Project title:	Sweet peppers: a review of the current scientific knowledge & commercial experience of using supplementary lighting for AYR production
Project number:	PC 270
Project leader:	CT Pratt FEC Services Ltd, Stoneleigh Park, Kenilworth, CV8 2LS
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Keywords:	Sweet pepper, supplementary lighting, high pressure sodium, all year round production

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

Authentication

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

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Grower Summary

Headline

Although there are no technical barriers to prevent the use of high pressure sodium supplementary lighting for sweet pepper production in the UK, the level of investment required combined with cost of energy may limit its widespread uptake.

Background and objectives

Over recent years techniques have developed which have allowed growers to produce salad crops under light all year round (AYR). The lead in this area has come from the Dutch with UK growers following on by adopting some of the techniques to suit their industry culture and investment profile.

The tomato sector was the first to adopt the technology and recent estimates are that there are now 250Ha of AYR tomatoes grown in the Netherlands. This area is still increasing. As a consequence Dutch tomatoes are now a common sight in UK supermarkets in the winter. It is estimated that 12Ha of AYR tomatoes are now grown in the UK (5% of production).

Dutch cucumber production has followed in a similar way. However, in the UK, despite the success of the CGA/HDC AYR cucumber project (PC 201) no AYR cucumbers are produced. This has been without doubt due to the significant increase in energy prices that occurred shortly after the project started and which adversely affected the economics of the system. The project has nevertheless left the industry well positioned to adopt this growing system when market forces and economics combine to make it viable.

AYR pepper production is, in comparison, in its infancy and is probably five years behind AYR tomato growing in its market and technological development. The UK industry lags well behind the Dutch in pepper lighting developments and therefore this project provides a timely catch-up.

The principle objectives of this project were:

- To ensure that UK sweet pepper growers remain well informed about developments in AYR production;
- To identify any gaps in current knowledge allowing a longer-term R&D strategy for AYR sweet pepper production to be developed.

Results

Lighting Installations

The luminaire

High pressure sodium (SONT) lamps continue to be the most cost effective (capital and running cost) lamp type. LED's continued to attract interest but they still have to improve significantly before they are a viable option for supplementary lighting in commercial horticulture. This is likely to remain the case for at least five years.

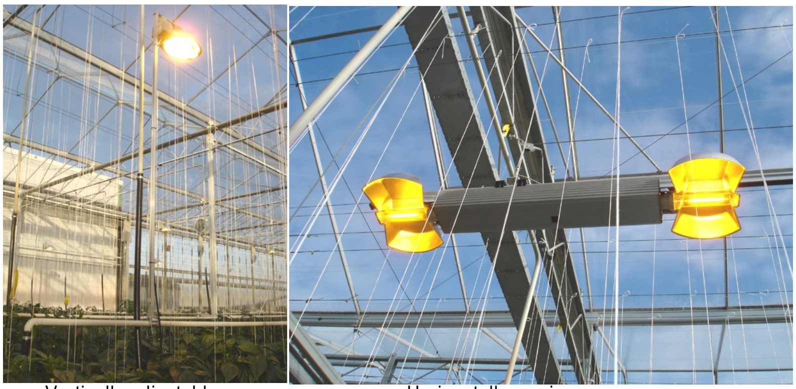
The most modern installations in the Netherlands have moved on from using iron-core ballasts to electronic control gear. This is the technology of choice due to improved efficiency, increased lamp life and reduced weight.

Mounting

Three different ways of mounting the luminaires were seen, these being:

1. Vertically adjustable.
2. Horizontally moving.
3. Fixed.

Figure 1 – Lighting installations



Vertically adjustable Horizontally moving

1. Vertically adjustable – these luminaires can be lowered to focus their radiant heat output on the head of the crop. This is thought to encourage fruit set. The average light level at the nursery that used this approach was 3,500 lux.

2. Horizontally moveable – these installations are claimed to have lower capital cost per m^2 whilst ensuring uniform light distribution (when considered over a period of time). Note however that although a lower cost per m^2 could be achieved this was at a lower average light intensity. In fact cost per 1,000 lux was higher compared to a fixed installation. The installation on the nursery visited gave a peak light intensity of 18,000 lux but an average of 1,800 lux over a complete movement cycle. It has been claimed that moving lights give greater canopy penetration and can significantly improve light use efficiency; however, these claims have not been supported by scientific studies.

3. Fixed – this is the more conventional approach. The average light level at the nursery visited was 3,600 lux.

Light intensity

Average light intensities ranged from 1,800 lux to 3,600 lux. The latter appears to be the level that Dutch growers will use going forward. Light levels as high as 10,000 lux have been used in the Netherlands in the past but they were not considered to be economically viable.

Operating regime

All three nurseries used similar operating strategies. At the time of the visit (mid February) the lights were turned on between 04:00 & 06:00 and off at around 16:30.

Although seemingly contradictory the supplementary lighting day-length was only increased (02:00 start) when natural light levels were high. This was due to plant related effects discussed in the plant response section.

The total operating hours of the lights was in the range of 1,200 to 1,500 hours p.a.

Plant response

Yield

The impact on yield was notably different for green fruit compared to coloured fruit (red, orange, yellow). With green fruit a yield increase of 5 - 10kg/m^2 was claimed whereas an increase of only
1 – 1.5kg/m^2 was claimed for coloured fruit. Of possibly greater importance was the impact of light on yield pattern i.e. the ability to start picking fruit earlier in the year and in greater quantities. In some cases this brought premium, early season prices. However returns depended very much on the success or failure of crops in the Mediterranean and Israel.

Day-length effects

Growers limited their hours of lighting to prevent the heads of the plants 'going dark', particularly when ambient light levels were low. This phenomenon is thought to be due to an increase in chlorophyll concentration, something which has been observed in a number of species, not only peppers. Generally though, pepper plants can tolerate long day-lengths or even continuous light, and a number of trials have indicated that the highest pepper yields result from 17 – 20 hours of lighting per day. Nevertheless lighting too early can affect plant balance. Trials by Wageningen UR showed that while lighting for up to 17 hours per day increased pepper yield the plants went out of balance and became too vegetative; plants were more balanced when the day-length was reduced.

Other

Other issues which could be potentially influenced by extended season/AYR sweet pepper operation, but were not assessed within the remit of this work are:

Pest control / IPM

- Reduced activity of bees due to the inability to navigate in 100% supplementary lighting;
- Reduced activity of beneficial insects (predators) during winter months due to lower greenhouse temperatures;
- Minimal/no empty period in the greenhouse to allow a clean start allowing carry over of pests.

A positive benefit with inter-planting (if used) is that established populations of beneficial insects could transfer between crops; however this also means that pests can transfer as well.

Disease

An increase in all types of disease could be expected due to reduced pipe rail heat input; a consequence of the waste heat from the lights.

Labour/greenhouse infrastructure

Supplementary lighting will ultimately deliver a taller crop at the end of the season. This may require layering of the crop where the height of the greenhouse is limited.

Economics

Two main factors determine the economic viability of using supplementary lighting for AYR/extended season sweet pepper production:

1. Energy costs.
2. Price premium for out of season/early season produce.

Neither of these areas have been precisely quantified in this work. However, Table 1 below provides an indication of the electricity costs for 1Ha with a fixed lighting installation providing 3,600 lux. It has been assumed that the increased heating requirement of a longer cropping season is offset by heat from the lights (see PC 201 (2007)). An estimation of maintenance costs has also been included.

Table 1 – Operating & maintenance costs for supplementary lighting

		Total hours p.a.					
Electricity		1,000	1,200	1,400	1,600	1,800	2,000
MWh		305	366	427	488	549	610
Electricity cost £/MWh		Cost of electricity					
	30	£9,150	£10,980	£12,810	£14,640	£16,470	£18,300
	40	£12,200	£14,640	£17,080	£19,520	£21,960	£24,400
	50	£15,250	£18,300	£21,350	£24,400	£27,450	£30,500
	60	£18,300	£21,960	£25,620	£29,280	£32,940	£36,600
Maintenance p.a. @ £40/10,000 hours per fitting							
		£2,000	£2,400	£2,800	£3,200	£3,600	£4,000
Cost £/MWh		Total cost of lighting 1Ha p.a.					
	30	£11,150	£13,380	£15,610	£17,840	£20,070	£22,300
	40	£14,200	£17,040	£19,880	£22,720	£25,560	£28,400
	50	£17,250	£20,700	£24,150	£27,600	£31,050	£34,500
	60	£20,300	**£24,360**	£28,420	£32,480	£36,540	£40,600

At the time of writing this report the cost of mains electricity was £60/MWh. At the lower end of the operating hours suggested (1,200 hours p.a.) it represents a total cost of £24,360/Ha p.a.
(£2.43/m2 p.a.). No allowance has been made for depreciation of the lighting installation.

The capital cost of the lighting installation alone is expected to be around £100,000/Ha. This does not cover the cost of light pollution (blackout) screens or increased electricity supply capacity.

A significant limiting factor is the apparent negative impact on sweet peppers of long day-length when natural light levels are low. This restricts the total operating hours of the lighting installation, the total amount of light energy delivered to the crop and therefore the yield potential.

Conclusions

- Economics aside, the technology and knowledge is available to successfully grow sweet peppers with supplementary lighting in the UK without the need for any further R&D work;
- The availability of a significant price premium for early season produce is a fundamental requirement for growing sweet peppers with supplementary lighting;
- Energy represents the biggest single increase in variable cost that must be recouped if adopting this approach;
- The quality of light produced by high pressure sodium lamps is adequate for supplementary lighting sweet peppers;
- Most growers light from between 04:00 and 06:00 to 16:30 in mid February. Lighting earlier causes dark heads. While yields are likely to increase with lighting for longer, care is needed with regards to plant balance;
- Increases in pest and disease incidence are possible and effective methods of control will be required;
- Reliable, detailed data on yield patterns and energy use is required to help sweet pepper growers assess more accurately the economics of supplementary lighting.

AYR sweet pepper R&D strategy

The following areas have been identified as the factors limiting the adoption of AYR/extended season sweet pepper production in the UK.

Area 1 – yield data

Although indicative yield data was obtained it was vague at best. The economic viability of AYR production is highly dependent on yield in terms of kg/m^2 and the pattern of production especially during the ‘out of season’ period. Accurate, reliable information in this area is therefore required.

Area 2 – energy data

Energy has been highlighted as the biggest single increase in production cost over conventional production. The figures given in the report are indicative. Although energy cost is dependent on market prices which are beyond a grower’s control, accurate energy consumption data is essential if more reliable budgeting is to be undertaken.

Area 3 - physiological effects on the crop and crop management

A long day-length combined with low light intensities appears to cause difficulties in managing the vegetative/generative balance of a sweet pepper crop. Although this has been observed with other crops the impact on sweet peppers is more significant. The current solution to this problem is to restrict the operating hours of the lights when natural light levels are poor. This in turn reduces the increase in yield and therefore the return on investment in the lighting installation. A better understanding of the mechanisms involved in this area are required if solutions are to be identified.

Area 4 - pest & disease incidence

Unlike the previous points this is important to both natural season as well as AYR production. As such, work is already being carried out in this area. The pathology and control of disease is unlikely to differ from a natural season crop therefore a specific focus on this area is low priority. However, pest development & control (IPM in particular) is likely to be affected as has been demonstrated in commercial AYR tomato crops. The project PC 251 (2007) currently in progress is focussing on AYR tomatoes and it is likely to also produce results of relevance to sweet peppers. The results of this work should be reviewed to assess the implications for sweet peppers.

Science Section

1 Introduction and Background

Over recent years techniques have developed which have allowed growers to produce salad crops under light all year round (AYR). The lead in this area has come from the Dutch with UK growers following on by adopting some of the techniques to suit their industry culture and investment profile.

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2 Objectives

The principle objectives of this project were:

- To ensure that UK sweet pepper growers remain well informed about developments in AYR production;
- To identify any gaps in current knowledge allowing a longer-term R&D strategy for AYR sweet pepper production to be developed.

The specific actions required to deliver these were:

- To determine to current level of experience with AYR sweet pepper production on commercial nurseries in the Netherlands;
- To identify the limits/constraints encountered, especially those relating to crop management and plant physiology;
- To identify the current gaps in knowledge about the response of sweet peppers to artificial light to enable AYR production;
- To develop a R&D strategy for AYR sweet pepper production.

These were principally met by:

- A tour of commercial sweet pepper nurseries using supplementary lighting in the Netherlands;
- A literature review.

3 Results

Additional notes relating to the nursery visits appear in Appendix 1.

Lighting technology

Lamp type

In all cases high pressure sodium lamps (SONT) were used. The average light intensity provided was between 1,800 – 3,600 lux. ‘Spot’ intensities of 18,000 lux were used with horizontally moving luminaires. This compares with other edible crops such as tomatoes and cucumbers where
10,000 – 15,000 lux are commonly used.

Light emitting diodes (LED’s)

LED’s are being promoted as the next significant step forward in lighting technology. There is no doubt that, unlike SONT lights, they offer potential improvements in light quality (wavelength spectrum). Manufacturers consulted at Hortifair 2007 suggested that the efficiency of LED’s (µmol/m^2/s per W input) is currently half that of SONT. Costs are also higher. A 300W ‘high output’ LED cluster that was being promoted for use in growth cabinets cost about 3,000 Euro. Compared with 160 Euro for a 600W SONT fitting.

Lighting equipment manufacturers such as Philips are making significant investments in LED research and considerable progress has been made in terms of improved efficiency and reduced cost. However, in the short to medium term LED’s are unlikely to be an option for supplementary lighting in commercial horticulture.

Gear type

On the sites visited a mix of lamps with iron core ballasts and electronic ballasts was evident, with newer installations favouring the higher efficiency electronic ballasts. Where iron core ballasts were used these were either lamp mounted or, in the case of one nursery, remotely positioned with the lamp gear away from the lamp and reflector. This reduces shading and allows the waste heat from ballasts to be more effectively utilised.

Current state-of-the-art luminaires now include electronic ballasts. They have a lower heat emission than iron core ballasts and are much more compact. Remote gear positioning is not required and therefore ‘single unit’ luminaries are used. One of the nurseries visited had luminaires of this type. These are expected to be the luminaire of choice for most new installations.

Mounting

Significant differences were seen in the way that the luminaires were mounted. This was irrespective of the ballast type used. There were three variants:

1. Lights that could be moved in the vertical plane.
2. Lights that could be moved in the horizontal plane.
3. Fixed lighting.

Figure 2 - Height adjustable reflector

Vertical movement (as seen at 4Evergreen Nursery)

It was possible to adjust the height of the luminaires relative to the head of the crop. The benefit was claimed to be that lowering the luminaires allowed the radiant heat produced by the lamps to be focused on the head of the crop. This was considered to be a useful additional means of manipulating plant development especially at the time fruit is set.

Figure 3 – Horizontal lighting installation

Horizontal movement (Grootscholten Nursery)

Pairs of luminaires fixed to an overhead track moved along the length of the rows of plants. These delivered a ‘spot’ light intensity of 18,000 lux. The luminaires moved backwards & forwards over a distance of 14m. Over a complete cycle of movement the mean light intensity delivered was 1,800 lux.

This was considered to deliver better penetration of light into the crop canopy and to provide the plant with a ‘kick start’ enabling it to utilise lower light levels more effectively.

Delivering relatively low average light intensities whilst ensuring good uniformity can be difficult especially where the mounting height is restricted. In such situations horizontally moving lights can deliver levels of uniformity (over time) that might otherwise not be possible with other systems.

Fixed (Koorneef Nursery)

This was what the majority of UK growers would consider to be a standard lighting installation. Due to the high potential mounting height and reflector design the luminaires were fitted to the trellis beams. The design light intensity was 3,600 lux.

Operating period

All three nurseries used similar operating periods. At the time of the visit (mid February) the lights were turned on between 04:00 & 06:00. The earliest they were turned on was 02:00 but only when power prices were low and natural light levels were high.

Although seemingly contradictory the supplementary lighting day-length was reduced when there were prolonged periods of poor natural light levels (more detail on this in Section 3.2.4).

Effects on plant growth and development

Lamp type – effects of light quality

Scientific literature makes no reference as to whether peppers respond differently to different qualities of light from different light sources compared with other species. High pressure sodium lamps were used on all of the nurseries visited and whilst these lamps have an output that is not ideal if used as the only source of light, they are regarded as being suitable and very efficient when used to supplement natural light levels in winter.

With reference to LED lighting, studies (Brown et al., 1995; Schuerger et al., 1997) have shown that when used as the only light source, red LED lights reduced plant biomass, leaf number, stem thickness, leaf thickness and chloroplast numbers when compared with metal halide lamps. This effect was less evident when the red LED lights were supplemented with a small amount of blue light. Plant height was increased when the red LED's were supplemented with far-red light.

It is expected that these effects would be much lower or negligible where LED's were used for supplementary lighting as the daylight component of light would be sufficient to correct any photomorphagenic effects.

While LED lamps are currently inefficient when compared with HID lamps, they do provide the advantage of being cool at the source of output. This could be very advantageous for inter-row lighting, where light fittings could be positioned in such a way that light could reach lower leaves without being shaded by the canopy. Inter-row lighting has the potential to increase the net canopy photosynthesis even when ambient light levels are high and the upper leaves are light saturated.

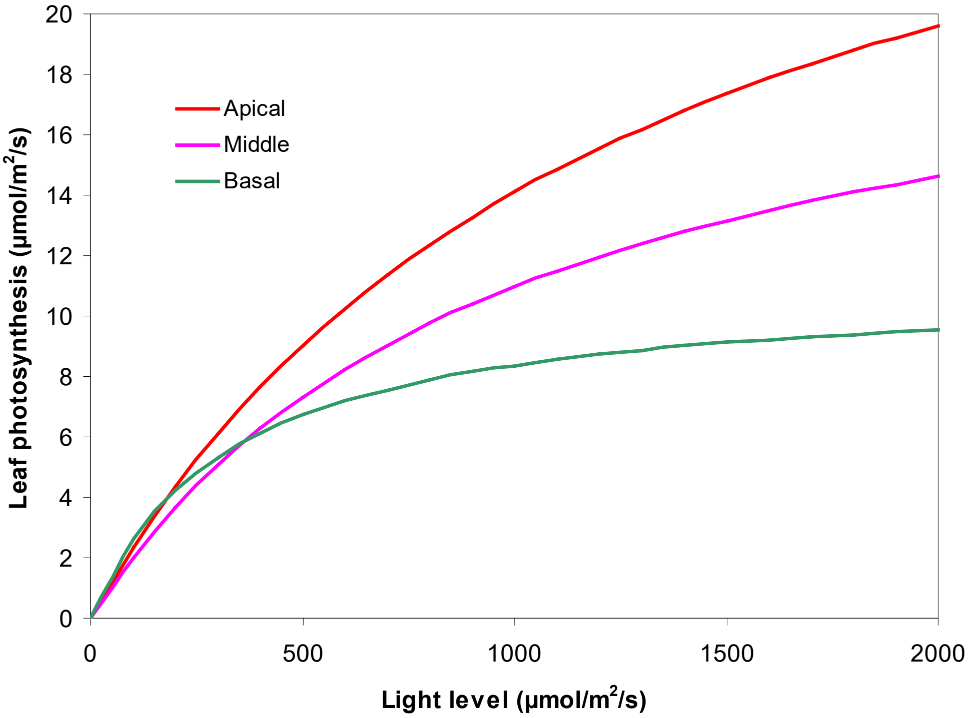
When comparing lamps, lux should not be used as the yardstick, as this is a measure of light output as perceived by the human eye and not the plant. If considering a new light installation, ask for light outputs in $\mu mol/m^2/s$ or W/m^2 PAR (400 - 700nm). This will give a better indication as to which lamps will give the best photosynthetic response.

Effect of irradiance

When plants are subject to low light levels this can limit the availability of assimilates and cause flower and bud abscission in many species including sweet pepper. Turner and Wien (1994) showed that reducing light levels from 500 - 550 $\mu mol/m^2/s$ to 30 - 35 $\mu mol/m^2/s$ decreased net photosynthesis by around 90%. Buds from the shaded plants had lower glucose and sucrose levels after just one day of shading; in pepper, sucrose is the main sugar that is transported and this is converted into glucose and fructose in the growing parts of the plants. When the shading was removed the net photosynthesis returned to previous levels. Supplementary lighting can be used to increase net photosynthesis and the availability of sugars, therefore manipulating fruit abscission and plant balance.

The effect of light level (PPFD) on leaf photosynthesis was investigated by Alvino et al. (1994) for sunlit and shaded leaves under two watering regimes. They showed that the apical leaves had a higher photosynthetic efficiency when compared to either middle or basal leaves (Figure 4). They also demonstrated that water stress reduced net photosynthesis, although the reduction was greater at the top of the plants.

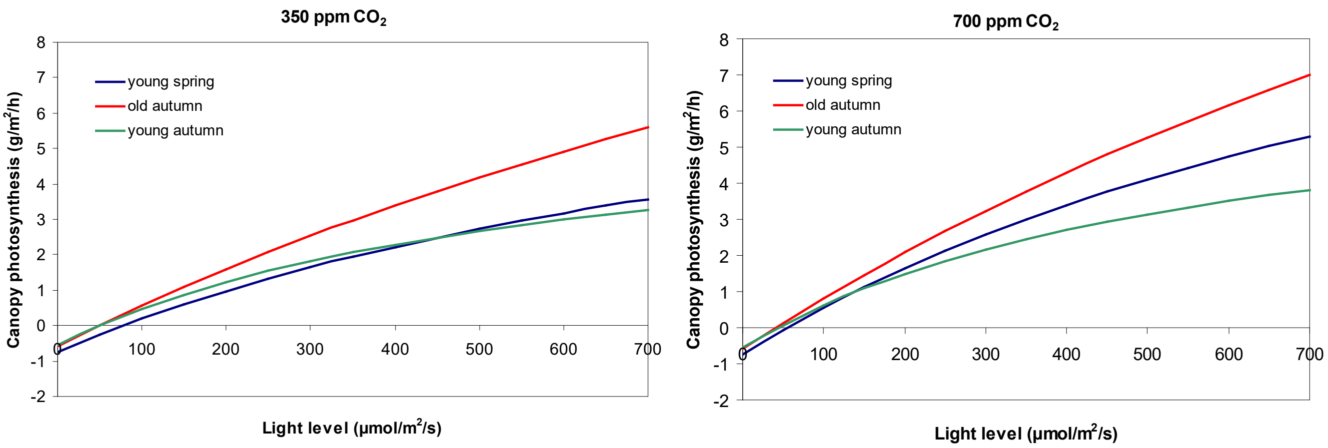
Figure 4 - The effect of light level (PPFD) on leaf photosynthesis of sweet pepper. The graph is reproduced from Alvino et al. (1994). Measurements were made at the top (apical), middle or bottom (basal) of the canopy.



The effect of supplementary light on photosynthesis can be predicted from Figure 4. However, this data is from measurements of individual leaves and care needs to be taken when estimating the likely effect on the whole canopy. The canopy as a whole does not reach the maximum level of photosynthesis until higher light levels are applied. This is because while the upper leaves might be light saturated, increasing the light level further increases the light penetrated into the canopy therefore continuing to increase the photosynthesis of lower leaves. Shaded leaves at the bottom of the plant may be below the compensation point (net sinks rather than sources of assimilates) even when it's sunny.

A better, but more complicated, approach is to measure the response of whole plants or canopies. In 1980 Nilwik looked at the photosynthesis of whole pepper plants by growing some plants inside a cylindrical Perspex chamber which was sealed. Subsequently, Nederhoff and Vegter (1994) estimated canopy photosynthesis in glasshouse compartments containing sweet peppers grown in stone wool and grown following commercial production practices. They used nitrous oxide as a tracer gas to estimate the air exchange rates of the glasshouses and CO_2 was then dosed to maintain a constant concentration. From this CO_2 uptake by the plants (net canopy photosynthesis) was computed. The experiments conducted by Nederhoff and Vegter included a young sweet pepper crop measured in spring and again in autumn (old crop), together with a second young crop in autumn. Data from high light levels were not included due to difficulties in measuring air exchange when ventilation rates were high.

Figure 5 - The effect of light level (PPFD) on canopy photosynthesis of sweet pepper. The graphs are reproduced from Nederhoff and Vegter (1994). Canopy photosynthesis is expressed as grams of CO_2 taken up per m^2 of floor area.



The older crops in autumn showed the highest rates of canopy photosynthesis due to the fact that the crop had a greater leaf area at this time; the leaf area index (LAI) was 6.7 (i.e. 6.7m^2 of leaf per m^2 of floor area) compared with 2.8 and 2.7 for young crops in spring and autumn, respectively (Figure 5). The differences in the two young crops might have been due to seasonal acclimatisation and differences in leaf thickness.

From the relationship published by Nederhoff and Vegter (1994) the effect of supplementary lighting on canopy photosynthesis can be predicted (Table 2). As one would expect, the effect on photosynthesis (as a percentage) increases as the ambient light level decreases or the supplementary light level increases. Yield is likely to be proportional to canopy photosynthesis.

Table 2 - The effect of different levels of supplementary lighting on the predicted increase in canopy photosynthesis (as a percentage when compared with no supplementary lighting) at 700ppm CO_2.

Crop	Ambient PPFD (µmol/m²/s)	Sup. light 1,000 lux (12 µmol/m²/s)	Sup. light 3,000 lux (37 µmol/m²/s)	Sup. light 10,000 lux (122 µmol/m²/s)
Young (spring)	100	25.7	75.5	235.3
	400	2.7	8.0	25.2
	700	1.2	3.6	11.4
Old (autumn)	100	19.9	59.1	189.2
	400	2.9	8.5	27.3
	700	1.4	4.1	13.3

Fixed vs. mobile lights

The study tour looked at lamps that were fixed (Koorneef Nursery) as well as at nurseries where the luminaries were capable of moving in both the vertical (4Evergreen Nursery) or horizontal planes (Grootscholten Nursery).

Some incredible claims have been made for mobile lighting systems, but without scientific proof. Mobile lights have been said to give better light penetration. There were claims in the Netherlands that for roses, mobile lights could give a similar yield to fixed lights despite a much lower installed wattage and therefore cost. However, recent scientific studies have disproved these claims.

Experiments conducted on commercial nurseries by Wageningen UR have compared fixed and mobile lights for a number of crops including peppers (Hogendonk et al., 2004). Sweet pepper cv ‘Ferrari’ was planted on 10 November 2003 and the experiment ended 01 November 2004. Lights were on 0 - 2 hours before sunrise until 0 - 1 hour before sunset, but were switched off when ambient levels were above 350W/m². All of the treatments provided the same light level (60µmol/m²/s). While the treatments with mobile lamps set and were harvested one week earlier, the cumulative production was higher under the fixed lights from May onwards. The final production was 31.8kg/m² under fixed lights, compared with 30.6kg/m² under mobile lights and 29.2kg/m² for combined (fixed plus mobile) lighting (Heuvelink, et al., 2006).

The effect of mobile lights has also been examined for gerbera grown in Canada (Zheng et al., 2006). While the potential photosynthetic efficiency increased under moving lights, in reality growth was reduced. Plants grown under the moving lights showed reduced net leaf photosynthesis, stomatal conductance, leaf chlorophyll contents, leaf area, and fresh weights. Similarly Marissen et al., (2006) showed that in rose, for a given average light level, the fresh weight was greater with static than with mobile lighting. A possible explanation for this is that plants are unable to respond at the speed the light levels change with moving installations. This is backed up by data collected at Valley Grown Nurseries for PC 269. Leaves were left in the dark and then suddenly exposed to high light levels (1000 or 2000µmol/m²/s). It was established that at these light levels stomatal conductance needed to be greater than 300mmol/m²/s for CO_2 to move into the leaf at a rate that

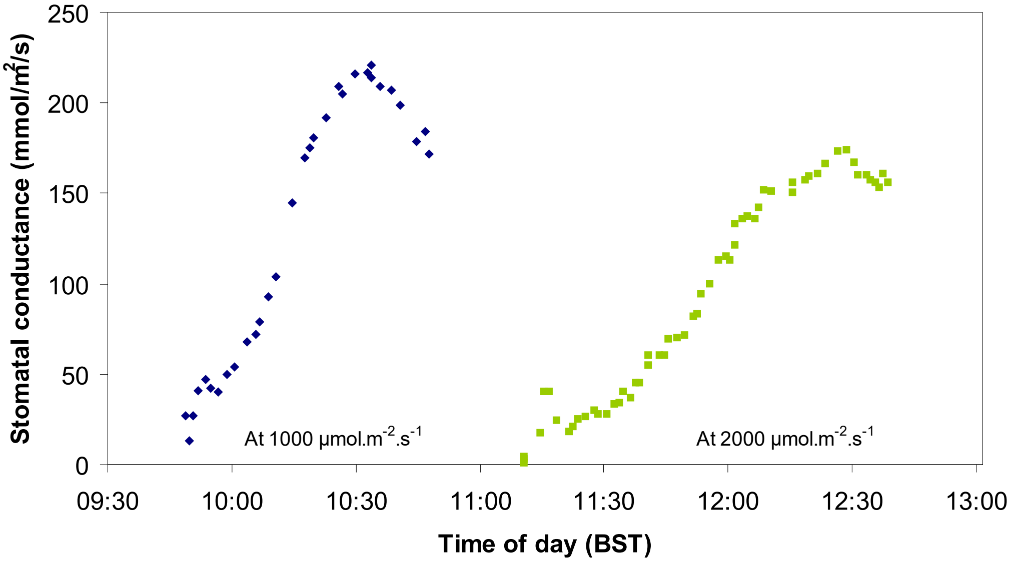


Figure 6 - The change in stomatal conductance over time for two leaves measured at Valley Grown Nurseries on 26 July 2007. The measurements were made on leaves that had been in the dark and were then exposed to a light level of 1000 or 2000µmol/m²/s.

did not limit photosynthesis. However, sometimes pepper leaves were still opening after several hours. In some the stomata never fully opened (Figure 6). Clearly one advantage of mobile lights is the reduced capital and running costs when compared to a typical fixed installation with higher light levels. In 2004 a typical mobile system was said to cost 12.5 Euros per m^2 compared with 65 Euros per m^2 for a typical fixed installation (Vale, 2004). However, the average light level would only be about 10% of that for the fixed system and so the cost per unit of light output would actually be greater. As such, these systems are likely to be less cost effective given that the claims of better plant response do not appear to be correct. Interestingly the grower with mobile lights (Grootscholten Nursery) indicated that if he was building a new block he would now go for fixed not moving lights. Nevertheless, if low average light levels are desired, mobile lights appear to allow the light to be evenly distributed (over time) in situations where there would be insufficient height to do so with fixed lamps at a wide spacing.

The advantages and disadvantages of vertically moving systems are a little harder to quantify as there is little related information in the scientific literature. Lowering the lamps is said to steer the crop giving a generative action, increasing fruit set. Reducing the height of the lamps will clearly increase the light intensity and radiant heat directly under the lamp, and presumably it is the light that has greatest impact on fruit set. The impact of the radiant heat is harder to quantify as higher light levels and more radiant heat will tend to increase crop transpiration, thus cooling the plant and negating some of the effect on the radiant heat. However, moving the lamps closer to the heads is likely to cause greater spatial variation resulting in greater plant to plant variability. As a result some care is required if this is to be used as a mechanism to steer the crop. The biggest advantage would appear to be early in the season when the crop is short. A vertically moving light system enables the distance between the lamp and head of the plant to be kept constant while the plant grows.

Day-length

A number of growers commented that plants went 'dark' if lights were used for too many hours. At 4Evergreen lights were normally used from 04:00 to 16:30, when they started to light at 03:00 the leaves went dark. Grootscholten normally lit from 05:00 to 16:00 and commented that the leaves went black when they experimented with lighting from 02:00. The problem was felt to be worse when ambient light levels were low. Koorneef Nursery generally lit from 06:00 to 16:30 although they started lighting later and finished earlier when ambient light levels were low.

Clearly there are issues with the timing of lighting and this is confirmed by an experiment conducted by Wageningen UR (Heuvelink et al., 2004). In 2001 - 2002 'Special' and 'Oblix' were grown with no lights, and 125 or 188μmol/m^2/s supplementary lighting from HPS lamps. The lights were used for either 13 or 17 hours per day. Increasing the light intensity and hours of lighting increased yields, but the plant balance was affected and the plants became too vegetative. In the following season the same light levels were used on 'Special' and 'Fiesta' but only between sunrise and sunset. This produced a yield increase through increased numbers of fruit set (fruit size was much the same), a better balanced plant also resulted.

Unlike some species peppers can be grown in continuous light without showing photo-oxidative damage. While Nilwik (1981) found that pepper plants dropped their leaves under continuous light, researchers in Japan (Masuda and Murage, 1998) have shown that continuous lighting can in fact increase the growth and fruit set of young pepper plants by increasing the total light integral. There was also a higher chlorophyll concentration on a leaf area basis. However, these benefits appear to be short lived. Demers et al., (1998) showed that pepper plants with continuous lighting initially had higher shoot weights and yields when compared with plants lit for 14 hours, but after 7 to 8 weeks the trend reversed. They hypothesised that this may have been due to starch or sugar accumulation in leaves. When lit for 16, 20 or 24 hours per day the crop with 20 hours lighting had significantly more yield. Similarly Dorais et al., (1996) showed that pepper yields were greater with 18 hours of lighting when compared with 12 hours or continuous lighting.

The cause of dark leaves in not entirely clear, although this may be due in part to increased chlorophyll content. Langton et al., (2003) showed that in four bedding plant species (geranium, impatiens, pansy and petunia) long-day photoperiodic treatments (low light levels) increased leaf greenness (chlorophyll contents) and generally increased plant growth. Similarly Hurd (1973) showed that in tomato, long day lighting increased leaf chlorophyll concentration by 34% on an equal leaf area basis. Increase in net photosynthesis was estimated at 6%. Furthermore, Adams (2003) showed that the chlorophyll content of tomato leaves increased with long-day lighting to a greater extent when ambient light levels were low. Similarly growth was promoted with day-extension lighting under low, but not high, ambient light levels. This phenomenon does not appear to occur in all species (Adams and Langton, 2005).

So, the anecdotal evidence from talking to growers is backed up by the scientific literature, and it seems clear that lighting for long periods each day will cause darker leaves especially when light levels are low. Although dark leaves are not necessarily a problem, tomato growers in the Netherlands have had similar concerns about dark heads and have been reducing their lighting hours. However, a recent study by PRI (Boonekamp, 2007) has shown that 18 hours lighting at a high intensity (12,500 lux) not only gives the highest yields, but also improves the average light use efficiency. In peppers, starting to light early has been shown to affect plant balance and therefore care is needed if this is being considered.

4 Economics

The scope of this project did not allow a comprehensive economic assessment to be carried out.

Income

As far as income is concerned the key difference compared to a natural season crop is the yield increase and higher ‘out of season’ prices for the fruit. The latter was identified as the most important factor by the growers visited in the Netherlands.

Capital cost

Lighting installation

To achieve an average light intensity of 3,600 lux on 1Ha, as produced by the fixed lighting installation at the Koorneef Nursery, approximately 500 x 600W high pressure sodium light fittings would be required. A typical installed cost in the UK would be £200 per fitting i.e. £100,000/Ha.

Other equipment

This would depend on the existing facilities and local conditions. Major capital items that may need to be considered are:

- Light pollution screens - £40,000 - 50,000/Ha;
- Bigger electricity supply or CHP – highly variable.

Running cost

The most obvious impact here is the cost of operating & maintaining the lights. There is also the extra heating requirement of the extended cropping year. Results from PC 201 (AYR cucumbers) showed that the amount of heat required for AYR production was similar to that for natural season production because of the additional heat available from the lights. The nurseries visited were clearly somewhat different to PC 201 as the light levels were much lower and they were simply extending the production season and not producing AYR.

Other running costs likely to be affected include:

- Labour;
- Fertiliser;
- Biological control.

These have not been quantified in this project.

Table 3 below details the anticipated operating & maintenance costs based on typical UK costs and a range of operating hours & electricity prices.

Table 3 – Operating & maintenance costs for supplementary lighting

				Total hours p.a.			
Electricity		1,000	1,200	1,400	1,600	1,800	2,000
MWh		305	366	427	488	549	610
Electricity cost £/MWh				Cost of electricity			
	30	£9,150	£10,980	£12,810	£14,640	£16,470	£18,300
	40	£12,200	£14,640	£17,080	£19,520	£21,960	£24,400
	50	£15,250	£18,300	£21,350	£24,400	£27,450	£30,500
	60	£18,300	£21,960	£25,620	£29,280	£32,940	£36,600
Maintenance p.a. @ £40/10,000 hours per fitting							
		£2,000	£2,400	£2,800	£3,200	£3,600	£4,000
Depreciation on lighting installation (5 year write down)							
		£20,000	£20,000	£20,000	£20,000	£20,000	£20,000
Cost £/MWh				Total cost of lighting 1Ha p.a.			
	30	£31,150	£33,380	£35,610	£37,840	£40,070	£42,300
	40	£34,200	£37,040	£39,880	£42,720	£45,560	£48,400
	50	£37,250	£40,700	£44,150	£47,600	£51,050	£54,500
	60	£40,300	£44,360	£48,420	£52,480	£56,540	£60,600

At the time of writing this report the cost of mains electricity was approximately £60/MWh. At the lower end of operating hours suggested (1,200 hours p.a.) this would result in a total electricity cost of £44,360/Ha (£4.44/m^2).

5 Other

This section of the report lists other areas which may be affected by the adoption of extended season/AYR sweet pepper production. Experience with commercial AYR tomato crops and with cucumbers via PC 201 has highlighted a number of issues that may be equally applicable to sweet peppers.

Pest control / IPM

- Reduced activity of bees due to the inability to navigate in 100% supplementary lighting;
- Reduced activity of beneficial insects (predators) during winter months due to lower greenhouse temperatures;
- Minimal/no empty period in the greenhouse to allow a clean start allowing carry over of pests.

A positive benefit with inter-planting in particular is that established populations of beneficial insects can transfer between crops. PC 201 (2007) also showed that leaf removal associated with the high-wire production system helped with pest control as eggs were removed on the leaf before they hatched. However, this is unlikely to be the case with peppers because of their comparatively slow growth.

Disease

One grower commented on higher disease levels in the pepper crop grown with supplementary lighting. This has often been the case with AYR tomato and cucumber crops. The biggest factor influencing this is that less heat is required at the base of the crop because of the supplementary heating coming from the lights. This means that the humidity conditions, albeit fine at the head of the crop, tend to be worse at the base of the crop than with a conventional system.

Labour

This has synergies with cucumbers where a significant increase in labour was required to train & layer the crop. Peppers grow much more slowly and layering may only be required towards the end of the cropping cycle (depending on the height of the greenhouse). However, if layering is required additional investment in layering systems will be needed. The ease with which a pepper crop can be layered is also unknown.

6 Discussion

Lighting technology

High pressure sodium lamps were used on all the nurseries visited. They continue to offer the best combination of light quality, cost and efficiency. Electronic ballasts are now considered to be the preferred technology for new supplementary lighting installations regardless of the crop being lit. LED lights are still some way from application in commercial horticulture.

Major differences were seen in the mounting system i.e. fixed, vertical movement & horizontal movement. All the growers visited, even the one with fixed lights, were convinced of the benefits of moveable lights (vertical & horizontal). However, they all agreed that the higher cost of moveable systems outweighed the benefits. Furthermore, some of the initial claims made by manufacturers regarding the benefits of horizontally moving lights have been discredited in scientific trials. It therefore appears unlikely that moveable systems will find widespread use with any crop.

It was not possible to verify, from an engineering perspective, the effect of moving systems. Although conceptually at least the effects described would seem to have some foundation.

Plant physiology

While the benefits of lighting on leaf and canopy photosynthesis are well understood and can be quantified, it is harder to establish exactly what yield increase a grower might achieve with the installation of supplementary lights. Indeed the benefits may be more to do with timing of first pick. As such this will be very business specific.

It would appear that optimal yields are likely to be achieved by lighting for 17 - 20 hours per day as the light given at night can be used more efficiently by the plants. This would also maximise the return on the capital investment. However, due to the fact that plants go dark when the lights are turned on too early, growers tend not to light before 04:00. Having said that there is no real evidence to suggest that dark heads are a physiological problem; the darker colour might well be due to higher chlorophyll concentrations. Plant balance can be affected by lighting for long periods each day and so perhaps the best approach would be to adjust the lighting strategy to steer the crop. In the same way that vertical lighting systems can be lowered to give a generative action, the hours of lighting (day-length) of a fixed system could be increased when more fruit set is desired.

Economics

A comprehensive economic assessment was not possible as only a limited amount of information was available. However, as with other AYR protected edible crops, product marketing and energy costs will be the two biggest factors affecting the viability of both AYR and extended season production. PC 201 (cucumbers) showed that a yield increase of 100% could be achieved. However, energy costs in particular have meant that no cucumber growers have invested in AYR production since the project was completed. The conflict between carbon footprint vs. local supplies for out of season produce has also added uncertainty to the market.

Commercial nurseries in the Netherlands are successfully growing sweet peppers using supplementary lighting. There are therefore no technical barriers to adopting this approach in the UK. However, it is clear that the economics are at best questionable unless a significant marketing premium can be achieved. The impact of day-length when natural light levels are low is also an important factor as it limits the operating hours of the lights. This means that it is not possible to maximise the return on the capital invested in lighting by increasing the operating hours and therefore yield.

Other

Pest control/IPM issues with AYR tomatoes are currently being investigated as part of PC 251. There is significant synergy with AYR/extended season peppers and it is likely that many of the lessons learnt can be transferred to a pepper crop.

Although the need to layer the crop has been highlighted as a possibility this is considered to be unlikely/minimal. Any grower installing supplementary lighting is likely to do so in a relatively tall greenhouse to facilitate as uniform a light intensity as possible. It should therefore be possible to raise the crop wires to accommodate any increase in growth.

7 Conclusions

- Economics aside, the technology and knowledge is available to successfully grow sweet peppers with supplementary lighting in the UK without the need for any further R&D work;
- The availability of a significant price premium for early season produce is a fundamental requirement for growing sweet peppers with supplementary lighting;
- Energy represents the biggest single increase in variable cost that must be recouped if adopting this approach;
- The quality of light produced by high pressure sodium lamps is adequate for supplementary lighting sweet peppers;
- Most growers light from between 04:00 and 06:00 to 16:30. Lighting earlier causes dark heads. While yields are likely to increase with lighting earlier care is needed with regards to plant balance;
- Increases in pest & disease incidence are possible and effective methods of control will be required;
- Reliable, detailed data on yield patterns & energy use is required to help sweet pepper growers assess more accurately the economics of supplementary lighting.

8 Sweet pepper AYR R&D strategy

A major objective of this project was to develop an R&D strategy to fill the gaps in knowledge highlighted and resolve factors which currently restrict the adoption of supplementary lighting for AYR production of sweet peppers. Such a change in growing systems will impact on almost every aspect of growing. The areas considered to be of greatest importance and most significantly affected by using supplementary lighting would be:

- Yield;
- Energy consumption/cost;
- Physiological effects on the crop and crop management;
- Pest & disease incidence.

Yield – priority 1

Although indicative yield data was obtained it was vague at best. The economic viability of AYR production is highly dependent on yield in terms of kg/m^2 and the pattern of production especially during the ‘out of season’ period. Accurate, reliable information in this area is therefore required.

Energy cost – priority 2

Energy has been highlighted as the biggest single increase in production cost over conventional production. The figures given in the report are indicative. Although energy cost is dependent on market prices which are beyond a grower’s control, accurate energy consumption data is essential if more reliable budgeting is to be undertaken.

Physiological effects on the crop and crop management – priority 3

A long day-length combined with low light intensities appears to cause difficulties in managing the vegetative/generative balance of a sweet pepper crop. Although this has been observed with other crops the impact on sweet peppers is more significant. The current solution to this problem is to restrict the operating hours of the lights when natural light levels are poor. This in turn reduces the increase in yield and therefore the return on investment in the lighting installation. A better understanding of the mechanisms involved in this area are required if solutions are to be identified.

Pest & disease incidence – priority 4

Unlike the previous points this is important to both natural season as well as AYR production. As such work is already being carried out in this area. The pathology and control of disease is unlikely to differ from a natural season crop therefore a specific focus on this area is not considered to be a priority. However, pest development & control (IPM in particular) is likely to be affected as has been demonstrated in commercial AYR tomato crops. The project PC 251 (2007) is focussing on AYR tomatoes and it is likely to also produce results of direct relevance to sweet peppers. The results of this work should be reviewed to assess the implications for sweet peppers.

Appendix 1

Study tour to the Netherlands on 23rd February 2007.

Present – Gary Taylor (Valley Grown Nursery Ltd), Joe Coletti (Glinwell Marketing plc), Steve Adams (Warwick HRI), Tim Pratt (FEC Services Ltd).

4 Evergreen - Steenbergen

Nursery overview

The nursery covered a total area of 25Ha and was built over the previous 3 – 4 years. In addition to mains gas fired boiler plant two $3MW_e$ combined heat & power units (CHP) were also installed. A third CHP was planned to provide heat & electricity but not CO_2.

In addition to the pipe rail heating a grow pipe was used which utilised low grade heat from the CHP and was used to aid fruit ripening. Although at the time of the visit they were located just above the head of the crop to aid fruit set.

Lighting installation

Supplementary lighting was installed in two separate greenhouse blocks (6Ha & 7Ha). In both cases high pressure sodium lights were used. The fitting was the 'remote' type i.e. the ballast box was mounted separately from the reflector with a cable connecting it to the reflector and lamp holder above the crop. The crop was grown on the floor in a double row format with the ballast box located between the rows (Figure 7). The fittings were of the 400 volt type and used iron-core ballasts as they were installed before electronic versions were available.

Figure 7 – Ballast box located between rows of plants

The design light intensity was 3,500 lux. It was possible to adjust the height of the reflectors according to the height of the growing point of the crop. This was considered to deliver benefits by allowing the radiant heat from the lamp to be concentrated on the head of the crop at key points in plant development e.g. fruit set. At the time of the visit the position of the reflectors in the horizontal plane was fixed.

Figure 8 – Height adjustable reflector

Operating hours

The lights were typically operated between from 04:00 to 16:30 during February. This was extended to 03:00 to 16:30 dependent on the condition of the plants and the price of electricity.

The lights were viewed, to some degree, as an energy management tool. If the wholesale electricity price was high the operating hours of the lights were reduced and vice-versa.

Crop information

The red variety Ferrari was grown under the lights. The plant density was 3/m^2 with 7.5 heads/m^2. Indications were that higher levels of Fusarium occurred with the lights. This was thought to be due to the requirement for less heat in the bottom of the crop via the pipe rail.

The economics of the lighting installation were dependent on obtaining a premium price early in the cropping season. No significant increase in yield was achieved.

Rick & Mark Grootschoolten - Zevenhuisen

Nursery overview

The nursery covered a total area of 8.3Ha and was built in 2004. In addition to the pipe rail heating a grow pipe was used which utilised low grade heat from the CHP.

Lighting installation

High pressure sodium supplementary lighting was installed on the whole nursery. The installation allowed the lights to be moved in the horizontal plane (14m stroke) but not the vertical plane (Figure 9). The design light intensity directly below the lights was 18,000 lux. However, the average light intensity delivered over a movement cycle was 1,800 lux.

Figure 9 – Horizontally moving light

Operating hours

The lights were typically operated between from 05:00 to 16:00 during February. They were turned off whenever the outside light level rose above 320W/m^2. The lights were turned off completely in early June.

The total operating hours were 1,200 – 1,500 per year.

The general feeling of the grower was that moveable lights delivered a benefit compared to a fixed lighting installation. However, this did not justify the additional cost. Any future installations would have fixed lights.

Crop information

The red variety Spider was grown under the lights. The original sowing date was 15th September. However, this has since been changed to 15th October. The lights allowed red fruit to be picked approximately one week earlier than an unlit crop and gave an increase in yield of 1.0 – 1.5kg/m^2.

If green peppers were grown a yield increase of 5 – 10kg/m^2 was expected.

As with other nurseries the economics of the lighting installation were dependent on obtaining a premium price early in the cropping season.

Arjan Koorneef – Berkel en Rodenrijs

Nursery overview

The nursery covered a total area of 8.3Ha and was four years old. In addition to mains gas fired boiler plant one 4.8MW$_e$ CHP was also installed.

Unlike the other nurseries visited a grow pipe was not used. The grower felt that they could have a negative impact and therefore required a high level of management.

Lighting installation

High pressure sodium supplementary lighting was installed on the whole nursery. Unlike the other nurseries visited the lights were fixed i.e. could not be moved either horizontally or vertically (Figure 10). The design light intensity was 3,600 lux.

The grower considered moveable lights. However, his costings showed that it was possible to achieve twice the light intensity with a fixed installation for the same capital cost.

Figure 10 – Fixed lighting installation

Operating hours

The lights were typically operated between from 06:00 to 16:00 during February. They were turned off whenever the outside light level rose above 300W/m^2. The total operating hours were 1,500 per year.

Crop information

A yellow variety (cv Kelly) was grown under the lights. Once again the economics of lighting were dependent on delivering early season yield and a premium price. The grower said that he needed an additional 2 - 3kg/m^2 of yield up to June and a price premium of 1.50 Euros.

An early season yield increase of 3kg/m^2 was achieved. However, there was a 1kg/m^2 loss in yield due to the early turn around in September – October. There was therefore only an increase in total yield of 2kg/m^2 per year.

The grower considered that a significant factor affecting the performance of peppers under lights was slow plant development. This means that floor coverage and therefore light interception is poor.

The Improvement Centre / GreenQ - Bleiswijk

This was a new research facility comprising 11 x 1,000m^2 greenhouse compartments. Although no pepper lighting trials were being carried out it was still worthy of comment. Ongoing trials included:

- Closed greenhouse – tomatoes with supplementary lighting;
- Closed greenhouse – sweet peppers without supplementary lighting;
- Novel light reflector designs – tomatoes.

The last one was of clear relevance to this project. The reflectors were designed to focus the light directly above the crop row. This reduced the amount of light falling directly on the floor between the rows of plants. This has clear synergy with the comment made by Arjan Koorneef about the slow development of pepper plants and resulting poor light use efficiency.

Figure 11 – Sweet pepper crop trial in a closed greenhouse

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