Horticultural Fellowship Awards

Final Report Form

Project title:	Securing skills and expertise in crop light responses for UK protected horticulture, with specific reference to exploitation of LED technology (EMT/AHDB/HTA Fellowship)
Project number:	CP85
Project leader:	Dr G M McPherson, STC
Report:	Final report, 2017
Previous report:	4th Annual report, Nov 2016
Fellowship staff:	Dr Martin McPherson, Science Director, STC (Lead Fellowship mentor) Prof. Nigel Paul, Lancaster University (Mentor)
("Trainees")	Dr Phillip Davis, Business Manager,
Location of project:	Stockbridge Technology Centre
Industry Representative:	Chis Plackett, FEC Russel Woodcock, Bordonhill James Bean, Crystal Heart Salads Neal Wright, Micropropagation Services Simon Budge, VHB Ltd (Herbs) Colin Frampton, Consultant Steve Carter, PO Geoffrey Smith, Mapleton Growers (PE - Lettuce)
Date project commenced:	1 October 2012
Date project completed	30th September 2017

AUTHENTICATION

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

Dr Phillip Davis
Project Manager
Stockbridge Technology Centre

Signature .... Date ....

Report authorised by:

Dr Martin McPherson
Science Director
Stockbridge Technology Centre

Signature .... Date ....

CONTENTS

Progress Against Objectives

Objectives

Training

Objective T1. To provide the Fellow with the knowledge, understanding and practical skills to undertake applied plant science in the area of plant light responses, lighting and cladding materials.

Objective T2. To establish the Fellow with a network of contacts within the major commercial producers of horticultural LEDs (and cladding plastics).

Objective T3. To establish the Fellow with a network of contacts in the science base in fundamental and applied plant photobiology in Europe and beyond.

Objective T4. To provide the Fellow with a solid appreciation of the "business basis" for horticultural R&D, including aspects such as staffing, costings and the range of possible funding routes.

Objective T5. To establish the Fellow with a network of contacts from the industry, including applied horticultural consultants currently active in supporting UK protected cropping, and through their respective technical groups, representatives of the major protected cropping sectors in the UK.

Objective T6. To expand the training objective of the fellowship program enabling Dr Davis to train other members of the team at STC. Much of this training, during 2015 and 2016, was given to Dr Beynon-Davies. This training has been highly successful and Rhydian moved to a new role at G's/Harper Adams. This fellowship has also provided opportunities for several students at different stages of their careers to gain experience in the use of LEDs for horticultural purposes. Tom Watkins, an under graduate student at Askham Bryan College performed a research project titled "A study on the benefits of using LED for HPS lighting systems in ornamental plant production" at STC in parallel with some of the trials that were performed in the CP125 project. We have hosted several undergraduate students for 9 month placements at STC during which they have gained experience with LED lighting systems. Dr Davis has co-supervised three PhD students during the fellowship, Dr Richard Boyle at Lancaster University (an AHDB studentship), Kayla McCarthy at York University and Gulce Onbasili (an AHDB studentship) at Lincoln University.

Research

Objective R1. For the fellow to undertake an initial, objective review of current developments and progress in lighting technology with support from the leading manufacturers and including a brief fact-finding tour overseas.

Objective R2. To objectively assess the properties of a selection of LEDs currently available or proposed for use in UK horticulture in terms of total irradiance (intensity), spectrum, efficiency and response to dimming.

Objective R3. Based on R1 and R2 to identify gaps in current scientific knowledge with respect to crop responses (using existing Arabidopsis light response knowledge) to LEDs relevant to UK production and to undertake pilot-scale experiments into the responses of selected UK protected crops (particularly leafy salads, ornamentals & herbs) to LEDs found to have useful properties in R2. Information obtained under R3 will identify the potential of appropriate lighting systems for specific UK crops. The knowledge gained will be used to design further R&D studies, subject to additional external funding, for future commercial implementation in the UK (See Objective R5).

Objective R4. In addition to the Fellowship reports, to produce (i) a technical review of the "state-of-art" of LED lighting in Horticulture, (ii) an article in HDC News summarising the results of the Fellowship and the current status of LED lighting in horticulture and (iii) to participate in a programme of visits, workshops and conferences for growers, including those at the new STC facility.

Objective R5. This fellowship is intended as being a major element in securing long-term R&D in to LEDs (and other light-based approaches to production) in UK horticulture, but does not in itself deliver a major "stand-alone" research programme.

Objective R6. In the current research environment, there is a growing need to increase collaboration between organisations like STC, Universities and industry. In order to develop links with Universities it is necessary to further develop my scientific credentials through publication of our research in academic journals. This will both boost awareness of our research in academic circles but also demonstrate our scientific expertise in a manner that can be quantified.

Objective R7. The skills necessary to acquire project funding and run lighting projects are currently in development under objective R5 and through management of the 'Understanding crop and pest responses to LED lighting to maximise horticultural crop quality and reduce the use of PGRs' (CP125) project. However, this program will be expanded to encompass development of collaborative projects with Universities and companies both within the UK and as part of EU projects. Developing collaborative projects will require increased interactions with the network of contacts developed in training objectives T2-T5.

Objective	**Original Completion Date**	**Actual Completion Date**	**Revised Completion Date**
Objective T1.	December 2012	December 2012	
Objective T2.	December 2013	This is an on-going exercise as new companies move into the area.	September 2017 and beyond.
Objective T3.	December 2013	Trainees have made many contacts across the industry and this will be an ongoing exercise.	September 2017 and beyond.
Objective T4.	December 2013	This process will continue throughout the fellowship	September 2017 and beyond.
Objective T5.	December 2013	This process will continue throughout the fellowship	September 2017 and beyond.
Objective T6	September 2017	September 2017	-
Objective R1	December 2013	February 2013	-
Objective R2	January 2013	March 2013. Completed at Lancaster university and continued through contribution to CP 139 with Prof. Pearson (Lincoln Uni). -	
Objective R3	December 2013	This work contributed to the development of the CP125 research project as well as other efforts to gain research funding via multiple routes including commercial, EU, N8, research council and CHAP projects.	
Objective R4	December 2016	August 2015 and ongoing. This work resulted in the AHDB Lighting Technical guide package, published in 2015, an	

		academic publication (Davis & Burns 2016) and several AHDB grower articles.
Objective R5	September 2017	Dr Davis developed the CP125 project and is continuing to develop new projects based on ongoing research activities, interactions with growers, other researchers (in UK and beyond) and as new technologies hit the market.
Objective R6	September 2017	Considerable efforts have been made to create new links with UK researchers and develop collaborative research efforts. We have received funding for three N8 research projects and are planning future research council funding bids.
Objective R7	September 2017	Dr Davis's efforts have resulted in STC receiving funding via 3 EU projects. Additional EU projects are currently under review. Political changes in the last year have created some challenges in this area but we will continue to explore routes for new funding opportunities.

Summary of Progress

In its final year, this Fellowship has continued to progress well and a substantial amount of knowledge has been gained regarding plant light responses as well as the economic implications that LED lighting systems have on the industry. Dr Davis has completed a three-year AHDB funded research program CP125 which has answered many questions regarding crop and insect responses and highlights relevant areas of future research. Dr Davis has become the go to person for information on LED lighting systems for horticulture and is regularly contacted by companies and growers for information. Dr Davis has developed a network of contacts at UK Universities and has several collaborative projects underway and in development. Dr Davis is currently co supervisor of two PhD students. Dr Davis has also continued to develop his network of contacts at research centres throughout Europe and has been involved in several applications for EU funded projects. He is involved in the EUVRIN network as a steering committee member for the working group on Greenhouse Crops. Dr Davis has engaged with several University research groups to explore opportunities for new research projects. To date he has received funding for three N8 research projects which will hopefully lead to further funding opportunities. STC's involvement in the Crop Health and Protection (CHAP) innovation centre has provided Dr Davis with additional networking opportunities and has provided funding for the development of a new LED facility providing additional capabilities to STC facilities.

Milestones not being reached

None

Do remaining milestones look realistic?

NA

Training undertaken

Conferences attended (those attended in the last 12 months)

September 2016.

Dr Phillip Davis attended the LpS 2016 conference and present at the Hi LED project workshop. *Plant light responses and their manipulation for horticultural purposes*

October 2017

Dr Phillip Davis presented at the CGA. *An update of LED work at STC.*

February 2017

Dr Phillip Davis gave a presentation at Liverpool University. *Lighting the future of horticulture.*

May 2017

Dr Davis gave a presentation at the Horticulture Technologies event held at Teagasc, Dublin. *Lighting the future of horticulture.*

Dr Davis presented at the Horticulture Lighting conference Europe . *Lighting the future of horticulture.*

Dr Davis presented at the Waitrose Farm Assurance Meeting. *Lighting the future of horticulture.*

June 2017

Dr Davis presented at CRD. *Urban Farming*

July 2017

Dr Davis attended an N8 conference at Durham University.

Expertise gained by trainees

The work performed for the fellowship this year has increased Dr Davis understanding of the economic impacts of LED lighting systems.

Dr Davis has developed the skills to lead and direct commercial R&D projects and manage research teams. Through these interactions he has gained the ability to build collaborations and make links between companies that have common business goals.

Dr Davis has kept up to date with the advances in LED technology and the growing availability and diversity of lighting systems for horticulture.

Involvement in bids for EU funding has helped develop Dr Davis' understanding of international collaboration and funding. The political issues that have been created in the last year has created considerable uncertainty in this area but we will continue our efforts to remain involved in the EU R&D and maintain our contacts.

Dr Davis has continued to keep up to speed with changes in funding strategies at AHDB to ensure he is able to make successful applications as part of collaborative projects.

Other achievements in the last year not originally in the objectives

Dr Davis has received EU funding as part of a larger international project called TomRES. This project will be investigating breeding new tomato varieties with resistance to combined water and nutrient stress.

Dr Davis has received Innovate funding as part of team aiming to develop a robot tomato harvester. This project encountered difficulties due to the withdrawal of the main project partner. Dr Davis used his growing contact base to rebuild the project with new partners, this project is ongoing and will be completed in February 2019.

Dr Davis is involved in a small EU funded cereal trial examining the use of biopesticides to control wheat fungal diseases.

Dr Davis has performed several consultancy contracts on highly diverse range of projects involving lighting systems.

Dr Davis has engaged with several research groups in the N8 Universities and has received funding for three projects. These small-scale projects will create preliminary results that will enable development of larger project proposals to AHDB or research councils.

Through STCs involvement in the CHAP innovation centre, we have received funding to build a new LED R&D facility. This facility will consist of 2-4 large compartments suitable for production of large quantities of plants and will be able to perform economic assessments of Urban Farms that the current facility was not designed to perform.

Dr Davis is also using his expertise in lighting to aid AHDB-Pork team with their work on optimisation of lighting for different stages of the pig production cycle.

Changes to Project

Are the current objectives still appropriate for the Fellowship?

NA

GROWER SUMMARY 1: Implications of ongoing increases in LED efficacy.

Headline

LEDs continue to increase in efficacy resulting in reduced electricity bills. We have assessed how advances in LED technology impact current and future installation and running costs.

Updated LED calculators have been created that will be available on the GrowSave website.

Background

The use of lighting in horticulture provides many benefits for season extension or year round production. However, while crop yields and quality can be improved with lighting, the costs associated with installing and operating those lights impact on profitability. LED lighting systems have gained considerable interest in recent years due to the potential for reduced electricity usage. The best way to compare different lighting systems is to examine how much light (assessed as numbers of photons) they produce per watt of electricity. This parameter is referred to as lamp efficacy and has units of micro-moles per joule ($\mu mol\ J^{-1}$). The efficacy of LED lighting systems continues to improve and the most advanced LED lamps now achieve an efficacy of 3.0 $\mu mol\ J^{-1}$. However, not all LED systems are made equal and efficacy varies considerably with design and spectrum (AHDB Technical guide, 2015, Lighting: In Practice).

Understanding how the differences in efficacy effect the installation and running cost as well as total electrical load are important when planning large installations. Here we have examined several aspects of LED design and how they influence those costs. In making these calculations we have also revised the calculators on the GrowSave website to account for advances in LED technology.

The energy savings provided by LEDs have created the potential for urban farms (controlled environment rooms with no sunlight) to compete financially with traditional growth systems for production of certain crops. While these systems allow crops to be produced in locations where they could not otherwise be produced, sunlight is free and rising energy costs could disrupt urban farm economics. Solar panels form one renewable source of electricity that could be compatible with urban farms and potentially reduce energy bills. Solar panel technology is advancing at a similar pace to LED technology. While sunlight is free, only 42% of its energy is available for photosynthesis. The best solar panels can convert 46% of the energy in sunlight into electricity (affordable solar panels are currently able to convert up to

22% of solar energy). Here we have explored the potential for combined solar panel and LED technologies to generate more PAR photons than are available directly from sunlight.

Summary

We calculated the maximum theoretical LED efficacy for all colours of light. Red LEDs have the potential to produce almost 50% more photons than blue LEDs because red photons contain less energy than blue photons. Current, red and blue LED technologies achieve efficacies that are about half the theoretical maximum demonstrating the potential for considerable future improvements in LED efficacy. Current green LEDs have considerably lower efficacies and inclusion of green LEDs in lighting systems would be expected to reduce lamp light output. White LEDs currently provide the most energy efficient source of green light, and produce a more favourable light environment for human workers.

As lamp efficacy increases, energy consumption decreases non-linearly (Figure GS1). This means that each increase in efficacy provides a smaller energy saving. So increasing efficacy from 2 to 3 µmol J^{-1} provides an energy saving of 33% but increasing from 3 to 4 µmol J^{-1} provides a smaller, though still favourable, additional 25% saving. In addition to reduced energy saving, increased LED efficacy can result in an increased light output per lamp (assuming the wattage of the lamp remains the same). This means that as efficacy increases, fewer lamps are required to achieve the same light level at the crop canopy (Figure GS2). This should result in reduced installation costs for a given type of lamp.

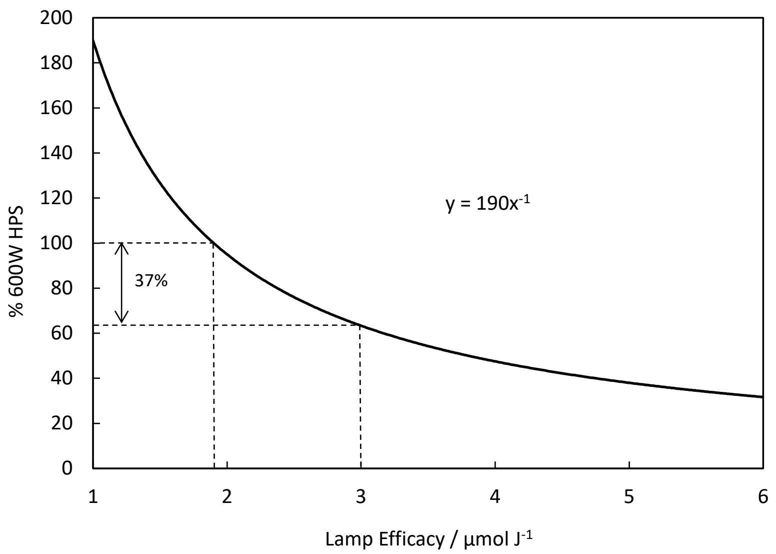

Figure GS1. The influence of lamp efficacy on the electricity requirements expressed as a percentage of the energy used by a 600W HPS lamp. Increasing efficacy from 1.92 (HPS lamp) to 3.0 µmol m^{-2} (Philips Gen 3 inter-light) reduces energy consumption by 36.7%. Note these values are independent of light intensity.

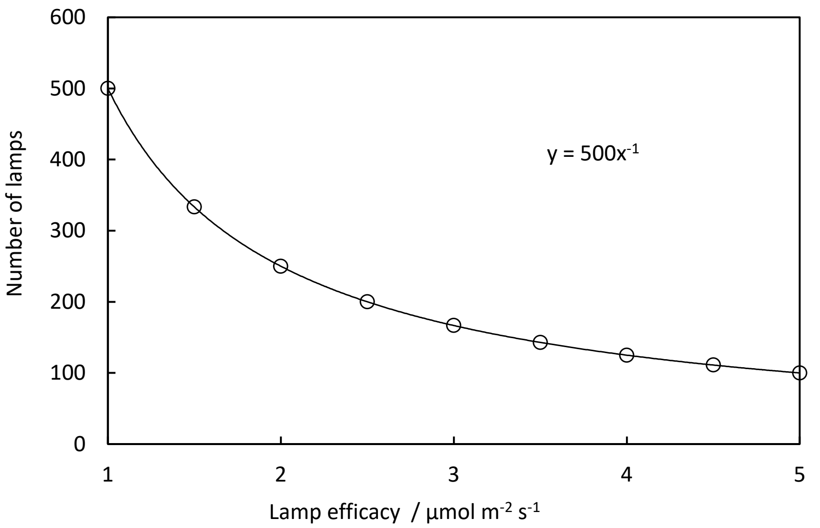

Figure GS2. The influence of lamp efficacy on the number of 40W lamps required to illuminate a 100m^2 growing area to an intensity of 200 µmol m^{-2} s^{-1}.

While performing the calculations used in this report we have created updated calculators that will be made available via the GrowSave website. These calculators can be used to determine the numbers of lamps required to light a crop to a certain light intensity, how much electricity they would consume and their lifetime cost.

To provide a compelling argument that LEDs and solar panels could provide better crop performance than sunlight alone, the system would need to create at least the same number of PAR photons as sunlight, this is referred to here as 'solar equivalence'. Current commercial technology (LEDs with an efficacy of 3 µmol J^{-1} and solar panels and efficiency of 22%) would only be capable of producing 33% of the PAR photons available in sunlight. The most efficient solar panels (efficiency = 46%) with the best currently available LEDs could produce 70% of the PAR photons available in sunlight. If LED efficacy can be increased to 4 µmol J^{-1}, solar equivalence could be achieved with solar panels converting 48% of the energy in sunlight. While it is expected to be some time before such systems are affordable there is scope in the future for increasing food production through the application of technology.

Financial Benefits

While lighting systems can open new market opportunities or help develop new product ranges, there are significant operating costs due to increased input requirements (installation, electricity and heating costs). The decision to install lighting systems to extend growing seasons has a profound influence on business economics. However, comparing lights with different technologies can be challenging.

The information in this report will help growers understand the implications of different aspects of lighting technologies and how it is expected to alter installation and running costs. It will also help growers put manufacture's claims in perspective with other technologies and make informed decisions regarding selection of appropriate lighting systems.

The extrapolations of the potential future developments in LED technology will help businesses plan for the future. For example, for companies where the economics of winter production do not currently add up, the information in this report could help them determine at what point in the future (at what LED efficacy) the economics shift in favour of installing lamps. Equally, for companies that already have lighting installations, this work can help them decide if or when a new installation makes sense.

The updated calculators (to be made available via the GrowSave website) will help growers to quantify the lifetime costs associated with different lighting systems. Lifetime costs are an important consideration when deciding on large-scale installations as they allow a thorough evaluation of the long term impact on business economics. These calculators will help growers make informed decisions and help them avoid making costly mistakes. The calculators have been revised so they will not go out of date and will remain continually useful.

Action Points

1. Define the aim of the proposed lighting installation. The best choice of lighting system will differ between crops and production systems. If the main aim is to drive biomass and yield, lights with lower percentages of blue light will provide the best choice of lighting. If compact plant morphology is required, a higher proportion of blue light will be required (see CP125 final report and the AHDB lighting guides for more information). As highlighted in this report, the efficacy of lamps is strongly influenced by their spectra and when assessing installation and running costs, the data for the specific model of lamp should be used, don't assume two similar LED systems have the same efficacy.

2. Read the full report including the evaluation of economics of glasshouse supplemental lighting. Additional information can be found in the AHDB lighting Guides. Consult with specialists to help you through the process.

3. Go to the GrowSave website and download the relevant calculator, three are provided, each examining different growing systems (multi-tiered systems, glasshouse supplemental, night break lighting). Follow the instruction on how to use the calculators.

4. The calculators require several bits of information that must be manually inserted (including lamp efficacy in µmol J^{-1}, wattage of each lamp, cost of lamps, cost of installing the lamps, size of production area and duration of lamp usage) they have been created like this so the information within them does not go out of date. All of this information

should be relatively easy to gather from a reputable lamp manufacturer and/or installer companies.

5. Consider small-scale test installations to confirm the lights and crops perform as desired before making large-scale investments. If crop performance is suboptimal, consider whether the spectrum or intensity of the light is appropriate. More information on the effects of light spectrum and intensity can be found in the CP125 project reports and in the AHDB grower guides. If necessary, seek expert support to ensure lighting systems will meet your crops requirements.

SCIENCE SECTION 1: Implications of ongoing increases in LED efficacy.

Introduction

The energy within light is contained in discrete units called photons. The energy within a photon is inversely proportional to its wavelength; as their wavelength increases photons contain less energy (Alonso & Finn 1968). At the surface of the earth, sunlight contains photons with wavelengths ranging between 280nm and 4000nm (Figure 1). Photosynthesis is only able to utilise photons with wavelengths between 400 and 700nm, referred to as photosynthetically active radiation (PAR; McCree 1971). Across the PAR range the efficiency with which plants use light for photosynthesis varies due to differences in leaf light absorptance and due to the presence of protective pigments that absorb light preventing it reaching the reaction centres that initiate photosynthesis (see Lighting: The Principles for a more detailed explanation). However, if the energy from a photon is passed to a reaction centre, a red photon drives the same amount of photosynthesis as a blue photon despite its lower energy content. In contrast, to generate a blue photon with a light source, a greater input of electricity is needed than to generate a red photon. For this reason red light sources can produce more photons and therefore photosynthesis per wat of electricity. The mechanisms by which different lamp technologies generate photons differ considerably but in all cases some electrical energy is converted into photons and some into heat. Comparisons between different types of lamps can be made by assessing their efficacy. The efficacy of a lamp reflects how many photons are created per watt of

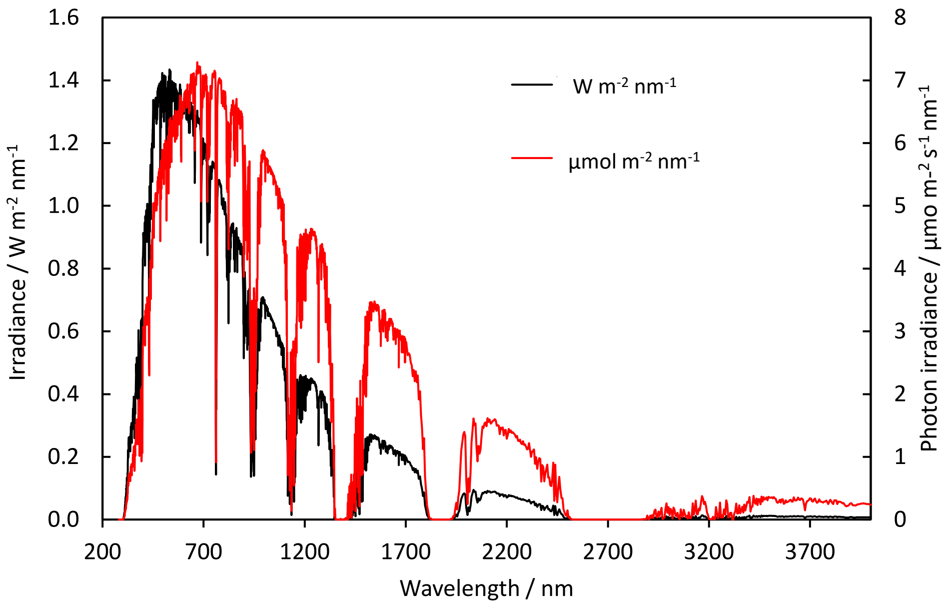

Figure 1. The full ASTM solar spectrum. Black line shows the spectrum in units of W m^{-2} nm^{-1} and the red line shows the spectrum in units of µmol m^{-2} s^{-1} nm^{-1}.

electricity (it does not directly relate to the percentage of energy turned in to heat), the higher the efficacy the more photons and, therefore, photosynthesis than can be powered.

During the course of this fellowship, LED lighting systems have advanced at a considerable rate and the efficacy, design and range of manufactures of LED systems has increased greatly. The most efficient LED lighting system currently available (September 2017) has an efficacy of 3.0 μmol J^{-1} (Philips GEN 3.0 HO 250cm inter-light). In this report we examine how these advances influence the costs associated with lighting systems and how far these advances can be expected to continue. While the spectral effects of LEDs provide many opportunities for manipulating plant responses (see CP125 and AHDB Lighting guides) and can alter crop productivity and quality, this report will focus only on the effects of different spectra on lamp efficacy and running costs. In particular, we will explore the answers to these questions:

1) How does wavelength influence efficacy?
2) How much energy can be saved by using LEDs?
3) Will LEDs only ever be used produce flavour?

This last question perhaps requires some further explanation. It relates to a question I have encountered on several occasions asked in different ways from different perspectives. In the first instance, it was asked as posed here in response to the observation that many Urban Farms (multi-tiered controlled environment growing systems lit with LED not sunlight) currently focus on production of micro herbs and other flavoursome crops with a short shelf life and of high value yet providing little calorific value. A similar and related question is why use LED lighting to grow plants when the sunlight is free? There are many compelling reasons for the potential inclusion of urban farms to fulfil specific needs of the food production system (including food security, food safety, pest and disease exclusion, consistent food quality, enhanced flavour or nutritional value), however, here we will make these assessments purely based on energy use efficiency.

Solar panels provide a source of renewable energy and can be located in places that are unsuitable for crop production but large areas are required to generate significant amounts of power and land suitable for food production is often used for solar farms. The choice on use of land is often decided on financial benefits associated with power generation over food production. However, as the population increases and/or as food supplies are challenged (via climate impacts or social unrest), food security and energy security may come into conflict.

The large area requirement of solar farms is partly due to the low efficiency of solar panels. The majority of commercially available solar panels are currently able to convert between 14 and 22% of the energy contained in sunlight into electricity (EnergySage website). However, the best solar panels currently achieve conversion efficiencies of up to 46% (Hicks 2016) and advances in solar panel efficiency are progressing at a considerable rate. The theoretical upper limit of solar panel efficiency has been determined to be 69% (de Vos & Pauwels, 1981) so there is considerable room for improvement. To put these values in to context only 42% of the energy in sunlight can be used by plants for photosynthesis and variability in light intensity means plants rarely achieve maximum light use efficiency. This means the best solar panels are better than plants at using sunlight. Here we explore the potential for future advances in LED and solar panel technology to increase the number of PAR photons available for photosynthesis in comparison to direct use of sunlight. As part of this assessment, we have incorporated a new parameter 'solar equivalence' the point at which a combination of LED and solar panel technology can generate the same number of PAR photons as are incident on a solar panel from sunlight. If solar equivalence can be achieved, optimised light systems in multi-tiered systems would be expected to produce far-more food than can be achieved with direct use of sunlight. Furthermore, if solar equivalence can be exceeded, solar panel could power the growth of more food than farmland and sell surplus energy to the grid.

Materials and methods

Calculating the theoretical limit of the efficacy spectrum

The theoretical lamp efficacy was calculated assuming no loss of energy (production of heat) occurs as electrical energy is converted to photons. The energy contained with a photon (*E*) was calculated as:

$$E = \frac{hc}{\lambda} \tag{1}$$

Where *h* is the Planck constant, *c* is the speed of light in a vacuum and λ is the wavelength. The theoretical maximum efficacy (ε with units of μmol J^{-1}) was then calculated by determining how many photons can be generated from one Joule (*J*) of electricity (one joule per second = 1 Watt):

$$\varepsilon = \frac{J/_E}{L} \tag{2}$$

Where *L* is the Avogadro constant which has a value of 6.02×10^{23} mol^{-1}.

Calculating lamp running costs

The efficacy (ε) of a lamp (actual or theoretical) was used to determine how many watts of electricity ($W_{[electricity]}$) must be used to achieve a certain photon irradiance (I) per meter squared (m^2) using equation 3 (this is an approximation because losses due to reflector inefficiencies and lamp location are not accounted for in this generalised approach):

$$\boldsymbol{W_{[electricity]} m^{-2} = \frac{I}{\varepsilon}} \qquad (3)$$

The number of lamps per meter squared required to achieve I was determined as lamp wattage divided by the calculated wattage per m^2.

Calculating lamp energy requirement

Using equation 3 the energy required to light a 10 m^2 area was calculated for three different light intensities 100, 200 and 300 µmol m^{-2} s^{-1} and for lamp efficacies between 1 µmol J^{-1} and 6 µmol J^{-1}. The change in energy consumption in response to changing efficacy was determined relative to the energy consumption of a 600W HPS lamp (efficacy 1.92 µmol J^{-1}, AHDB Technical Guide 2015, Lighting: In Practice)

Running costs

In the calculators, running costs are calculated by multiplying energy consumption by the total annual hours of operation and by the energy price. A fixed energy price (which can be changed in the calculators) is used in the calculations.

Solar panel efficiency

Light measurements made at STC were used to calculate the electricity generation potential using solar panels of differing efficiencies. Solar panel efficiency is calculated as the percentage of solar energy (measured in $W_{[light]}$ m^{-2}) that is converted into electrical energy (measured in $W_{[electricity]}$ m^{-2}). To calculate the electricity production we simply multiplied the STC light measurements by the efficiency ratings of the solar panels.

Results and Discussion

Theoretical lamp efficacy

During the course of this fellowship, LED lighting systems have advanced at a considerable rate and LED efficacy has increased from 1.89 (Philips production modules used the LED4CROPS facility) to 3.0 (the latest Philips LED inter light). But how much further can efficacy improve? The physics of light places constraints of the maximum energy efficiency that can be achieved by lighting technology. We have presented these limits with the aim of developing grower understanding of how different light spectra influence lighting systems but also to highlight the potential for continued development in the lighting industry. The theoretical efficacy of a perfect light source (no energy lost during photon generation) increases as the wavelength increases (Figure 2), this is because photons with longer wavelengths contain less energy. This means that one Watt of electricity can potentially be used to generate a greater number of red than blue photons. The dashed line in Figure 2 shows the efficacy of a Philips LED Inter-light which currently has the highest efficacy commercially available (3.0 µmol J^{-1}). The spectral mix of this light is over 90% red light. As can be seen in the graph there is considerable room to increase the efficacy, almost double for red LEDs. The red triangles in Figure 2 show the efficacies of several commercially available LEDs (data taken from Cocetta et al., 2017). These data demonstrate the drop in efficacy that occurs with current LED technology in the green

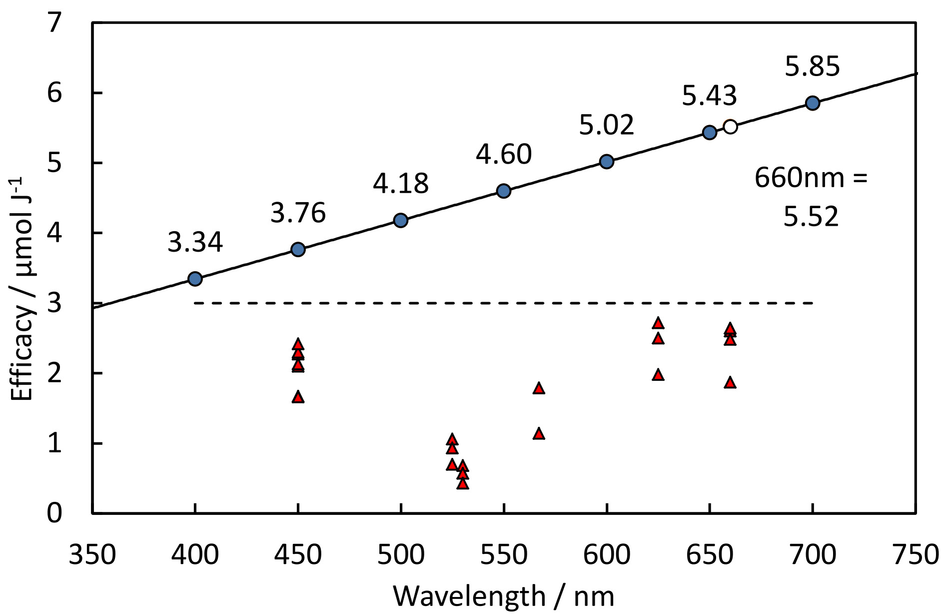

Figure 2. The spectrum of maximum theoretical efficacy that could be achieved with a perfect light source. The dashed line indicates the efficacy of the latest Philips inter-light which has a market leading efficacy of 3.0 µmol m^{-2}. The red triangles indicate the efficacies of a range of commercially available LEDs as reported by Cocetta et al., 2017.

region of the spectrum. For this reason white LEDs (blue or UV LEDs with a phosphor coating currently provide the most energy efficient way to generate green light. The differences in LED efficacy for different coloured LEDs are reflected in efficacy ratings reported for different lamps in CP139. Systems containing predominantly red and blue light have higher efficacies than multi coloured LEDs and red : blue systems with higher blue percentages have reduced efficacy compared to those with low blue percentage. With current LED technology white LEDs provide the best source of green light.

Efficacy and energy consumption

Increasing lamp efficacy results in a decrease in energy consumption (at a given light intensity). This is one of the main factors that has attracted attention to LEDs in the horticulture sector. The results above suggest that there is potential for LED efficacies to continue increasing for some time but how would improvements in efficacy influence the running costs of lamps. The energy inputs required to achieve three different light intensities as lamp efficacy changes are shown in Figure 3. As lamp efficacy increases energy consumption decreases with a negative power function. This means that future advances in lamp efficacy will provide smaller increases in energy saving. When the energy savings are calculated relative to a standard 600W HPS lamp (Figure 4) we can see that the best LEDs currently available provide a 36.6% energy saving. This is a significant

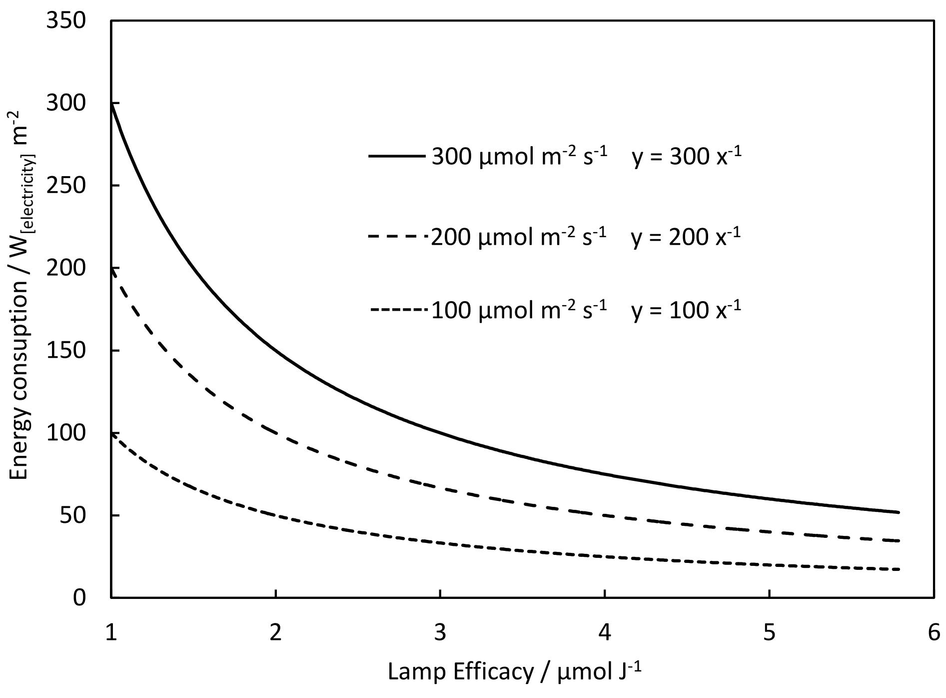

Figure 3. Influence of light intensity and lamp efficacy on electrical wattage required to illuminate a 10m^2 area.

energy and cost saving and future advances in LED technology will continue to reduce running costs. The upper limit to energy saving in comparison to HPS would be 65% (100% red LED at the theoretical limit) but it is highly unlikely this value will ever be achieved. A more reasonable efficacy target would be to assume LEDs can be developed that achieve 75% of their maximum efficacy. An LED with a 10% blue : 90% red spectrum would have an efficacy of 4 µmol J^{-1} and would result in a 52% energy saving compared with HPS.

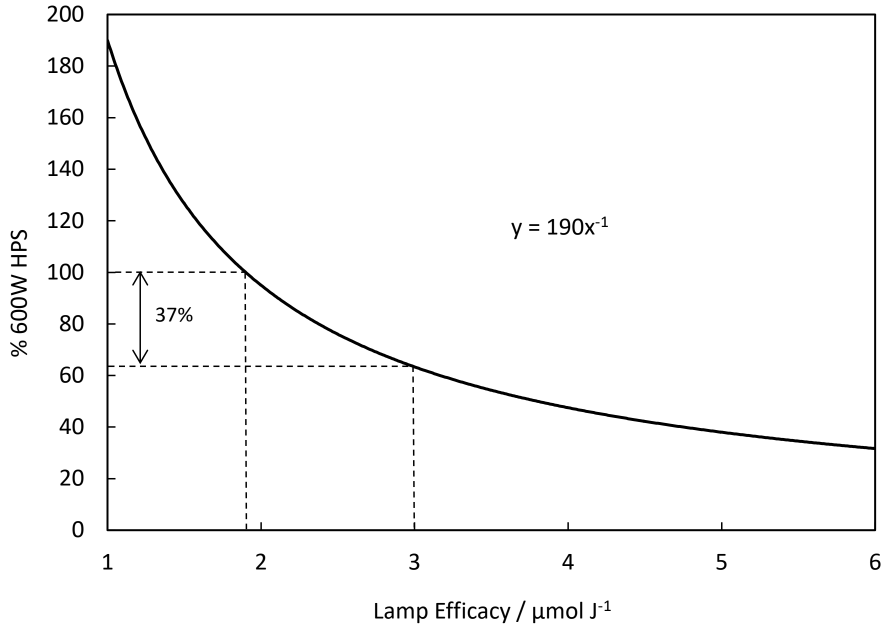

Figure 4. The influence lamp efficacy on the electricity requirements expressed as a percentage of the energy used by a 600W HPS lamp. Increasing efficacy from 1.92 (HPS lamp) to 3.0 µmol m^{-2} (Philips Gen 3 inter-light) reduces energy consumption by 36.7%. Note these values are independent of light intensity.

Number of LED modules required to achieve specific light intensities.

LED system design is highly variable between companies and will potentially change as advances in technology occur. As LED efficacy increases system designers are afforded two options 1) reduce lamp wattage to achieve the same light output or 2) keep the wattage the same and produce more light. Each design choice will have different implications. If the wattage is reduced the same number of lamps will be required to light an area, this will mean easy integration in to existing setups and may help retain light uniformity were lamps are located close to plants as occurs in multi-layered growing systems. If the light output is increased, fewer lamps will be required to light a given area (Figure 4) which will decrease the installation costs as well as the running costs. Having fewer lamps illuminating an area may impact the light uniformity meaning lamp spacing and optics need revising, this is not an issue for new installations but may provide added costs if replacing an existing installation.

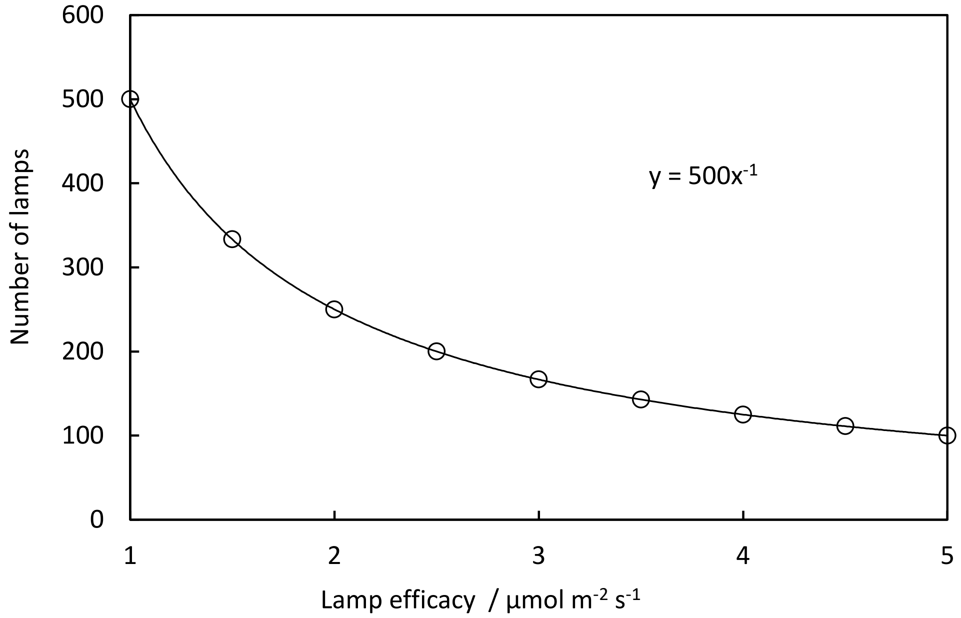

Figure 4. The influence of lamp efficacy on the number of 40W lamps required to illuminate a 100m^2 growing area to an intensity of 200 µmol m^{-2} s^{-1}.

Solar panels

As stated above increases in LED efficacy will only be able to reduce energy consumption so far. If further reductions in our reliance on fossil fuels are to continue alternative power sources will be required. Solar panels provide one source of renewable energy that requires no ongoing inputs making them low maintenance power sources suitable for grower operations. However, as plants use light for growth there is conflict between the idea of generating electricity rather growing plants. We set out to determine if advances in LED and solar panel technology could potentially be used to increase plant yields in comparison to growing plants directly with sunlight. In Figure 5 and Figure 6 we have determined how efficient solar panels would need to be to achieve solar equivalence when combined with LEDs of different efficacies. LEDs with an efficacy of 2.7 µmol J^{-1} would just fall short of solar equivalence even with solar panels able to achieve the theoretical maximum efficiency (69%). LEDs with an efficacy of 3.0 µmol J^{-1} would achieve solar equivalence with solar panels with an efficiency of 65% just below the theoretical limit. If LEDs can be created that achieve an efficacy of 4 µmol J^{-1} solar equivalence could be achieved with a solar panels with an efficiency of 49% which is only slightly above the most efficiency solar panels currently available.

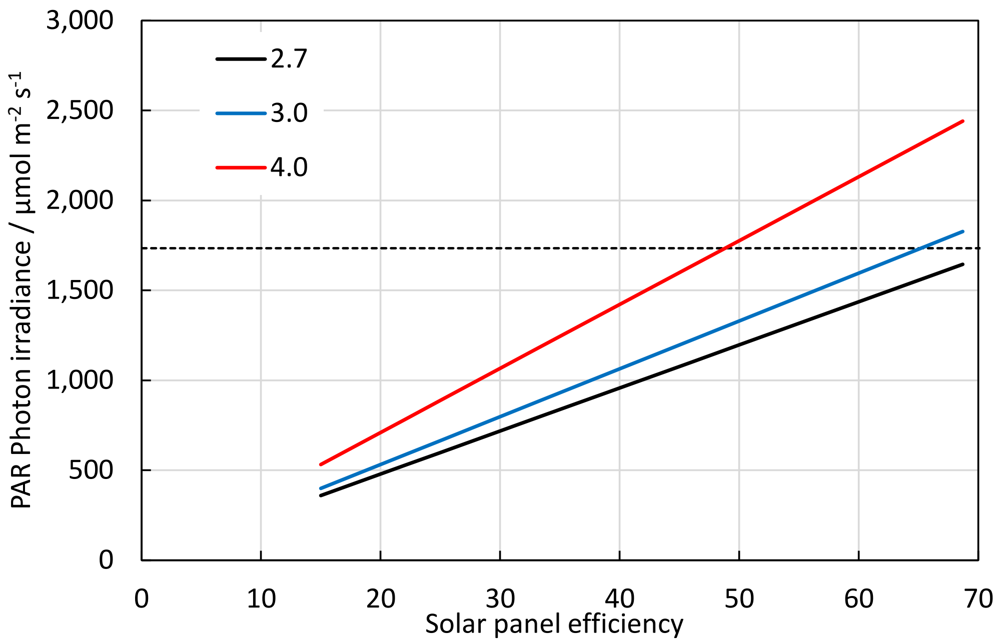

Figure 5. The number of photons that can be generated by lighting systems that have different efficacies when powered by solar panels of different efficiency. The dash line indicates the point of solar equivalence and represent the number of PAR photons present in the solar spectrum used in the simulations.

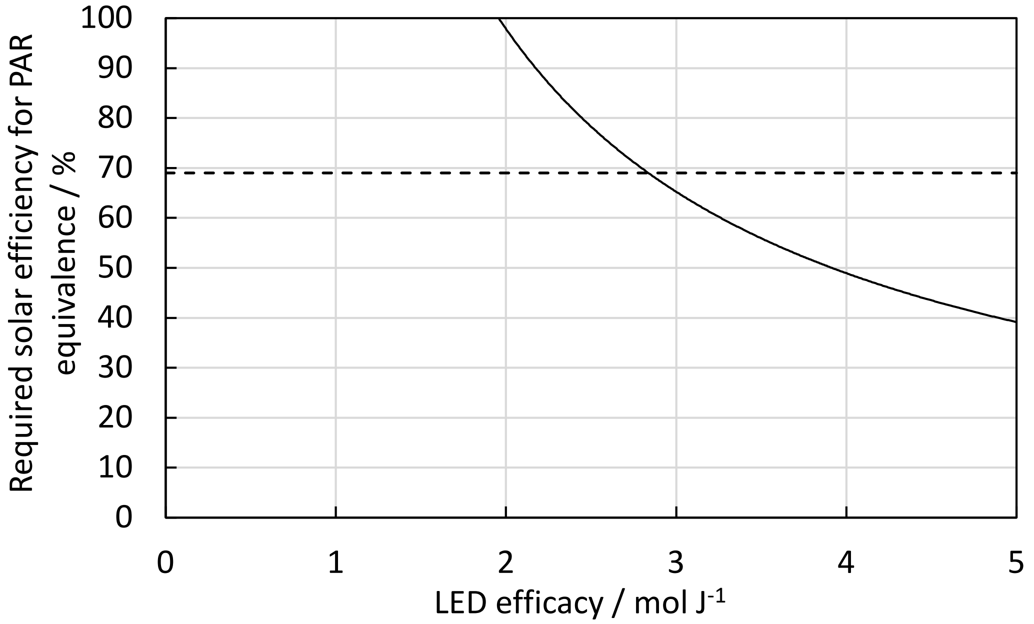

Figure 6. The Solar panel efficiency required to achieve solar PAR equivalence with LEDs of differing efficacy. The dash line indicates the theoretical limit to solar panel efficiency.

Conclusions

Advances in LED technology have been rapid of the last 5 years. The results presented here indicate there is considerable room for continued development. These findings should not be used to delay investments in LED technology if the economics are currently favourable but they may help growers plan for further advances in technology.

The updated calculators that have been produced during this work will provide growers new tools for comparing different lighting installations.

We have highlighted the potential for future advances in LED and solar panel technology to make better use of sunlight and potentially increase crop yields compared to direct growth of crops under sunlight. The efficiencies/efficacies required to achieve solar equivalence are not that far beyond current technology though it will be some time before they are affordable. However, both technologies are expected to continue receiving significant R&D investments and costs will come down.

GROWER SUMMARY 2: Economics of using supplemental LED lighting in glasshouses

Headline

Advances in lighting technology have the potential to reduce energy bills making winter production more profitable. Such lighting systems will, however, only make economic sense if crop sales are sufficient to cover the costs or deliver some other economic advantage. We have combined a supplemental lighting simulator with a tomato crop model to quantify the cost and yield implications of year round crop production with different lighting systems and energy pricing models.

Background

The use of lighting in horticulture provides many benefits for season extension or year round production. However, while crop yields and quality can be improved with lighting, the costs associated with installing and operating those lights impact on profitability. LED lighting systems have gained considerable interest in recent years due to the potential for reduced electricity usage. The efficacy of LED lighting systems continues to improve; the most advanced lamps now achieve an efficacy of 3.0 μmol J^{-1} which provides a 36% energy saving over 600W HPS lamps. However, reduced energy bills alone may not be sufficient for winter production to return a profit. Many factors impact business economics and many of these factors are site specific. Variability in sunlight is a major factor that impacts crop production and the number of hours supplemental lighting must be operated for to maintain plant yield and quality. Assessing the interactions between sunlight, supplemental lighting requirements and crop yields can be complex but accurate simulations could help businesses decide if or when to invest in lighting technology.

Summary

We have developed a model that can be used to simulate the supplemental lighting requirements of glasshouses based on site-specific light measurements and assess crop yields. The models have been used to simulate the effects of different lighting strategies on cost of production of a tomato crop. Running costs are proportional to the amount of time the lights are turned on and the cost of the electricity. The influence of changing electricity price on operational costs can be easily assessed as running costs vary linearly with cost per kWh. Different lighting strategies, however, result in nonlinear changes in running costs because solar light levels vary nonlinearly through the seasons (Figure GS5). Increasing the efficacy of the lamps reduced costs nonlinearly are shown in grower summary one. With variable electricity pricing, electricity costs were found to peak at 5pm. Avoiding turning the lights on at 5pm had little effect on the overall running costs in these simulations, though these simulations don't account for any penalties that may be encountered by lighting during these periods nor do they account for the potential benefits of exporting electricity during these hours.

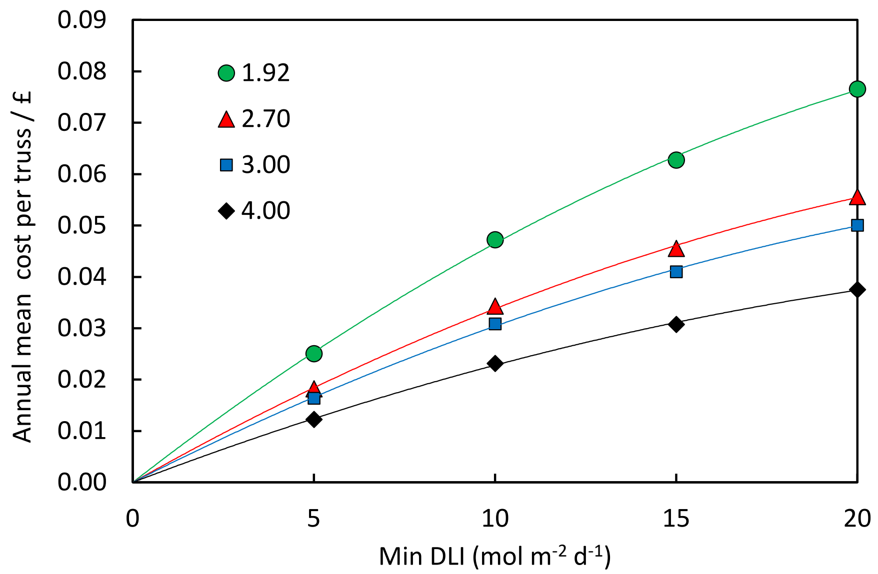

Figure GS 5. Effect of lighting strategy and lamp efficacy (different colours), on the mean annual electricity cost per truss. Electricity price was set to 4.8 p kWh^{-1} for these simulations.

Financial benefits

In the first science section of this report (Implications of ongoing increases in LED efficacy) we examined the running costs of different lighting systems based on their efficacy and provided updated calculators for comparing lighting systems. While those simple calculators provide useful information for comparing different lighting systems they are too simple to assess expected running costs in specific glasshouse systems. Here we have developed a more detailed model that includes a crop performance model. The simulator uses natural light levels to determine the hours of supplemental lighting required to maintain crop performance based on crop light requirements. The simulator includes various electricity costing structures, fixed or variable pricing, and can be used to assess the benefits and costs associated with different lighting systems, lighting strategies and energy costing models.

These models can be used to help businesses quantify the costs of operating lights based on the natural lighting environment at their location. The model is currently parameterised for a tomato crop but can potentially be applied to any crop if sufficient data is available. Energy costs can be calculated based on glasshouse area or on a per sales unit basis (in this case cost per tomato truss). Where lighting systems have been installed and crop data is already available the model can be validated and used to help refine lighting strategies and assess benefits of updating lighting systems or assessing the potential impacts of different energy pricing models.

Action Points

The simulations presented in this report aim to demonstrate the potential of this modelling approach and to highlight the potential for using site specific information to examine the likely impact of different lighting strategies on yield and production costs. To gain insights directly relevant to your site/business the models should be applied to data gathered at your site and be based on likely electricity pricing structures. For access to the models and support, contact STC. For the model to be successfully implemented the following data should be collated:

1) Light data from your site. Half hourly data is ideal but the models can be implemented based on daily light integrals if that is the only data available. If no measurements have been made at the site, other sources of light data may be available.
2) Crop performance data can be used to assess the crop lighting requirements if data can be compared to light measurements made over the cropping period. Data for at least one complete cropping season would be required but model accuracy will be increased if more data is available.
3) An indication of which lighting systems are of interest. STC can also provide advice regarding the benefits of different lighting systems if necessary.
4) Information regarding the energy pricing at your site. This is not necessary but is useful as a starting point. The models can be used to explore how electricity prices impact profits.

SCIENCE SECTION 2: Economics of using supplemental LED lighting in glasshouses

Introduction

In the UK, many glasshouses operate seasonally because winter production requires use of supplemental lighting and heating. Even when lighting systems (predominantly HPS lighting) are used to drive year round production, high energy prices have a significant impact of profits which may result in poor economics. However, with advances in energy efficient LEDs, the running costs of lighting can be reduced in comparison with 600W HPS lamps. These reduced energy bills have the potential to make winter production economically more favourable.

While LEDs offer energy savings, they are currently more expensive to buy (LEDs are more expensive per unit than HPS), but lower power ratings means infrastructure installation costs may be lower. This additional cost can potentially be repaid in energy savings over the lifetime of the lamps. The speed at which the additional costs are repaid, however, is important as ROI periods need to be shorter than 5 years to gain investment support. The speed of repayment will be dependent on the energy prices and annual hours of usage.

Reduced energy bills and short ROI periods only provide part of the analysis that must be performed when assessing the potential for lighting installations. Crop performance and sales must also be taken into account to ensure significant financial losses are not incurred Winter production will always cost more than summer production though winter sales also have the potential for higher sales value. An accurate assessment of crop yields will be important for predicting sales revenue. Site-specific information such as natural light levels should be accounted for when making these assessments as they will impact crop production.

Here we have developed a model that uses site-specific light data to assess lighting hours, electricity costs and determines crop yields. The model can be used to assess the impacts of different lighting systems, different lighting strategies and energy pricing on the total annual electricity costs and crop yields. For the simulations presented in this report we have used a year round vine tomato as the example crop. However the methods can be applied to any crop where sufficient data is available to develop an accurate crop model. The simulations run here are aimed at demonstrating the potential of the model and how specific factors influence production costs.

Methods

Sunlight measurements

The simulations in this work are based on light measurements made at STC. Light measurements were made using a global radiometer ($W_{[light]}$ m^{-2}) and daily light integrals (DLI) were calculated and recorded by STC's site computer. Light data from 2014 were used in these simulations.

Conversion between light measurement units

Many sites, including STC, have long term records on sunlight that have been measured in units of $W_{[light, global]}$ m^{-2}. When used to calculate DLIs, the measurement units become J m^{-2} d^{-1}. When making light measurement relevant to plant growth it is more desirable to make measurements in terms of photosynthetically active radiation (PAR) with units of moles of photons per meter squared (mol m^{-2}). Also, LED lighting system specifications are increasingly expressed in terms of micro moles. Here we converted sunlight measurements in $J_{[light, global]}$ m^{-2} to $mol_{[PAR]}$ m^{-2} by multiplying with a conversion factor of 1.957 (see AHDB Technical Guide Lighting: the Principles 2015 for information on unit conversion factors).

Crop light requirements

Supplemental lighting hours were determined based on crop light requirements. In this simulation we have used tomato crop as an example. Tomato crop light requirements were calculated as 150 J m^{-2} d^{-1} for plant growth plus 35 J d^{-1} per truss. Plants were assumed to have 8 trusses per head. So in a glasshouse where the head density was 3 heads m^{-2} (24 trusses m^{-2}), daily light requirement would be 990 J m^{-2} d^{-1}. These values are based on light measurements performed outside the glasshouse. To enable easy comparison between solar radiation and supplemental lighting we calculated the solar light inside the glasshouse and converted the units to mol m^{-2} d^{-1} using a conversion factor of 1.957. Light penetration into a glasshouse was assumed to be 70% (Kozai, Goudriaan & Kimura 1978) for the purposes of these calculations. So the light requirement for a tomato crop with three heads m^{-2} would be 13.56 mol m^{-2} d^{-1} (150 J m^{-2} d^{-1}= 2 mol m^{-2} d^{-1} & 35 J m^{-2} d^{-1} = 0.48 mol m^{-2} d^{-1}). The crop light requirement data was used to either set the minimum light requirements for the simulations or to determine the head density that could be supported by different lighting scenarios.

Supplemental lighting hours

The model was designed to explore the impacts of different supplemental lighting strategies and operates on a 30 minute time step. In the simulator, lighting can be turned on and off based on any input variable. In the simulations tested here, lighting was switched based on DLI values and/or based on time of day. The maximum lighting hours was set to 22 hours, with the dark period between 10pm and midnight.

Energy Pricing

Two energy pricing scenarios were explored 1) fixed energy pricing and 2) variable electricity pricing. For the fixed energy pricing, several different fixed electricity prices were used to determine the impact of cost of production costs. For variable pricing models, FEC provided actual real time variable prices on a 30min time step for the period between 2013 and 2016. With the variable pricing models we performed a cost thresholding exercise were lights would be turned off when the cost goes above the threshold. This approach limits the spend on electricity but also reduces the light available for the crop, reducing yield.

Results and Discussion

Lighting strategy

Light data measured every 30 minutes at STC in 2014 (Figure 7A) demonstrates the large seasonal fluctuation in available sunlight. Four different lighting strategies were applied to this light dataset to ensure a minimum daily light integral (DLI) was achieved each day of the year. For the majority of simulations minimum-DLIs were set to 5, 10, 15 or 20 mol m^{-2} d^{-1}. Based on the light intensity supplied to the crop by the simulated lighting installation (200 µmol m^{-2} s^{-1} in these simulations) the model calculates the number of hours a day that must be applied to achieve the minimum-DLI levels (Figure 7B). At STC in the winter months, the lamps would need to be on for nearly 24 hours per day to achieve a DLI of 20 mol m^{-2} d^{-1}. The simulated total DLI values achieved with each strategy are shown in Figure 7C. Note that DLI drops below 20 mol m^{-2} d^{-1} occasionally when more than 24 hours of lighting would be required to achieve these light doses. Greater minimal DLI light settings would be unnecessary for most applications as it would not increase winter light levels but would result in lights being on during the summer months.

Electricity costs per floor area

With the lighting hours defined, it is possible to determine the annual running costs of a glasshouse of given size and to assess the impacts of different energy prices and lamps of different efficacy. With a fixed energy pricing, the running cost increases linearly with increased electricity prices (Figure 8). Altering the minimum DLI setting results in a non-linear change in running costs (Figure 9). At low minimum DLI settings (<5 mol m^{-2} d^{-1}) the annual running costs increase slowly as even during the winter months sunlight is often

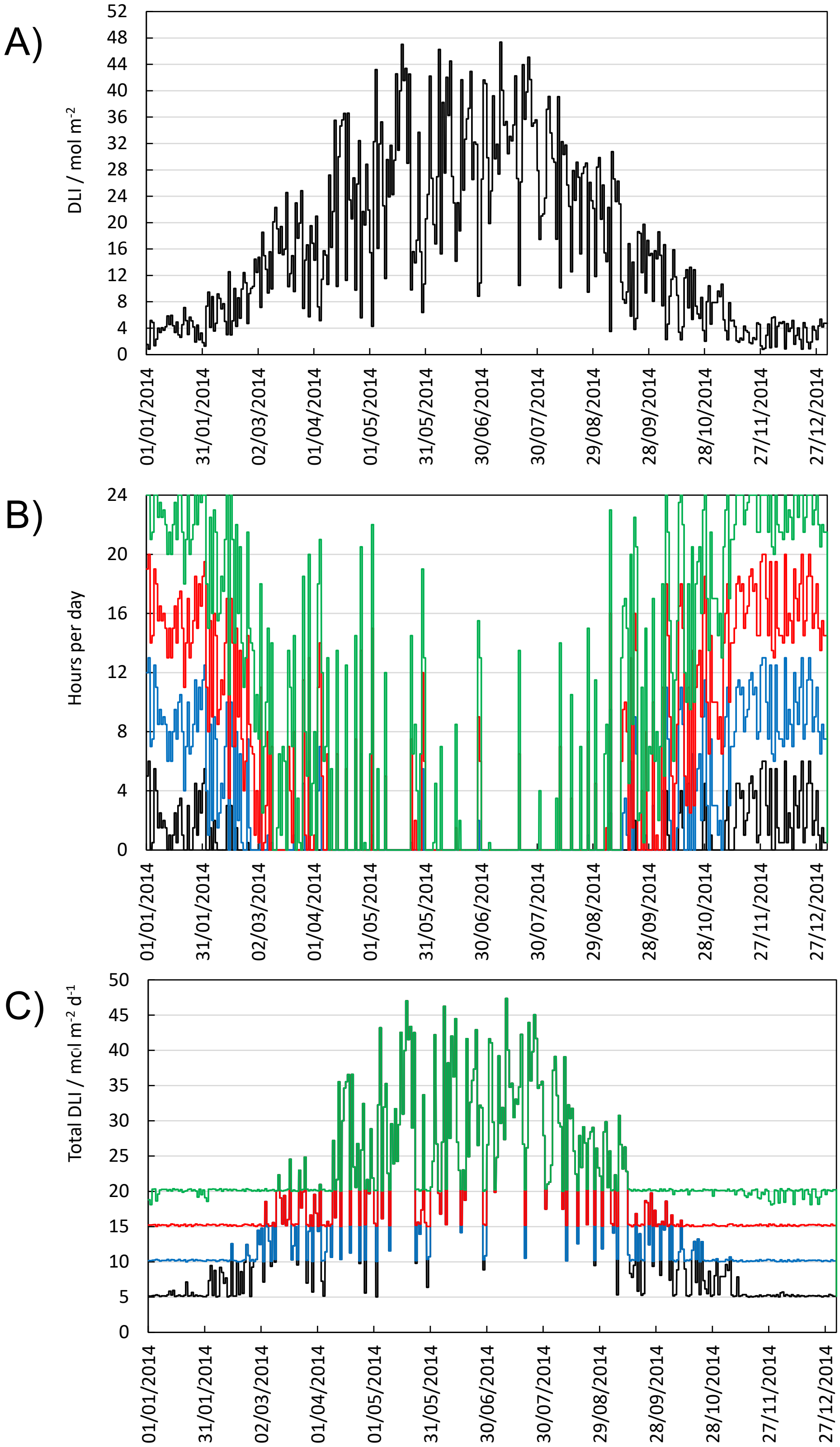

Figure 7. A) Measured DLI at STC during 2014. **B)** The number of hours lights must be on to achieve the four minimum DLI values 5, 10 15, 20 mol m^{-2} d^{-1}. **C)** Total DLI (sunlight + supplemental) values achieve when lights are operated to the hours shown in B).

sufficient to achieve these light levels. As the minimum DLI setting increases (5-20 mol m^{-2} d^{-1}) the running costs increase rapidly as lights remain in operation for long periods through to the equinox. At higher DLI settings (>20 mol m^{-2} d^{-1}) the running cost continue to increase and lights would remain on even in mid-summer. The non-linearity of the response is governed by the non-linear changes in natural light through the year.

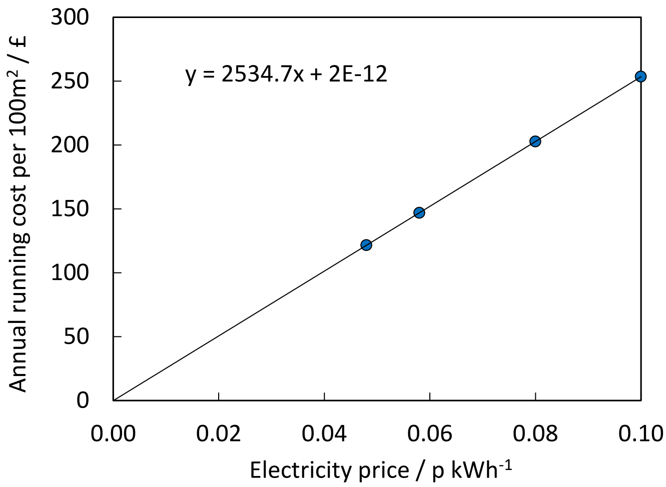

Figure 8. Influence of different fixed electricity prices on running costs. The simulation assessed the costs of 100m2 glasshouse lit with 600W HPS lamps (efficacy of 1.9) and a lighting strategy set to achieve a minimum DLI of 5 mol m^{-2} d^{-1}.

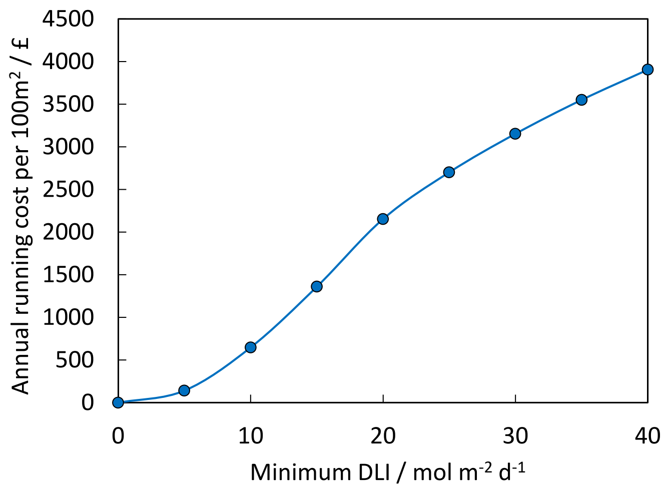

Figure 9. Influence of lighting strategy on running costs. This simulation assessed the costs of 100m2 glasshouse lit with 600W HPS lamps (efficacy of 1.9) and the electricity price was set to Electricity price set a 4.8 p kWh^{-1}.

We next assessed the impact of light sources of different efficacies on annual running costs of the tomato crop. Three LED systems with different efficacies were compared to 600W HPS lamps. Two existing LEDs were examined, Philips top lights with and efficacy of 2.7 µmol J^{-1} and the Philips inter light with and efficacy of 3.0 µmol J^{-1}. A third theoretical LED system with an efficacy of 4 µmol J^{-1} was also included in the simulation (Figure 10). For the 20mol m^{-2} d^{-1} setting the annual energy cost in a 100m^2 glasshouse decreased from £1852 when lit with 600W HPS lamps to £1200 when lit with LEDs with an efficacy of 3 µmol J^{-1}. Increasing lamp efficacy decreases the annual electricity bills non-linearly as defined in the 'Implications of ongoing increases in LED efficacy' section of this report. A lamp with an efficacy of 3.0 µmol J^{-1} resulted in a 34% energy saving compared to 600W HPS lamps.

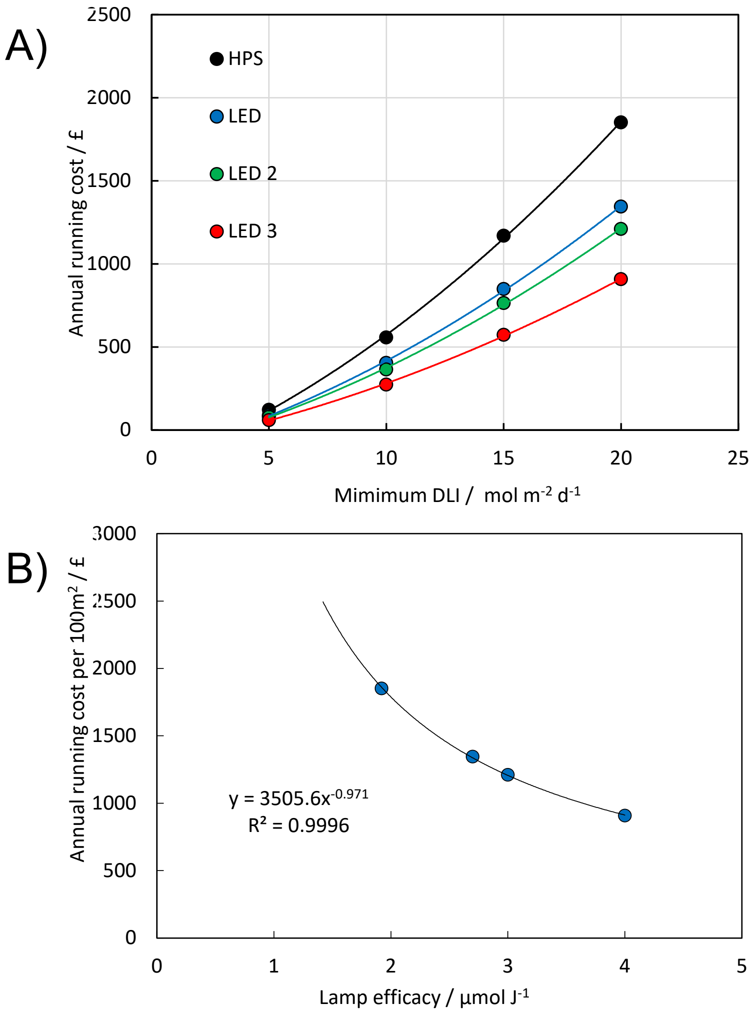

Figure 10. Influence of lamp efficacy on running costs. **A)** The annual running cost calculated for the different lighting strategies and different lighting systems. This simulation assessed the costs of 100m^2 glasshouse lit with 600W HPS lamps (efficacy of 1.9) and the electricity price was set to Electricity price set a 4.8 p kWh^{-1}. **B)** The correlation between running costs for the 20 mol m^{-2} d^{-1} lighting setting and lamp efficacy.

Electricity costs per tomato truss

While costs per floor area are relevant, the costs per sale unit have greater relevance for the cost of production and whether lighting crops makes commercial sense. Based on the light levels achieved with the different lighting strategies, crop light requirements were used to determine the number of tomato number of heads m^{-2} that could be maintained (Figure 11), the maximum density was set to 5 heads m^{-2}. Assuming the temperature control is sufficient each head should produce one truss per week. With this assumption annual truss harvests can be determined from the head densities. Yields increased as the supplemental lighting setting was raised (Figure 12) mostly due to increased winter production.

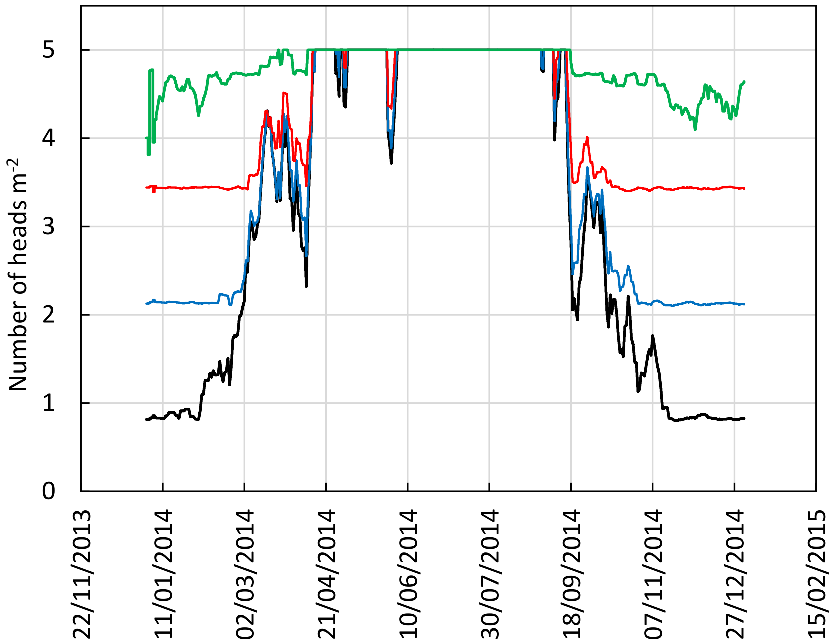

Figure 11. The calculated number of tomato heads that could be sustained in a glasshouse lit with supplemental light when the supplemental lighting hours were set to achieve different minimum daily light integrals (black = 5 mol m^{-2} d^{-1}, blue = 10 mol m^{-2} d^{-1}, red = 15 mol m^{-2} d^{-1}, green = 20 mol m^{-2} d^{-1}). Maximum head densities were set to 5 heads m^{-2}.

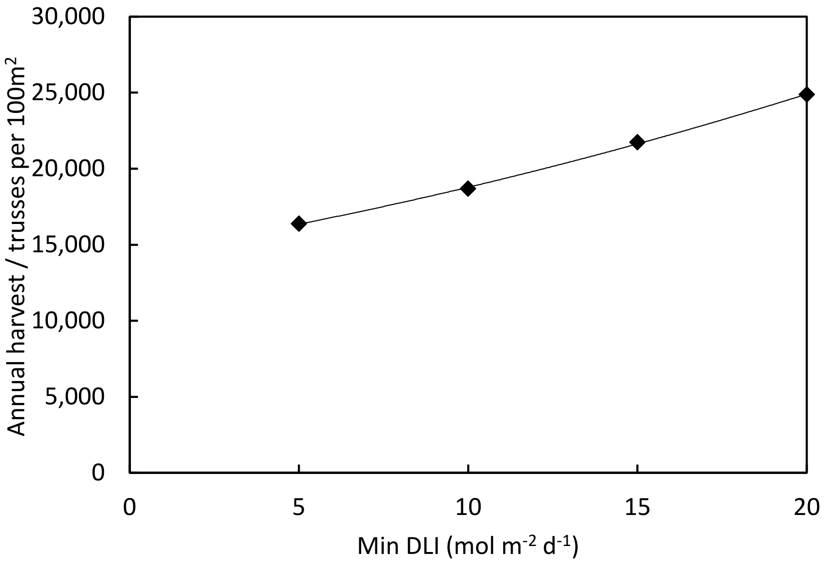

Figure 12. Number of trusses harvested in 100m^{-2} annually when grown with different supplemental lighting strategies.

Cost per truss varied through the season (Figure 13, 22p in winter to 0p in the summer) based on changes in lighting hours but also the proportion of total light provided by supplemental lighting. Maximum electricity cost per truss (Figure 14) is largely independent of lighting strategy because during the winter months on certain weeks the majority of the light is provided via supplemental lighting even with the lowest light setting. The annual mean electricity cost per truss, however, (Figure 15) increases as the minimum DLI settings are increased despite the increased yields. This is due to the increased proportion of total light provided by the supplemental lights compared with sunlight. Increasing the efficacy of the lamps decreases the costs (Figures 14, 15 & 16). Increasing the efficacy from 1.92 to 3.0 reduced the maximum electricity cost per truss by 6p and lowered the average annual cost per truss for the 20 mol m^{-2} d^{-1} treatment from 7.6p to 5p (a 34% energy saving).

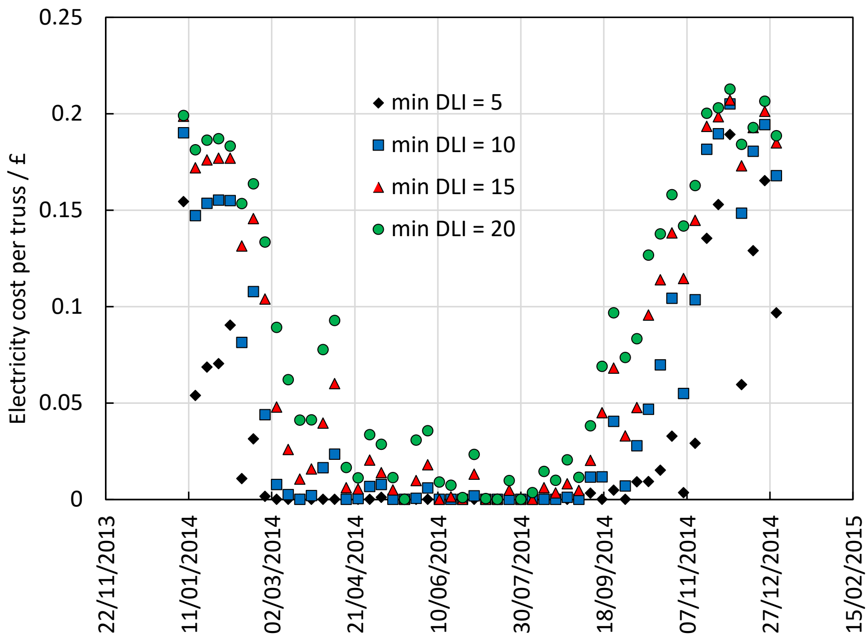

Figure 13. Cost per truss for the four minimum DLI different light settings (min DLI) through the year. Values calculated from HPS lamp and an electricity cost of 4.8p kWh.

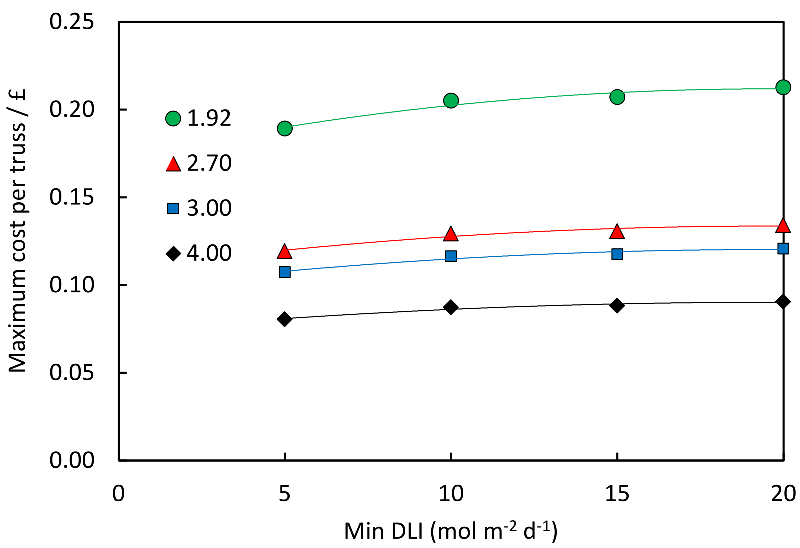

Figure 14. Effect of lighting strategy and lamp efficacy (different colours) on maximum electricity cost per truss. Prices calculated with an electricity price of 4.8 p kWh^{-1}

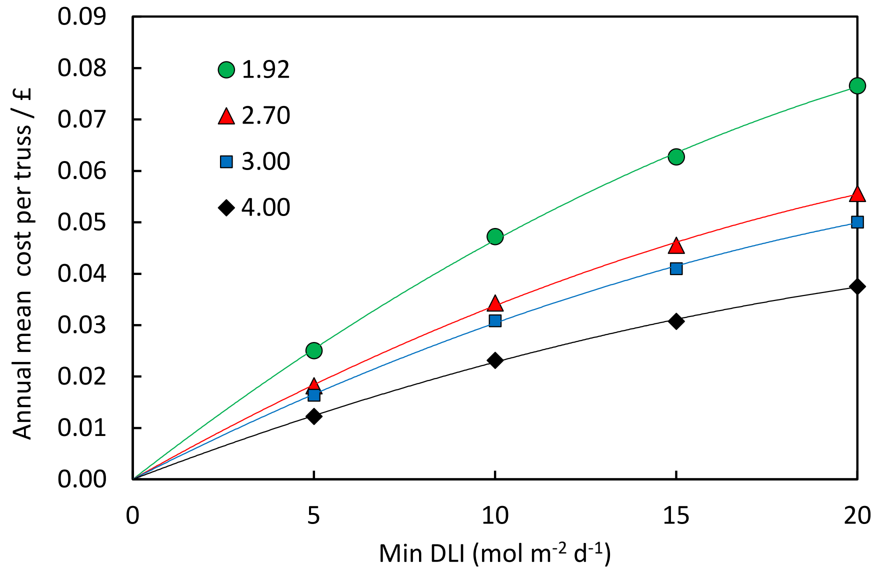

Figure 15. Effect of lighting strategy and lamp efficacy (different colours) on annual electricity cost per truss. Prices calculated with an electricity price of 4.8 p kWh^{-1}

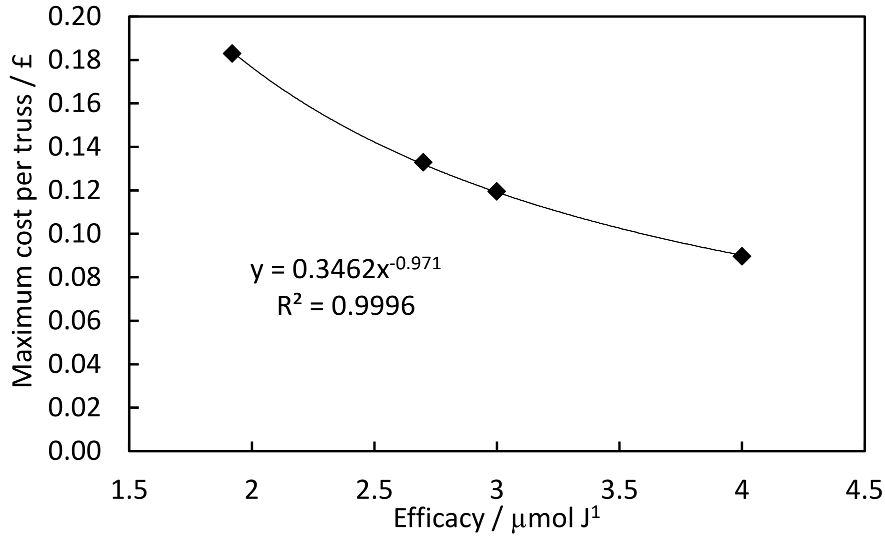

Figure 16. The relationship between lamp efficacy and maximum cost per truss. Prices calculated with an electricity price of 4.8 p kWh^{-1} and for the 20 mol m^{-2} d^{-1} lighting strategy.

Variable electricity costs

Variable electricity prices were provided by FEC for a four-year period. All simulations used the STC light data from 2014 so differences in the results for simulations using the different energy data sets are only associated with the pricing and not differences in light data. These simulations also all used HPS lamps. Prices varied through the year, between years (Figure 17) but also through the day (Figure 18). Energy prices were highest at 5:00pm but another peak was observed at 9:30 am. The lowest price was observed at

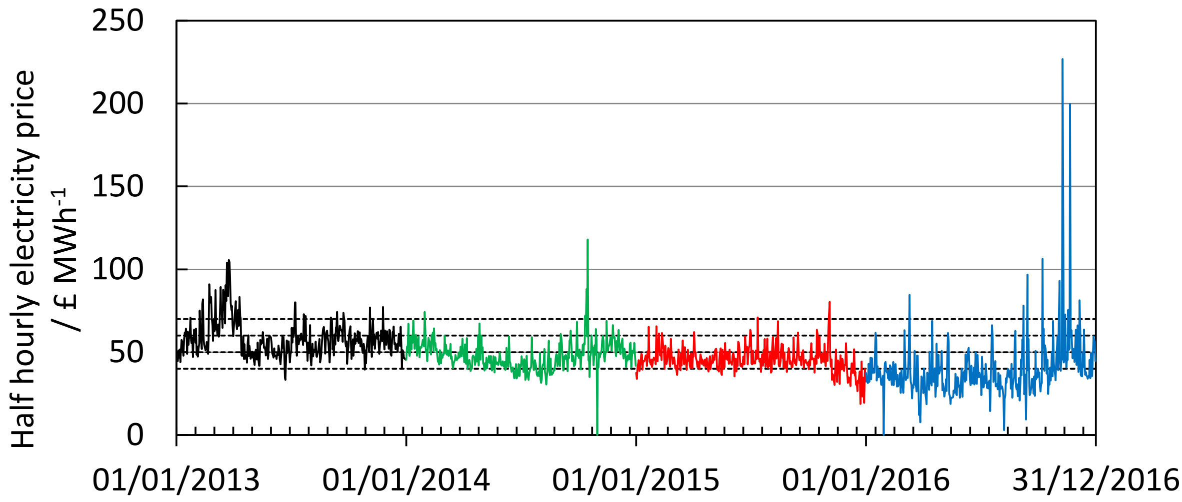

Figure 17. The real time energy prices over a 4 year period (2012-2016). Dashed lines indicate the four example price thresholds used to turn the lights off in the simulations.

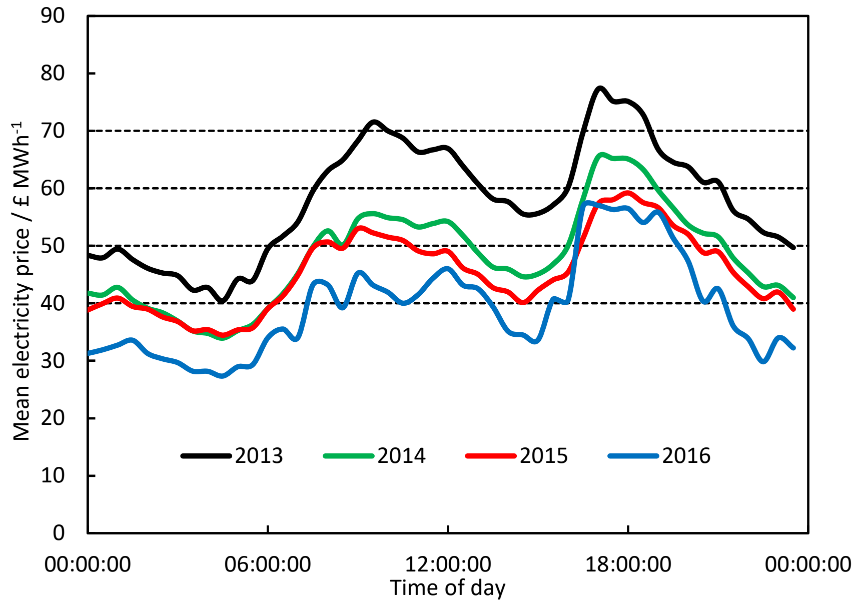

Figure 18. The changes in energy price through the day. Each line is the mean values for one of the four years examined. Dashed lines indicate the four example price thresholds used to turn the lights off in the simulations.

4:30am. With the variable electricity pricing we assessed the impact of different threshold prices. In these simulations in addition to the other lighting controls, lights were switched off when the energy prices exceeded the price threshold. For these simulations the minimum lighting hours were set to 20 mol m^{-2} d^{-1}. With a price threshold of 7p kWh^{-1} a daily light integral of 20 mol m^{-2} d^{-1} could be maintained for the majority of the year (Figure 19). Filtering out the short term spikes in electricity price has little impact on the annual electricity

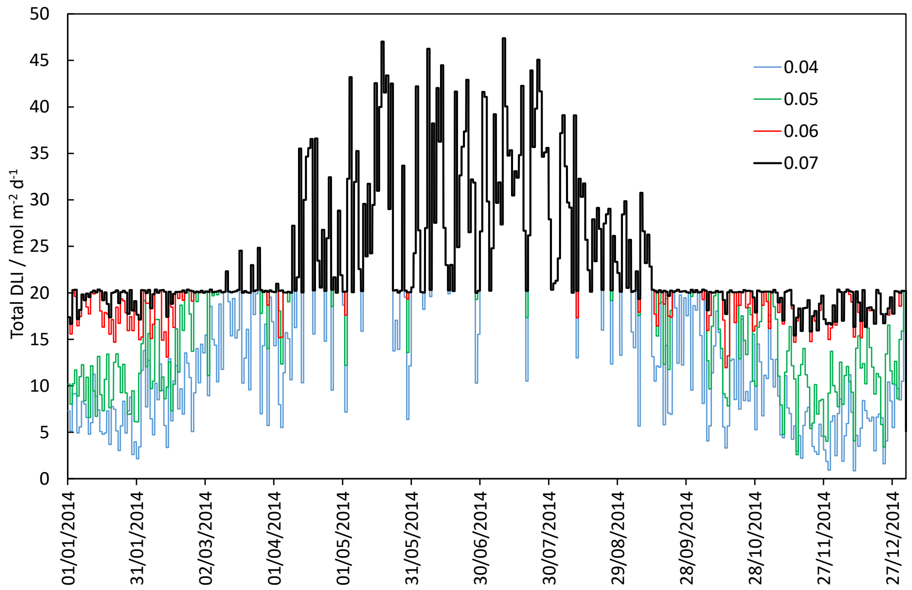

Figure 19. The total daily light integrals that were achieved when simulating the effect of different electricity pricing thresholds above which the lights were turned off. In this example the 2013 electricity prices were used.

bill nor the yields. As the price threshold was decreased further, the lights remained on for progressively less time and this impacted the total DLI that could be achieved in the glasshouse. With lower DLI values, crop head densities would have to be lowered to maintain crop quality which would significantly impact total yields (Figure 20). Due to the differing energy prices over the four years the different threshold values impacted the yields

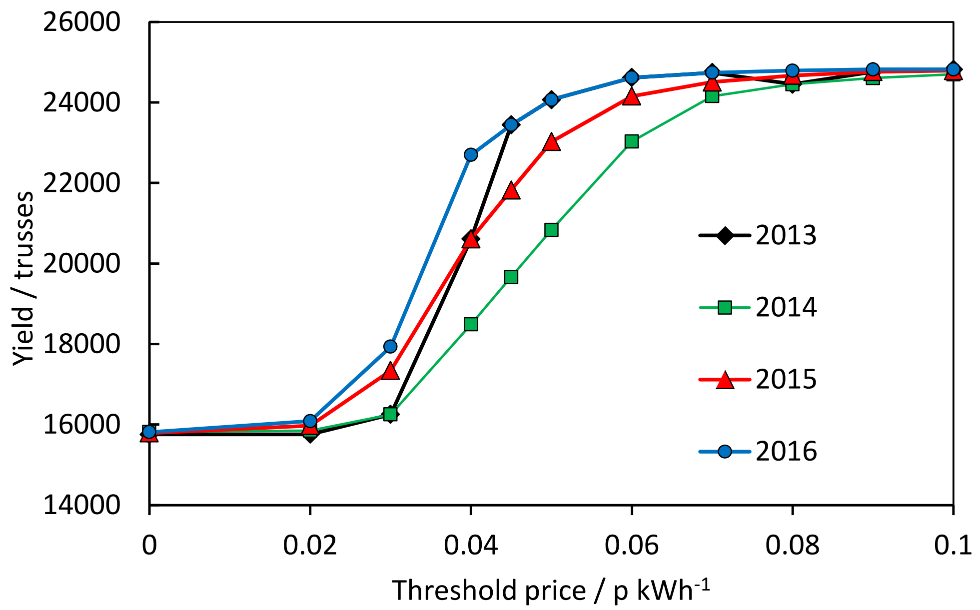

Figure 20. The influence of threshold electricity price on the annual yield (total number of trusses). Data are shown for the variable energy prices from four different years.

differently in each year. However, in these simulations total yields were reduced when price thresholds were lower than 6p kWh^{-1} and the greatest decreases in light hours and yield occurred as the threshold prices approached mean energy price for that year (4 to 6 p kWh^{-1}). Maximum electricity costs per truss (Figure 21) were greatest in 2013 (22p per truss) and cost only decreased when the threshold dropped below 4 p kWh which coincided with the drop in yield in that year. Maximum electricity costs per truss were lowest (up to 15p per truss) in 2015 and 2016 and these costs decreased when thresholds were lower than 6p kWh^{-1}. When the annual average cost per truss was determined, the greatest cost (9p per truss) was observed in 2013 and the lowest price (5.5p truss) in 2016 (Figure 22).

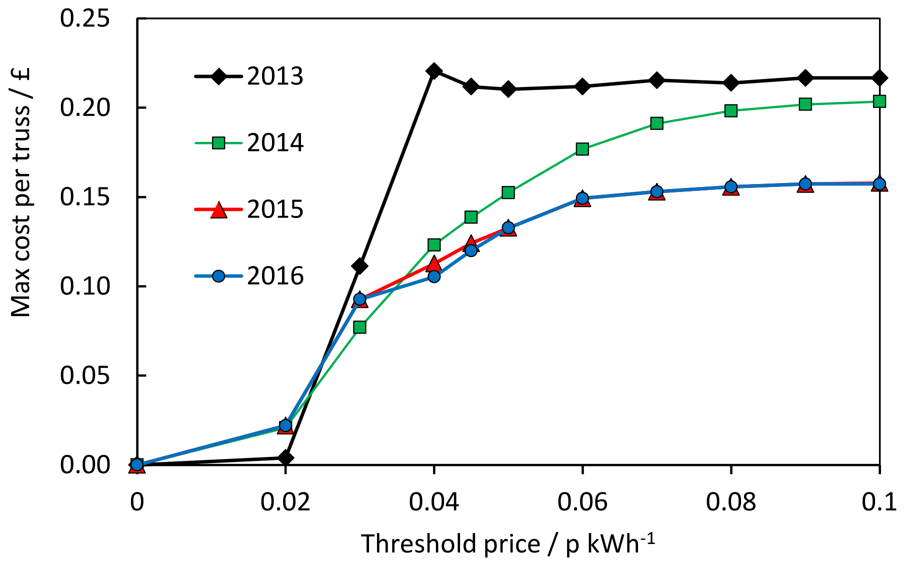

Figure 21. The influence of threshold electricity price on the maximum cost per truss. Data are shown for the variable energy prices from four different years.

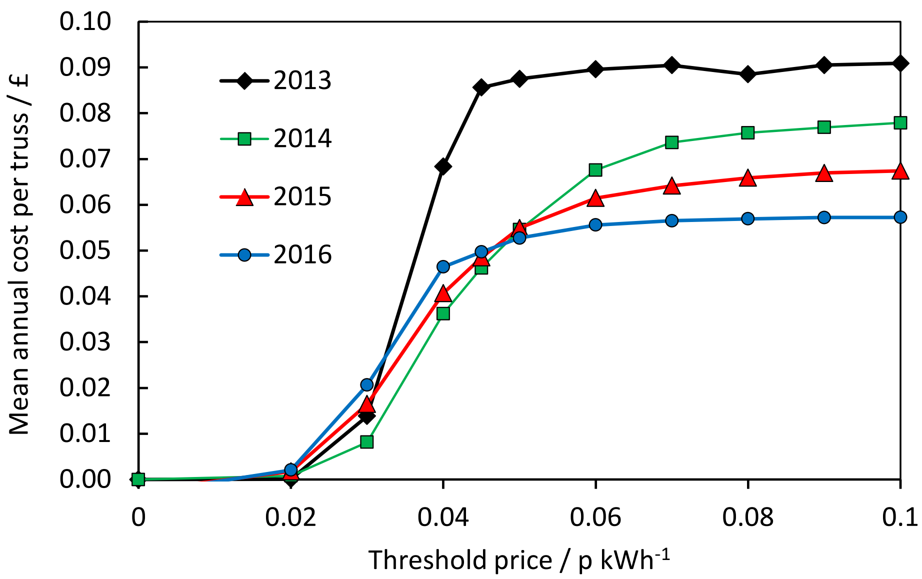

Figure 22. The influence of threshold electricity price on the annual mean cost per truss. Data are shown for the variable energy prices from four different years.

Annual Profits

These analyses do not account for the full costs of production (heating, labour, overheads etc.) and so a full profits and loss analysis cannot be performed without additional information. However, if we assume each sale unit (one truss in these calculations) generates a net profit (after the costs not included in these assessments are accounted for) we can assess the effect of different lighting strategies on the annual profit. To calculate the annual profit we assigned different net profits per truss values and used the yield calculations to assess the total sales return before subtracting the cost of the electricity. We performed this analysis on the 2013 variable energy price data set (Figure 23). If the net profit per truss is set to be equal to the mean annual electricity cost per truss (9p), the profit decreases as the threshold value increases above 0.02, the point when the lighting hours begin to increase. In this scenario, the running cost of the lights equals total annual profit. If the net profit per truss is increased to 22p (the maximum electricity cost per truss), the total annual profit is larger and remains similar as the price threshold is increased. In this pricing scenario, the higher net profit covers the costs of winter production but the increased winter production does not result in an increase annual profit. If the net profit per truss is increased to 30p per truss the total profits are again increased. However, in this scenario the profits increase as the threshold values increased above 4p kWh^{-1}. This increase in annual profit occurs as the lighting hours increase and winter yield increases. With the net profit per truss exceeding the electricity cost, total annual profits are increased buy the additional winter production. The dashed lines in Figure 23 indicates the influence of increasing the lamp efficacy (efficacy = 3 µmol J^{-1} rather than 1.9 µmol J^{-1}) on the annual profits. With a 34% reduction in the energy costs the winter production cost are reduced which improves the potential for profit. In these calculations, the energy saving increased the annual profits by £780 per $100m^2$ (equal to £78,000 per hectare).

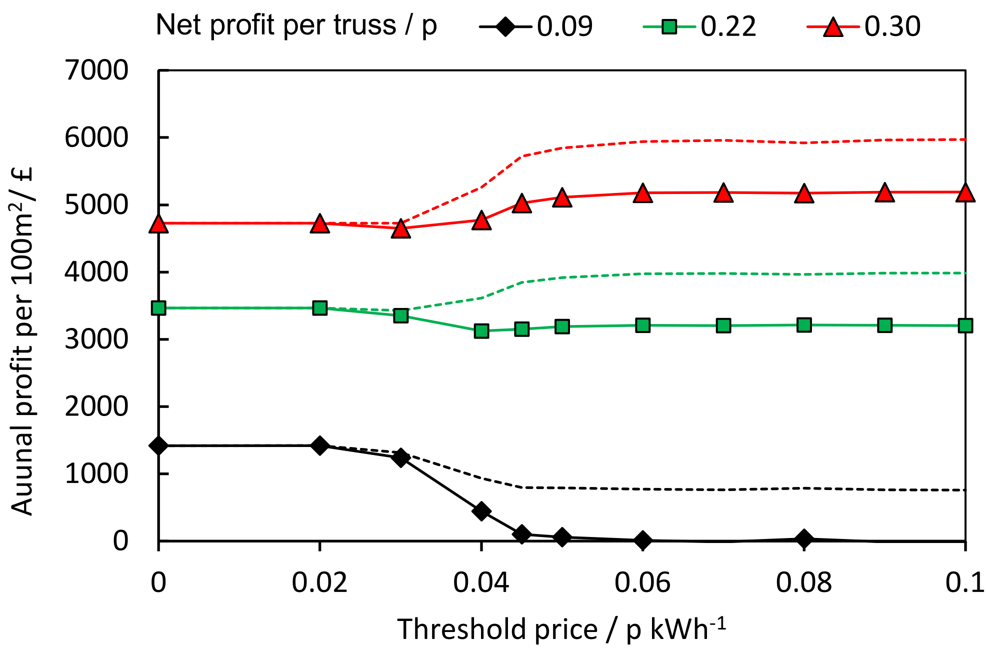

Figure 23. The influence of sales price per truss (data for three different prices are presented the three colours) and electricity price thresholds on the annual profit of a 100m^{-2} glasshouse. Solid lines indicate the profits that would be achieved with HPS lamps and the dashed line indicate the profits that could be achieved with LEDs (efficacy of 3 µmol J^{-1}). The values were calculated using the 2013 energy prices.

Assuming a lighting installation costs £1millon pounds per hectare to install we can calculate the net profit per truss required to cover the investment costs over a five year period based on the increased winter sales. For these calculations we used the variable pricing model (we used the energy prices for the four years), with the light controls aiming for a minimum DLI of 20mol m^{-2} d^{-1} and using HPS lamps with an efficacy of 1.98 µmol J^{-1}. With a net profit per truss of 44p, installation costs could be paid back within a five year period, based on the additional winter yields. If the HPS lamps are replaced with LED with an efficacy of 3 µmol J^{-1} then the installation costs can be returned in five years if the net profit per truss is 37p. With the lighting hours required to achieve these goals, LEDs would last for between 7 (lamps rated to 25,000 hours) and 15 years (lamps rated to 50,000 hours). Obviously, these calculations don't account to the different heating requirements for the different lights systems nor the additional costs associated with heating glass houses through the winter compared to summer. However, these additional costs could be included in the model with further development allowing detailed assessments of the economics of production.

Conclusions

A model that uses natural light levels to determine artificial light requirements and predict yield was developed. This model allows electricity costs per sales unit to be defined and to assess how different lighting systems and energy prices can influence yield and costs. The model has been used to run a range of simulations to examine how different lighting strategies and energy pricing structures impact costs and yields. The model was used to demonstrate that:

- Running costs are linearly proportional to electricity prices.
- Running costs are non-linearly proportional to lighting strategies, producing higher winter yields results in increased costs which can reduce annual profits.
- Increasing lamp efficacy reduces the costs of production which means the economics of winter production can be more favourable.

With further development of the model heating costs and labour could be included to allow more detailed simulations of different management strategies.

Knowledge and Technology Transfer

Interest in the LED work at STC remains high and we continue to receive visitors. In the last 12 months we have shown 31 groups of visitors round the facilities. Visits are logged as diary events recorded in the calendar and are not a count of the number of people that have visited the facilities. Visitor groups range in size from individuals to large groups with over 50 visitors. Many additional interested parties have visited the facilities but have not been logged. While the number of visitors is still considerable, the demographics of those visitors has changed. The number of academic visitors has increased this year indicating an increased academic awareness of the work we are performing in the LED facilities but also a shift in the funding landscape that may increase the diversity of avenues available for STC to become involved in new research projects. We have also seen an increase in the number of LED manufacturers that are becoming interested in manufacturing LED systems for horticulture. It is hoped that an increase in competition in the market place will lower costs, though it is important that quality and efficacy is not compromised.

As the fellowship has progressed the emphasis has changed subtly from an initial focus of training Dr Davis to Dr Davis providing training to others. The primary recipient of Dr Davis' training was Dr Rhydian Beynon-Davies. Rhydian greatly advanced his understanding of plant light responses and performing light experiments while working at STC and has since used his knowledge to gain a new position as Harper Adams / G's where he is a KTP Associate -Utilising novel lighting, irrigation & nutrient strategies for leafy crop production. Rhydian's move to a more industry-focused role demonstrates the benefits the industry receives through the fellowship training schemes. The training efforts have provided multiple students with a better understanding of the potential benefits of LED lighting in horticulture and will hopefully encourage these students to fill future roles in the industry.

HDC news / AHDB Grower articles

Colour reactions. December 2014/January 2015 issue pages 16-17.
Colour co-ordinated pest monitoring. (Cover picture) December 2015/January 2016 Issue
LEDs: recipes to mix for ornamentals. October 2015 issue 217 pg. 16-18.
219 pg. 12-14.
STC trial test scope for LED lighting. November 2015 issue 218 pg. 10
LEDs: recipes to mix for edible crops. November 2015 issue 218 pg. 15-17.
Coloured judgment, Balanced decision . (Cover picture) December 2016.

AHDB Technical guides – (all guides can be accessed from the AHDB website)

Lighting: The review (author)

Lighting: The principles (author)

Lighting: In practice (contributor)

Peer reviewed articles

Phillip A. Davis & Claire Burns (2016) Photobiology in protected horticulture. Food and Energy Security **5**: 223:238.

STC LED Open days (follow the links to view resources on the AHDB website)

These events were held as part of CP125 research project

30th November 2016 What does the future hold for the use of LEDs in protected edible plant production?

1st December 2016 - What does the future hold for the use of LEDs in ornamental plant production?

Public engagement

As well as attending numerous grower events, we have also made efforts to engage with the general public to make them aware of the advances the horticulture industry is making and helping them understand how food is produced. We attend the Great Yorkshire show every year. We have been on several TV and radio shows, including One Show, Country File, Bang goes the theory, to discuss our work on LED lighting.

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De Vos A, & Pauwels H (1981) On the thermodynamic limit of photovoltaic energy conversion. Applied Physics 25: 119-125.

Hicks W (2016) Claims for Solar Cell Efficiency Put to Test at NREL. https://www.nrel.gov/news/features/2016/21635.html

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