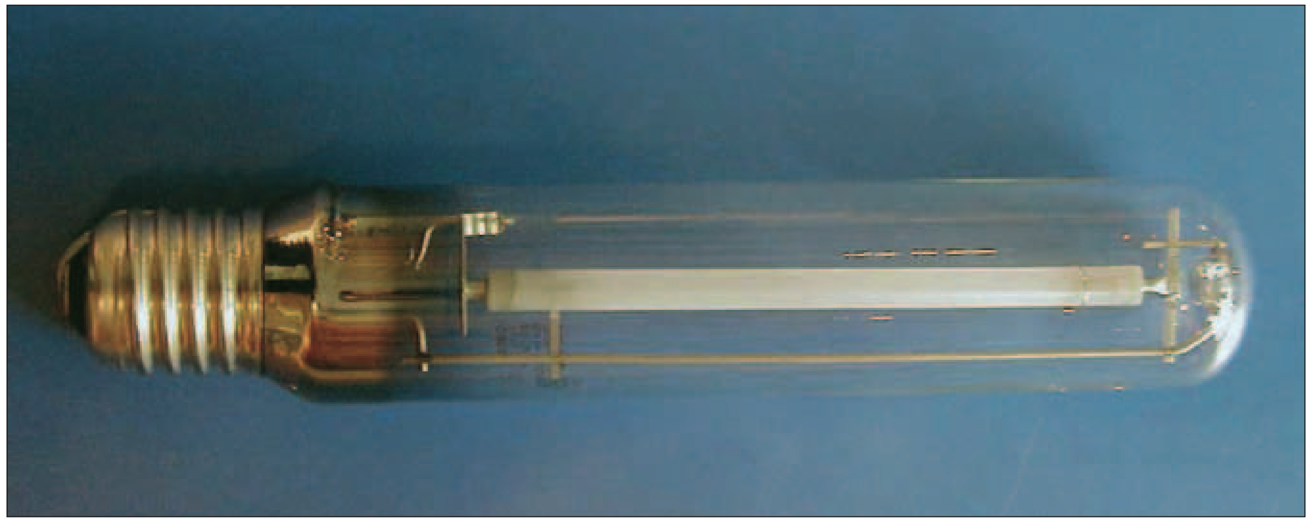
The value of light energy fall-off (per thousand hours of lamp use) increases with lamp age as shown in Graph 3 (using lamp depreciation data for a 400 W HPS lamp from PC 176, and an electricity cost of 6.5 pence/kWh). In contrast, the direct lamp replacement cost (also per thousand hours of lamp use and using a lamp cost of £12), declines as the duration of lamp operation increases, and it can probably be tempting to delay lamp change to reduce this further. However, both elements need to be taken into account, and Graph 3 combines these to give an objective measure of the additional costs associated with frequency of lamp change.

The combined additional costs are high when lamps are changed very frequently, but decline to reach a minimum when the frequency of lamp replacement is around every 10,000 hours of use. Thereafter, they increase again. This trend indicates that lamps should be changed after around 10,000 hours of use and that 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 3) are vital to direct light down from the lamps to the plants below. Light that fails to reach the plants is lamp output wasted. 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 3), 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

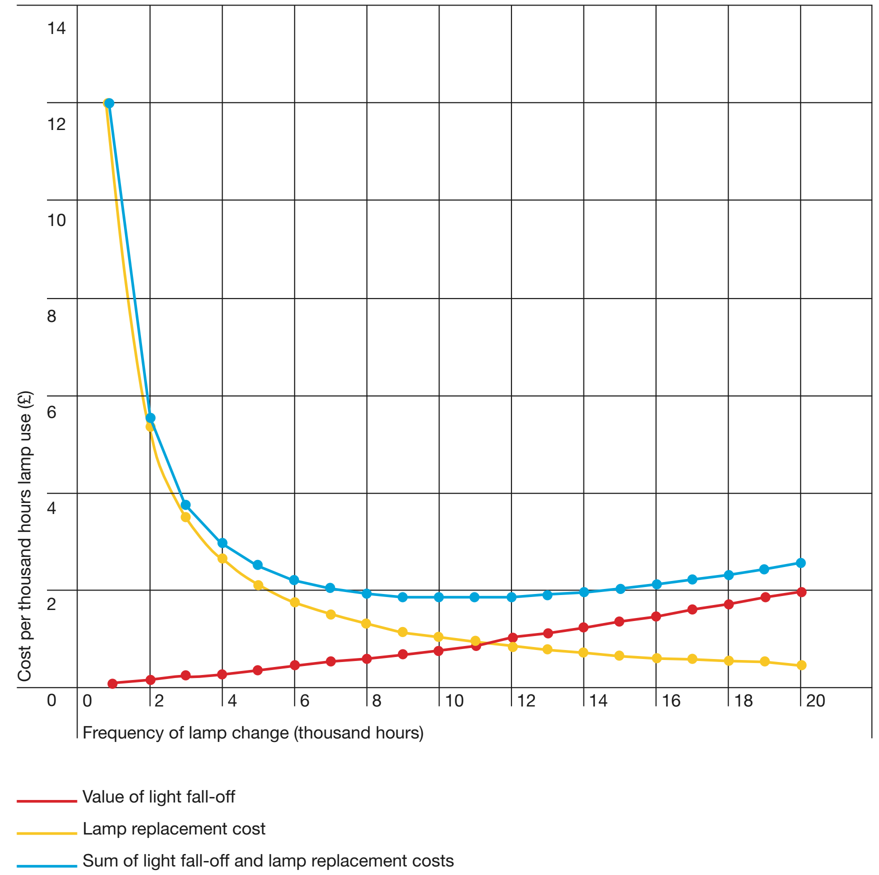


2 High pressure sodium (HPS) lamp – relatively cheap to purchase and run (specialised horticultural versions now available)

Table 2 Typical lamp efficiencies based on manufacturers' data and the published data of Ir J J Spaargaren

Lamp	Voltage (V)	Ballast type	Actual power (W)	Lamp output (μmol/s)	Lamp efficiency (μmol/s/input W)	Comparative efficiency (%)
Standard HPS 400 W	230	Electro-magnetic	450	630	1.40	–
Horticultural HPS 400 W	230	Electro-magnetic	450	725	1.61	+15
Horticultural HPS 600 W	230	Electro-magnetic	670	1,100	1.64	+17
Horticultural HPS 600 W	400	Electro-magnetic	670	1,150	1.72	+23
Horticultural HPS 600 W	400	Electronic	635	1,150	1.81	+29
MH 400 W	230	Electro-magnetic	450	540	1.20	-14

Graph 3 The effect of frequency of lamp change on the sum of light energy fall-off and lamp replacement cost for a 400 W HPS lamp (using data from PC 176)



3 Standard (left) and wide beam (right) reflectors

not be used with high-mounted installations since they will waste energy by giving too much light scatter.

Some nurseries in the Netherlands have mobile lighting systems, and it is claimed that these give greater yield increases. However, there is no scientific evidence to justify this claim and mobile systems are much more expensive to install than fixed systems (see project PC 270).

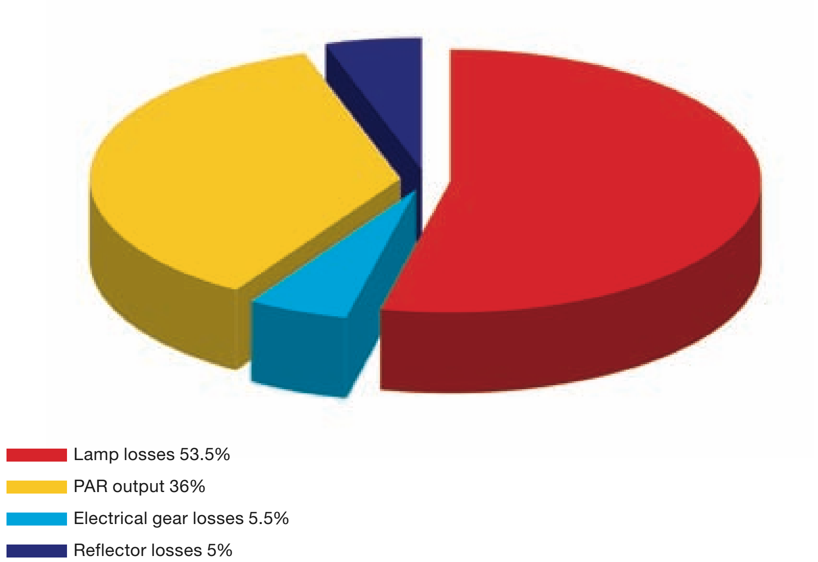
With age, reflectors tend to become coated with spray deposits and dirt, and surfaces become oxidised. This can be as detrimental to PAR reaching the crop as lamp ageing. To avoid this, reflectors and lamps should be regularly cleaned. As a rough estimate, a 2.5% reduction in light can be expected for 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 are now offering replacement reflectors made from high reflectivity materials, and claim that these reduce light losses by up to 5% when compared to re-anodised reflectors. The cost of a replacement reflector is likely to be higher than re-anodising, but in some cases an upgrade of this type could be economically viable.

Electrical input – PAR output

Although HPS lamps designed for use in horticultural applications are more efficient that older designs in converting electrical energy to PAR, energy losses are still large (Graph 4). Overall, from an electrical consumption of 635 W, a 600 W lamp with an electronic ballast running on 400 V will give a PAR output representing, at best, 36% of this. The remainder will be dissipated into the glasshouse as heat and this will offset heating costs (see 'Heat from the lamps' Section later).

Graph 4 Energy balance of a modern 600 W HPS lamp with an electronic ballast running on 400 V



4 If at all possible: remove the lamp, reflector and electronic luminaire in summer to reduce crop shading

Minimising shading

As noted above, 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 4). Care needs to be taken to avoid obstructions between the lamps and the plants since heating pipes, irrigation lines, screen mechanisms etc can easily give 3–5% light losses.

Lighting strategies

Care has to be taken to ensure that best use is made of supplementary lighting and that energy is not wasted. This was the objective of Hort LINK project 12 (PC 128) led by Professor Paul Hadley of The University of Reading. The study was based on bedding plug production, but the conclusions can be expected to apply more generally:

- Benefits of supplementary lighting were greatest when background light levels were low. Thus, lighting at 9.6 W/m² 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% (Graph 5). Clearly, lighting should only be applied when commercial benefits will accrue.

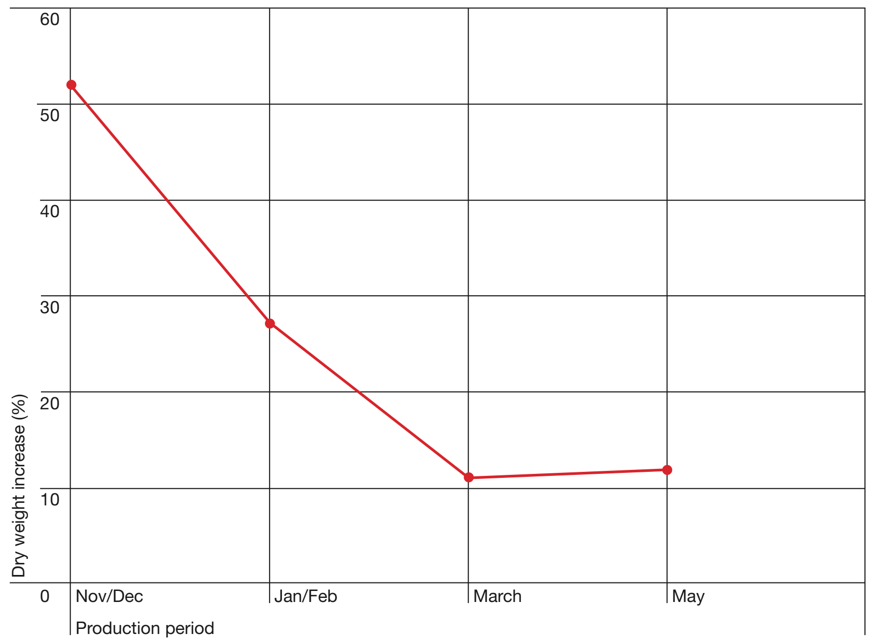
- Lighting during the final phase of plug production had far more effect than lighting earlier. This was because the leaf area was larger during the final weeks, and light interception was improved. Lighting during the final two weeks of production was more beneficial than lighting in the final week 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 h. When the natural daylength was 8 h, 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 very 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.

It can be important to target supplementary lighting to specific phases of crop growth. For example,

Graph 5 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/m² PAR (PC 128)



5 Chrysanthemum cv. Mirimar stuck in week 45 and grown with 9.6 W/m² PAR (left) and 4.8 W/m² PAR (right) of supplementary lighting

lighting pot chrysanthemums at high irradiance for only the first three weeks of short days will reduce production time and increase crop throughput in winter. However, it will have little beneficial effect on pot quality. In contrast, lower irradiance lighting given throughout short days will markedly improve pot quality, particularly flower number, but will have only a marginal effect on production time (Grower Guide PC 92e).

A key decision relating to supplementary lighting, and the one with the biggest influence on energy use, is choice of lighting level. In PC 92d doubling the irradiance of supplementary lighting from 4.8 W/m² to 9.6 W/m² PAR was shown to hasten marketing by 2 to 3 days and increased bud and flower numbers (Figure 5 - previous page). Ornamental crops are frequently lit at around 10 W/m² 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 PC 92e for pot chrysanthemums stuck in week 45, supplementary lighting needs to be given at 12.4 W/m² PAR at Kirton to give the same total PAR (and, presumably, quality) as that at Lymington with supplementary lighting at 4.8 W/m² PAR.

Photoperiod lighting

Other than knowledge relating to chrysanthemum, there is very little specific information to guide commercial photoperiod lighting. Of necessity, therefore, the following is largely based on chrysanthemum lighting. However, a new HDC project to address this problem is due to start in October 2009 (PC 296).

Control of flowering

Daylength 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 8 hours after the start of darkness.

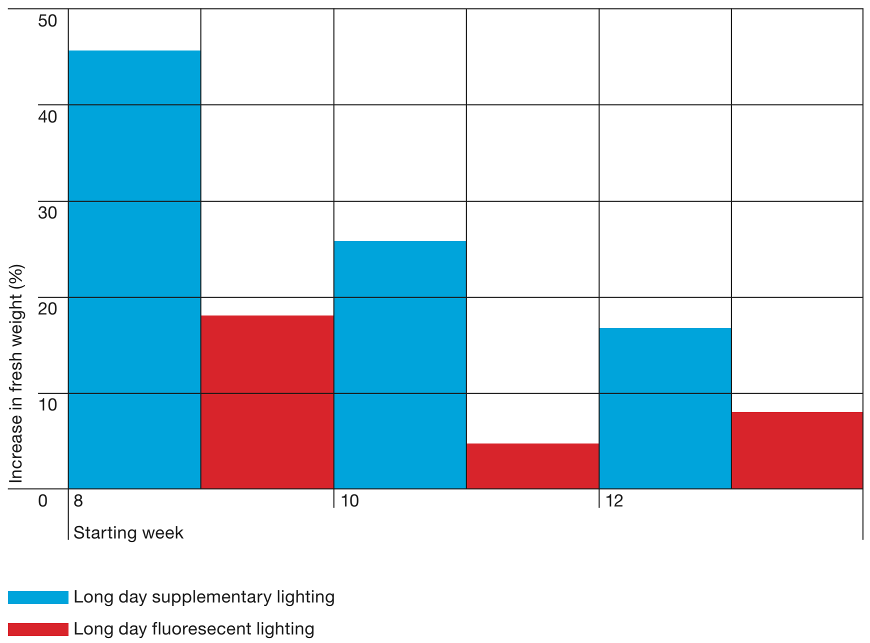
Flowering in SDP can also be delayed or prevented by using day-extension (DE) lighting. However, NB lighting is usually more cost effective than DE lighting. To give a long day (16 hours) in winter by DE lighting, for example, would mean lighting for up to an extra 8.5 hours, whilst as little as a few 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 4 hours (at around 0.4–0.5 W/m² PAR using tungsten lamps) are the norm in commerce.

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

Enhancement of growth

DE lighting has been shown to promote dry weight increase (Defra project HH3603SPC). For example, Graph 6 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/m² PAR) or HPS lamps (8.6 W/m² 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. 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.

Graph 6 Average increases in fresh weight given by long-day lighting during plug production of six bedding plant species: supplementary lighting at 8.6 W/m² PAR and fluorescent lighting at 0.5 W/m² (HH3603SPC)



Overall, replacing tungsten bulbs with compact fluorescent lamps improves energy efficiency, but festoons will need to be modified.

Chrysanthemum growers tend to use HPS lamps for supplementary lighting, and it will probably be 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.

Lamps

Light levels for photoperiod lighting are typically much lower than for supplementary lighting, and the light source of choice has, up until now, been the 100 W or 150 W tungsten (incandescent) bulb. This is because tungsten bulbs are effective and cheap, and in spite of their tendency to cause plant stretching. However, Government has announced the phasing out of tungsten bulbs over the period Jan 2008 to Dec 2011. The obvious alternative is the compact fluorescent lamp (Figure 6), and work at GCRI some years ago showed that these work as well as tungsten bulbs for chrysanthemum, so long as plants receive a similar level of PAR from them.

Because PAR levels have to be maintained, the replacement of tungsten bulbs by compact fluorescent lamps will not be 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 will probably have to be replaced by 30–35 W of compact fluorescent lighting and, given the available sizes of these lamps, it is likely that more lamp fittings will be required. Furthermore, whilst tungsten lamps can be cycled for energy saving (often halving the number of hours that they are 'on'), there are drawbacks to doing this with fluorescent lamps. This will increase the number of hours of fluorescent lighting and, pro rata, increase energy use.

6 Compact fluorescent lamps can be effective sources of photoperiod lighting for some species

It may be that for some species, the optimal light quality for NB treatment is different to 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. Longer term, LED lighting arrays may provide a better alternative to fluorescent lamps.

LED lighting

LED technology has advanced greatly since the first high-power (1W) light-emitting diodes (LEDs) were developed in 1999. LED lamps can be manufactured to give light of any given wavelength (colour), and some of the latest monochromatic devices are as efficient as HPS lamps. White LEDs are also available; these give light across the whole PAR spectrum through the use of a phosphor coating, but tend to be less efficient in terms of light output. It should be possible in the future to design LED systems that maximise growth, improve habit or control the flowering time of a given species. It should even be possible, by incorporating differently coloured LEDs on a single array (Figure 7), to change the light quality environment over the course of a day.

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 should be a major advantage if used, for example, for inter-row lighting of high-wire edible crops. However, LEDs do create heat which has to be conducted out of the rear of the device.

LEDs are robust and do not contain hazardous materials. They also have a much longer life expectancy than other lamp types, and this is not shortened by repeated cycling. While LEDs offer many advantages, high cost is currently an issue, although this is likely to come down over time. There are also design issues that need to be resolved before they can offer a viable alternative to HPS lamps for supplementary lighting.

7 LED lighting used for display purposes

System considerations

CHP

CHP installations generate both heat and electricity simultaneously and offer energy savings by reducing the inefficiencies that are inherent in traditional heat and electricity generation techniques. CHP is particularly well suited to horticultural applications because it is possible to recover the CO_2 from the flue gases of a well designed system.

It might be thought that CHP will be particularly attractive to growers using supplementary lighting because of the high electrical usage associated with this. However, total lighting hours generally fall short of the typical ‘break-even’ figure of 4,500 hours that is normally needed to make CHP economically viable. Annual lighting hours are around 2,000 for chrysanthemum production, and around 3,000 for tomato production. This means that CHP is only feasible if high mains electricity upgrade costs would otherwise be incurred, or if alternative uses can be found for the electricity during the rest of the year when lighting is not needed.

Heat from the lamps

Around 65–70% of the total electrical energy used to power HPS lamps is dissipated into the glasshouse as heat (Graph 4), and this makes an important contribution in off-setting 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/m²/year of heating.

Further information

Factsheets in this series:

- HDC Factsheet 05/09 – Energy management in protected cropping: Good housekeeping
- HDC Factsheet 06/09 – Energy management in protected cropping: Manipulation of glasshouse temperature
- HDC Factsheet 07/09 – Energy management in protected cropping: Humidity control
- HDC Factsheet 08/09 – Energy management in protected cropping: The use of screens
- HDC Factsheet 09/09 – Energy management in protected cropping: Horticultural lighting
- HDC Factsheet 10/09 – Energy management in protected cropping: Management of CO_2 enrichment

Additional information:

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