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

AUTHENTICATION

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

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GROWER SUMMARY

Headline

There might be an opportunity to reduce energy consumption and CO_2 emissions for LED lit Controlled Environment Agriculture (CEA) systems by adopting the following:

- Identifying the right lighting recipe for selected crop
- Adopt DC rather than intrinsic AC power supply systems to feed LED lighting for plants; saving from grid AC to DC conversion losses occur at every lighting module
- Using LEDs at lower currents for increased efficiency and lifetime of the system
- Partially dim lights in conjunction with sunlight
- Consider use of renewables to supplement the grid power use

Background

Protected cultivation has developed rapidly worldwide to meet the increasing demand for fresh vegetable and horticulture crops. Greenhouses with supplementary lighting and plant factories are the most recent phases of modern protected horticulture. Artificial lighting systems can be used to improve the quality and quantity of agricultural products. The trend towards protected horticulture has several reasons such as, growing world population meanwhile declining arable lands leads to farming in smaller fields with bigger yields, increasing food demand, urbanisation problems which create overpopulated cities, food security issues which has been highlighted by a global pandemic, unsustainable pesticide and chemical usage in agriculture, water scarcity, fluctuating yield over the year, meanwhile the market demands all-year-round supply [1,2]. Optimisation of LED lighting systems has great significance for modern agriculture, as supplementary lighting in greenhouses or the sole light source in plant factories.

Summary

The overall aim of this research is to maximise energy efficiency of plant growth using LEDs for application in CEA, while also considering carbon footprint and cost. This involves firstly understanding how plants respond to different light and secondly, it involves understanding of LED device and whole artificial lighting system energy consumption. These are researched by both experimental and software/modelling-based methods.

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Firstly, neural network analysis on LED lighting for lettuce was investigated with the aim of aiding the prediction of optimal light recipes. A series of data sets from various literature on lettuce growth using LEDs was collected and normalised such that the data was maximally compatible with each other and the experimental results from year 1's work to use as neural network input data. A deep neural network was then fitted to the data using MATLAB to test performance. Fitting results show that there is a general tendency for the neural network to fit to the target data, with an R value of around 0.8 for all data sets and an error histogram which is significantly better than one which would represent random prediction data. There is however significant variation in the error, with some large errors in neural network predicted verses target data. This was thought to be due to the incoherence between the different studies in the literature. Not only were many of the studies looking at different variants of lettuce, but they also had different experimental conditions and approaches beyond the lighting input data. As Ozawa *et al.* stated in their work comparing two studies with very similar conditions two years apart, there was significant different in output data even in identical lighting conditions for the same crop [58]. This shows that although neural networks could indeed prove to be very useful in predicting optimal light recipes, difficulty comes when collating data from different studies. If enough data on growth of a species under several LED light recipes was available from a single source with identical experimental conditions and procedure, fitting of data using neural networks could potentially give considerably better results.

Secondly, we investigated the theoretical basis for potential energy savings that can be achieved through improved lighting system design. The following CEA power saving considerations were investigated in a simplified conservative approach, which showed:

1. Energy saving from appropriate choice of the spectral recipes based on the literature. A comparison of purely white Osram LED boards vs an energy optimal [59] red/blue/white mixture with the same PPFD output value gives:

   A Calculated Energy Saving of **21%**

2. Calculations based on dimming LED boards during sunlight hours on clear days gives:

   A Calculated Energy Saving of **8%**

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3. DC rectifier use in place of AC could increase efficiency and would be less likely to break since fewer components and therefore increase average lifetime of modules which provides:

   An Estimated Energy Saving of **10%**

4. Operating LEDs at half the forward current increases power output efficiency and will also lower LED junction temperature and therefore increase lifetime, while making the modules more compact by reducing heatsink requirements; so higher investment of LED number is balanced by energy saving and increased time before replacement giving:

   An Estimated Energy Saving of **6%**

5. Dynamic and model aided control of CEA light environment would allow efficient use of natural lighting to minimize energy use in supplementary artificial lights, as well as helping sole artificial lighting setups to grow plants.

These savings have been calculated to give a significant combined total estimated energy savings of approximately **38.5%** when compared with a system which doesn't employ any of the energy saving methods investigated. A costing analysis is ongoing.

Thirdly, the HOMER software, which is a piece of software used to model and evaluate possible designs for both off-grid and grid-connected power systems, was used with system input load requirements, energy cost tariffs and installation costs along with four different grid connected and off-grid supply setup regimes to investigate accurate geographical energy consumption and cost for electricity supply for a CEA system. A model system was built based on the strawberry growing facility at the University of Reading. My simulation results based on this model show that a grid connected system with wind installed would be the cheapest and most environmentally sustainable option, with a calculated capital cost saving of 5%, a levelized cost of electricity saving of 24% and a reduction of CO_2 emissions by 41%.

Finally, power distribution to lighting setup was considered. Arguments for DC grid supply in place of AC grid supply to LEDs were discussed, referring to existing literature on other DC grid application areas such as data centres, residential power networks and office buildings, which realise electricity and cost savings from the application of a DC grid. Schematics of a DC based greenhouse system were discussed followed by modelling of both DC-DC buck

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converter and rectifier coupled with buck converter in MATLAB Simulink. Full efficiency and power loss calculations are currently in progress.

Financial Benefits

The savings outlined in the summary have been calculated to give a significant combined total estimated energy savings of approximately **38.5%** when compared with a system which doesn't employ any of the energy saving methods investigated. A costing analysis is ongoing.

Action Points

Growers using LED CEA systems or LED supplementary light in a glasshouse can do the following to reduce energy consumption:

- **Careful choice of LED device model** – Efficiencies can vary significantly as demonstrated in the science section of this report (14% difference in energy consumption for same light output shown), the μmol/J gives indication of this efficiency.
- **Consider running LEDs at lower current** – This requires a higher number of lights operating to reach the same level of light intensity, but due to the higher efficiency at lower currents, running LEDs at half of the nominal current gives a 6% reduction in energy consumption. Also, lower currents significantly increase the lifetime of the LEDs which could compensate the extra cost of investing in more to begin with.
- **Using DC main rectifier + DC-DC converters to power all LED modules with DC electricity** – This eliminates the need for each LED module to include its own AC/DC converter and therefore electrical efficiency is increased, by an estimated amount of 10%. Additionally, fewer components means lower frequency of faults occurring therefore saving in cost of replacement.
- **Consider weather on a daily basis to dim the LED system appropriately** – This is estimated to decrease energy consumption by at least 8% for a 3-tier vertical strawberry growing greenhouse as setup at the UoR.
- **Consider variation of electricity prices throughout the day** – By varying the start and end time of the photoperiod seasonally to minimise cost, 8.8% yearly cost saving is calculated (when in conjunction with dimming). For a solely LED lit system, cost saving calculated at **28%,** based on tariff electricity prices available for a standard UK supplier.

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SCIENCE SECTION

Introduction

Protected cultivation has developed rapidly worldwide to meet the increasing demand for fresh vegetable and horticulture crops. Greenhouses with supplementary lighting and plant factories are the most recent phases of modern protected horticulture. Artificial lighting systems can be used to improve the quality and quantity of agricultural products. The trend towards protected horticulture has several reasons such as, growing world population meanwhile declining arable lands leads to farming in smaller fields with bigger yields, increasing food demand, urbanisation problems which create overpopulated cities, food security issues which has been highlighted by a global pandemic, unsustainable pesticide and chemical usage in agriculture, water scarcity and fluctuating yield over the year, meanwhile the market demands all-year-round supply [1,2]. Optimisation of LED lighting systems has great significance for modern agriculture, as supplementary lighting in greenhouses or sole light source in plant factories.

Light is the sole energy source for photosynthesis and one of the main factors that shapes plant growth and development. For each plant and each developmental stage, light requirements vary, and this fact gives emphasis on research for light recipes to manipulate the growth of desired species and manipulation of any stage of growth to reach the target yield and quality. Development of solid-state light sources gave great opportunity to experiment and optimise the light spectrum for plant growth, from effectively infinite spectrum possibilities which LEDs have enabled. Among the related literature, red, blue and compound white light are accepted as highly beneficial meanwhile green, purple, yellow and orange are secondarily contributing. UV and far red lights are beneficial even though they are outside of the photosynthetic active radiation (PAR) region which is from 400 nm to 700 nm in spectrum; UV-B (280-320 nm) and UV-A (320-400 nm) are important spectral components for vegetable production [2]. Light is acting on chlorophyll for photosynthesis, also it acts on cryptochrome, phototropin and the other photoreceptors after being absorbed by photosynthetic tissue. Plant growth and development are regulated by light quality, light intensity and photoperiod.

LEDs are solid-state, narrow bandwidth lighting devices that give unique opportunity to realise precise management of light quality to obtain optimal plant responses, such as morphology, yield and nutritional quality. Determination of plant light recipes and optimisation of light sources will save energy by removing the unnecessary light spectra from horticulture lighting while increasing yield and product quality.

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Literature Review and Background

This project focuses on experiments and modelling, so it's important to understand the context of LEDs in plant growth, as well as to understand what is and isn't currently known about how different plants respond to different types of light.

The field has many gaps of knowledge due to the vast number of possible setups to investigate, but there still exists a significant amount of research providing a foundation of knowledge to build on.

Lighting and LEDs

Light is required throughout the entire lifespan of a plant. Plant performance is determined primarily by three important light parameters, these are quantity, quality and duration, all of which effect plants in different ways [3].

- **Light Quantity (Intensity)** - This parameter mainly affects the photosynthesis of plants. The energy from the light is used to induce a photochemical reaction converting carbon dioxide into carbohydrate in the chloroplasts.
- **Light Quality (Spectral Distribution)** - This refers to the spectral distribution of radiation in terms of wavelength composition of light. Plants respond best to red and blue light with regards to photosynthesis. Spectral distribution affects more than just linear growth of plants, it influences shape and development, as well as playing an important role in the flowering process.
- **Light Duration (Photoperiod)** - The photoperiod refers to the duration of light per day. This would influence the rate of growth and in many cases the flowering of the plant.

The radiation received from the sun contains a continuous spectrum of light, including all visible frequencies. However, plants only absorb discrete wavelengths according to their photochemical reaction mechanisms. The most photo-synthetically active region lies between around 400 and 700nm, which is approximately the visible spectrum [4].

Due to the flexibility of LEDs in all three of the parameters described above, particularly in their wavelength specificity, they are an extremely useful tool to study the ideal lighting for any species of plant. LEDs emit in discrete wavelengths making them much narrower than other conventional sources of lighting used for plant growth. This means that LEDs have the potential to be extremely efficient and perfectly tuned to fit their purpose, but the design process is challenging. It involves choosing a discrete combination of wavelengths which match the optimum biological response of the specific plant of interest. This is an endeavour

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which requires a vast amount of data, and as worldwide research accumulates, a database of light formulae can be built to identify optimum light recipes for particular plant species.

The specific and customisable nature of LEDs also means that plants can be grown in different ways, to produce different shapes and compositions, this is interesting since aesthetics and taste can potentially be changed by LED wavelength choice. Currently, much research exists detailing LED compositions which give the best responses from plants, typically depending on the plant type [5,6]. The huge number of different plant species/varieties that are grown in CEA makes research complex, also each plant adopts different shapes and properties throughout its lifetime, so different light environments may be optimum at different stages of a plant's life [7,8]. This coupled with the huge number of combinations of wavelength, intensity and photoperiod etc. make the field of LED plant response research extremely complex.

LEDs are also advantageous in other ways: they are compact, energy efficient, relatively durable and don't emit much heat, allowing them to be close to the plants while remaining cool, thus reducing watering and ventilation maintenance. Many of these factors add to their overall efficiency, allowing the overall energy consumption to be reduced by up to 70% relative to traditional light sources, such as fluorescent, incandescent, high pressure sodium (HPS) and metal halide lamps, which have low electrical efficiency in comparison, since they emit many frequencies which aren't useful for plants and they also produce waste heat [9].

A recent study reported that a HPS lamp with 150W power had a similar effect on the flowering pattern of bedding plants to a 14W LED. This considerable difference in power output and efficiency shows how beneficial adoption of an LED system can be on an economical level for greenhouse growers' energy consumption [10]. In terms of installation and initial investment costs, LED systems are comparable to HPS systems, despite HPS being more established [11]. The study also notes that the lifetime of an LED fixture is up to 50,000 hours, more than twice that of the 20,000-hour HPS lifetime.

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Comparison	Incandescent	HID	Fluorescent	LED
Power efficiency	5%	30%	40%	60%
Utilization of radiation	low	low	low	high
Lifetime	low	medium	medium	high
Heat productivity	high	high	low	low
Spectrum Adjustment	no	no	no	yes
Price	low	medium	medium	high

Table 1 - Comparison of different lamps in protected horticulture [12]. Note that HID (High intensity discharge) lamps include HPS in this case.

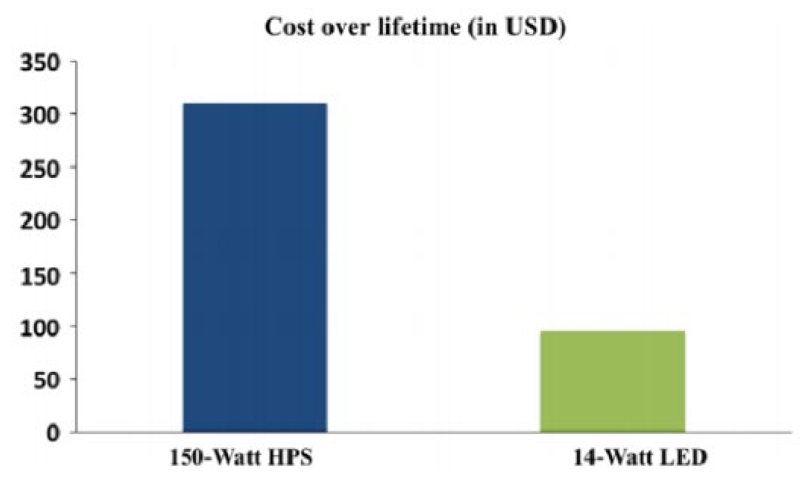

Figure 1 - Lifetime cost comparison of a 150W HPS lamp and a 14W LED [12].

LED systems are applicable to indoor applications. Greenhouses are an important area of application for this field, thus starting with the common issues arising in greenhouse growth and their relation to LEDs is useful. Greenhouses are often dense environments with vertically or intensively grown plants, this means that insufficient light intensity and illumination time are common problems. Due to greenhouses often relying on natural light, seasons and weather are also factors which can cause issues with plant growth or even crop failure [13]. Implementation of LEDs is desirable in many ways: LED systems are easy to power, can run

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using a DC supply, and they are energy efficient and economical. They are also sufficiently cool, such that lights can be placed close to the plants.

LEDs are semiconductor diodes which permit current to flow in one direction only. This diode is formed by using two slightly different materials to form a PN junction. In a PN junction, the N side contains electrons, and the P side contains electron holes. When a forward voltage is applied to the PN junction, electrons move from the N side towards the P side and holes move from the P side towards the N side and combine in the depletion zone between the PN junction. Some of these combination events radiate energy in the form of photons (Figure 2).

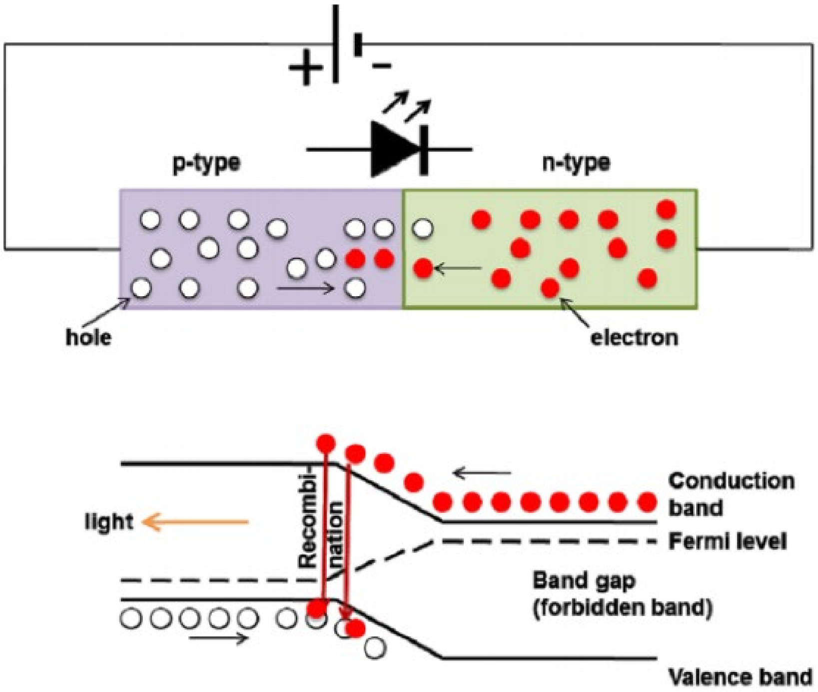

Figure 2 - Schematics of light emission mechanism inside an LED chip [14].

The photon energy is approximately equal to the band gap energy (E_g). The conservation of energy from electrical to optical requires a forward voltage (V) through the LED which is equal to the band gap energy. The following equation is derived from energy conservation.

$$V = \frac{h\nu}{e} \approx \frac{E_g}{e}$$

There are mechanisms that cause the forward voltage to differ from the above value. For example, the diode could have series resistance causing voltage loss or energy loss due to holes. These mechanisms change the forward voltage equation of an LED. On the other

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hand, forward voltage has temperature dependence. The below equation shows the I-V characteristic of an ideal LED.

$$I = I_s\left(e^{\frac{eV-E_g}{kT}} - 1\right)$$

Where I is forward current for the LED, I_s is saturation current of LED, V is forward voltage drop of LED, k is Boltzmann constant, T is temperature, e is electron charge. Diode forward voltage is temperature dependent even if the drive current of LED is constant. Voltage drop across the diode will change. Solving the equation brings the forward voltage as a function of temperature.

In the equation below, the right side is the change of energy level with respect to temperature. As temperature increases, the energy gap of semiconductors decreases. The reason of the LED voltage change is; the recombination process becomes easier and voltage drop decreases by 2mV for each degree as the temperature rises [14].

$$V_T = \frac{kT}{e} ln\left(\frac{I}{I_s}\right) + \frac{E_g T}{e}$$

Figure 3 shows the band-gap energies and corresponding wavelengths for two major semiconductor materials used for LEDs today. InGaN (indium gallium nitride) is used for violet, blue, and green LEDs. Whereas InGaAlP (indium gallium aluminium phosphide) is used for green, yellow orange and red LEDs [14].

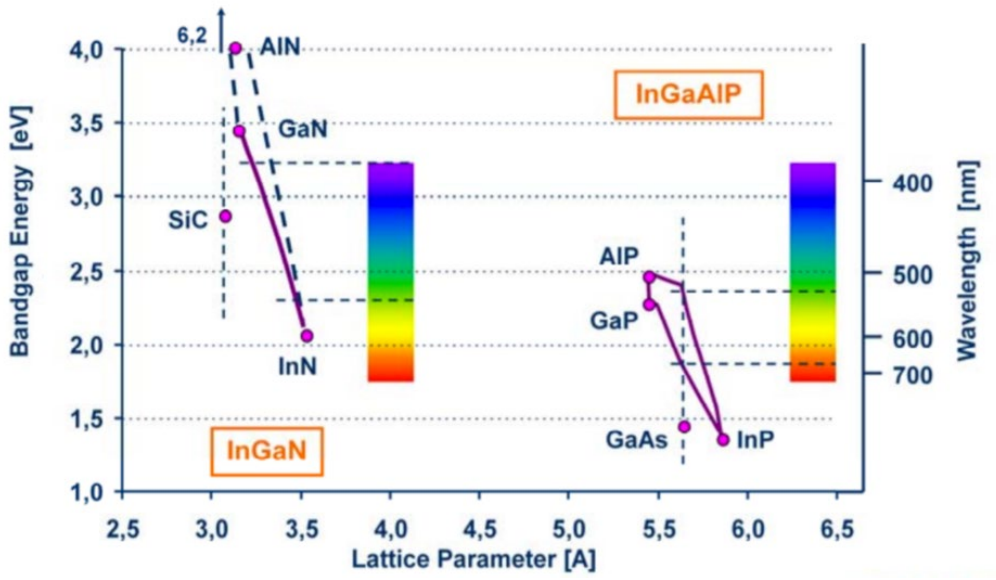

Figure 3 - Band gap energies & wavelengths [15].

The wavelength of light is determined by its energy. The energy of a photon emitted by an LED is equivalent to the band gap of the semiconductor material used, which is an intrinsic feature of the semiconductor material itself. Manufacturing an LED with a designated wavelength is all about engineering the semiconductor materials and their bandgaps.

A single colour, or monochromatic LED emits light in a narrow spectral band. The Spectral Power Distribution represents the radiant power emitted by a light source, as a function of its wavelength. InGaN (indium gallium nitride) and InGaAlP (indium gallium aluminium phosphide) are the two primary semiconductor materials and slight changes in the composition of these alloys changes the colour of the emitted light [14].

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Aside from monochromatic LEDs, white LEDs are also used in several applications (Figure 4). One approach to generating white light utilizes the combination of RGB colours: red, green, and blue LEDs. Another approach is to use blue and yellow LED chips together in a certain ratio to produce white light.

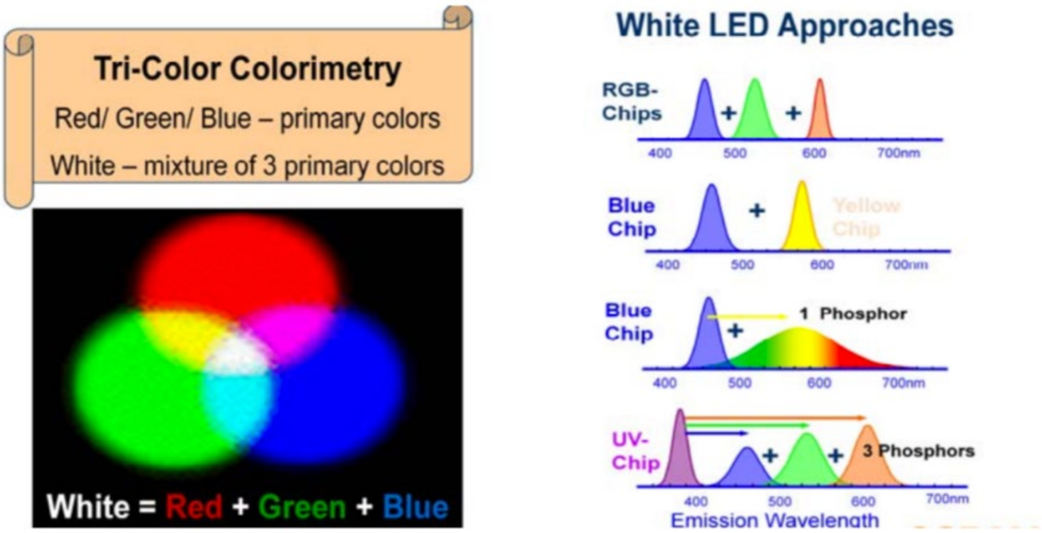

Figure 4 - White LED production strategies [15].

A third approach would be to use a blue chip and a yellow phosphor to generate white light. Finally, using a UV LED to excite red, green, and blue phosphors is also another approach. The most widely adopted approach to produce a white LED is to use a blue LED chip combined with a phosphor (Figure 5). This method is preferred due to its low cost and ease of application. The phosphor layer absorbs some of the blue light and emits light at longer wavelengths; the phosphor concentration defines how much of the blue light is converted.

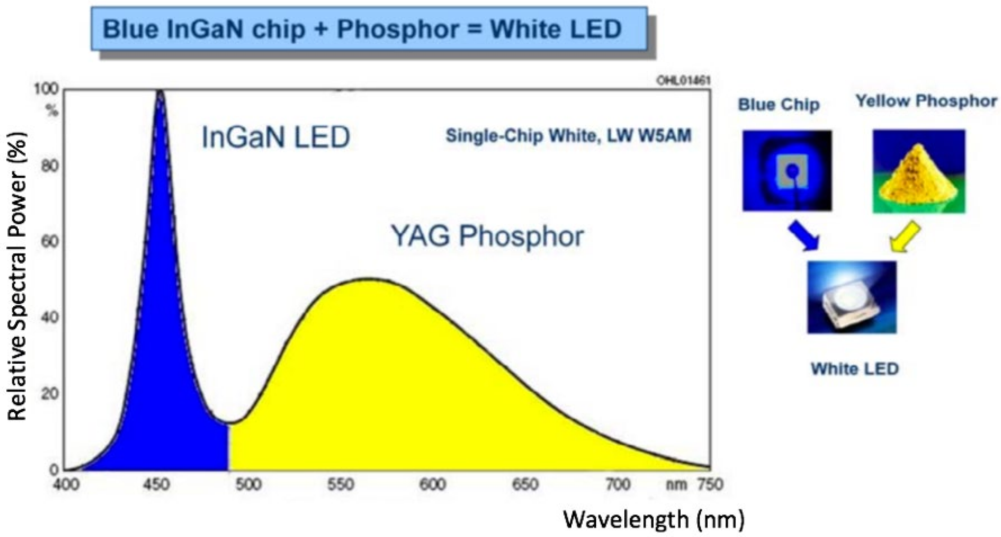

Figure 5 - Spectral composition of blue LED with yellow phosphor coating [15].

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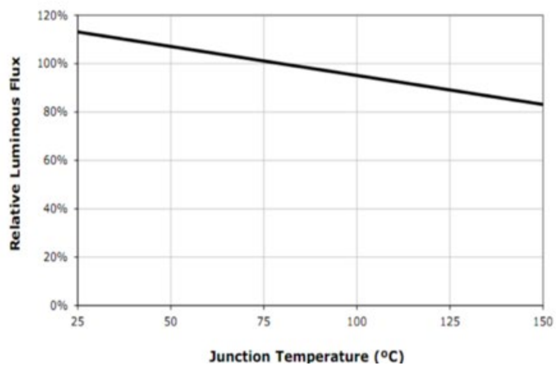
Changing the phosphor content enables different colour temperatures of white light. The colour correlated temperature (CCT) for a light source gives a good indication of the lamp's general appearance but does not give information on its' spectral power distribution. In other words, two lamps may appear to be the same white colour, but their spectral composition could be different such that a plant for example would respond very differently to them both.

As previously discussed, thermal properties and variations on an LED have significant consequences for its lumen output, electrical characteristics and also lifetime. Thus, for LEDs to function optimally, heat generated by them must be managed, being easily transferable away from the LED area, particularly the PN junctions of the LEDs must have their temperature regulated. This is done through careful consideration of the LED's assembly and operation [16].

Thermal resistance is a material's ability to resist heat flow through it, high thermal resistance means a slow transfer of heat. Thermal resistance has units of Kelvin per Watts. Thermal capacity is the second important parameter and is the ability of the material to store thermal energy. The temperature drop on a material can be calculated with respect to these two variables.

Thermal calculations are performed with the thermal model of the circuit element and used for various electronic components which dissipate heat [15]. For heat transfer, the thermal model is used to calculate the temperature value at the junction point of LED or the expected thermal resistance value for the heat-sink. The temperature difference between two points from ambient to LED junction is found by calculating the total thermal resistance between two points. LEDs dissipate some of their power as heat and some as light.

An LED's lumen output is highly dependent on the current of the LEDs. As shown in Figure 6, the change of 500 mA creates around 100% luminous flux output difference [15].



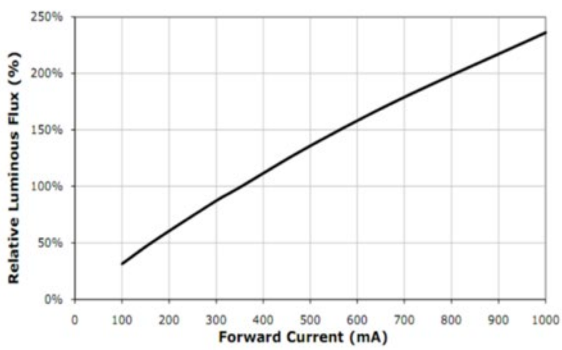


Figure 6 - Junction temperature effect on luminous flux and luminous flux vs forward current [15].

The basic drive circuit for LEDs includes linear DC drivers which involve a voltage regulator such as LM317 or an op-amp and active switch. These devices are used as current-sink or

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current-source circuits in order to comply with constant current output for LEDs. These drivers are preferred based on ease of application and no EMI radiation. However, these devices have some limitations; LED voltage must be smaller than the supply voltage and voltage differences between supply and LEDs must be low. This voltage will drop on the active device, and this device dissipates this as excess power. Linear drivers are inefficient solutions because of their operation principle. Another concern is that power dissipation radiates with heat and this can be transferred with a bulk heat-sink. If the supply voltage and LED-voltage have a significant difference, the circuit cannot be applied because of heat and device size conditions. Linear power supplies have been declining in popularity for years, being replaced by Switch Mode Power Supplies (SMPS), which is superior in size and efficiency.

A DC-DC converter, also known as a switching regulator, is a power converter that converts a DC energy source from one voltage level to another. Average output voltage is controlled by varying the conduction time of the switch. The DC-DC converters can be designed with regulated output voltage. For the LED drivers especially, the converters have regulated output currents.

DC-DC converters are a necessity for LEDs to have regulated output and high-power efficiency. Typically, first generation converters are used because of ease of application and low cost. The fundamental converters are Buck (Step-Down), Boost (Step-Up) and Buck-Boost (Step-Up and Step-Down). Transformer type and developed converters have a wide range of the output voltage and power like; Flyback, Forward, Push-Pull, Half-Bridge, Bridge and Zeta Converter. These converters have transformers and isolate the input and output circuit. Transformers add an extra property of changeable voltage gain with the ratio of transformer windings and isolation. Additionally, there are more developed converters like; P/O (positive output) Luo-converter, N/O (negative output) Luo-converter, Double output Luo converter, Cuk converter, Single-ended primary inductance converter (SEPIC). These converters have more components, having less output voltage ripple than the previous converters.

LEDs have been used in horticulture studies for around 20 years, with so much still unknown despite there being a great amount of data. This is in part due to many plant responses to wavelengths being species and life stage specific, whilst the effects of some wavelengths is clear.

Red light (600-700nm) has the highest quantum efficiency for photosynthesis, while also having many photomorphogenic effects on plant development mediated by the photo-reversible pigment phytochrome, such as: enhancing leaf expansion, biomass accumulation, stem elongation and seed germination.

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For blue light (400-500nm), there are also contributing effects on phototropism, stomatal aperture, leaf thickness, and chlorophyll content. Growth conditions seem very sensitive to blue light intensity when indoors more than outdoors and this is where blue lights can act as a growth inhibitor. Also, the contribution of blue light to any wavelength mixture is a question which hasn't been answered yet, the optimum mixture of blue light has been investigated in many studies and various conclusions have been drawn, complicated by plant specific responses.

Green light (500-600 nm) often is disregarded as an unimportant waveband in photosynthesis because absorption spectra of extracted leaf chlorophyll pigments indicate very weak absorption in the green region of the PAR [12]. Because chlorophyll has major absorption peaks only in the red and blue regions, researchers initially selected first red, later blue LEDs for first generation LED arrays to support plant growth. However, intact leaves do absorb a considerable amount of green light, and in a relative quantum efficiency curve for photosynthesis vs. PAR wavelengths, some wavelengths of broad band green actually are more efficient than certain wavelengths of the blue band. When leaf canopies close, red and blue light are absorbed strongly by upper or outer leaf layers, whereas green light penetrates to interior leaf layers, where it is subsequently absorbed and drives photosynthesis of the inner canopy. Thus, light sources containing a certain amount of green light can be more effective in stimulating crop growth than a red and blue mix alone. Additionally, the human eye perceives red, green and blue (RGB) combination light as white light, so if all three wavebands are present simultaneously in a plant growth lamp this will facilitate visual evaluation of the stress status of crops, the incidence of physiological disorders, and true leaf colour [12].

On the other hand, white LEDs (blue LED plus phosphor coating) have a wide spectrum and are the choice of many growers because of this quality, but it mainly lacks the red spectrum. Also, energy losses associated with the secondary broad-band photon emissions of the excited phosphor make white LEDs significantly less electrically efficient than emissions from pure monochromatic blue LEDs, additionally, the proportions of red, green, and blue wavebands in white LED obtained with phosphor coating varies widely among cool white, neutral white, and warm white LED types, that none of them are a close match for the RGB distribution of midday solar light. Therefore, to make white light from monochromatic RGB LEDs rather than using white light emitting LEDs has more electrical efficiency and precision potential [12]. Plants have become adapted to both UVA (320-400 nm) and UVB (280-320 nm) wavelengths that is contained within solar light. In CEA systems which lack ultraviolet wavelengths plant quality or appearance can be affected. There is a reluctance to introduce

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UVB into indoor commercial growth environments for safety reasons, but it may be possible to use UVA if certain worker precautions are taken [17].

Optical wavelength(nm)	The influence on the growth of plants
280–315	Minimal impact on morphological and physiological process
315–400	Chlorophyll absorbs less, photoperiod effect, tissue and stem elongation
400–520	Chlorophyll and carotenoid absorption proportion is the largest, the biggest influence on photosynthesis
520–610	The pigment absorption rate is not high
610–720	Chlorophyll absorption rate is low, have significant effects on photosynthesis and light cycle effect
720–1000	Absorption rate is low, stimulate cell extended, affecting flowering and seed germination
>1000	Converted into heat

Table 2 - Effect of light wavelength on plant growth.

Plant Physiology

Light is a form of electromagnetic energy, which can be visualised as a wave. Visible light represents only a small part of the electromagnetic spectrum between 400 and 740 nanometres. A photon's energy carriage capacity is inversely proportional to that of their wavelength, so shorter wavelength light has higher energy. The strength of the photoelectric effect depends on the wavelength of light; short wavelengths are much more effective than long ones in producing the photoelectric effect. The highest energy photons, at the short-wavelength end of the electromagnetic spectrum are gamma rays, with wavelengths of less than 1 nanometre; the lowest energy photons, with wavelengths of up to thousands of meters, are radio waves. Within the visible portion of the spectrum, violet light has the shortest wavelength and the most energetic photons, and red light has the longest wavelength and the least energetic photons.

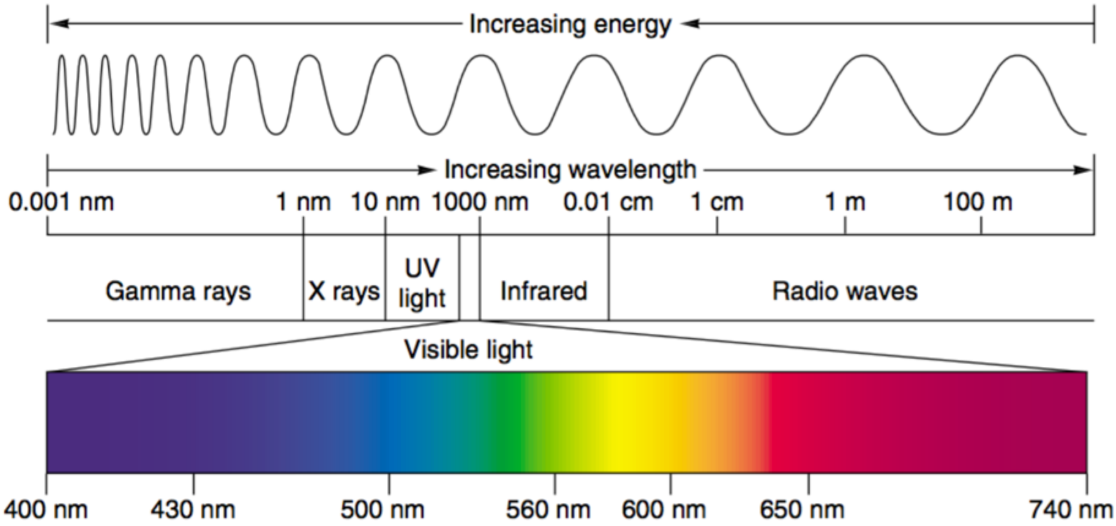

Figure 7 - The electromagnetic spectrum [18].

When a photon interacts with a molecule, its energy is either lost as heat or absorbed by the electrons of the molecule, boosting those electrons into higher energy levels. Whether or not the photon's energy is absorbed depends on how much energy it carries (defined by its wavelength) and on the chemical nature of the molecule it hits. To boost an electron into a different energy level requires just the right amount of energy. A specific atom can absorb only certain photons that correspond to the atom's available electron energy levels. As a result, each molecule has a characteristic absorption spectrum, the range and efficiency of photons it is capable of absorbing. Molecules that are good absorbers of light in the visible range are called pigments. Organisms have evolved a variety of different pigments, but there are only two general types used in green plant photosynthesis: carotenoids and chlorophylls. Chlorophylls absorb photons within narrow energy ranges [19]. Two kinds of chlorophyll in plants, chlorophylls (a) and (b), preferentially absorb violet-blue and red light. Neither of these pigments absorbs photons with wavelengths between about 500 and 600 nanometres, and light of these wavelengths is, therefore, reflected by plants that we perceive as green. Chlorophyll (a) is the main photosynthetic pigment and is the only pigment that can act directly to convert light energy to chemical energy and chlorophyll (b), acting as an accessory or secondary light absorbing pigment, complements and adds to the light absorption of chlorophyll (a). Chlorophyll (b) has an absorption spectrum shifted toward the green wavelengths. Therefore, chlorophyll (b) can absorb photons chlorophyll (a) cannot. Chlorophyll (b) therefore greatly increases the proportion of the photons in sunlight that plants can harvest. An important group of accessory pigments, the carotenoids, take an action in

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photosynthesis at the wavelengths that are not efficiently absorbed by either chlorophyll (a) or (b) [19].

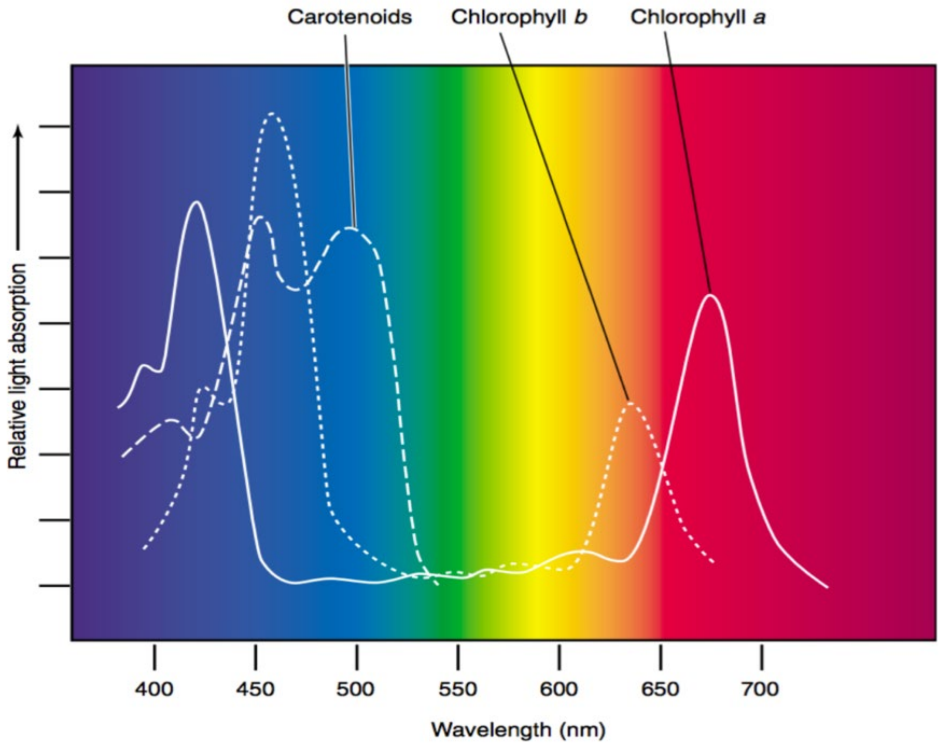

Figure 8 - The absorption spectrum of chlorophyll [19].

The peaks in Figure 8 represent wavelengths of sunlight that the two common forms of photosynthetic pigment, chlorophyll (a) and chlorophyll (b), strongly absorb. These pigments absorb predominately violet-blue and red light in two narrow bands of the spectrum and reflect the green light in the middle of the spectrum. Carotenoids absorb mostly blue and green light and reflect orange and yellow light. In photosynthesis, photons of light are absorbed by pigments; the wavelength of light absorbed depends upon the specific pigment.

LEDs as a source of plant lighting have been investigated for more than 20 years in research, with several reports having confirmed successful growth of plants under sole or supplemental LED illumination. Different spectral combinations have been used to study the effect of light on plant growth and development and it has been confirmed that plants show a high degree of physiological and morphological plasticity to changes in spectral quality. Circa in the 1990s for example researched photosynthetically active radiation and biological/physiological effects of blue and red light wavelengths and red and blue light combinations for lettuce [20], strawberry [21], pepper [22], wheat [23] and rice [24].

Red (610-720 nm) light is required for the development of the photosynthetic apparatus and photosynthesis, whereas blue (400-500 nm) light is also important for the synthesis of chlorophyll, chloroplast development, stomatal opening and photomorphogenesis. Several

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horticultural experiments with potato, radish and lettuce have shown the requirement of blue (400-500 nm) light for higher biomass and leaf area [25-27]. However, different wavelengths of red (660, 670, 680 and 690 nm) and blue (430, 440, 460 and 475 nm) light might have uneven effects on plants depending on plant species. Far red LED light (700- 725 nm) which is beyond the PAR has been shown to support the plant growth and photosynthesis.

Biomass yield of lettuce increased when the wavelength of red LED emitted light increased from 660 to 690 nm [28]. A comparative study on the physiology of red leaf lettuce showed that application of far-red (730 nm) with red (640 nm) light from LEDs caused an increase in total biomass and leaf length while anthocyanin and antioxidant potential was suppressed [29]. In a study in which red LED (640 nm) was sole source of light increased anthocyanin content was observed in red leaf cabbage [30]. Addition of far-red (735 nm) to the red (660 nm) LED light on sweet pepper resulted in taller plants with higher stem biomass than red LEDs alone [22].

Positive effects of blue (400-500 nm) LED light in combination with red LED light on green vegetable growth and nutritional value have been shown in several experiments. LEDs (440 and 476 nm) used in combination with red LEDs caused higher chlorophyll ratio in Chinese cabbage plants [31]. These cabbages can complete their life cycle under red LEDs alone, but larger plants (higher shoot dry matter) and greater amounts of seed are produced in the presence of red LEDs supplemented with a quantity of blue light. Similar experiments have shown increased nutritional value and enhanced antioxidant status in green vegetables: increased carotenoid, vitamin C, anthocyanin and polyphenol [32]. For example, a report [33]summarised the studies made previously with blue LEDs and reported that yield of lettuce, spinach, and radish crops grown under only red LEDs is less than for the ones which had additional blue LEDs, with same total photosynthetic photon flux (PPF) emitted from light sources. For peppers, a study which includes different colour combinations of LEDs' effect on leaf thickness and chlorophyll content of leaves, indicated that the blue LEDs combined with red LEDs are inducing more chloroplast in leaf cells than red and far red combinations [35], again lamps were having same PPF values. Also, research indicated that plants under red & blue and red & blue & green LEDs were considerably stronger and shorter, whereas plants treated with green, yellow and red light were weaker and higher compared with the white light.

Green light also contributes to plant growth and development in several experiments. Green LEDs with high photosynthetic photon flux are most effective to enhance growth in a crop of lettuce [32]. Green (505 and 530 nm) LED light in combination with HPS lamps contributed to the better growth of cucumber [35]. The effect of green (525 nm) LED light on the growth of of Arabidopsis seedlings was investigated and results showed that seedlings grown under

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green, red and blue LED light are longer than those grown under red (630 nm) and blue (470 nm) alone [36]. Supplementation of green light enhanced lettuce growth under red and blue LED illumination [37]. Green light alone is not enough to support the growth of plants however, as demonstrated in these studies green light does influence some important physiological effects.

Beyond red, blue and green LEDs, other frequencies are being considered for use; wavelengths like yellow, orange, purple, cyan etc. can have potential for horticultural crops to some extent under certain circumstances [38,39]. Also, there are many studies which investigate the potential of using supplemental selected UV irradiation [40,41]. UV radiation can be regarded as a stress factor which is capable of significantly affecting plant growth characteristics. Generally, plant height, leaf area, leaf length have been showed to decrease, whereas leaf thickness was increased in response to UVB radiation [42].

Light-regulated plant development known as photomorphogenic effects are mainly mediated by Phytochromes. Phytochromes Pr (red) and Pfr (far red) mainly influence germination, plant growth, leaf building and flowering. The phytomorphogenic effects can be controlled by applying a spectrum with a certain mix of 660nm and 730nm in order to stimulate the Pr and Pfr phytochromes. One influence of far red light on a plant is the active shade escape reaction. If the plant is illuminated mainly with 660nm it senses that it is illuminated in the direct sun and grows normally. If the plant is illuminated mainly with 730nm it senses that it is growing in the shadow of another plant that shades the sun light. Therefore, the plant reacts by elongating growth to escape the shadow. This leads to taller plants but not necessarily impacting the cumulated biomass. Pr and Pfr convert back and forth. Pr is converted into Pfr under red light illumination and Pfr into Pr with far-red light. The active form which triggers flowering is Pfr [43]. Pr is produced naturally in the plant. The ratio of Pr to Pfr is in equilibrium when the plant receives light (day) because Pr is converted into Pfr by red light and Pfr is converted back to Pr by far-red light. Back conversion of Pfr is however also possible in a dark reaction, so it is the night (dark) period which mainly affects the ratio of Pr to Pfr and controls the flowering time in plants. Ornamental plants are of high economic importance, therefore manipulating this mechanism with LEDs would contribute positively to this sector.

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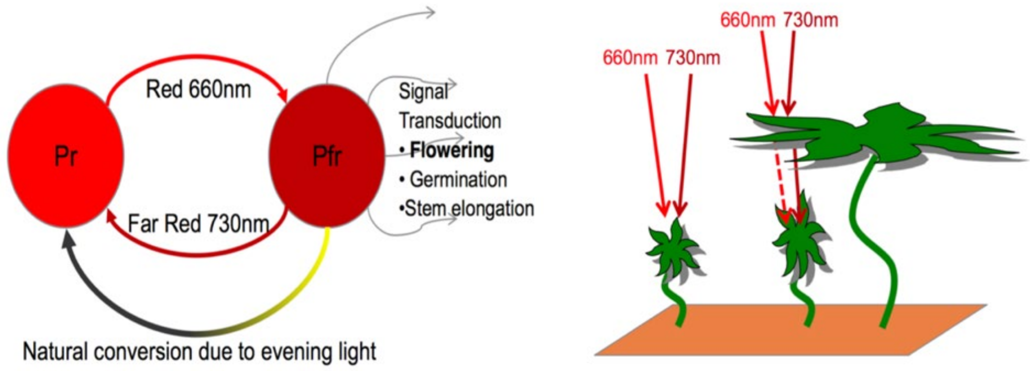

Figure 9 - Pr-Pfr cycle and shade avoidance [43].

Research Aims

The overall aim of this research is to maximise energy efficiency of plant growth using LEDs for application in CEA, while also considering carbon footprint and cost. This involves firstly understanding how plants respond to different light and secondly, it involves understanding of LED device and whole artificial lighting system energy consumption. These are researched by both experimental and software/modelling-based methods.

For understanding plant response to light, experimentally, data obtained on plant growth under different light can give important information about which conditions give the most desirable plant growth results, regarding not only size and speed of growth simply, but other aspects such as aesthetic appeal (for ornamentals) or taste quality (for food crops). From a modelling perspective, software along with mathematical models can be used to simulate lighting arrangements and help elucidate the light recipes which best favour plant growth. For example, this can involve testing reflector systems to maximise light utilisation on the plant. The modelling approach can also include using machine learning tools and/or mathematical modelling to find patterns in plant growth behaviour under different lighting conditions in order to predict optimal light recipes.

For understanding energy consumption in LED lit plant growth systems, there are many different aspects and solutions to explore and optimise: Consideration of LED device market options and respective device efficiencies, LED board circuit setup and chosen operating forward current to maximise efficiency, power supply to whole system (AC vs DC), dynamic dimming of LED boards synchronised with sunlight to save energy and also augmentation of system energy supply with renewables based on local geographical potential, to reduce carbon footprint and energy costs.

The aims of this project are therefore to develop understanding of how plants respond to light, obtained from modelling and experiment and also investigate the most energy efficient setups for LED lit CEA systems. Sophisticated lighting systems can then be designed and tailored to

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optimise plant growth and maximise energy efficiency for growing a particular crop in a particular geographical location.

Preliminary Work: Establishing the Lettuce Test Experimental Setup (Year 1)

Firstly, a set of experiments for Little Gem Lettuce growing were prepared. This includes some of the treatments from the systematic test plan outlined in Table 3. These are red (660nm), blue (440nm), green (525nm), green & red, blue & red and warm white (2600-3200K). The initial idea was to purchase high brightness SMD LEDs for higher W/m^2 values and fewer components, as well as the fact that the LEDs from reputable companies have the ray-files for the TracePro software which can be very useful for precise modelling of the light source. However, to use LEDs with physically bigger packages is more manageable if a problem occurs, since it is easier to repair the circuit by hand if necessary. For this reason, it was decided as the more convenient approach for these tests. A linear constant current circuit and LED board were designed with Altium Designer program, they were then printed and all components including the LEDs were hand soldered.

	Percentage of Chips						Chip numbers			
TREATMENTS	UV	Blue	Green (or white)	Red	Total	Total chip number	UV	B	Green (or white)	Red
1	0	33.333	33.333	33.333	99.999	24	0	8	8	8
2	0	50	50	0	100	24	0	12	12	0
3	0	50	0	50	100	24	0	12	0	12
4	0	100	0	0	100	24	0	24	0	0
5	0	0	50	50	100	24	0	0	12	12
6	0	0	100	0	100	24	0	0	24	0
7	0	0	0	100	100	24	0	0	0	24
8	0	0	0	0	0	24	0	0	0	0
9	25	25	25	25	100	24	6	6	6	6
10	33.333	33.333	33.333	0	99.999	24	8	8	8	0
11	33.333	33.333	0	33.333	99.999	24	8	8	0	8
12	50	50	0	0	100	24	12	12	0	0
13	33.333	0	33.333	33.333	99.999	24	8	0	8	8
14	50	0	50	0	100	24	12	0	12	0
15	50	0	0	50	100	24	12	0	0	12
16	100	0	0	0	100	24	24	0	0	0

Table 3 - Systematic test plan for LED boards.

LED Product Selection

LEDs in the selected wavelengths of the company Bridgelux were chosen for preliminary tests since, as previously mentioned, they are of appropriate size for hand soldering and ease of repair. The main systematic tests that were implemented include boards with 24 chips, since it allows variation of ratios of selected wavelengths. For the circuit design, 1W chips were selected. LEDs have a uniform distribution of light with a 120° viewing angle and each LED has a forward current of 350 mA (except red LEDs which have 400 mA). Maximum junction temperature is 115°C. Heat tests for junction temperature were conducted and circuits supplied with minimum necessary voltage values.

Figure 11 displays the introduction of the selected LEDs to Trace Pro software for modelling the light distribution, to simulate light on and around the tray of lettuces. The model can be used to calculate the level of light which is wasted and optimise the setup accordingly. The software can also model the change of irradiation between the centre and the corners of the plant tray. (Figures 16-21). This software can be particularly useful when considering more elaborate lighting models, such as those with reflectors; modelling can be done to optimise light use on plant surfaces.

Figure 10 - Bridgelux LEDs chosen for preliminary tests (left) and Osram's more compact LED design (right).

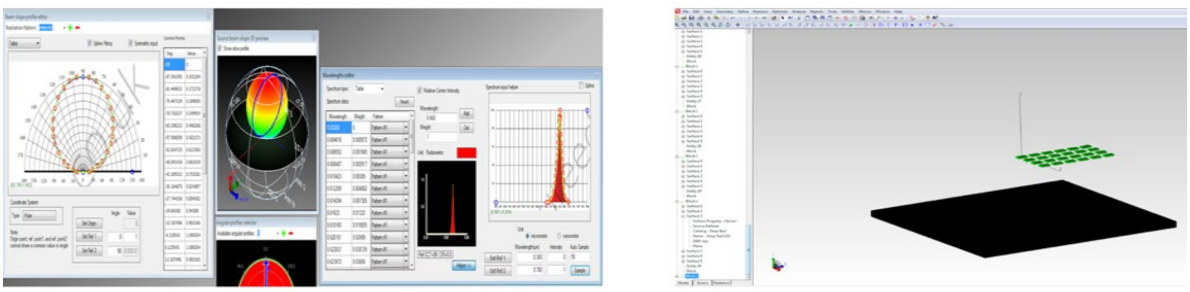

Figure 11 - Introduction of angle radiation pattern and relative spectral distribution of selected LED to Trace Pro software.

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Board Designing, Building and Heat Testing

Different board geometries and combinations were designed using the Altium Designer, these can be seen in Figure 13. Due to the test plant trays being rectangular, rectangular boards were used for circuit printing. The circuit board was planned to be both simple and robust. LED chips and constant current circuit was designed on the same board on different sides for ease of connection. Each board consisted of series connection of 6 LEDs per branch and 4 branches per board, with a constant current circuit with LM317t linear regulator chosen as is a robust solution for such low current values rather than sensor control.

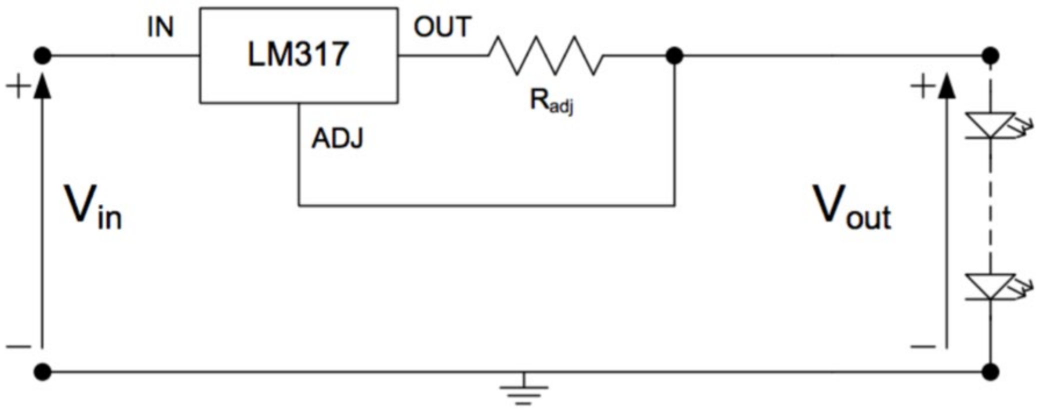

Figure 12 - Constant current circuit that implemented 4 channel per board.

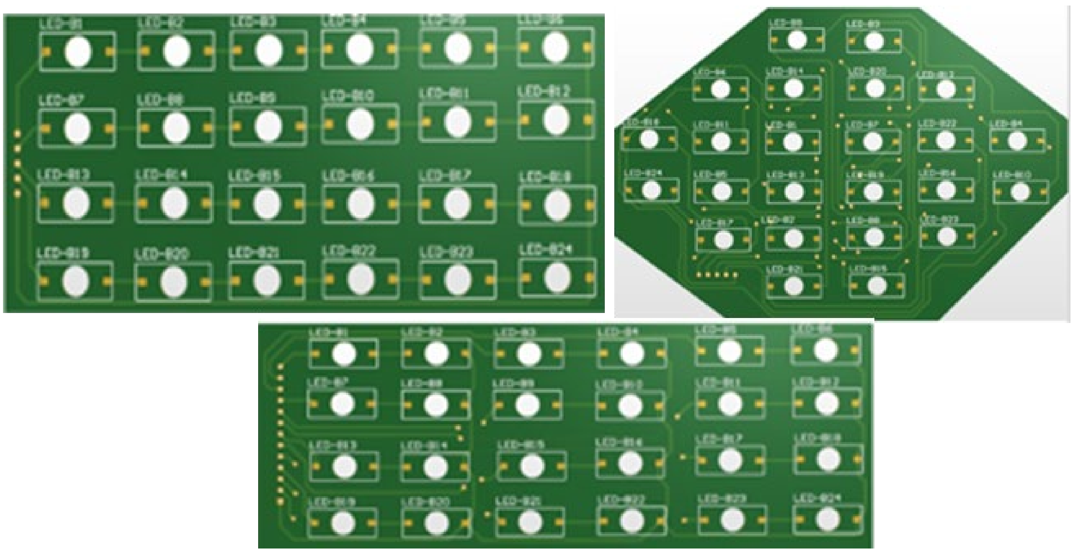

Figure 13 - LED board circuit designs. The top left side shows the design used for the experiment. The top right shows alternative geometry, more suitable for a single plant or axisymmetric trays for example. The bottom side shows a design with more channels, increasing capability to customise colour combinations (up to 12).

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Once all boards were assembled and soldered, the circuits were tested without plants in a closed tent environment and the temperature measured to make sure overheating would not be a problem for either the components or for the plants. The LEDs have a 115°C max junction temperature threshold and the threshold is 125°C for LM317t. The maximum growing temperature for the selected plant (Little Gem Lettuce) was defined as 25°C and multiple heat tests were made to reassure the safety of grow tents while the experiment is running. As a result of these tests, use of a cooling fan was found necessary to maintain the temperature below 25°C, even if the supply voltages for circuits were just at minimum necessary values. For cooling, 3600rpm 12V 0.41A brushless DC fans were found to be sufficient for the cooling of 1 tent. The tents already had 2 holes for ventilation, so a fan was placed over the bottom hole and the setup was arranged such that airflow was not blocked (Figure 18). This was achieved by building a middle tent barrier which had gaps at the side to allow air through but was sufficiently large so as not to allow interference between tent compartments. The barrier was also covered with light reflective material to maximise internal light reflection on to the plants.

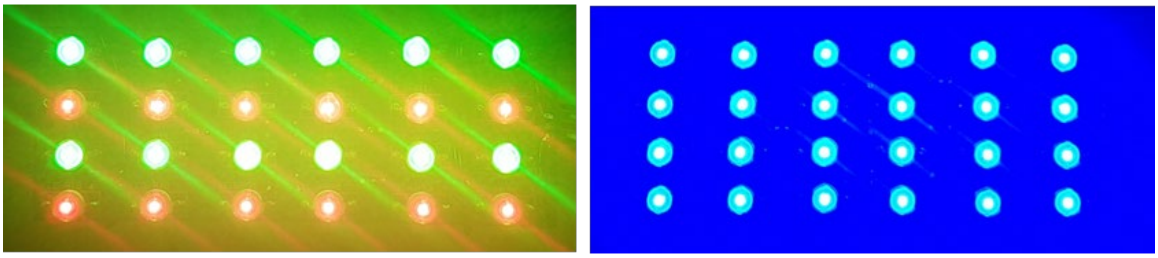

Figure 14 - Two of the working LED boards: red & green (left), and blue (right).

Experimental Setup

After LED boards with aforementioned wavelengths were designed, built and implemented with a suitable cooling solution found, the experimental setup allowing 6 LED boards to run simultaneously was set up. Each tent divided to two compartments by reflective surfaces, the inside of the tents is also reflective and the outside is opaque, thus for each compartment, interference is minimised while internal reflection is maximised. For the electrical power, one power supply with rating 30V/10A was used to feed all branches with 350 mA - all LED channels apart from the red LED channels which require 400 mA or forward current and feed from another power supply separately.

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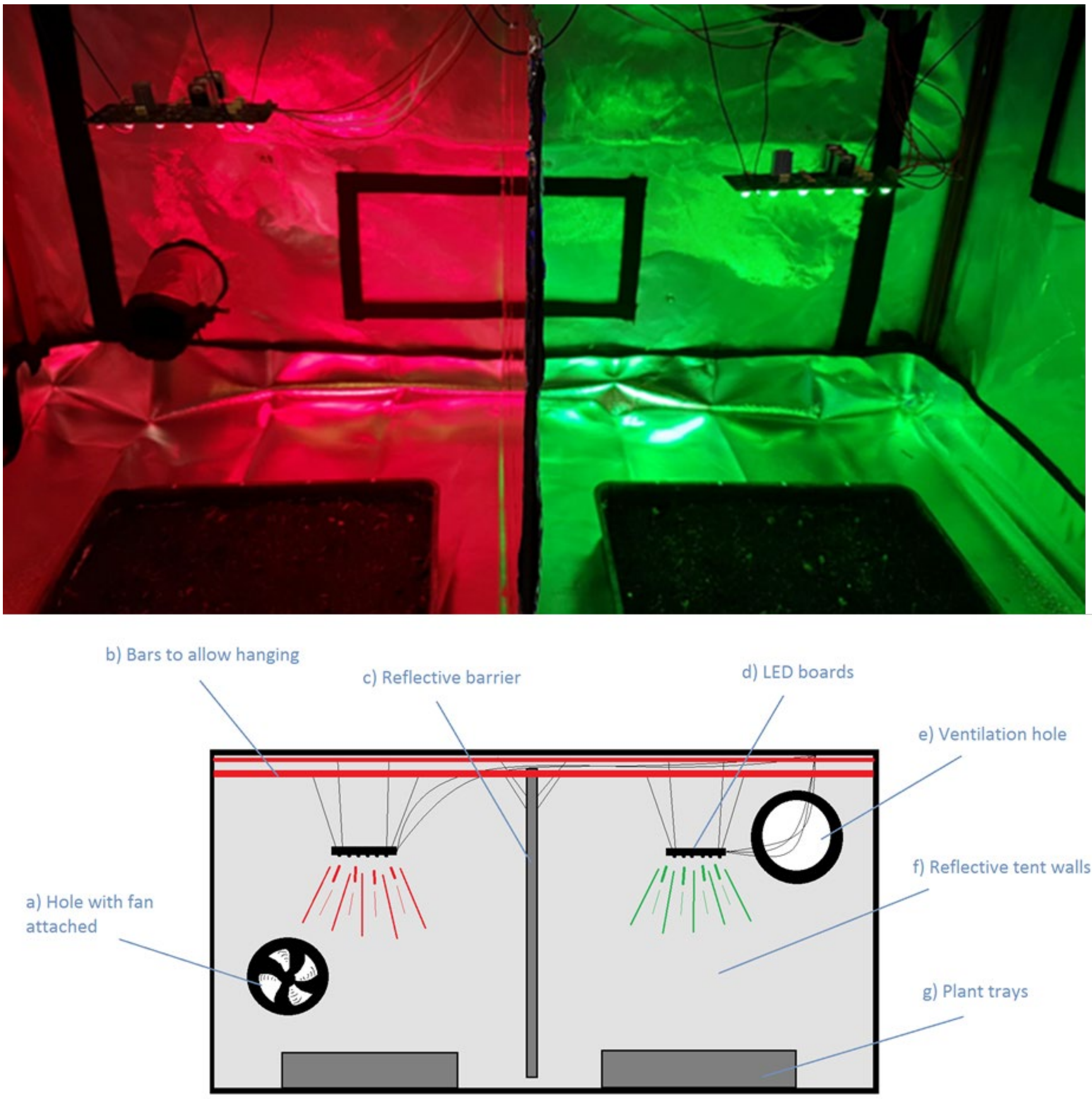

Figure 15 - Setup of the preliminary tests. The top figure shows a photograph of the tent functioning. The bottom figure shows a schematic drawing of the setup, labelling the important parts. Note, the dimensions of the tent are 70cm x 70cm x 140cm, where the 140cm length is divided into two compartments, thus the compartments are effectively cubic.

Temperature probes were put into tents during the experiment to be regularly checked, observed maximum temperature was 24°C and average was 22°C. The power supplies were connected to the mains via a timer which remained on for 16 hours and off for 8 hours. For optimal plant lighting, lights were on 16 hours per day to emulate summer daylight hours, from 6am until 10pm along the 21-day experiment.

Little Gem Lettuce as a model species, due to it being one of the easier, faster and more reliable plants to grow. In each tray 12 lettuce seeds were sown, to ensure the lights' effect on multiple plants and also to account for the fact that each batch of seeds has some variation of quality and some of them won't germinate. Nine trays of Little Gem Lettuce seeds (Lactuca

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Sativa) were sown and left in the heated greenhouse until germination. After germination, which took approximately 7 days in the heated greenhouse, 7 of the trays were collected to be experimented under prepared light test rigs and one left in the dark, but with the same temperature and water as the trays under lights. This was to observe how long the plants will sustain without any light. Finally, the last tray was left in the heated greenhouse as reference to the LED experiment to compare the results.

Once the equipment was in place, the rectangular trays were placed below the LED board parallel to its orientation. Spectrometer and luxmeter were then used to determine light intensity in terms of absolute irradiance unit and photometric unit of light intensity created according to human eye perception which is lux. Table 4 shows the results for lux for each tray. Spectrometer measurements were made from the middle of the tray on top of canopy levels, and at each of the 4 corners of the tray to observe the intensity deviation from the centre of tray, if any. Figures 16-21 were created from spectrometer data from middle of the tray and 4 corners of the tray for each colour combination.

Board Colour	Lux Value
Red	2520
Green	2670
Blue	7930
Red & Blue	4480
Red & Green	2820
White	4860

Table 4 - Lux values for LED boards at the separation distance of the trays, describing apparent light intensity.

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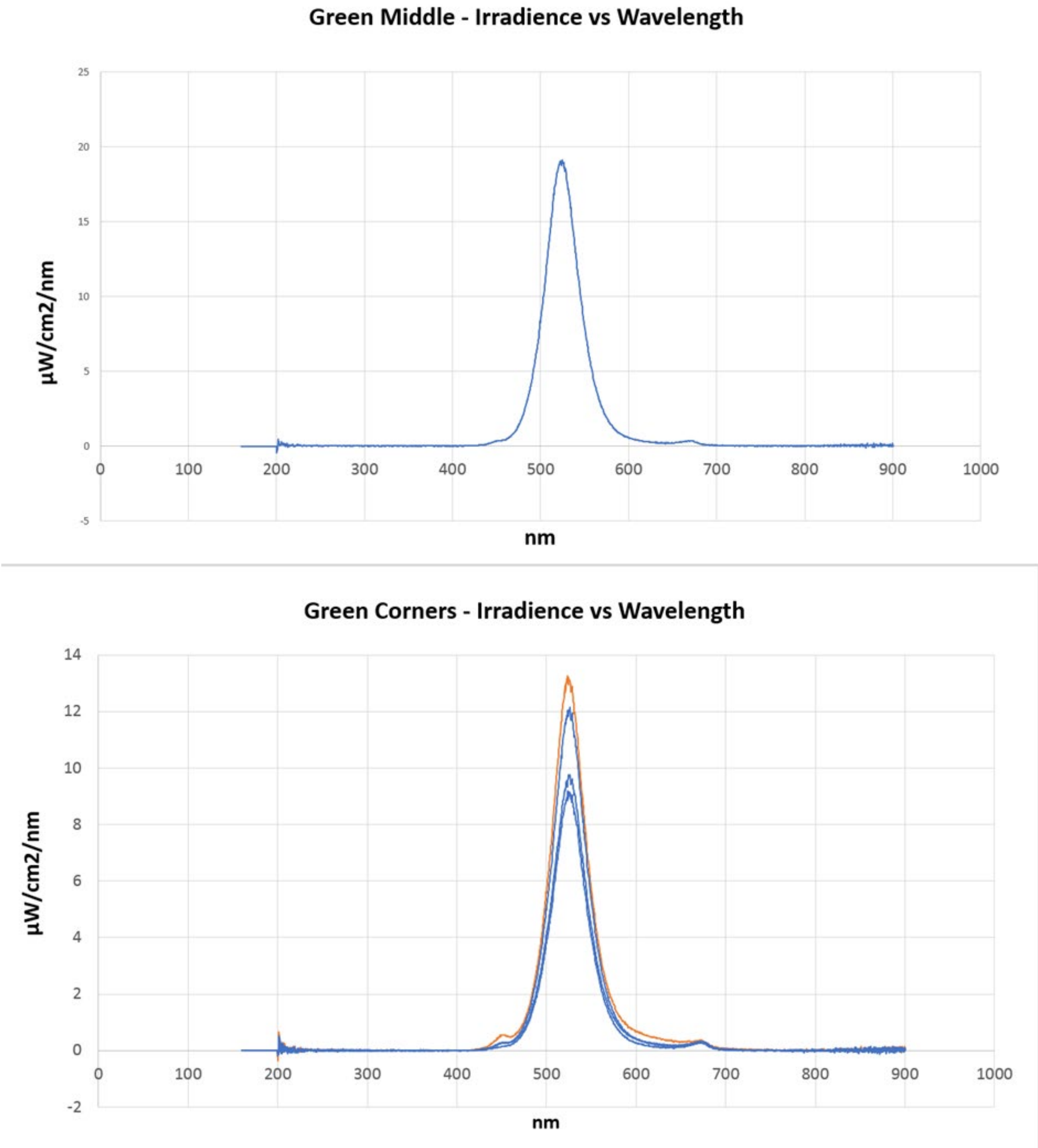

Figure 16 - Green board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

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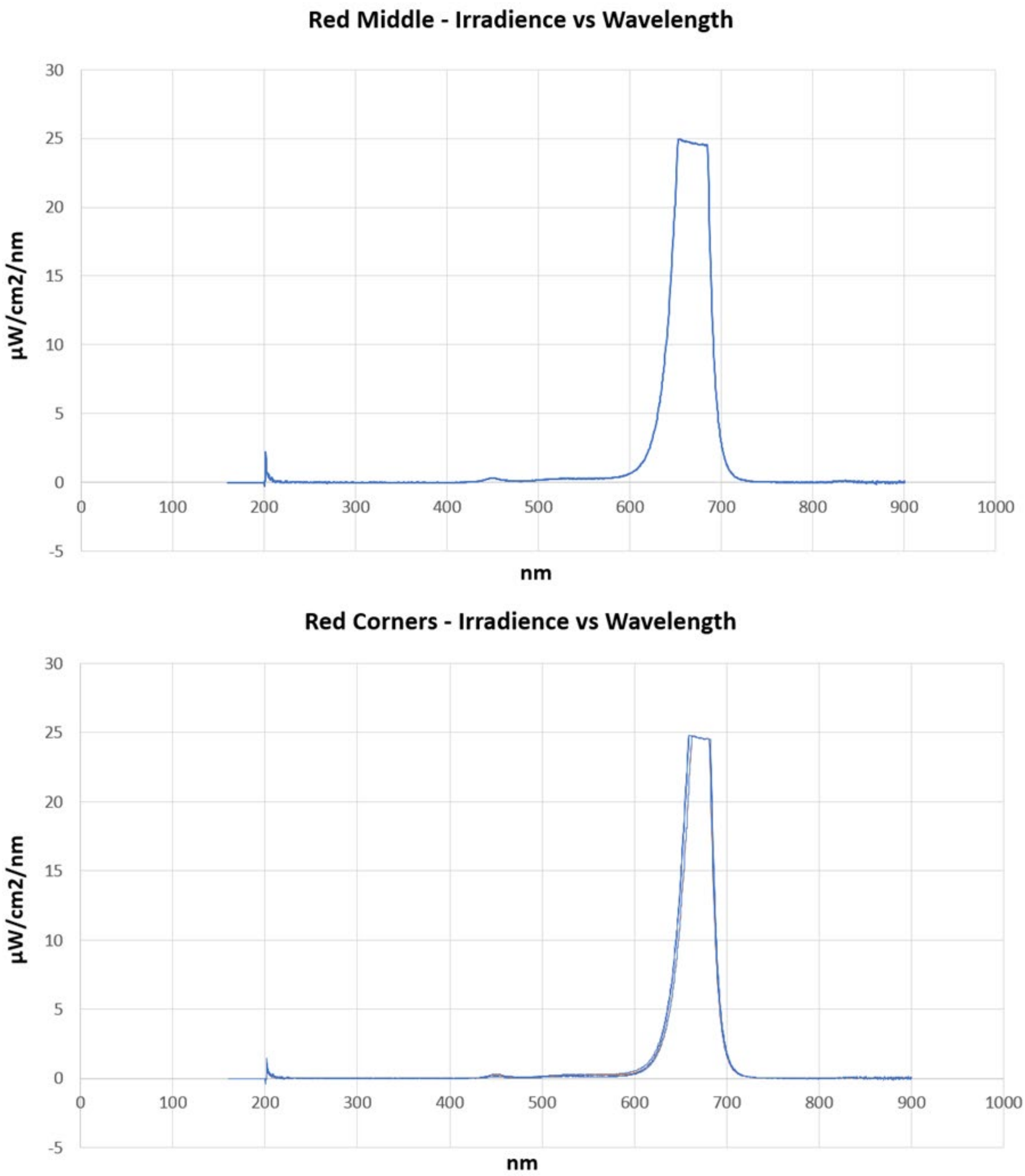

Figure 17 - Red board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

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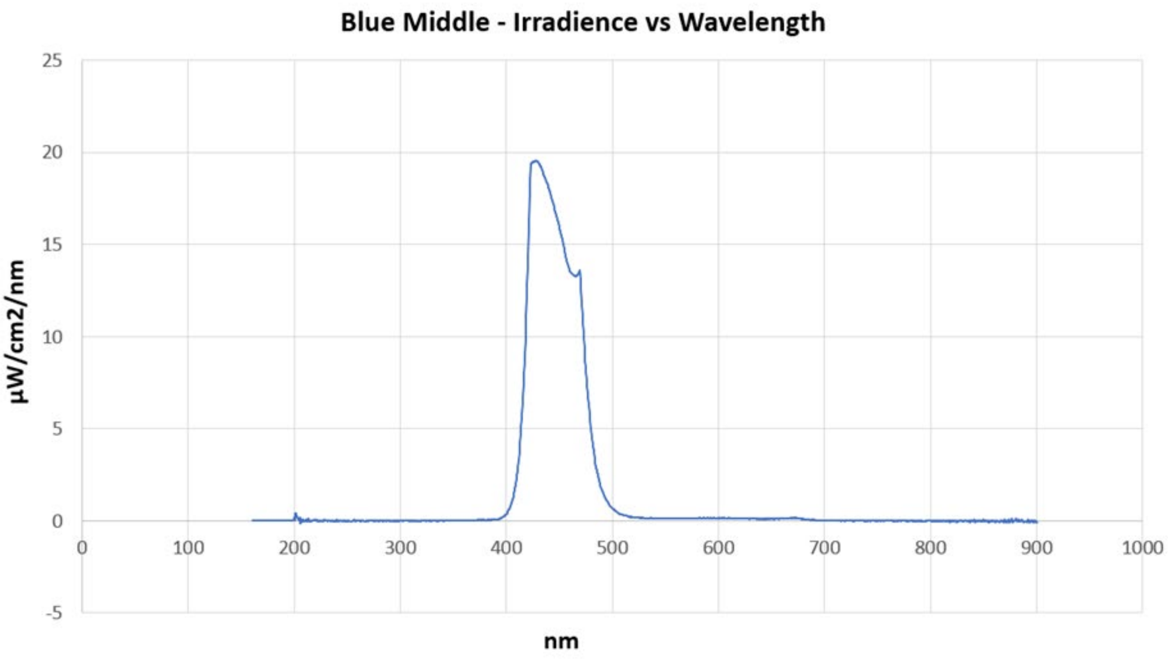

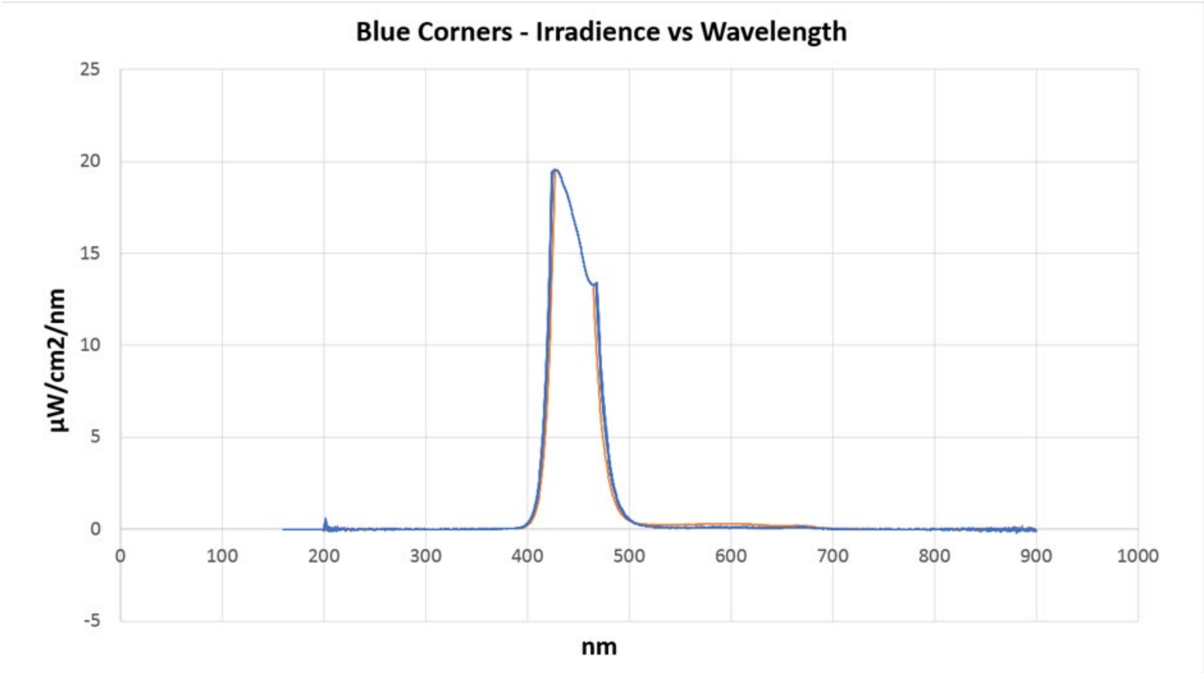

Figure 18 - Blue board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

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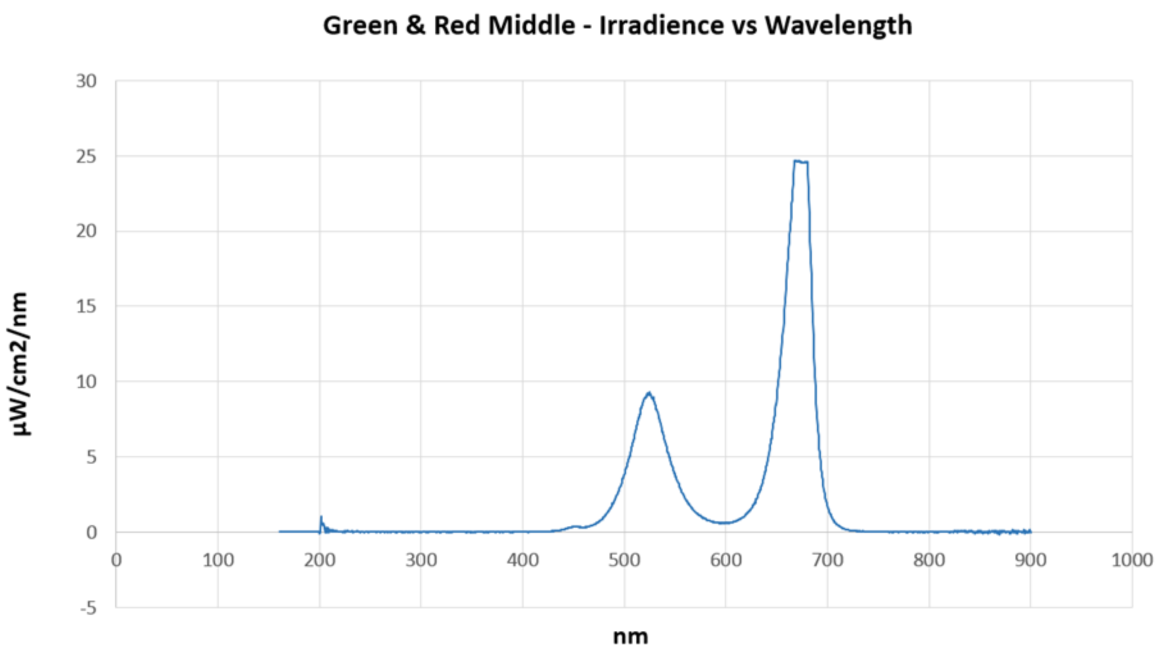

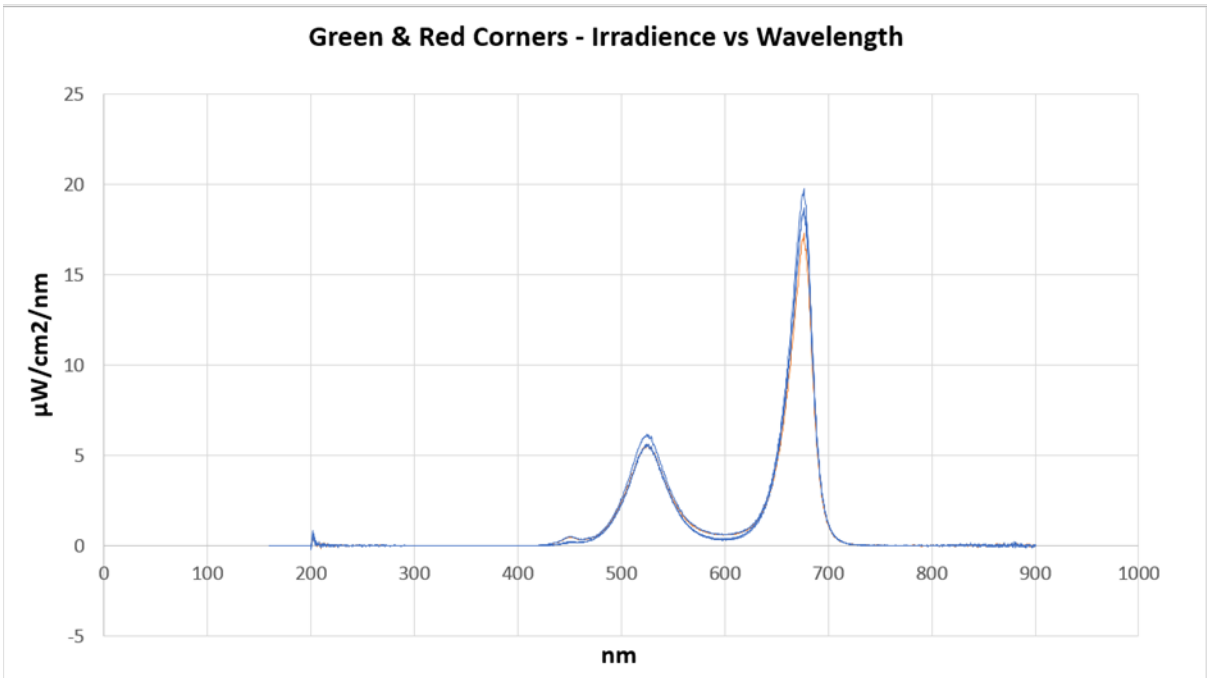

Figure 19 - Green & red board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

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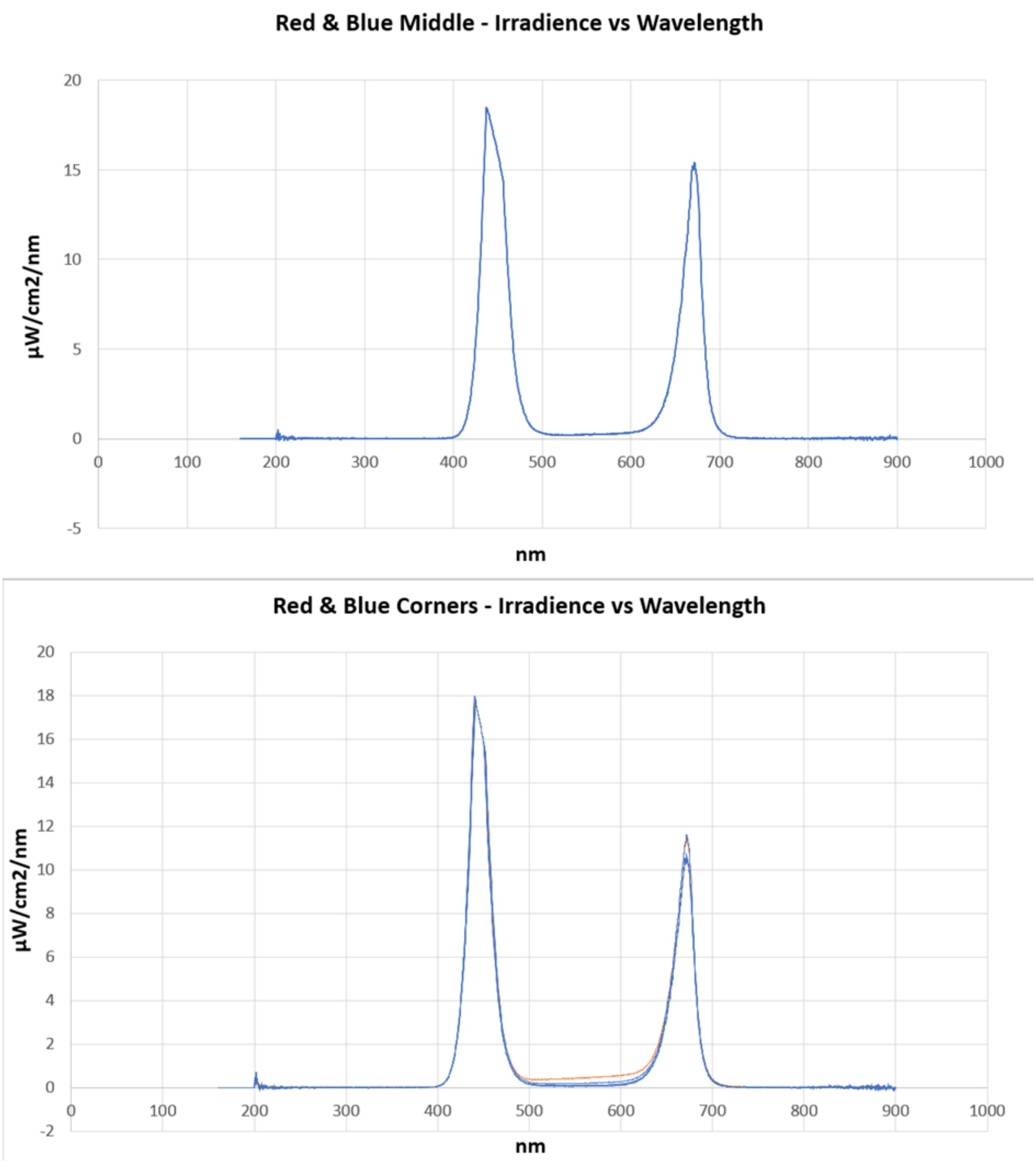

Figure 20 - Red & blue board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

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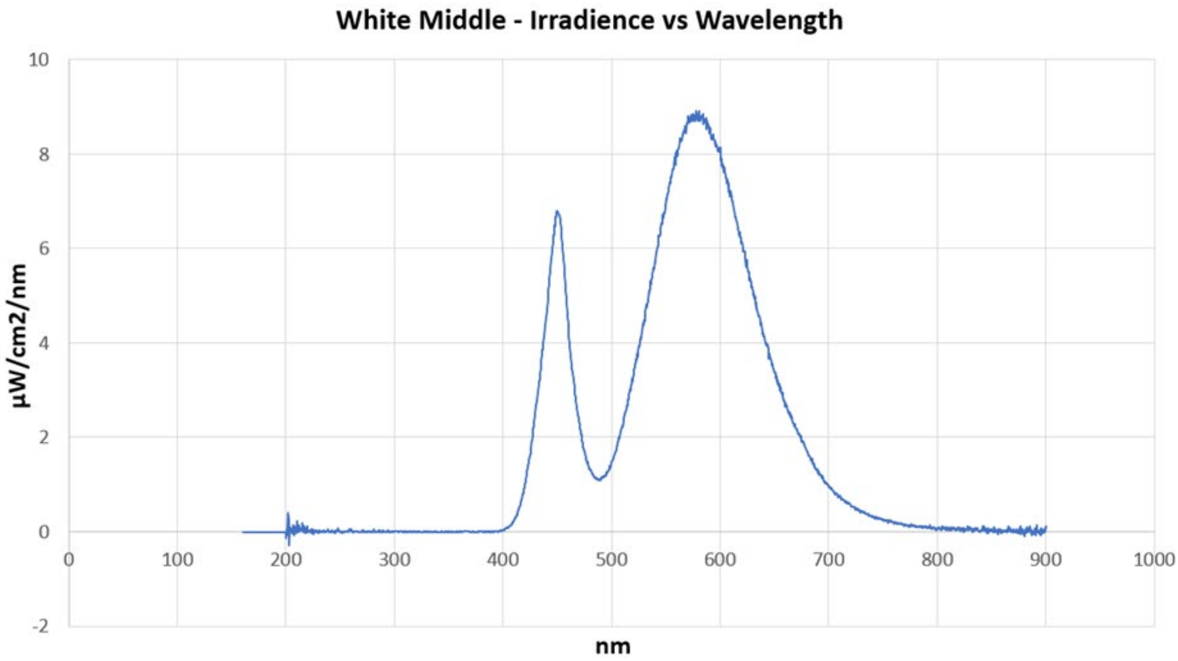

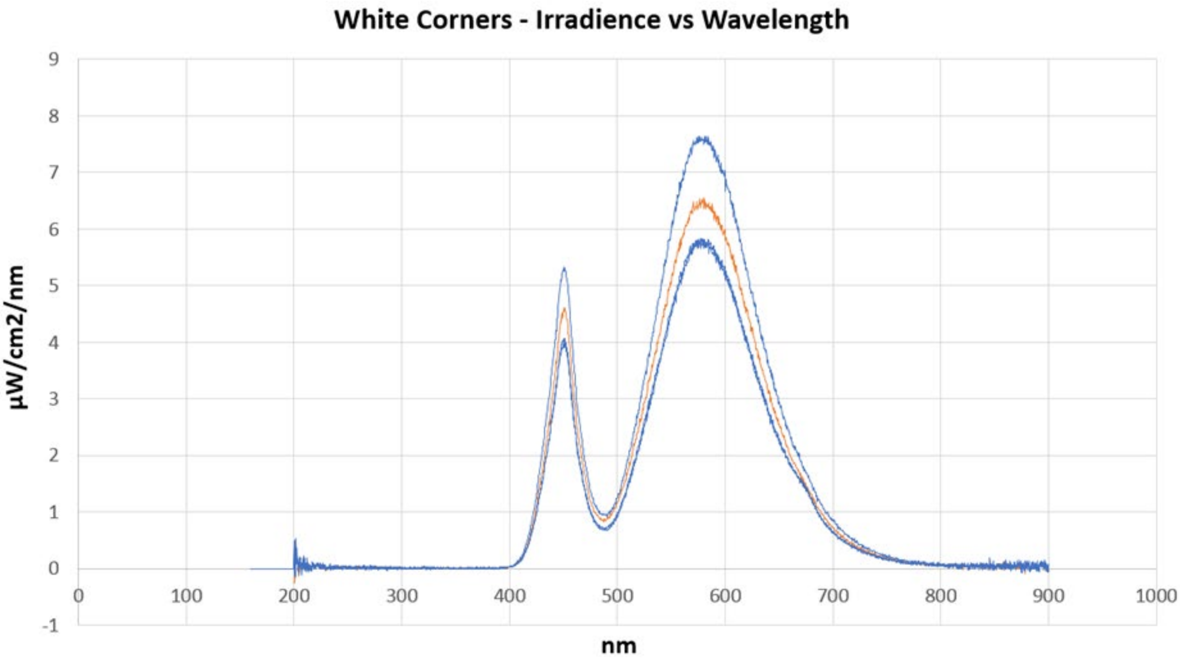

Figure 21 - White board irradiance, with the upper graph showing the irradiance at the centre of the tray and the lower figure showing the four superimposed graphs of irradiance at each corner of the tray.

Table 4 shows the lux values for the different LED boards, measured at the position of the centre of the trays. All values give over 2500 lux which suggests that none of the trays were too far from the lights to be disadvantaged by dimness.

From the irradiance plots, mixed behaviour is observed regarding deviation in the corners; for some boards there are clear differences between peaks, such as for the green, red & blue, green & red, and white lights, where irradiance peaks are clearly lower at the corners than in

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the centre, as one would expect. In most cases there are also differences in the peaks between corners, which one may also expect from an imperfect experimental setup, where some corners are closer to the light source than others.

The confusing element of these results lies within the cases which do not show a notable difference between the corners and the centres, i.e. in the cases of red and blue. The cause of this isn't yet apparent but may be due to problems regarding either the equipment or software by which it works. Another possibility is that because the growth containers were reflective, some of the light could be reflecting from the edges of the containers to the spectrometer at the corner of the plant tray. The general trend however shows that there is a non-negligible difference in irradiance between the centre and corners of plant trays, thus future tests and modelling should aim to acknowledge and accommodate for this difference.

Methodology and Measurement

The light treatments consist of LED boards of 24 W power with various wavelengths, running from 6 am to 10 pm (16-hour photoperiod) to emulate summer daylight on Little Gem lettuces. The tent's inside temperature was controlled, between 20°C- 24°C while outside the tent is set at 20°C. Watering the lettuces was a process which was learned by observation, the volume and periodicity of watering was perfected after around 3 days of trial and error. This was mainly due to the tent conditions being much dryer than greenhouse, as soil is dried much faster by the fans and the intense light for 16 hours per day, than the soil under only winter sunlight. After 3 days, 150 ml per day was given and the watering process done after 10pm when lights had switched off, this watering process was then continually conducted until the end of the experiment.

After 21 days the following was measured: fresh weight (g), dry weight (g), leaf area (cm^2), leaf number, leaf height and width (cm) and apex length (cm). These measurements were indicated in the literature as suggested assessments for plant growth and quality/harvestability of crops.

Plant Growth Assessments

From the lettuces that were initially planted, the tray under no light died within 1 week, while all the trays under light show growth (Figure 22). The lettuce tray left in the heated glasshouse (approx. 15°C) as a reference showed very slow development by the end of 21 days, this

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shows the effect of the winter short daylight hours as well as temperature sensitivity of little gem lettuces.

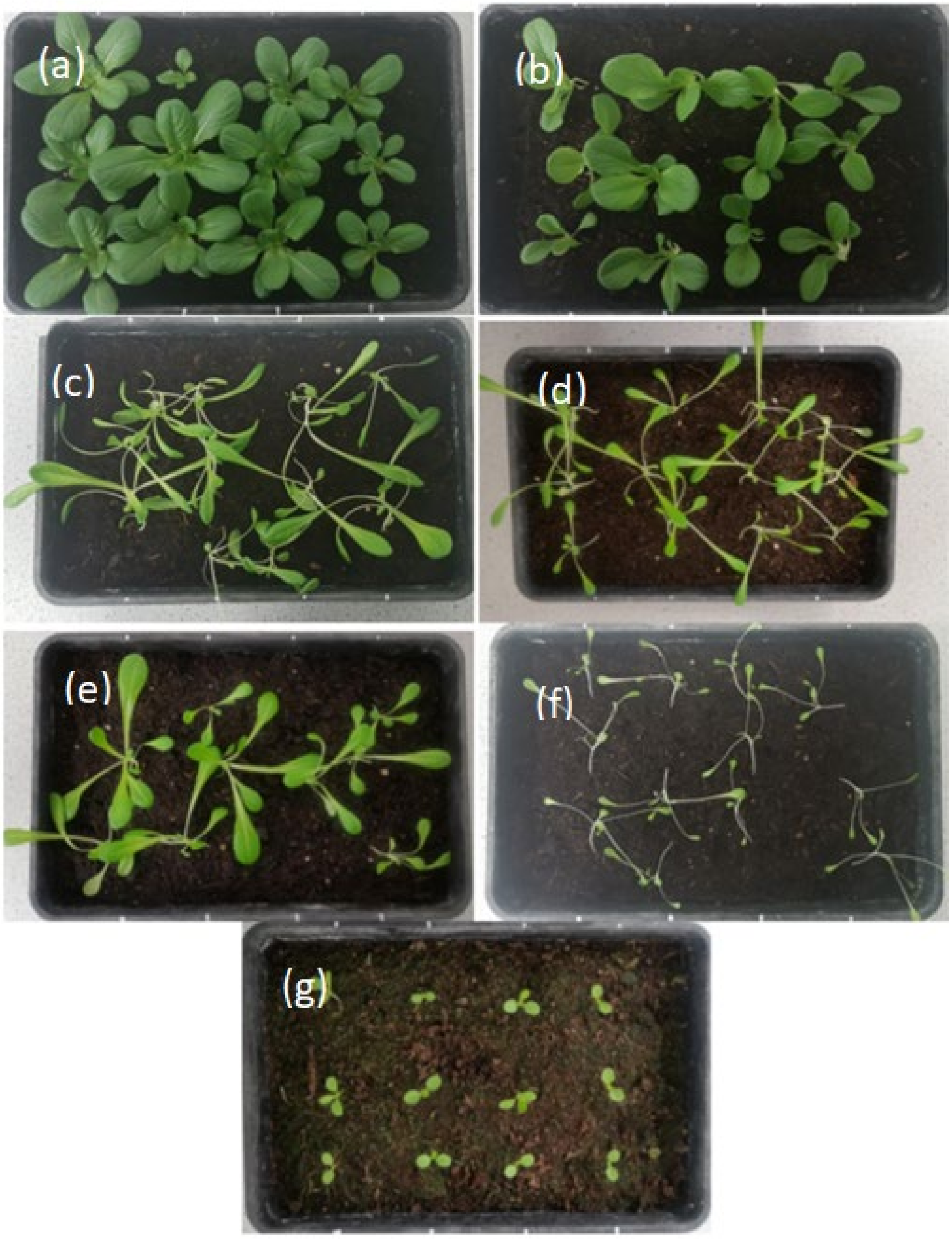

Figure 22 - Lettuce trays after 21 days of growing. Test treatments as follows: red & blue (a), blue (b), red (c), red & green (d), white (e), green (f) and the reference greenhouse (g).

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Lettuce Crops After 21 Days *Weight of Crop (g)*						
Blue & Red	**Blue**	**Red**	**White**	**Red & Green**	**Green**	**Greenhouse**
2.07	1.22	1.13	0.85	0.46	0.1	0.11
1.55	1.09	1.03	0.76	0.45	0.09	0.08
1.5	0.94	0.95	0.61	0.45	0.08	0.06
1.35	0.75	0.8	0.44	0.41	0.08	0.06
1.32	0.71	0.61	0.29	0.39	0.07	0.06
1.2	0.66	0.58	0.29	0.37	0.07	0.04
0.98	0.63	0.56	0.18	0.35	0.06	0.04
0.93	0.55	0.48	0.16	0.26	0.04	0.03
0.67	0.47	0.46	0.1	0.25	0.04	0.03
0.58	0.39	0.33	N/A	0.18	0.04	0.03
0.41	0.37	0.26	N/A	0.18	0.03	0.02
0.14	0.22	N/A	N/A	0.1	0.02	0.01
12.7	**8**	**7.19**	**3.68**	**3.85**	**0.72**	**0.57**

Table 5 - Lettuce crop weights after 21 days of growing, with green and red describing a relatively high and low weight compared to the mean of the crops respectively. The final value of each column is equal to the total of all the separate crops.

Board Colour	Weight (g)	Dry Weight (g)	**Fractional Loss**
Red	7.19	0.4	**0.94**
Green	0.72	0.14	**0.81**
Blue	8.00	0.6	**0.93**
Red & Blue	12.70	0.8	**0.94**
Red & Green	3.85	0.26	**0.93**
White	3.68	0.28	**0.92**
Greenhouse	0.57	0.18	**0.68**

Table 6 - Weight of crops before and after drying, to show water retention.

Treatments	White	Red	Blue	Green	Red & Green	Red & Blue	Greenhouse
Average Leaf Number	7.1	7.4	7.0	5.5	6.6	8.3	2.8
Maximum shoot (apex) length (cm)	1.7	1.2	1.5	2.5	1.5	1.0	1.5
Minimum shoot (apex) length (cm)	1.0	1.0	0.9	1.0	1.0	0.4	0.9
Average shoot (apex) length (cm)	1.3	1.2	1.2	1.8	1.3	0.6	1.1

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Maximum leaf area (cm²)	6.8	7.5	12.3	0.8	2.5	10.6	1.1
Minimum leaf area (cm²)	1.5	4.1	6.8	0.1	1.9	3.4	0.9
Average leaf area (cm²)	4.4	5.7	8.9	0.6	2.3	8.2	1.1
Maximum leaf height and width (cm)	H = 5.7 W = 2.2	H = 5.8 W = 2.2	H = 5.7 W = 3.7	H = 1.8 W = 0.7	H = 3.8 W = 1.9	H = 5.0 W = 4.5	H = 1.6 W = 1.6
Minimum leaf height and width (cm)	H = 3.0 W = 1.0	H = 4.5 W = 1.6	H = 3.3 W = 1.9	H = 0.5 W = 0.3	H = 3.0 W = 1.0	H = 3.0 W = 2.0	H = 1.4 W = 1.1
Average leaf height and width (cm)	H = 4.2 W = 1.6	H = 5.3 W = 1.8	H = 4.9 W = 3.0	H = 1.3 W = 0.6	H = 3.5 W = 1.4	H = 4.2 W = 3.0	H = 1.5 W = 1.2

Table 7 - Lettuce parameter measurements, including shoot lengths, leaf areas, and leaf geometries taken from five leaves from each tray, including the biggest, smallest and 3 typical ones.

In Table 5, the weights of all the crops are displayed, these represent the weights of the above ground tissue immediately after being cut. It is interesting to note the variation of weights both within one tray and across the experiment. The high variation in weight within trays under the same light as each other exposes a difficulty in controlling the experimental parameters. This makes it difficult to deduce general patterns about plant growth response to light, particularly based on relatively small sets of data.

Weight of the crops both immediately after cutting from trays and then after 12 hours of drying at 80 degrees are shown in Table 6. Most of the trays under LED lighting boards show a fractional weight loss of 0.92 - 0.94, apart from green which had a fractional loss of only 0.81. This could be possibly because, as discussed earlier, red and blue frequencies of light are more related to the photosynthesis process. Green is the only LED board without any element of red or blue. Also, for the very low fractional loss of the greenhouse tray, the conditions were very much colder and light intake levels much lower, thus the level of photosynthesis possible is also greatly inhibited.

Plant physiology varied greatly between trays after 21 days (Figure 22). Starting from Figure 22a, the plants were treated with red and blue (50%-50%) light mix gave the most healthy and compact result with big dark green leaves that have close length and width values, plants have a small apex length but are strong relative to the other lettuces. This tray gave the biggest yield.

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Figure 22b shows the second best growth results, from 100% blue light. The plants seem compact and having large and dark green leaves, apex length is small but not as strong as for the red & blue and has small bending, meaning mechanical drooping of the stem and plant due to weak plant relative to the stem length. Leaves have close length and width so has a compact look.

On the other hand the lettuces grown under 100% red light (Figure 22c) have the opposite growth pattern, with excess elongation at branches and very stretched leaves with poor length/width ratio of the leaves make the plant grow horizontally without the ability to hold their own weight and tangle with each other. However, this treatment had the third highest overall yield, both in weight and leaf area, although class one yield was not determined which is commercially important.

For the green and red light treatment (50%-50%) gave characteristics from the 100% red and 100% green treatments alone; having branch elongation and smaller leaves. Plants under green (100%) light treatment gave the weakest results by having smallest leaf area and long apex length with weak body. White LEDs gave a moderate result more similar to green-red mix but with slightly bigger leaves with better leaf L/W ratio. The plants which grew in the greenhouse appear to be in a much earlier phase of growth, similar to the growth observed at the end of the first week in plants grown under LEDs. This is due to short day length and 7-10°C temperature variation.

Overall, it is clear from both the photos and measurements of weight, water retention and leaf/shoot size that the treatments which produced the best plants were the blue, and blue & red lights, the latter being the best overall. Both the green and the greenhouse reference tray produced the weakest growth. As visual characteristics red & blue and blue gave best result in colour, compact growth and total weight. Sole green light is observed to produce the weakest crops among all other LED boards in the trial. Red light gave excessive elongation while having a reasonably good amount of leaf area and dry weight.

Neural Network Analysis on LED Lighting for Lettuce

Though some trends can be observed from experimental data about the response of plants to various spectral distributions of light, whole spectral modelling of plant spectral response can be difficult using traditional modelling techniques such as linear regression. This is because there are a large number of input conditions, including light intensity and spectral distribution, but also CO_2 concentration, photoperiod, temperature, humidity, choice of

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nutrients etc. Additionally, there are a vast number of measurable output parameters, all of which are related to each other in a complex way [44], which make choosing optimal light recipes based on simple modelling techniques such as linear regression difficult.

Neural Networks

One modelling methodology which is suitable for systems with nonlinear behaviour and many input and output parameters is neural network machine learning. Neural networks are based on the neural network structures in the human brain. They are commonly used for image recognition and function fitting and prediction. They are useful for modelling systems with large amounts of available data and can be useful for systems with a high number of input and output variables. Neural networks also have good generalisation to regions where data is not available, making them predictive. But due to the multilevel complexity of these networks, the function relating inputs to outputs, although analytical, is effectively impossible to understand.

More specifically in agricultural applications, neural networks have been tested for predicting plant growth and yield in greenhouse environments [45]. This study compared a neural network approach to other fitting methods such as non-linear regression and found it to be superior. It is for these reasons that this work tested neural networks using the neural network fitting app in MATLAB on LED recipes for growing lettuce.

To train a neural network on a data set, the input and output data is split into three sets:

1. **Training Set**: This is the set of data that the neural network analyses and learns from; both inputs and outputs are needed.
2. **Validation Set**: Used to validate the model and its structure, e.g., number of hidden layers; both inputs and outputs are needed.
3. **Test Set:** Test set: the data for which the model is used to predict the outputs; inputs only needed, although the outputs can be checked against observed.

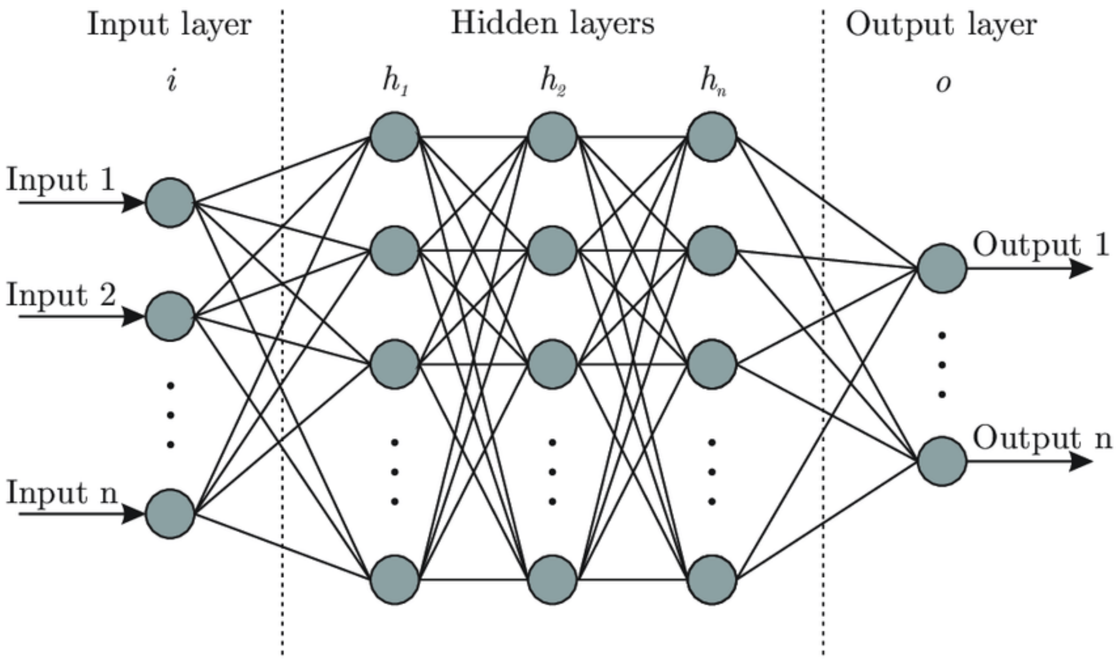

Figure 23 - Explanatory diagram of the architecture of a Neural Network [46].

Experimental Data Analysis

After obtaining the experimental results in Year 1, the data is explored in more detail in Year 2. Combining the data gained from Year 1's experiment with the data from the literature to analyse by neural network fitting required PPFD values to be predicted from Year 1's experiment in order to be compatible with the other data which used PPFD as the appropriate measure of light intensity.

The light intensity data from Year 1 was only taken from Luxometer data and not a PPFD measuring device due to the availability of equipment. However, as a spectrometer was also used on the boards, the PPFD values can be predicted by numerically finding the area under the curves in Figures 16-21. Spectral data was split into 3 graphic regions: Blue (400-500nm), Green (500-600nm) and Red (600nm-700nm). Then for each spectrometer irradiance plot, the area under the curve in each colour region was geometrically approximated to find the PPFD contribution of each colour.

Note, by integrating Figures 16-21, one can obtain $\mu W cm^{-2}$ values in each of the three colour regions. This can be converted to $\mu mol s^{-1} m^{-2}$ by firstly noting the following equation for light energy:

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$$E = N_\lambda \frac{hc}{\lambda}$$

where N_λ is number of photons at wavelength λ and h and c are the Planck constant and speed of light respectively. Appropriately converting units and writing energy as function of irradiance, one can then find the following relation for PPFD value in $\mu mols^{-1}m^{-2}$:

$$PPFD = 8.3488x10^{-3} \int I d\lambda$$

where the integral is the area under the curve in Figures 16-21. Values of PPFD for all boards in Year 1's experiment are given in Table 8.

		μmol/m^2/s		
Board	Blue	Green	Red	**Total**
Green	0	50.3	0	**50.3**
Red	0	0	70.2	**70.2**
Blue	43.1	0	0	**43.1**
RG	0	22.9	48.6	**71.5**
RB	24.4	0	24.3	**48.7**
White	9.8	28.3	20.5	**58.6**

Table 8 - PPFD contributions from blue, green and red light for all boards used in Year 1's experiment as calculated by Equation 5 with the integral calculated from the area under the curve in spectrometer data displayed in Figures 16-21.

Literature Review of LED Based Lettuce Growth

To begin with, the experimental data from the previous sections of this report was used for fitting. However due to the small amount of data in this experiment (six recipes), neural network training gave no meaningful fit. This is expected with only six inputs. However, with an extensive literature search of LED light recipe tests for lettuce variants data was gathered fitted to the model. The differences in data between each different experiment in the literature required extensive normalisation.

Firstly, the $\mu mols^{-1}m^{-2}$ values were established, both total and individual contributions from blue (400-500nm), green (500-600nm) and red (600-700nm) LEDs for all experiments in the literature as for Year 1's experimental data analysis described above. Output data was also gathered, with output variables c common across the literature and Year 1's experiment collated.

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Importantly, both input and output data was normalised such that in each experiment the highest total $\mu mols^{-1}m^{-2}$ value was set to 1, as were all of the highest output values, then all the other values were proportionally reduced, this is shown for Year 1's experiment in Table 8 This aims to increase compatibility between the different experiments, as the different experiments in the literature were conducted for different lengths of time, and the germination duration and conditions were also different, also importantly, most of the experiments looked at different types of lettuce, thus normalising their output values within each experiment is particularly important.

A large amount of data was gathered from the following experimental literature:

1. 'Light emitting diodes as a radiation source for plants' - **1991** [6]
2. 'Stomatal conductance of lettuce grown under or exposed to different light qualities' - **2004** [47]
3. 'Leaf Shape Index, Growth, and Phytochemicals in Two Leaf Lettuce Cultivars Grown under Monochromatic Light-emitting Diodes' - **2012** [48]
4. 'Effect of green light wavelength and intensity on photomorphogenesis and photosynthesis in Lactuca sativa' – **2012** [32]
5. 'Leaf Shape, Growth, and Antioxidant Phenolic Compounds of Two Lettuce Cultivars Grown under Various Combinations of Blue and Red Light-emitting Diodes' – **2013** [49]
6. 'Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system' – **2013** [50]
7. 'The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (Lactuca sativa L. var. capitata)' – **2013** [51]
8. 'Influence of Green, Red and Blue Light Emitting Diodes on Multiprotein Complex Proteins and Photosynthetic Activity under Different Light Intensities in Lettuce Leaves (Lactuca sativa L.)' - **2014** [52]
9. 'Photobiological Interactions of Blue Light and Photosynthetic Photon Flux: Effects of Monochromatic and Broad-Spectrum Light Sources' – **2014** [53]
10. 'Growth, Photosynthetic and Antioxidant Parameters of Two Lettuce Cultivars as Affected by Red, Green, and Blue Light-emitting Diodes' – **2015** [54]
11. 'Effect of the Spectral Quality and Intensity of Light-emitting Diodes on Several Horticultural Crops' – **2016** [55]
12. 'Growth and nutritional properties of lettuce affected by mixed irradiation of white and supplemental light provided by light-emitting diode' – **2016** [56]

13. 'Leaf Photosynthetic Rate, Growth, and Morphology of Lettuce under Different Fractions of Red, Blue, and Green Light from Light-Emitting Diodes (LEDs)' – **2016** [57]
14. 'Green light enhances growth, photosynthetic pigments and CO_2 assimilation efficiency of lettuce as revealed by 'knock out' of the 480–560 nm spectral waveband' – **2017** [58]
15. 'Improving "color rendering" of LED lighting for the growth of lettuce' – **2017** [59]
16. 'Growth differences among eight leaf lettuces cultivated under led light and comparison of two leaf lettuces grown in 2016 and in 2018' – **2019** [60]

The problem with inputting large amounts of data from multiple different experiments is that though the data on lighting intensity and spectrum is well documented, the other experimental conditions such as treatment in seedling phase, photoperiod, temperature and carbon dioxide concentration etc. are not identical. It is therefore difficult to find direct relations between lighting and output data across all the experiments.

Additionally, as noted by Ozawa *et al.* [60], the two sets of data for the lettuces from 2016 and 2018 experiments saw large differences in output results, even with the same light recipes and intensities; their results show that plants grown in 2016 had significantly lower fresh weight, leaf weight, and dry weight: one-sixth to one-eighth of those in 2018. This led them to conclude that: "When growing plants in a commercial plant factory, it might be necessary to use an automatic system for all of them. Furthermore, when conducting experiments even in a growth cabinet and chamber, one must grow plants during the same period and with the same people conducting experiments. The same experiments should be repeated even after changing the personnel conducting the experiments."

Given Ozawa *et al.*'s findings, it further highlights how sensitive output data is to slight variations in experimental conditions excluding light intensity and recipe. It is for this reason that the data inputted to the neural network fitting program is normalised, whereby each experiment was normalised with respect to its own maximum values such that no input or output value could be above 1 and that all other data points scale proportionally with the raw data. An example of this normalising method is shown for Year 1's experimental data in Table 9.

This normalisation is important in ensuring that experimental differences (excluding lighting) such as setup environmental conditions, germination time, photoperiod etc. are levelled out between different studies. The normalisation also aims to level differences between varieties of lettuce, as each variant has naturally different weight and size and dimensions, so by normalising the data the general trends of light effectiveness (both spectral contribution and

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light intensity) may be seen across multiple different experiments. With regards to testing models' accuracy and precision, normalised data is also much easier to analyse, with statistical errors etc.

Some of the experimental data in the literature didn't give information about PPFD contributions in micromoles, but like for Year 1's experiment, gave spectral distributions by which PPFD is deducible similarly to how was done for Year 1's experimental data. Also, regarding output data, from the 137 light recipes throughout all 16 papers, only 24 recipes had information about fresh weight, leaf area and stem length. Because of that limitation, for the neural network fitting, only fresh weight and leaf area were considered, this increased the number of data points from 24 to 77. So, although some output information is lost, 2 key output parameters are still available to fit to with 77 data points.

The data also needs to be in a random order before feeding into the neural network. The training set is the data set the neural network builds the model on, it then validates it on the validation set until performance is optimised, the finalised neural network is then tested on previously unseen test data to measure its predictive effectiveness. Randomisation is important to ensure experimental data from each of the independent experiments is randomly distributed throughout the three data sets. Otherwise data from the first experiments may be predominantly in the training set and latter data in the test data set and so forth.

Raw Data							
Board	**PPFD (mmol/m2/s)**				**Output Data**		
	Blue	**Green**	**Red**	**Total**	**Weight (g)**	**Shoot Length (cm)**	**Leaf Area (cm2)**
Green	0	50.27	0	**50.27**	7.19	1.16	5.725
Red	0	0	70.2	**70.2**	0.72	1.8	0.583
Blue	43.125	0	0	**43.125**	8	1.18	8.875
RG	0	22.85	48.6	**71.45**	12.7	0.55	8.1875
RB	24.375	0	24.3	**48.675**	3.85	1.32	2.275
White	9.75	28.334	20.52	**58.604**	3.68	1.34	4.375

Normalised Data							
Board	**PPFD**				**Output Data**		
	Blue	**Green**	**Red**	**Total**	**Weight**	**Shoot Length**	**Leaf Area**
Green	0	0.70357	0	**0.70357**	0.05669291	1	0.065690141
Red	0	0	0.98251	**0.98251**	0.56614173	0.644444444	0.645070423
Blue	0.60357	0	0	**0.60357**	0.62992126	0.655555556	1
RG	0	0.3198	0.6802	**1**	0.30314961	0.733333333	0.256338028
RB	0.34115	0	0.3401	**0.68125**	1	0.305555556	0.922535211
White	0.13646	0.39656	0.28719	**0.82021**	0.28976378	0.744444444	0.492957746

Table 9 - The normalisation of data from Year 1's little gem lettuce growing experiment.

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Neural Network Fitting Results

Multiple ratios of training/validation/test data were tested for neural networks of varying hidden neuron number. Figure 24 shows the best performing preliminary fitting results for a neural network with 5 hidden neurons and 70%/15%/15% training, validation and test data respectively. All plots show an R value of around 0.8 which shows reasonable fit to data generally, however the variance is high, meaning that the probability is low that any one data point is within a small error margin of the true value. An error histogram for this data is shown in Figure 25, where for all datasets, there are high errors.

Overall, this neural network generally fits well to the data and predicts output data with some accuracy. However, significant errors and large variations between accuracy in data points suggest that the model needs improvement.

It is likely that the error in this model stems from the incoherence in data from different experiments. As discussed in the literature, even the same research group repeating the same experiment two years apart have observed large differences in output data for the same lighting recipe and intensity [60], suggesting that subtle differences in the setup have large consequences. For a more accurate model to be developed, either the dataset must be much larger and contain additional input and output variables to account for variations in setup conditions between different experiments, or data must be gathered from the same research group at the same time with identical conditions and environments and only light recipe and intensity varied. In these circumstances, one might expect trends to become clear and fitting to be accurate via neural network modelling.

Additionally, neural networks could be useful to determine which output variables correlate most with light recipe and intensity. For example, leaf area and fresh weight may be less correlated with light recipe and intensity than stomatal conductance and dry weight. This would be easy to investigate due to the speed and ease of neural network fitting. But only experiments with large datasets investigating the same plant variant in the same environmental conditions can help elucidate trends via neural network fitting.

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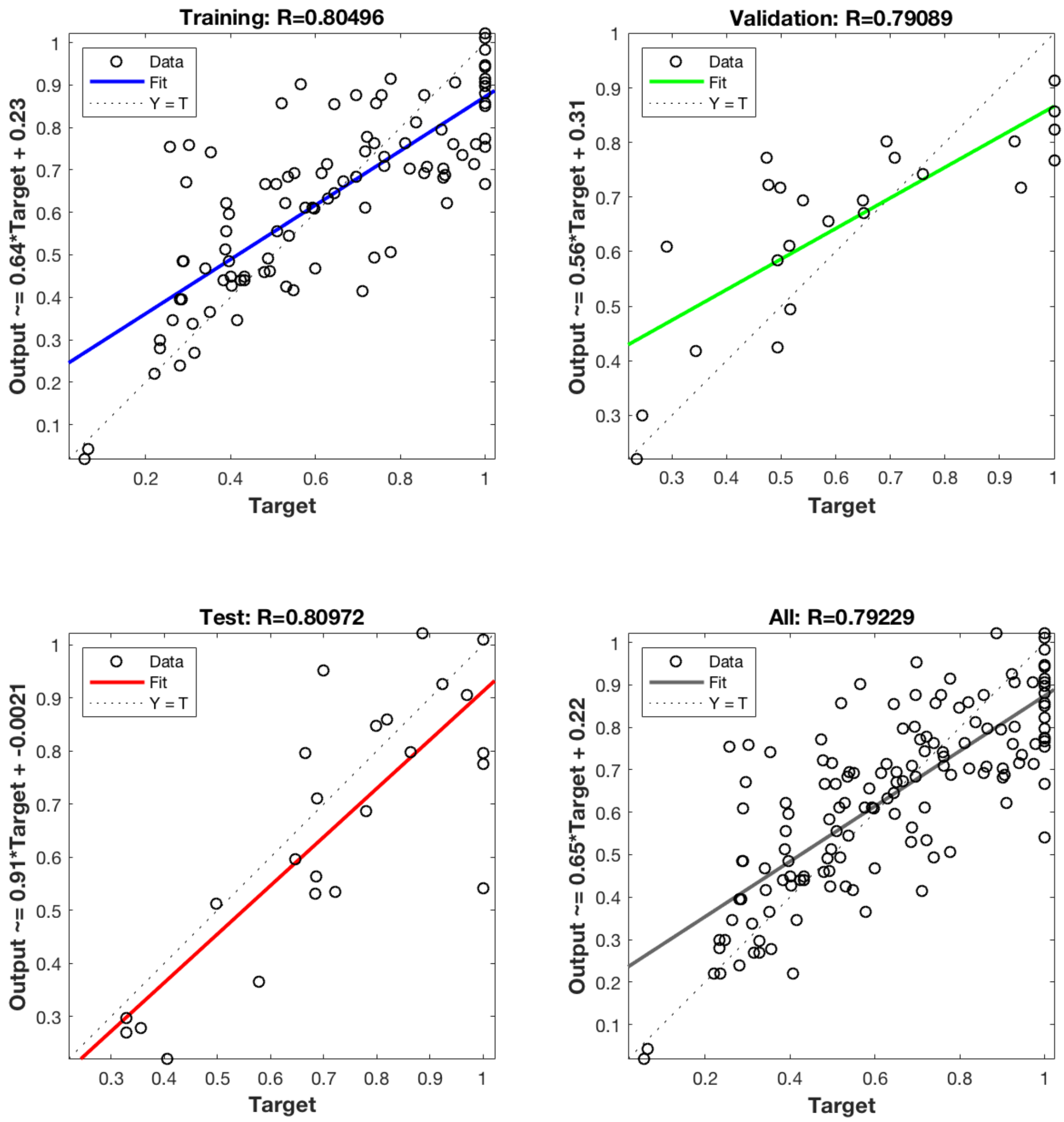

Figure 1 - Output values from neural network vs the normalised target output data from experiment, for training, validation, test and all data.

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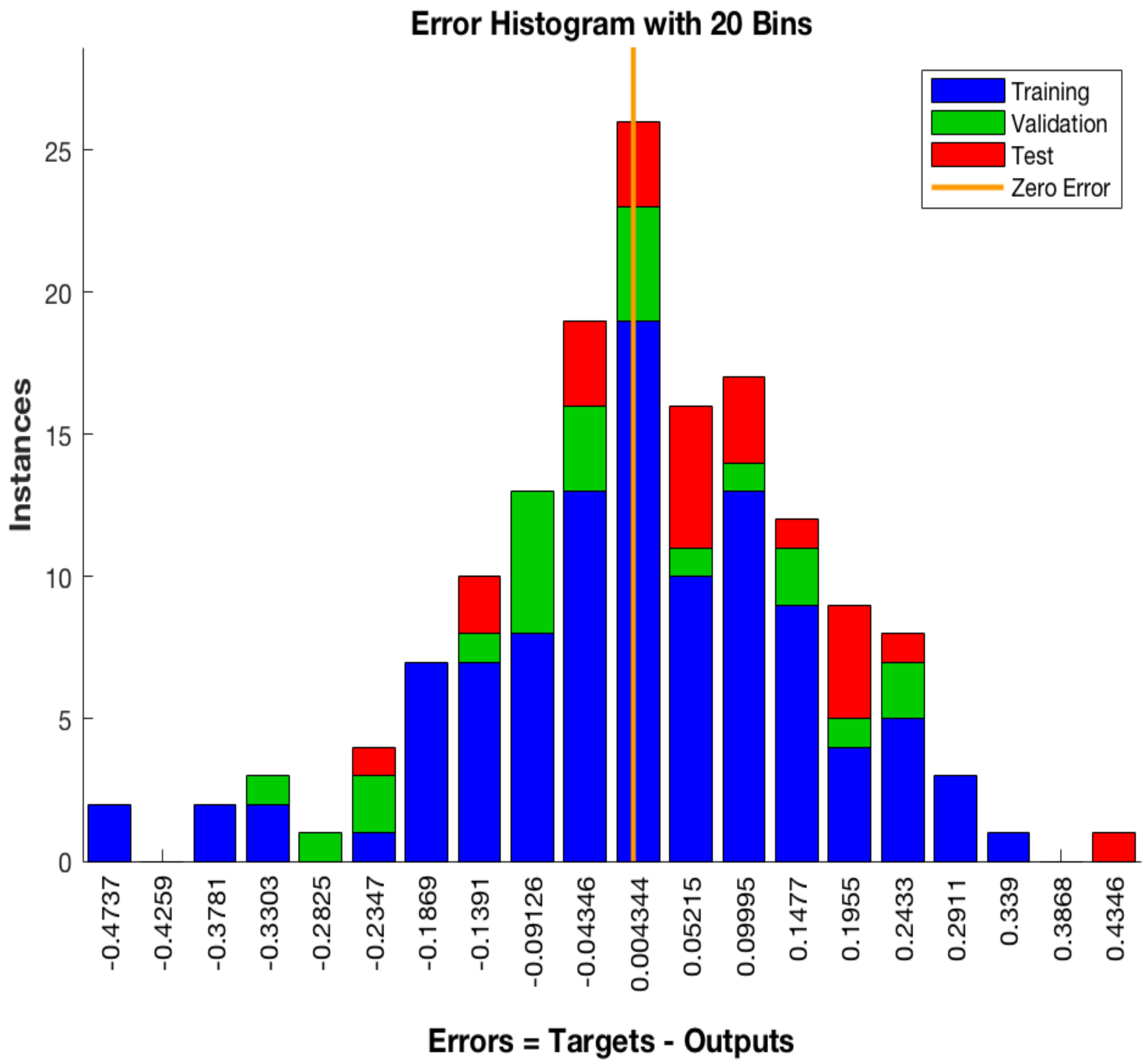

Figure 25 - Error histogram of difference between neural network predicted output and target data from experiment.

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Power Saving in LED CEA Systems

To study the likely impact of various approaches to reduce energy consumption, it is best to model our study on a working experimental system, so that any conclusions drawn about energy saving are practically relevant. The CEA facility growing strawberries at the University of Reading was chosen to base future calculations on.

In order to analyse power input verses useful power output, key parameters and the product details of the LEDs used were identified. The system uses Sulis series rectangular 56 W LED modules, each comprised of 56 x 1 W white bulbs. These modules are arranged in a configuration shown below in Figure 26:

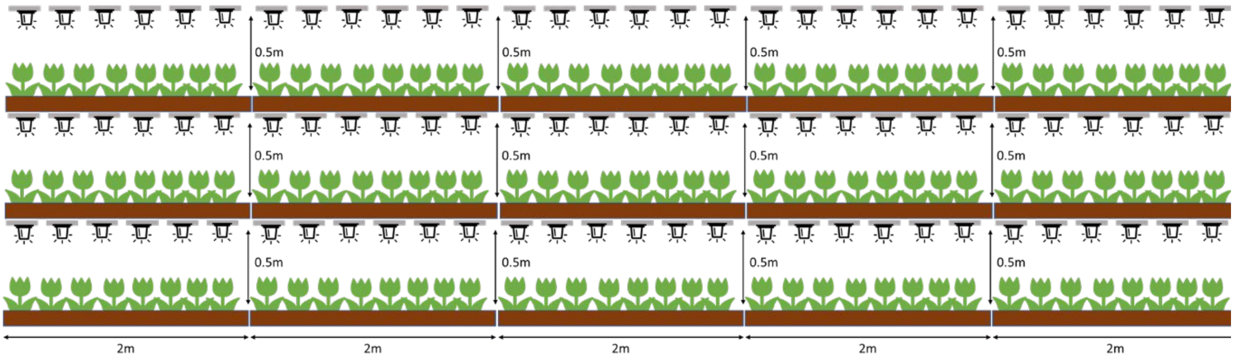

Figure 26 - Schematic visualisation of the setup of the strawberry indoor growing facility at the University of Reading, with each 2-metre-long strawberry tray containing 6 Sulis series rectangular modules of 56 x 1 W white LED bulbs. This is repeated 5 times along the row and 3 times vertically. The whole system shown was repeated 3 times in parallel aisles, making a total of [((6x3)x5)x4] = 360 modules.

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Technical Parameters	Rectangular Module
Power	50W
LEDs	56 x 1W LEDs
Size	265 x 115 x 40mm
Input Voltage	AC 85-165V AC 180-260V
Beam Wavelength Lighting	400nm to 730nm
PPFD	35umol/1m 15.5umol/1.5m
Irradiated area	3.02 m^2 /1m 8.13 m^2/1.5m
LED Lifespan	50, 000 hours
NetWeight	1.2 kg/pcs

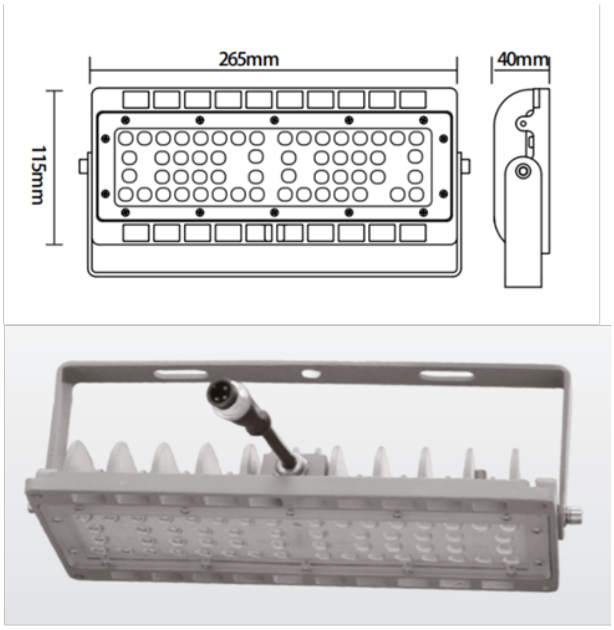

Figure 27 - Technical parameters of the Sulis LED boards used at the University of Reading strawberry growing facility. Schematic and photographic images are shown on the right.

The assumption was made that the ideal amount of light was being received by the plants in the existing setup, this is because in order to do a comparison of the initial system to systems with energy saving measures, the amount of photosynthetically active radiation received by the plants should be kept constant so that energy consumption remains the only key variable, without possibly affecting the amount of valuable light the plants would receive.

It is for this reason that the total amount of light required throughout the system was calculated using the parameters from the setup at the University of Reading with the technical data from the LED modules:

Installed Power:

$$P=[(1\ W \times 56)\times 6)\times 3 \times 5] \times 4$$

$$\mathbf{P=20.16\ kW}$$

Which is consisting of 20,160 x 1 W bulbs in total.

To get from the power input to the useful light output, technical information was gathered about the modules from the resources online, which state that for a 6 x 56 W unit at 0.5 m from the plants, the associated light output is 670 μmol, from which it follows that a single 1W bulb has a light output of 670/(6x56) = 1.99 μmol/s. Therefore, the whole system has a light output value of 20,160 x 1.99 μmol/s = 40118.4 μmol/s. The values based around the photosynthetic photon flux PPF (μmol/s) quantity are most valuable for LED lighting in plant growth as plant growth is related to the number of photons (in the photosynthetically active

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spectral region) interacting with the plant, with one molecule of CO_2 requiring 8-10 photons to bind for photosynthesis.

There is limited technical information about the Sulis series rectangular modules, particularly regarding efficacy at lower current, which is one of the aspects this project aims to investigate. Also, the Sulis system uses white light and therefore gives little room for varying recipe. For Osram LEDs however, the available information on the data sheets and in their online resources is more extensive particularly regarding operation at different current and their selection of products is larger and therefore more suitable for investigation.

Savings from Choice of Efficient LED Devices

Two sets of Osram LED were chosen for this study based on their recommendation in Osram's recent literature for CEA application: high power components (2.0 W) as displayed in Figure 28 and high-power components (1.0 W) as displayed in Figure 29:

High Power Components (2.0 W)

OSLON® Square 3.0 mm x 3.00 mm								
GH CSSRM4.24 Hyper Red 660 nm			GD CSSRM2.14 Deep Blue 450 nm			GW CSSRM3.PM White 4000 K, CRI 70		
mW	µmol/s	µmol/J	mW	µmol/s	µmol/J	lm	µmol/s	µmol/J
1025	5.6	4	1512	5.67	2.79	338	4.54	2.32

Figure 28 - High power components (2.0 W) Osram LED light, with Hyper Red, Deep Blue and White shown respectively [61].

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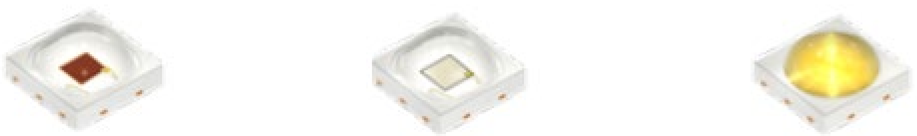
High Power Components (1.0 W)



OSCONIQ® P 3030 3.0 mm x 3.00 mm								
GH QSSPA1.24 Hyper Red 660 nm			GD QSSPA1.14 Deep Blue 450 nm			GW QSSPA1.PM White 5000 K, CRI 70		
mW	µmol/s	µmol/J	mW	µmol/s	µmol/J	lm	µmol/s	µmol/J
440	2.39	3,25	716	2.7	2.71	157	2.13	2.14

Figure 29 - High power components (1.0 W) Osram LED light, with Hyper Red, Deep Blue and White shown respectively [61].

First, a direct comparison of performance for Osram LEDs vs. those in the Sulis modules. The required light power output has been set as 40118.4 µmol/s, calculated in the previous section to be the light output in the system at the University of Reading working as it is. The number of Osram LEDs needed to match this requirement in the same experimental setup can then be calculated. This is also dependent on the choice of light recipes; thus 3 basic light recipes were chosen, and 1 recipe chosen based on findings in the literature for the most successful light recipe for the growth of strawberries [62]:

1. 100% White.
2. 75% Hyper Red and 25% Deep Blue.
3. 50% White, 37.5% Hyper Red and 12.5% Deep Blue.
4. 40% Hyper Red, 30% Deep Blue and 30% White.

Firstly, for the higher power components (2.0 W) displayed in Figure 28:

1. For 100% White LEDs requiring a light output of 40118.4 µmol/s, the number of LEDs required can be calculated from the µmol/s value in Figure 28 to be: 40118.4/4.54=8837 LEDs (rounded up to the nearest integer). The data sheet of this LED specifies that each bulb is at 1.96 W, therefore the total installed power for this system is: **P=17.32 kW**.
2. For 75% Hyper Red and 25% Deep Blue LEDs requiring a total light output of 40118.4 µmol/s, the number of LEDs required can be calculated from the µmol/s value in Figure 28 to be 40118.4/((0.75×5.65) + (0.25×5.22)) = 7239 LEDs (rounded

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up to the nearest integer) (5429 Red and 1810 Blue). The data sheet of these LEDs specify that the power of the Red and Blue bulbs are 1.4 W and 2.03 W respectively, therefore the total installed power for this system is: **P=11.27 kW**.

3. For 50% White, 37.5% Hyper Red and 12.5% Deep Blue, the number of LEDs and power input can be calculated from the previous 2 recipes to be: 4418 White, 2715 Red and 905 Blue LED bulbs, with a total installed power required of: **P=14.30 kW**.
4. For 40% Hyper Red, 30% Deep Blue and 30% White LEDs requiring a total light output of 40118.4 µmol/s, the number of LEDs required can be calculated from the µmol/s value in Figure 28 to be 40118.4/((0.4×5.65)+(0.3×5.22)+(0.3×4.54))=7733 LEDs (rounded up) (3093 Hyper Red, 2320 Deep Blue and 2320 White). Again, from the power information on the data sheets, the installed power required can be calculated as: **P=13.59 kW**.

Secondly, for the lower power components (1.0 W) displayed in Figure 29, the same set of calculations leads to the following results:

1. For 100% White LEDs: 18835 LEDs required, and installed power required: **P=17.89 kW**.
2. For 75% Hyper Red and 25% Deep Blue LEDs: 15460 LEDs required (11595 Hyper Red and 3865 Deep Blue) and installed power required: **P=12.22 kW**.
3. For 50% White, 37.5% Hyper Red and 12.5% Deep Blue LEDs: 17148 LEDs required (9418 White, 5798 Hyper Red and 1932 Deep Blue) and installed power required: **P=15.06 kW**.
4. For 40% Hyper Red, 30% Deep Blue and 30% White LEDs: 16289 LEDs required (6515 Hyper Red, 4887 Deep Blue and 4887 White) and installed power required: **P=14.22 kW.**

From these results, three key observations can be made:

A. For very similar light spectra and output, choice of manufacturer and product can make a significant difference in energy use, with installed power for the pure white LED systems showing a potential 14% power saving by choosing Osram 2.0 W high power component lights over the Sulis series modules.

B. The power consumption is very sensitive to light recipe. Despite the system's light requirements being at a fixed output µmol/s, there was still large variation in installed power values. More studies should therefore consider the impact of light recipe on both plant response and power consumption together to better optimise CEA systems.

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C. From the two different Osram bulb groups, the higher power 2.0 W bulbs use less energy and would be a better choice for lowering power consumption while maintaining fixed level of light output.

Running LEDs at Lower Current

Using the same parameters and photosynthetic photon flux requirement as in the previous section, the impact on power consumption is investigated by reducing the operating current of the LEDs. In this section, the Osram 2.0 W bulb group from Figure 28 were chosen as they gave the best results for power consumption previously.

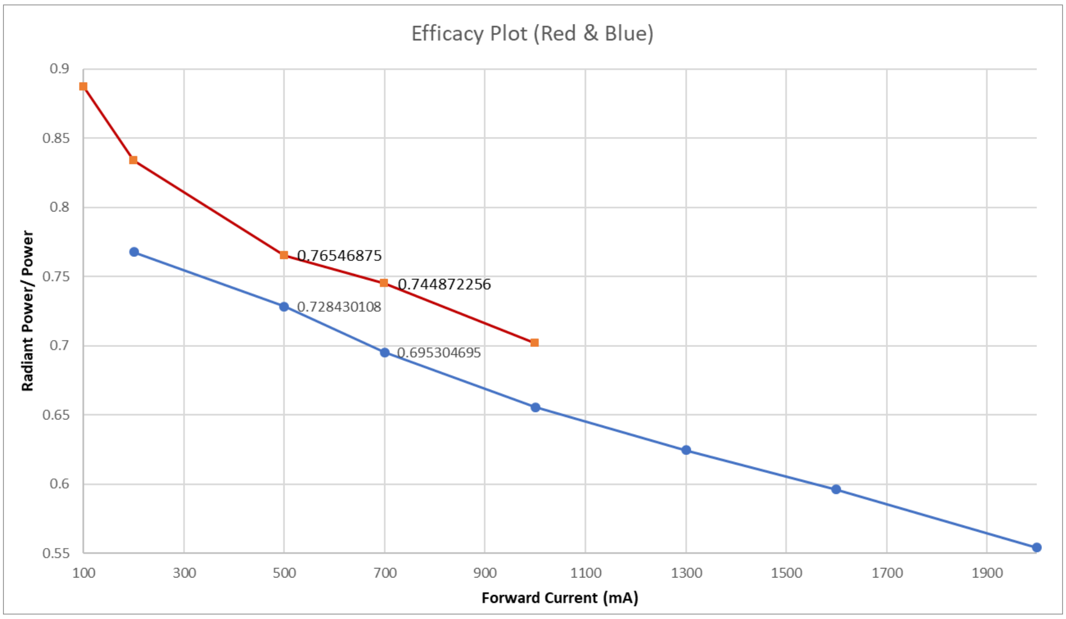

Figure 30 - Efficacy vs forward current for both red and blue Osram 2 W LEDs. Efficacy values highlighted for 500 mA and 700 mA.

It is stated in the data sheets that efficacy is increased by reducing the current in both the Hyper Red and Deep Blue LEDs. For the Hyper Red LEDs, efficiency is increased from 73% to 78% at 700 mA and 350 mA respectively. For the Deep Blue LEDs, efficiency increases from 69% to 72% at 700 mA and 350 mA respectively.

More detailed analysis of the relationship between efficacy and forward current was possible for the chosen Osram red and blue LEDs due to the graphs available on their data sheets, the graph in Figure 30 shows increased efficacy at lower forward currents, for LEDs of both red and blue (the same was also true for a white LED).

This section therefore considers how much energy would be saved if the PPFD requirement is again kept constant, but the current is lowered from 700 mA, this will also therefore mean more LEDs will be required.

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As only the Hyper Red and Deep Blue LEDs have available data on efficiency increase at lower current, only light recipe 2 (75% Hyper Red and 25% Deep Blue) from the previous section is selected for calculation of system running at 350 mA. Results for LED number required and installed power:

- For 75% Hyper Red and 25% Deep Blue LEDs: 13611 LEDs required (10208 Hyper Red and 3403 Deep Blue) and installed power required: **P = 10.60 kW**

The implications of this finding are that comparing to the previous section equivalent scenario, where the Osram 2.0 W system is running at 700 mA, there is an overall possible **power saving of around 6%** with the same light output, with the condition that the system has 1.88 times the number of lights. Alternatively, the case can be calculated for running the LEDs at 500 mA, giving a **power saving of 3.3%** and requiring 1.4 times the number of lights. This should also be expected for other Osram lights (i.e. white) and therefore for all light recipes discussed previously.

Additionally, running LEDs at lower currents would reduce the junction temperature, which not only increases efficiency of light output, but would inevitably increase the lifetime of the LED, further contributing to the energy and significant cost saving of the setup. Quantitative analysis of this is still pending; there is no available data showing how much lifetime is affected by variations in forward current. There is however existing data which shows that the difference in lifetime (L_{70}) between an LED with a forward current of 1 A and 1.5 A is more than double (> 35,000 extra hours), as shown in Figure 31 [63]. It is difficult to extrapolate the expected lifetime increase for the case of a reduction in current from 700 mA to either 500 mA or 350 mA. However, note that if the lifetime is increased by a factor of 1.88 or more for the 350 mA case, or 1.4 or more for the 500 mA case, the cost of installing extra lights initially will be outweighed entirely by the increased lifetime (less often need for replacement of LEDs), this is aside from the additional accumulated energy cost saving over the lifetime of the LEDs. For full quantitative analysis of this, data is needed on the relationship between forward current and LED lifetime.

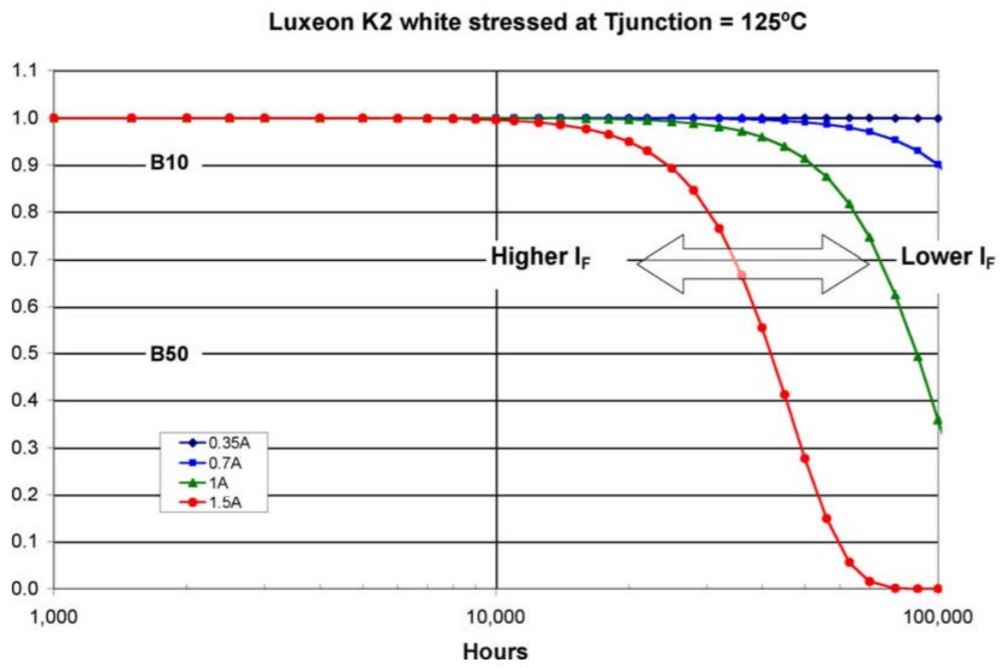

Figure 31 - How forward current effects the lifetime of an LED (whose nominal current is 1 W) [63].

Energy Tariff Considerations

Electricity supply and demand varies during the day, this means firstly that when demand is high, the grid relies more on non-renewable sources to supplement supply than when the demand is lower. Therefore, energy consumed in high demand periods is effectively less environmentally friendly. Secondly, the cost of electricity per kWh increases during peak times and decreases during off-peak times and at night. Overall, this means that considering the hours of the day when determining photoperiod for artificial lighting could lead to a reduction in both carbon emissions and energy cost.

Systems with Solely Artificial Lighting

Firstly, the carbon emission variation throughout the hours of the day is considered. Data on carbon intensity (grams of carbon dioxide emitted per kilowatt hour of electricity produced) for the UK grid is available via http://carbonintensity.org.uk/ , showing the national gCO_2/kWh values on a half hourly basis, with existing downloadable data going as far back as September 2017; it also offers 48 hour UK forecasts. Average half-hourly carbon intensity values were taken throughout 7-day periods in each quadrant of the year: the first week of October 2019,

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December 2019, March 2020 and June 2020 respectively. This is to give an indication of how the carbon intensity varies throughout the day seasonally, as it is expected that although the data varies on a non-repeating daily basis, trends would be visible seasonally.

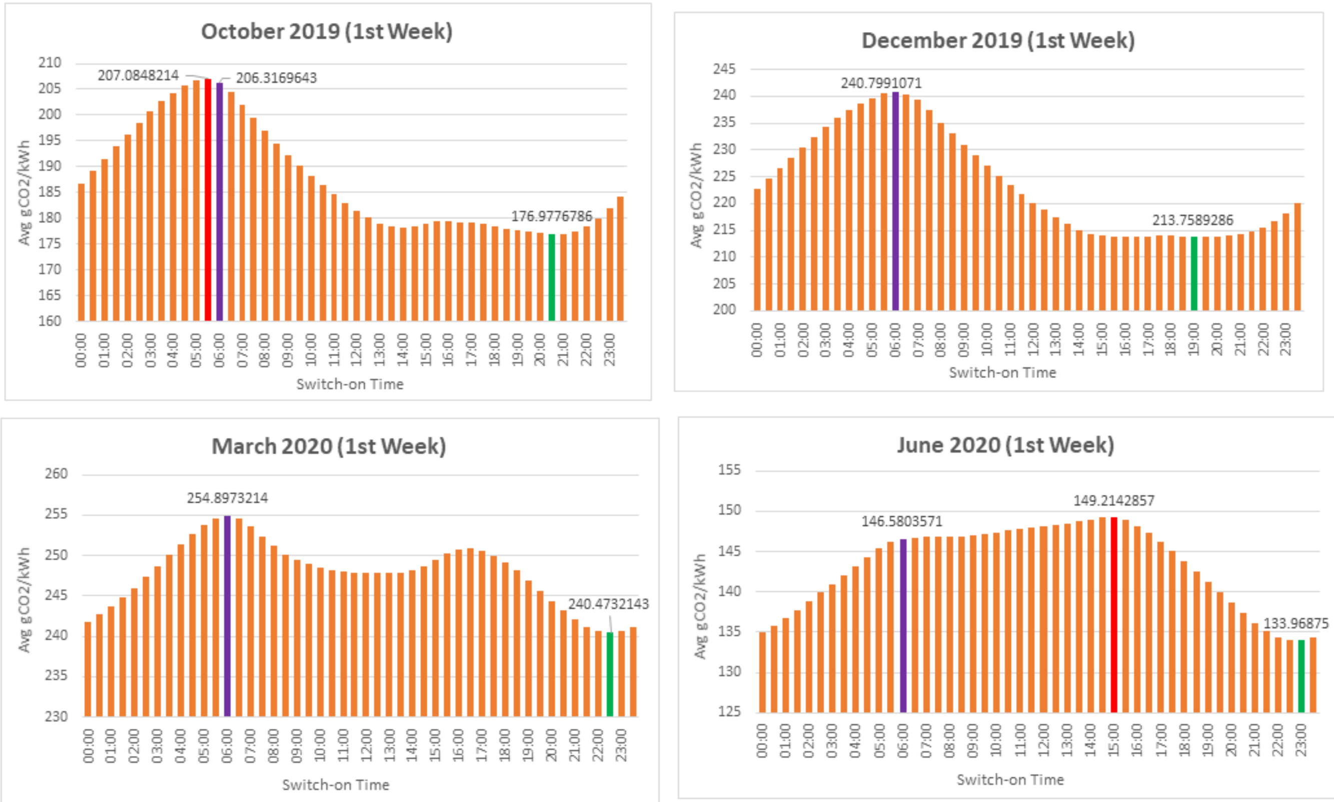

Figure 32 - Average carbon emission intensity throughout a 16 hour period dependent on when the LED cycle begins. Data was taken from http://carbonintensity.org.uk/ . Avg gCO_2/kWh values plotted were calculated from weekly averaged carbon intensity values. Red and green bars show the least and most environmentally friendly times to switch the LEDs on respectively. The purple bar shows the commonly chosen 6am-10pm cycle point.

Once this data was gathered, average carbon intensity values were found for all possible choices of 16-hour photoperiod, as shown in Figure 32. This figure shows that for each season, beginning a 16-hour LED photoperiod at 6am, which is a commonly chosen time, is the least environmentally friendly due to increasing the demand on the grid during higher carbon intensive energy supply periods. Beginning the 16-hour cycle instead in the evening is therefore the less carbon intensive option. %For October, switching an LED system on at 20:30 would reduce overall carbon emissions by 14% compared with a 6:00am switch on time. For December, March and June, the savings are 11%, 5.7% and 8.6% respectively. This implies an average possible saving of around **10% carbon emissions** yearly if choice of switch-on time is based on carbon intensity data. With a system the size of the setup for the University of Reading discussed previously, this would equate to an approximate carbon emission saving of 2.5 t CO_2 per year.

Another way to consider reducing emissions is to choose suppliers which offer green energy: electricity prices were noted for one such energy supplier (Bulb) in the UK offering electricity from 100% renewable sources. As the prices of electricity vary depending on the time of day, consideration must be given to minimise cost. For this supplier, the prices for electricity in the East Midlands area are:

- Off-Peak (8am-5pm & 8pm-12am) - 12.18 p/kWh
- Peak (5pm-8pm) - 25.47 p/kWh
- Night (12am-8am) - 8.2 p/kWh

With these prices, the calculated cost saving from choosing the cheapest (12am - 4pm) in place of the standard (6am - 10pm) 16-hour photoperiod is **28% cost saved**. It can also be seen that this cheapest photoperiod is consistent with the graphs shown in Figure 32 for the carbon intensity on the supply side.

Systems Working in Conjunction with Sunlight

The work in the previous section is only applicable to plant lighting environments which do not work in conjunction with sunlight such as plant factories. In these systems, one has complete freedom over when the artificial lighting is on and off. However, many CEA systems which use artificial lighting to supplement sunlight and so the choice of switch-on time for the 16-hour lighting cycles is limited to those spanning the daylight hours. More careful consideration therefore needs to be given to investigate emission and cost saving for these systems.

Average sunset times for each month of the year were noted and optimum 16-hour photoperiods chosen for each month which minimise price while ensuring the photoperiod spans the duration of the sunlight. Calculations for yearly savings give an approximate **cost saving of 11%**. This is significantly lower saving than for the above case in systems working with solely artificial lighting because in this case the months in the spring and summer with later sunsets coincide with peak hours. However, 11% is still significant cost reduction, especially considering that yield and energy consumption should remain exactly the same.

Dimming Artificial Lights with Sunlight

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Another energy and cost saving strategy involves dimming the artificial lighting when the sunlight is sufficiently strong to significantly contribute to the μmol on the plant surface. In reality, optimal solutions employ dynamic light sensors which adjust the artificial lighting's intensity based on real-time sunlight brightness values, but for the sake of this energy and cost saving study, dimming will be based on average seasonal data for sunlight to gauge an approximate amount of possible energy and cost saving.

To approximate the energy and cost saving, seasonal daily dimming levels were proposed for the UoR system modelled thus far, to gauge the energy and cost saving potential. These dimming values were estimated based on information from the literature. Firstly, Figure 33 shows the difference in PPFD for a sunny clear day and a cloudy day in the Summer in New Zealand [64]. The evidently large difference in the PPFD values dependent on these weather conditions lead to the following choice for dimming calculations: on cloudy days no dimming occurs. Only on clear days is dimming considered. Average data on UK weather gives a clear sunlight to daylight proportion of 0.41, 0.39, 0.31 and 0.25 for Summer, Spring, Autumn and Winter respectively. This means that for calculations, lights were only dimmed on 41%, 39%, 31% and 25% of days in Summer, Spring, Autumn and Winter respectively.

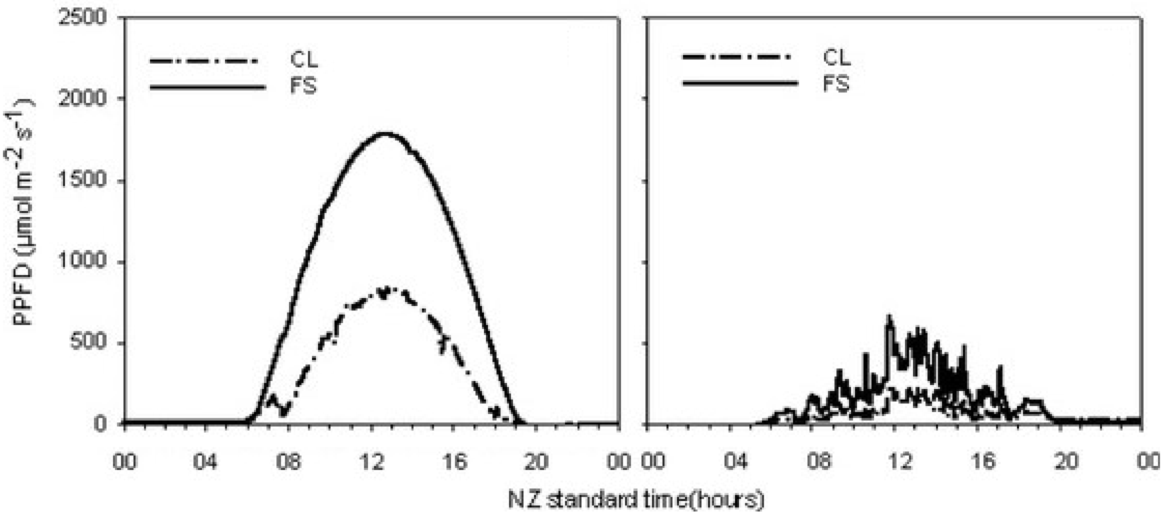

Figure 33 - Comparison of PPFD values throughout the day for a clear Summer day and cloudy Summer day in New Zealand are shown on the left and right respectively [64].

Additionally, sunlight intensity distribution throughout the day for each different season needs to be considered. The average seasonal hourly sunlight intensity is shown below in Figure 35. On a summer day, the peak shows an intensity of around 500 W/m^2, from various sources it is generally accepted that the summer peak sun produces around 2000 μmol/s/m^2 PPFD.

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As W/m^2 is approximately proportional to PPFD, the hourly PPFD on a clear day can be approximated for each season from Figure 35.

The amount by which the top lights are dimmed are based on these estimated PPFD seasonal values from Figure 35. The lights are dimmed such that the total PPFD value remains at least 200 μmol/s/m^2 throughout the 16 hour photo-period, as this is a suitable PPFD value for Strawberry [62], which is the system used in this case study and is also in the same desired PPFD region as for many other plant species.

Piecing together information from Figures 33 and 35, approximate PPFD values can be found throughout clear days in each season. With this information, the amount of dimming can be adjusted to keep the PPFD value received by plants at least 200 μmol/s/m^2.

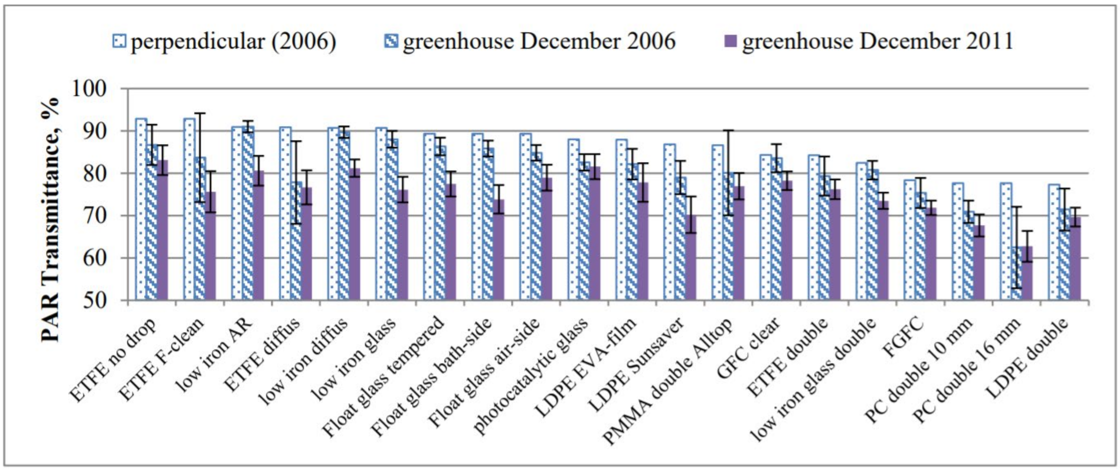

Figure 34 - PAR Transmittance of sunlight through 20 different greenhouse cover materials [65].

Table 10 shows dimming levels and their associated energy and cost saving. Calculations yield a total yearly energy saving of around 8.1%, this is arguably a low estimate too as firstly, dimming was only assumed to be for the top shelf of a three tier system as in the University of Reading, with that assumed, the dimming assumes that only the top shelf sees the sunlight and therefore the bottom two layers aren't dimmed, whereas in reality, particularly with diffuse greenhouse barriers, some fraction of the sunlight getting through would light at least the middle tier of plants as well. Secondly, it is also assumed that cloudy days give no contribution to the μmol/s/m^2 on the plants in the greenhouse. In reality even on cloudy days particularly in summer, the sun would give some μmol/s/m^2 contribution warranting some level of dimming to the LEDs.

Another important consideration is that when the sun is supplying more than 200 μmol/s/m^2, the growth rate would be increased. However, the relationship between electron transport rate (ETR) and PPFD is nonlinear and as PPF increases, the rate at which ETR increases

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lowers, this is shown in Figure 36. However, still this could be a contributing factor to further possible dimming, leading to more energy savings than stated in Table 10.

From a costing perspective, average yearly cost saving was calculated to be **8.8%,** as shown in Table 10. If this is combined with the previously derived **11%,** calculation gives **18% total yearly cost saving for dimming LEDs and working LEDs at cheapest suitable times**. Note, this is a simplified and conservative approximation. If a more in-depth simulation study was done for costing under more careful consideration, a higher cost saving would be expected.

Also, it at first seems suspect that cost calculations gave a 10% higher saving for solely artificial lit systems compared to dimmed systems working in conjunction with sunlight. However, this just highlights the magnitude of cost difference of electricity at night/off-peak hours compared to peak hours, particularly for the tarriff chosen, which sources all electricity from renewable sources.

A more elaborate study of such dimming and associate energy saving exists in the literature [66]. Watson *et al*. ran three simulations with increasing levels of sophistication, based around Athens in Georgia. As they explain:

"The first simulation leverages LED adaptive lighting. The second incorporates a daily decision, where the adaptive lights are turned off for the day when the expected daily solar radiation exceeds the ETR that optimizes growth. As to the third simulation, it leverages "within day" decision making, where the adaptive lights are turned off when the target solar radiation for the day has been achieved."

At the most sophisticated level of dimming strategy, they predict around a 66% energy and cost saving (they assumed a constant electricity cost per kWh) in comparison to their baseline level. However, this is based on data in a sunnier geographical location and also simulates a single tier greenhouse rather than a vertical stacked plant system.

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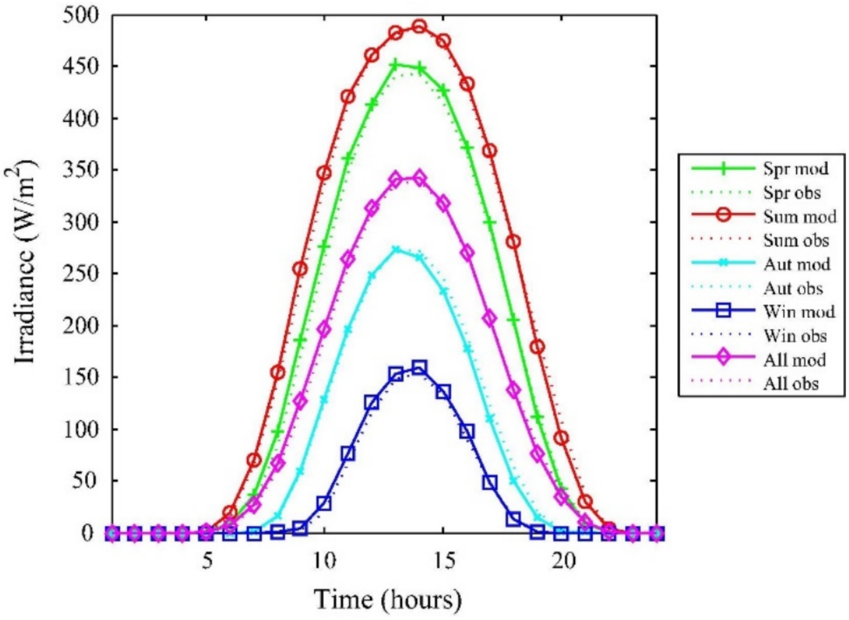

Figure 35 - Hourly sun intensity for spring, summer, autumn, winter and year average (for Leeds in the UK) [67].

Season	% Dimming	Sunlight/Daylight	% Energy Saving	% Cost Saving
Summer	6-7am & 8-10pm (16.7%) 7am-8pm (33.3%)	0.41	12.4	13.5
Spring	7-8am & 7-8pm (16.7%) 8am-7pm (33.3%)	0.39	9.8	10.1
Autumn	8-9am & 6-7pm (16.7%) 9am-6pm (33.3%)	0.31	6.5	7.4
Winter	9-11am & 4-6pm (16.7%) 11am-4pm (33.3%)	0.25	3.6	4.1
Yearly		**0.34**	**8.1**	**8.8**

Table 10 - Approximate total yearly energy and cost savings from dimming artificial lights during daylight hours on clear days. Dimming values are correlated with Figure 35 and dimming percentages represent dimming on clear days.

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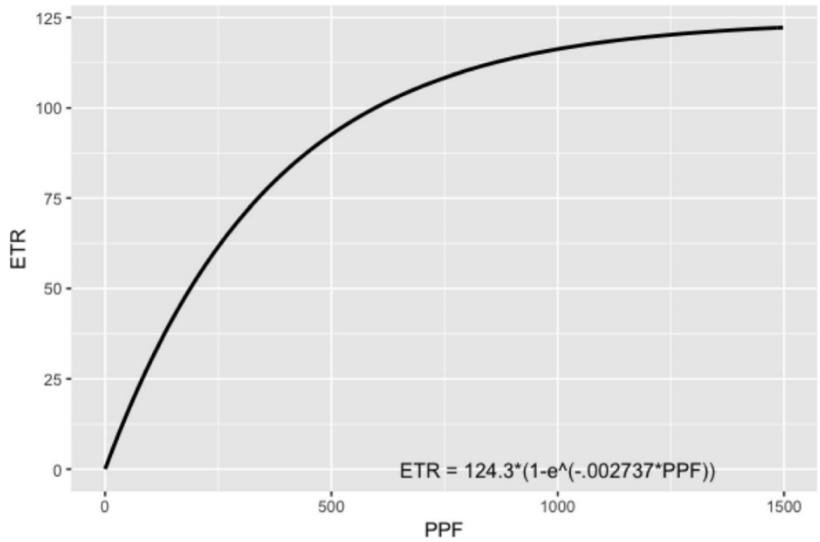

Figure 36 - Electron transport rate vs PPF for Lettuce [66].

Aiding CEA System with Renewables

The HOMER software by NREL is a useful tool for investigating renewable technology integration for a given load and system preferences, with grid option available. Using this software it is possible to calculate the net present cost, cost of electricity and importantly the CO_2 emissions for chosen generation options.

In simulations, some real tariff prices of the UK grid were introduced to the desired system from UoR as modelled in the previous section, with capital costs calculated for lighting and entered as well as the estimated load throughout a year. Three different renewable cases were simulated with a DC fed system for LED lighting load for greenhouse and compared to the pure grid supplied regime:

1. Off-grid system with entirely renewable sources: PV and wind turbine with higher sizing supported by batteries. Higher cost of electricity and capital, but zero CO_2 emissions.
2. Grid connected system with the aid of PV.
3. Grid connected system with the aid of wind turbine.

All power supplied to the lights was in DC form, using a market converter with competitive efficiency (between 90-95%) to convert the AC from grid supply, wind turbines and diesel generator to DC.

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From Figures 39-42, it is clear that the best system is a grid connected system with wind installed. This gives the lowest cost with low emissions. Importantly, comparing Figure 42 to Figure 39, simulations calculate the wind augmented system to be cheaper, both the NPC and COE values. There is also a significant reduction in CO_2 emissions (41% reduction).

Grid system with PV also gives competitive cost, firstly because PV produces DC electricity which is suitable for LED supply. Secondly, as grid prices are higher during the peak hours of the day and with LEDs having to work during peak times during summer (as discussed in the previous section), PV can supply electricity to the LEDs during the more expensive grid hours in the summer as it coincides with the times the PV panels produce significant amounts of electricity, thus saving on cost. PV also gives an even bigger CO_2 emission reduction of 45.5%.

Note, the net present cost (NPC) or life-cycle cost of a project is the present value of all the costs, including capitals costs, replacement costs, operation and management costs, fuel costs, emission penalties and costs of buying power from the grid over the project lifetime. This is given in each simulated case, with a project life-time of 10 years for this case.

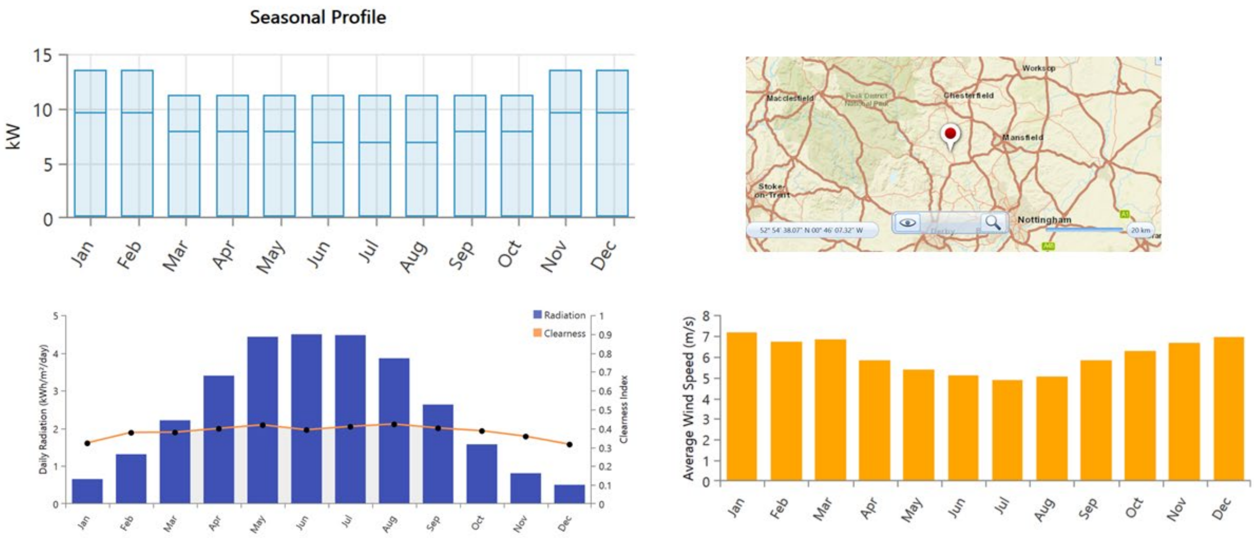

Figure 37 - Monthly load profile, geographical location, yearly solar irradiation and wind data at the specified location respectively.

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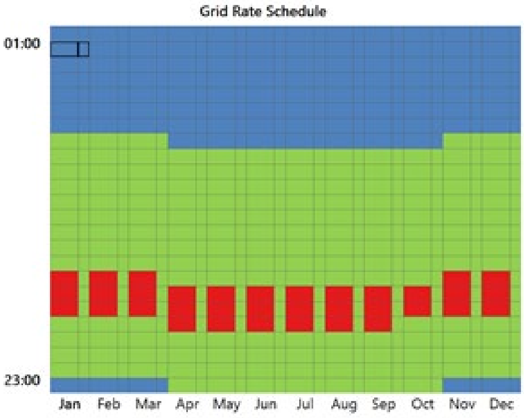
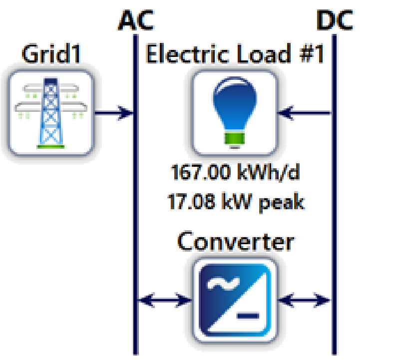
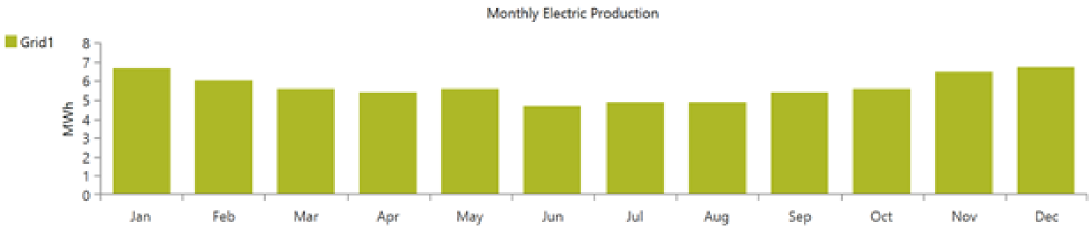


		Price £/kWh	Sellback £/kWh		
Off-Peak		0.1218	0.0000	Edit	
Night		0.0820	0.0000	Edit	
Peak		0.3078	0.0000	Edit	

Figure 38 - Hourly energy tariffs monthly for grid electricity.



Quantity	Value	Units
Carbon Dioxide	20,996	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	171	kg/yr



Scaled Average (167.00 kWh/d)

Total NPC:	£115,720.80
Levelized COE:	£0.1779

Figure 39 - HOMER simulation results for a grid supplied greenhouse system.

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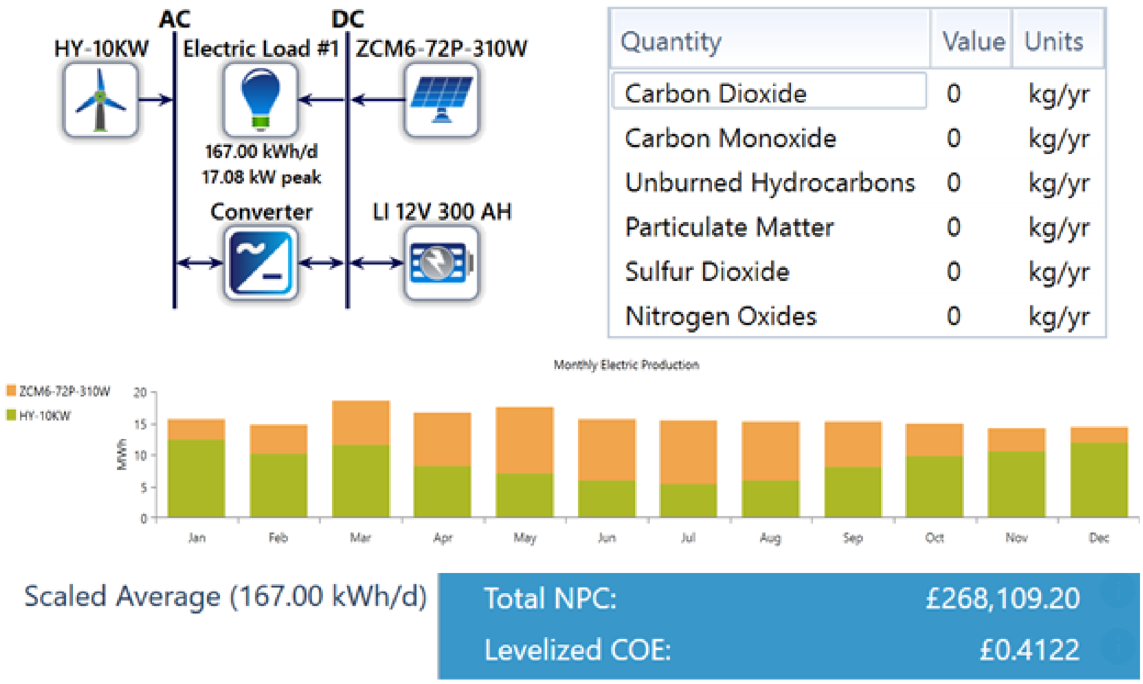
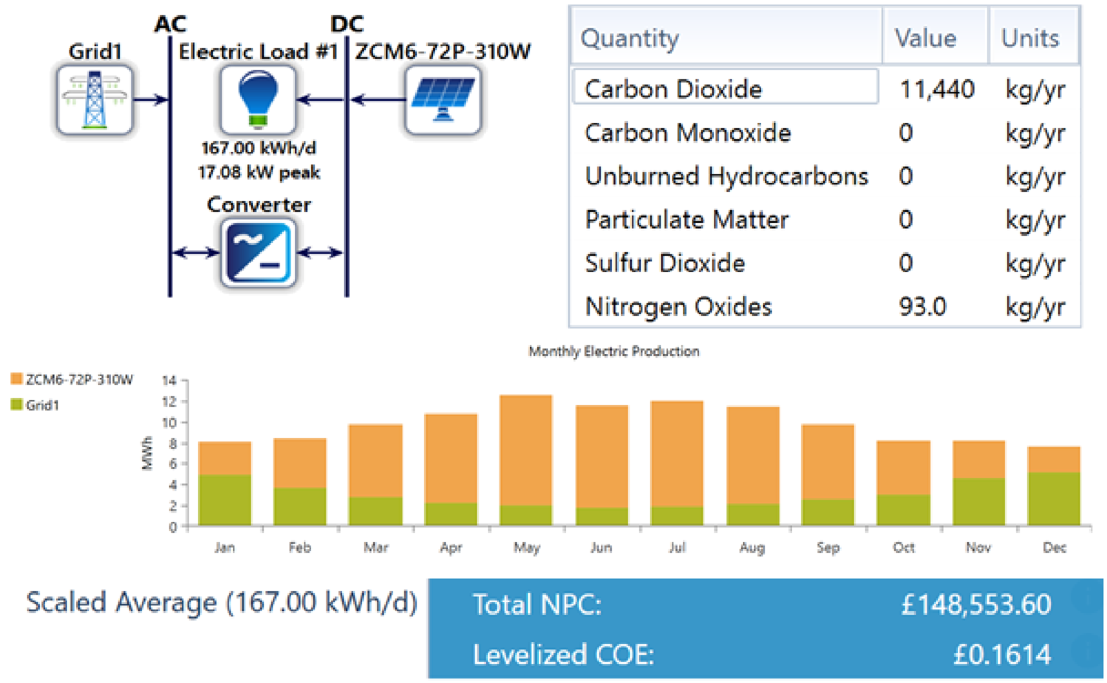


Quantity	Value	Units
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr

Figure 40 - HOMER simulation results for an **off-grid** greenhouse system with PV, wind turbines and batteries.



Quantity	Value	Units
Carbon Dioxide	11,440	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	93.0	kg/yr

Figure 41 - HOMER simulation results for a grid connected greenhouse system with PV installed.

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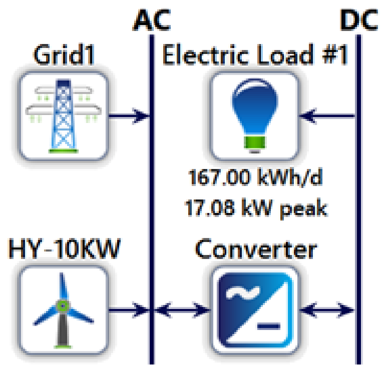
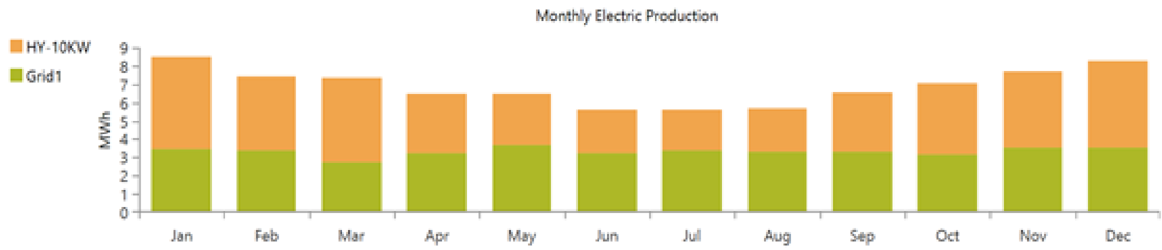


Quantity	Value	Units
Carbon Dioxide	12,401	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	101	kg/yr



Scaled Average (167.00 kWh/d)

Total NPC: £109,691.40

Levelized COE: £0.1351

Figure 42 - HOMER simulation results for a grid connected greenhouse system with wind turbines.

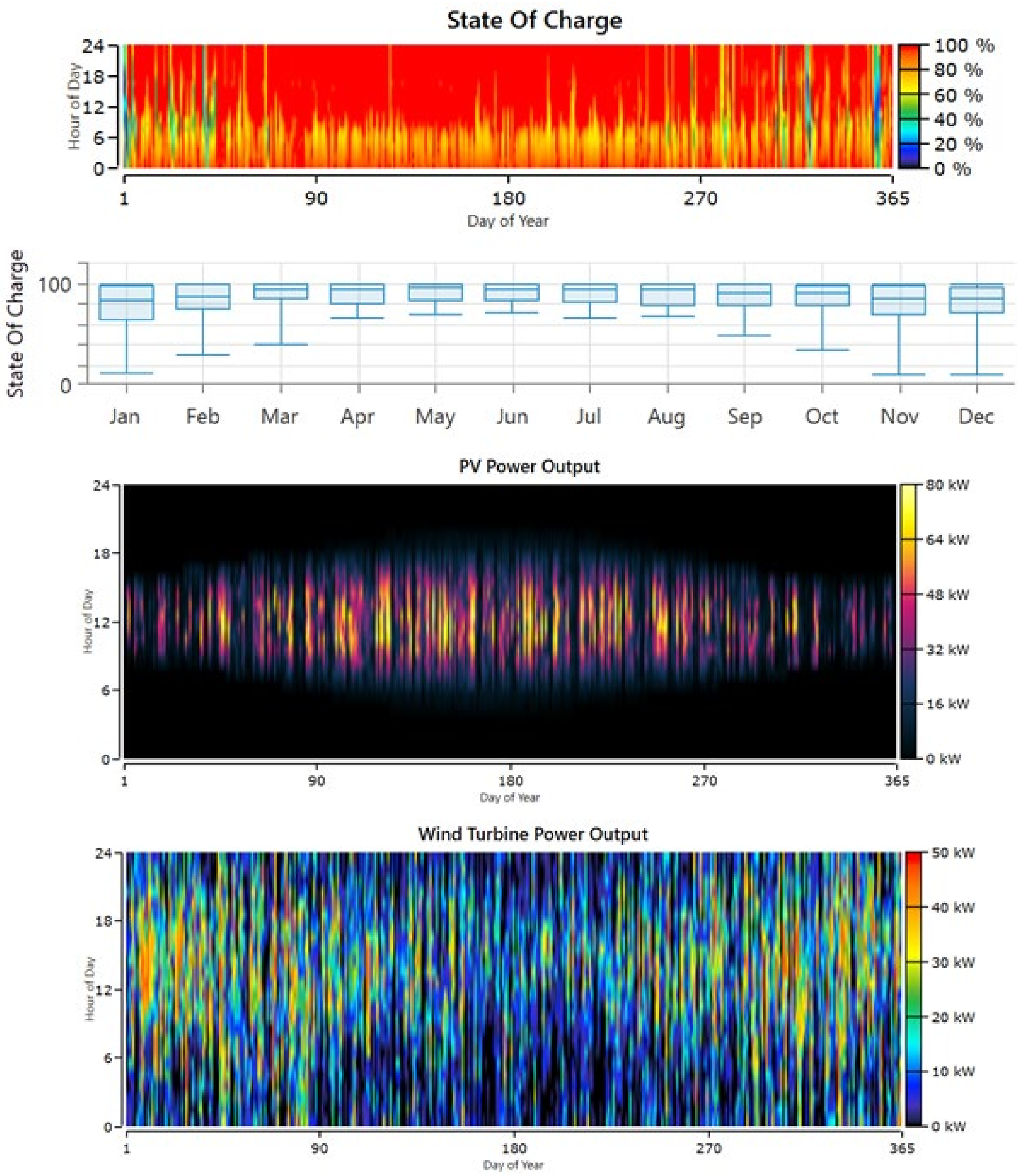


Figure 43 - HOMER simulation of battery state of charge, PV power output and wind power output throughout the year for the fully off grid case.

Case	NPC (£)	LCOE (£)	CO_2 Emissions (kg/yr)
Grid	115,720.80	0.1779	20,996
PV + Wind + Battery	268,109.20	0.4122	0
PV + Grid	148,553.60	0.1614	11,440
Wind + Grid	109,691.40	0.1351	12,401

Table 11 - Comparison of HOMER simulation results for cost and emissions, between the pure grid supplied case and renewable cases.

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Power Distribution to Lighting Setup

In this study a series of simple strategies were investigated individually and combined to show that an approach to energy saving measures employing multiple small improvements in energy efficiency will lead to great levels of energy saving on the whole system level. This section however looks more in depth at a specific energy saving strategy which considers AC grid supply vs DC grid supply.

An increasing amount of DC appliances and a growing number of integrated DC renewable sources has put emphasis on research of DC grids, especially in local scales, where loads are mainly DC. Normally as the grid supplies standard AC 230V, every appliance has to have a double stage conversion within, this consisting of AC-DC and DC-DC for desired rating of the device. This added conversion stage plus power factor correction (PFC) expectedly decreases efficiency and increases the complexity and bulkiness of each module.

DC Grids Review

DC distribution systems have been proposed and implemented successfully in data centres, where electricity savings between 7% and 28% have been estimated for a 380 V DC distribution system compared to an equivalent system operating at 208 V AC [68]. Commercial buildings in the United States, which currently consume 61% of their energy in electricity [69], have seen early adoption use cases for DC distribution systems, primarily in lighting applications, due to the high coincidence of solar generation and commercial end-use loads [70,71].

A number of studies have addressed the potential electricity savings from DC distribution systems in buildings [68,72-80]. For the commercial sector, the reported savings differ widely, from 2% [81] to as much as 19% [82]. Higher savings were reported in systems that were connected to a DC source such as PV and batteries. In general, the reported savings are highly dependent on the converter efficiencies for the AC and DC distribution systems, the DC distributions system topology and voltage levels, and the coincidence of loads with PV generation. US National Renewable Energy Laboratory (NREL) considered various commercial building types, operating schedules, system configurations, and climate zones to project 6%-8% electricity savings by using DC distribution.

Converters contribute the most to overall building network electricity loss, and the DC building network is designed to reduce the number of conversions. In general, the efficiency of converter products increases with power capacity and operating voltage. Each converter has a representative efficiency curve (i.e., efficiency as a function of its output power relative to

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its maximum output power capacity) based on data from converters currently available on the market. Efficiency data can be obtained as visual curves from data sheets. In order for a converter's efficiency curve to simulated, its rated power capacity must be known.

Study Type	Scenario	Electricity Savings
Modelling	Building with Battery Storage	2%–3%
	All-DC building (res. and com.) No battery storage	5% residential 8% commercial
	All-DC Residential Building	5% w/o battery 14% w/ battery
	All-DC Residential Building	5.0% conventional building 7.5% smart bldg. (PV-load match)
Experimental	LED DC system (no battery)	6%–8% (modelled)
	All-DC office building (battery, EV)	4.2%
	All-DC Building (battery, EV)	2.7%–5.5% daily energy savings

Table 12 - Literature review on energy savings from DC distribution over AC distribution. Top to bottom references: [68-71,81,83,84].

In summary, DC power distributions over DC networks have many benefits including:

- Higher power system efficiency due to fewer AC/DC or DC/AC conversion losses.
- DC system components tend to be more compact than equivalent AC components because of higher efficiency and due to not being frequency dependent.
- Lower capital costs due to fewer electronic components used (no inverters).
- Higher survivability (lower power control system complexity) when subjected to external and internal disturbances due to elimination of synchronization requirements associated with AC systems.
- Most distributed energy sources and storage devices have inherently DC outputs, making DC architectures more natural options for their integration.

The efficiency of AC/DC converters increases with the output power and also changes with loading conditions; at low-load conditions the efficiency can be very low, wasting a large amount of energy that goes through the converter as heat. Research shows that the average efficiency of individual AC/DC converters for individual appliances is 68% while that of centralized converters is 90% [85]. A single centralized conversion stage, as opposed to

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many dedicated conversion stages, reduce points of losses and thus improves reliability and overall efficiency [86]. AC/DC power supplies with a power rating under 100–150 W are considered as modular power supplies and the AC/DC power supplies rated above 1000–1500 W are considered as main power supplies. For DC/DC converters, where the first conversion stage in AC/DC converters is removed, the overall efficiency is about 2.5% higher, and thus a modular DC/DC power supply is 88.4% efficient while a main DC/DC power supply is 92.3% efficient [86]. When supply is AC sources, power is first converted to DC, then a DC/DC converter is used to reduce the voltage to the level required by the appliance. All these conversion stages are points of power losses. For a typical residential household, use of DC-technologies in DC-inherent appliances lead to an average saving of 33% in energy consumption.

Include current-controlled loads and loads with multiple internal voltage rails. LEDs are a current-controlled load since their luminosity is nearly proportional to their current. DC LED drivers are often 95-98% efficient, whereas AC LED drivers commonly have 86-93% efficiency [74,80]. In addition, AC LED drivers are more expensive because they must rectify the AC input, apply power factor correction (PFC), and cancel the 120 Hz AC power ripple with a large electrolytic capacitor.

DC Supply for LED Lighting Setup in CEA

Greenhouses and other CEA implementations are increasingly adopting LEDs because of their many advantages over traditional supplementary and sole lighting as discussed in previous sections, so consideration of AC supply vs DC supply for these systems is crucial to increasing LED lighting systems efficiencies and therefore decreasing the negative environmental impacts of CEA on climate, nature and overall energy consumption for perspectives of CO_2 contribution as well as economics of year-round production.

As LED use in agriculture is a relatively new area of research, the main sources of review for comparison of AC and DC scenarios in the previous section are in various other applications. Since LEDs are DC devices, there are more advantages for systems consisting of them to be supplied via DC distribution systems rather than systems with mixed loads (DC and AC appliances), which are still indicated as more beneficial over AC distribution systems. This is especially relevant for cases where there is aiding by locally installed renewable systems (as investigated previously in the report using the HOMER software) which is becoming increasingly integrated with grid in line with governments' targets to decrease net CO_2 emissions. The advantages of a DC grid for large scale CEA lighting systems consisting of

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many DC LED loads, in comparison to an AC fed system aim to be quantitatively investigated in this work.

Normally for LED lighting systems in agriculture, each LED module used has its own AC/DC converter (rectifier) as well as a DC/DC controller for supplying LEDs. Each of the components before the DC/DC LED driver has an associated loss and these combine to give total losses of around 10% more than the DC/DC LED driver case. Additionally, these components take up around 40% or more of the space in each printed circuit board, making the modules less space efficient. A higher number of components also decreases system reliability; generally, for LED modules, the power converter side is more susceptible to fail than LEDs themselves. Therefore, removing the AC/DC converter from each module would increase lifetime of the module as well as decreasing the converter loses.

If the AC grid is to supply a DC grid for lighting purposes, a central rectifier is needed. However, this central rectifier can be more efficient than those on individual LED modules due to its larger size. Its losses are estimated at about ~2% (generally smaller rectifiers have lower efficiency).

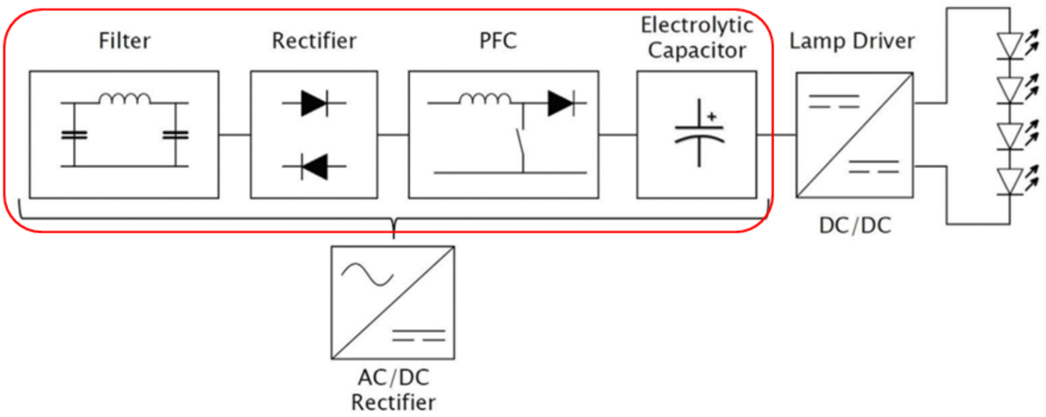

Figure 44 - Schematic diagram of a rectifier converting AC supply to DC [87].

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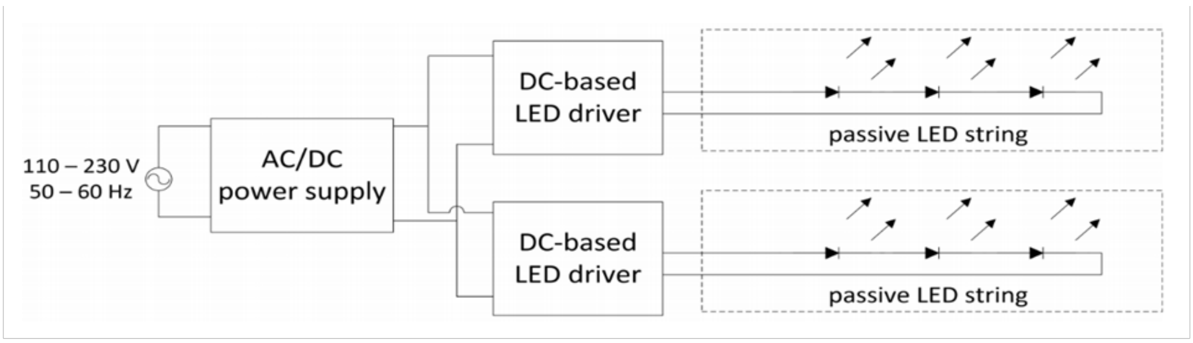
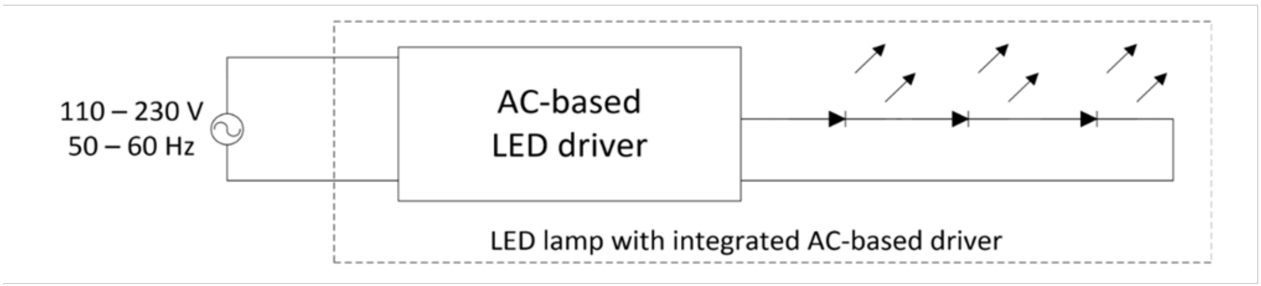
AC-Powered LED Drivers	Current (A)	Power (W)	Efficiency (%)
Osram OT FIT 50/220-240/1A0 CS	1.06	42.7	85.2
Mean Well NPF-40D-42	0.96	37.8	86.6
XP Power DLE45PS48	0.99	39.2	87.1

DC-Powered LED Drivers	Current (A)	Power (W)	Efficiency (%)
XP Power LDU4860S1000	0.90	35.2	95.1
Generic LED driver	1.07	42.8	96.3
Mean Well LDD-1000H	0.97	38.3	96.9

Table 13 - Efficiency comparison of AC vs DC LED drivers [88].



LED lamps with external drivers operating on a DC infrastructure.



LED lamps with integrated driver operating on AC mains.

Figure 45 - Schematic comparison of DC LED driver vs AC LED driver [88].

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Conversion Losses and Cabling Losses Comparison and Possibilities

DC/DC converters convert DC power from one voltage level to another. They are predominantly used in low power and voltage applications and are found in appliances with electronic circuits. High power DC/DC converters are typically more efficient than lower power models. Figure 46 below shows efficiency curves for step down DC/DC converters with power ratings above 1 and below 5 kW.

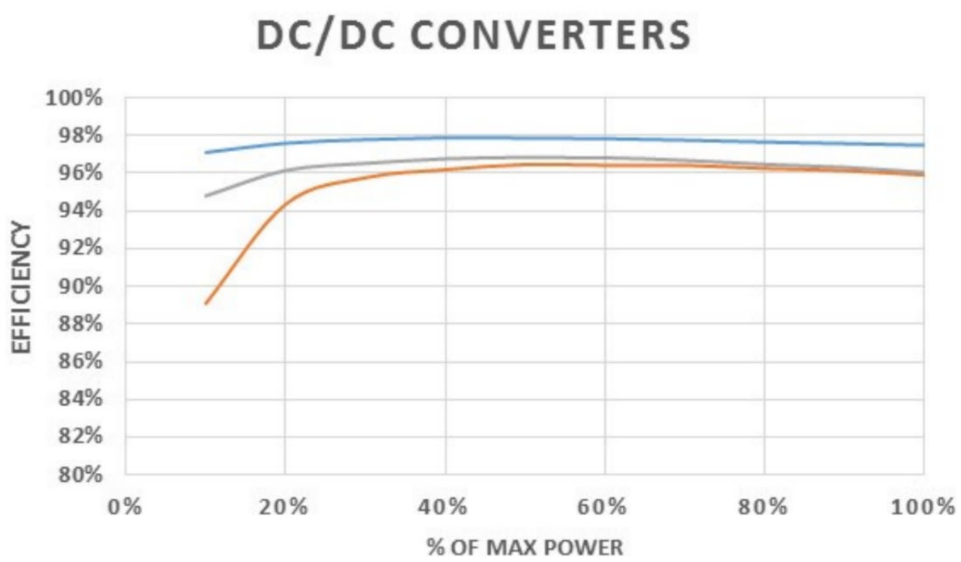

Figure 46 - Efficiency Curves for different DC/DC Converters (V_{in} < 140-400 V_{DC}, V_{out} = 48 V_{DC}, P_{max} : 1-5 kW) [69].

AC LED drivers typically convert AC power to a lower voltage DC. They also regulate voltage and current through the LED circuit. DC LED drivers operate similarly to their AC counterparts, but do not require rectification. Manufacturers of LED drivers include Philips, Delta Electronics, Meanwell, and others. Figure shows efficiency curves for AC LED drivers with power ratings less than 500 W and input voltage at 120V.

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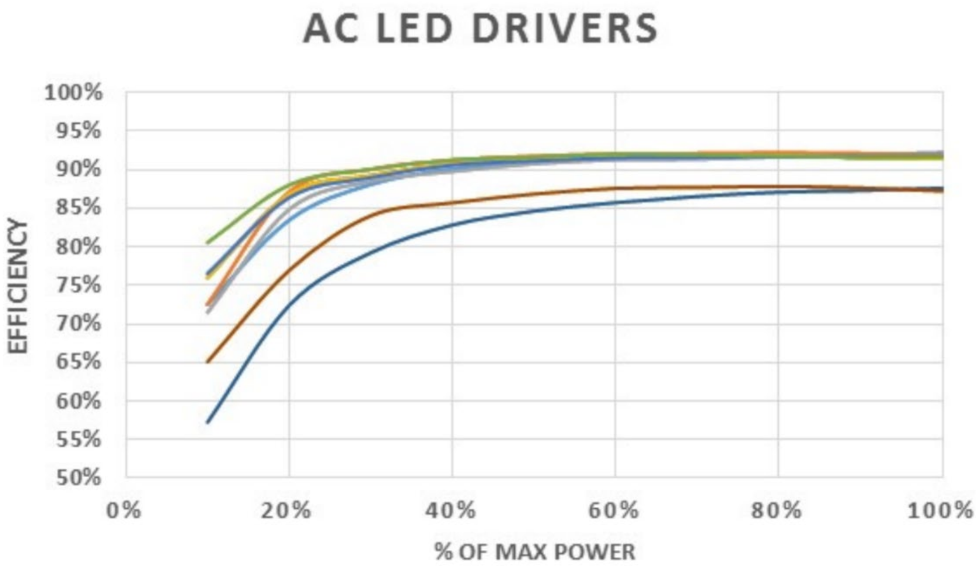

Figure 47 - Efficiency Curves for different AC LED Drivers (V_{in} = 120 V_{AC}, V_{out} = 48 V_{DC}, P_{max} < 500 W) [69].

Rectifiers are used to convert AC power to DC. In the AC distribution system, rectifiers are used in DC internal appliances. In the DC distribution system, one or more higher power rectifiers can be used to convert AC power from the grid to DC when power from the PV system or the battery is not sufficient for the building loads. Manufacturers for rectifiers include Eltek, Delta Electronics, Murata, XPPower, Emerson, and others. Figure 48 shows the efficiency curve for rectifiers rated at 1-12 kW. Also, higher power rectifiers are more efficient than those rated at lower power.

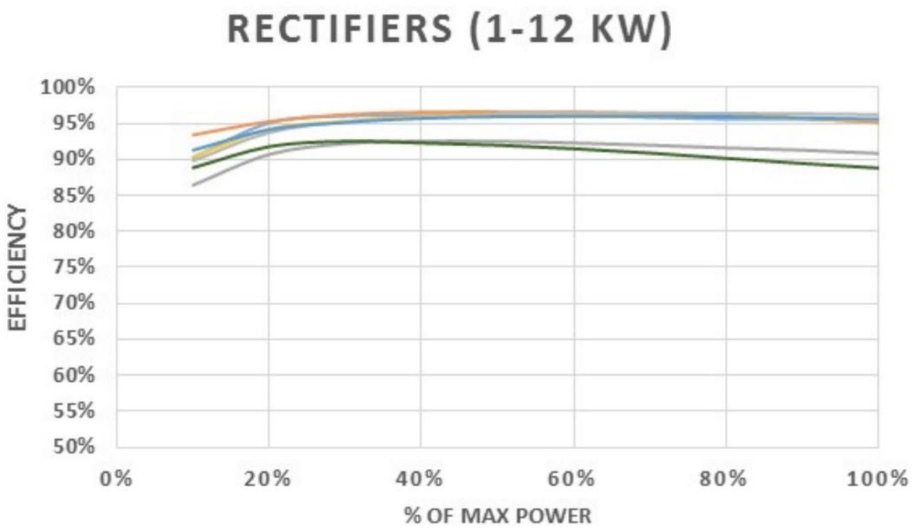

Figure 48 - Efficiency Curves for different Rectifiers (V_{in} = 120/277/480 V_{AC}, V_{out} = 48 V_{DC}, P_{max} : 1-12 kW) [69].

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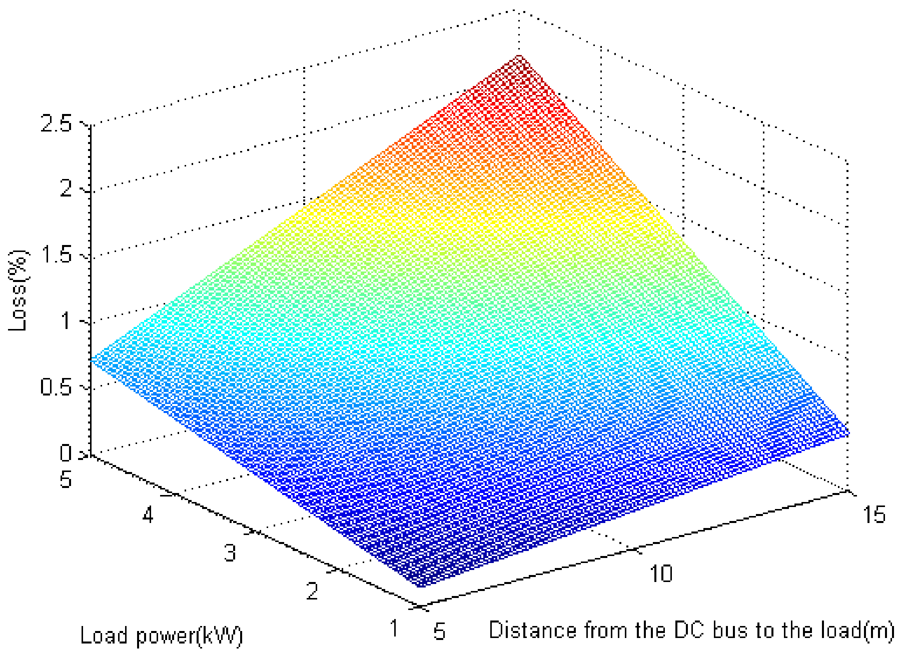

Figure 49 - Line power loss in relation to the load power and L_{dis} (the distance between the DC bus and the load) for 120 V DC and AWG 8 copper wire [89].

Voltage drop and power loss are two important indexes for determining wise voltage levels and wire cross-sections.

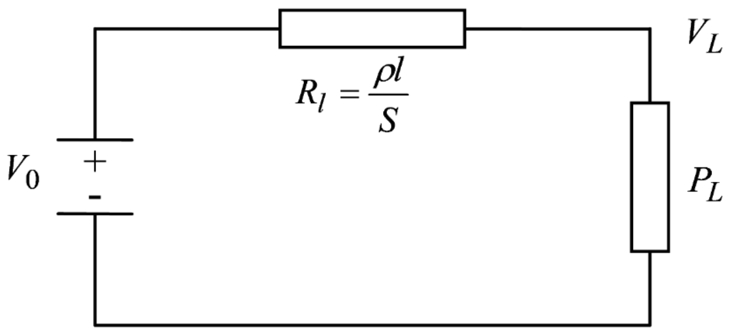

Figure 50 - A simple two bus DC circuit.

For simplicity, a two-bus DC circuit shown in figure is used to derive the formulations for both voltage drop and power loss. R_l denotes the line resistance from the load to the source. V_0 is the source voltage. P_L and V_L are the load power and voltage. Thus, the ratio of the line power loss (P_{loss}) to the load power can be expressed as:

$$\frac{P_{loss}}{P_L} = \frac{2\left({P_L}/{V_L}\right)^2 R_L}{P_L} = \frac{2P_L}{{V_L}^2} R_L$$

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Since the line voltage drop (V_{loss}) is required to be significantly less than V_0, the ratio of V_{loss} to the source voltage can be approximately calculated below:

$$\frac{V_{loss}}{V_0} = \frac{V_0 - V_L}{V_0} \approx \frac{V_0 - V_L}{V_L} = \frac{2P_L}{{V_L}^2} R_L$$

Thus, we can derive:

$$\frac{V_{loss}}{V_0} \approx \frac{P_{loss}}{P_0} = \frac{2P_L}{{V_L}^2} \frac{\rho l}{S}$$

where ρ, l and S are resistivity, line length, and cross-section, respectively.

The line voltage drop ratio is approximately equivalent to the line power loss ratio, and it is proportional to PL and l, and inversely proportional to   and S. In addition to the voltage drop and power loss, the wire thermal limit is another important index to be taken into consideration for the design of an indoor micro-grid.

Design of Buck Converter and Rectifier

To accurately calculate efficiency and power losses for a system converting AC grid electricity to DC, the components are modelled first in MATLAB Simulink.

Considering the system of interest at UoR, we need to simulate a string of 17 2W LEDs lower than max suggested current (700 mA) at 500 mA. The voltage per LED is 2.8 V and their total internal resistance is 100 Ω. Line requirements of 50 V at 0.5 A are simulated with and without a rectifier.

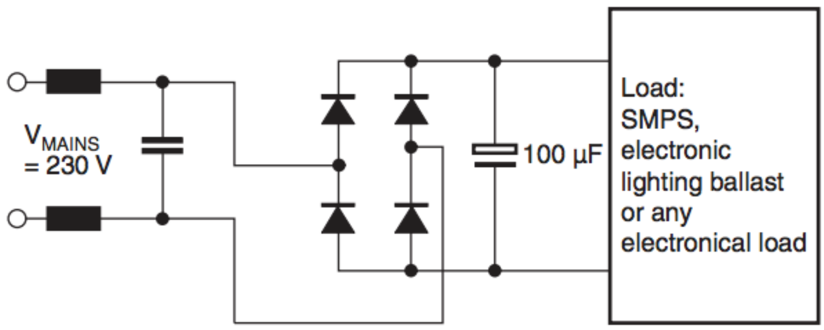

Figure 51 - Schematic circuit of a rectifier.

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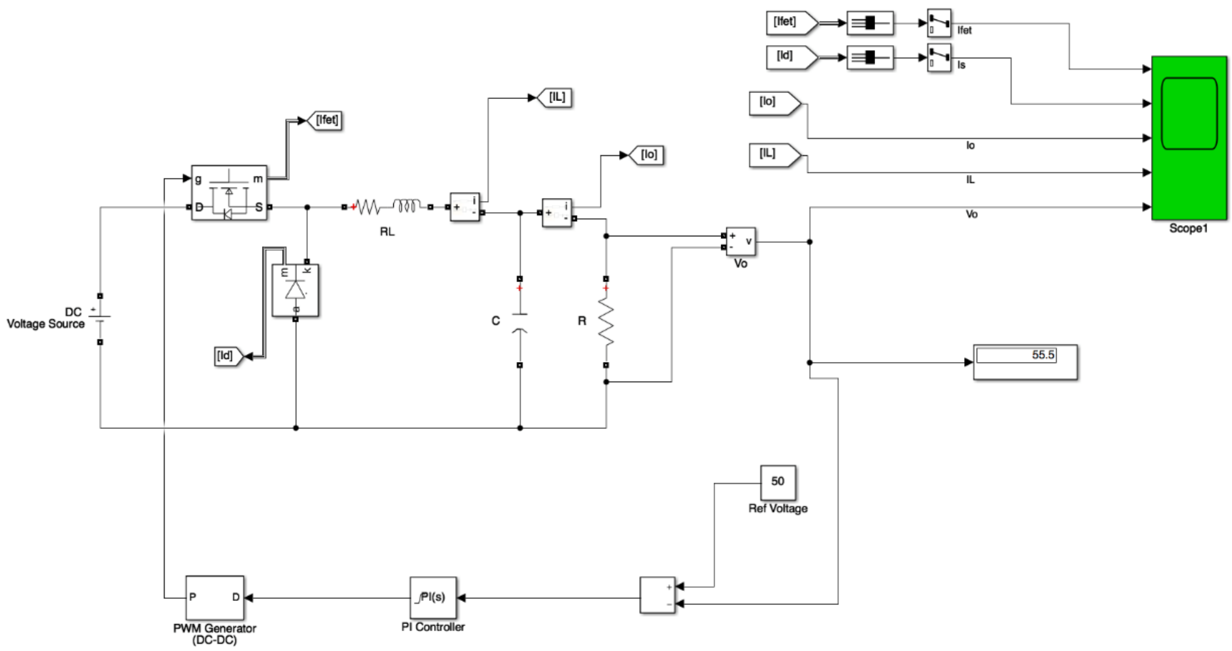

Figure 52 - Circuit diagram for a buck DC-DC converter on MATLAB Simulink.

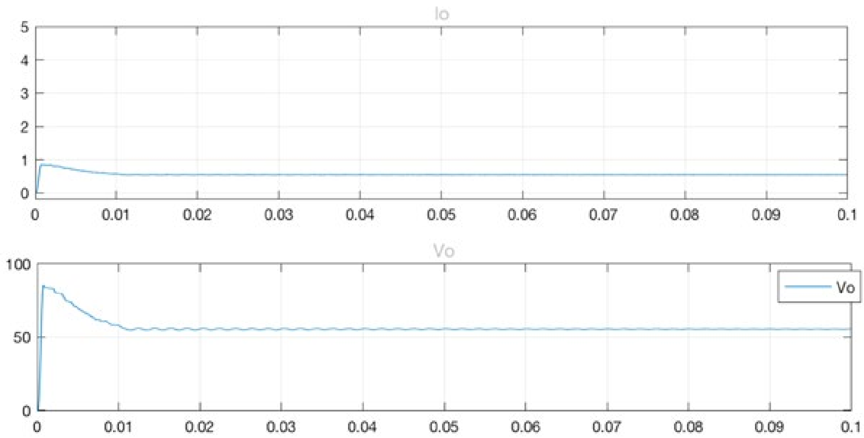

Figure 53 - Current vs time and Voltage vs time graph for the buck DC-DC converter.

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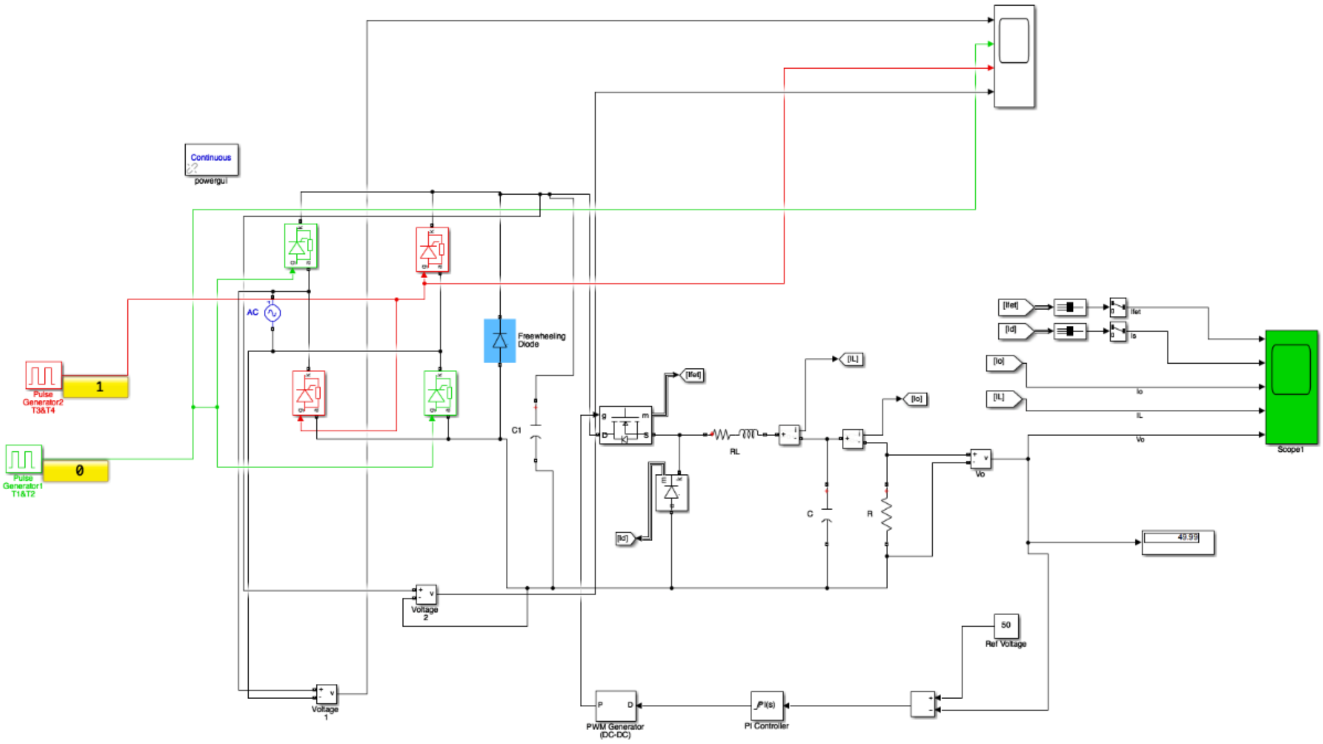

Figure 54 - Circuit diagram for a single phase rectifier and buck converter on MATLAB Simulink.

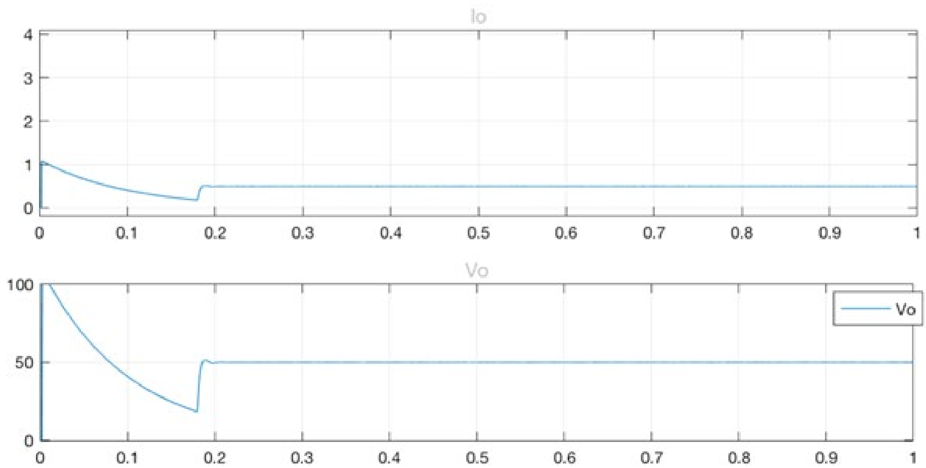

Figure 55 - Current vs time and Voltage vs time graph for the single-phase rectifier and buck converter.

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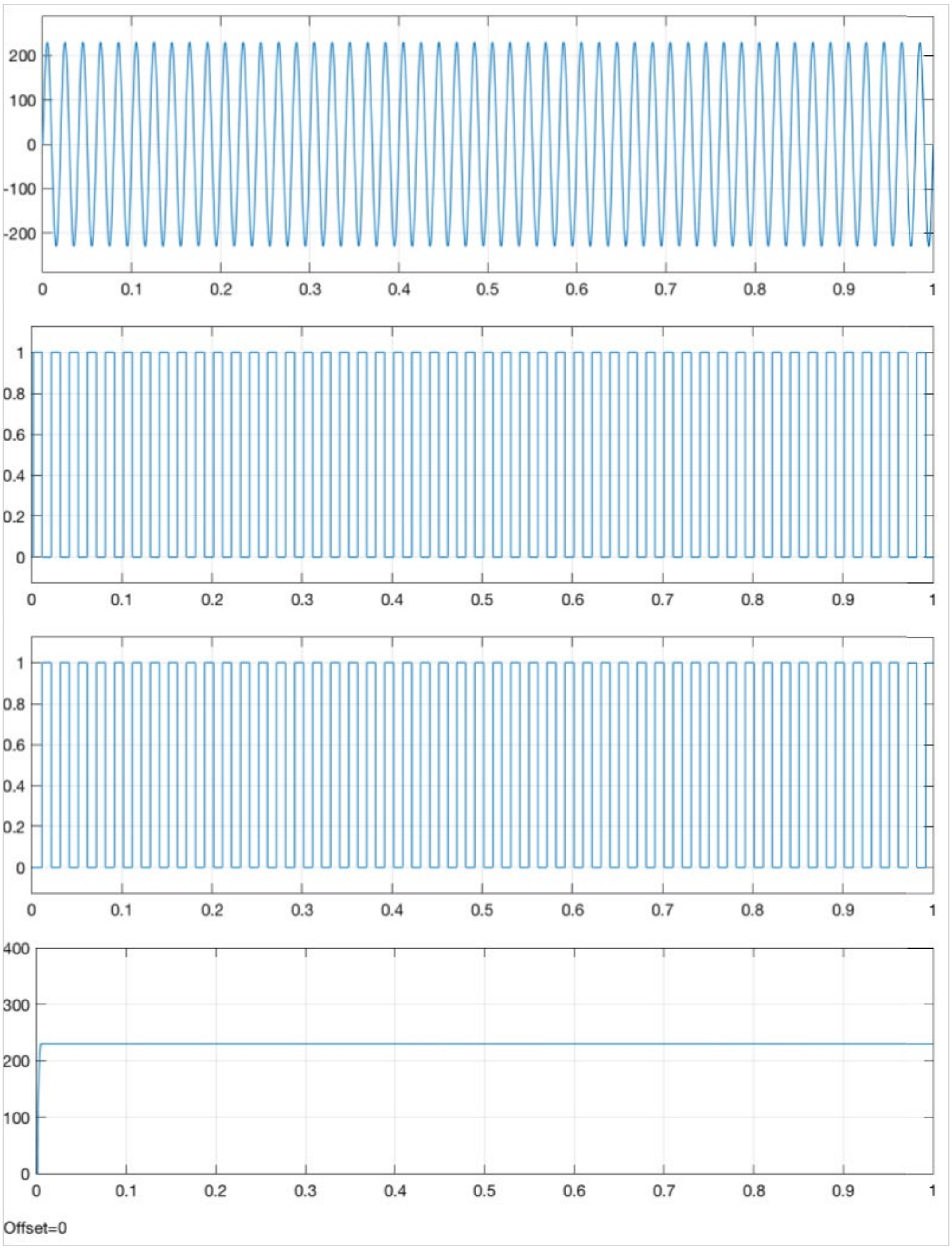

Figure 56 - Rectifier inputs, control signals, output.

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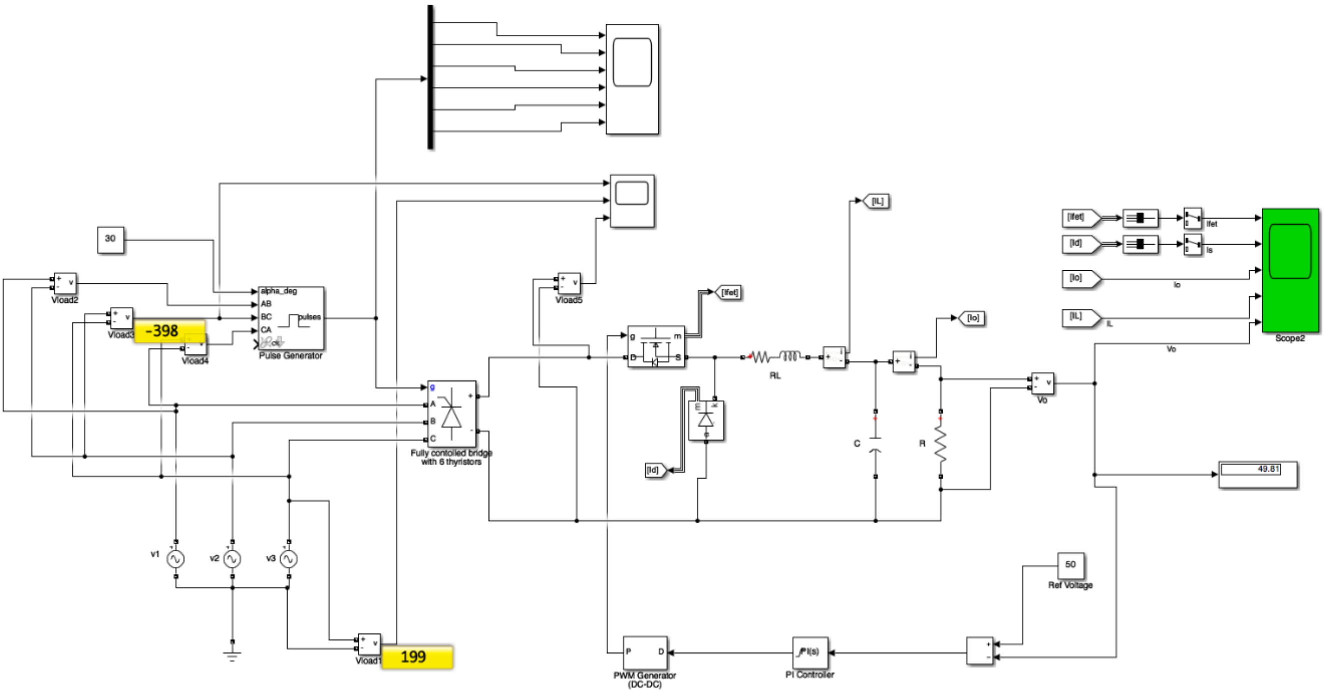

Figure 57 - Circuit diagram for a three-phase controlled full wave bridge rectifier with buck converter on MATLAB Simulink, for supplying proposed setting above.

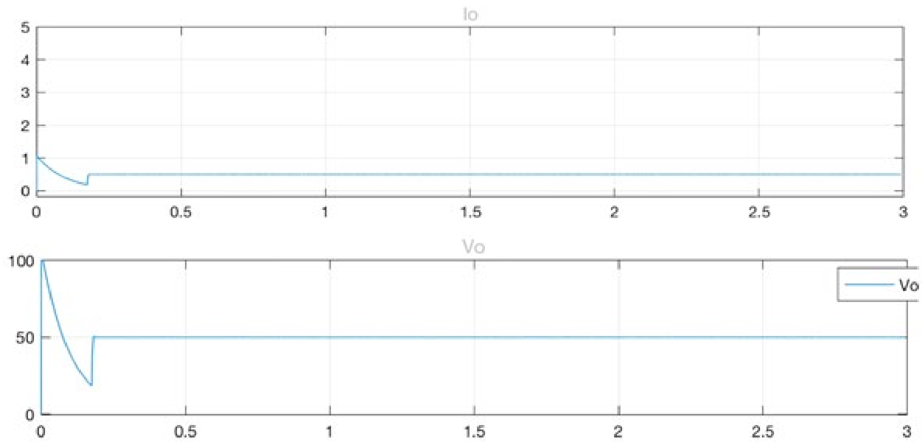

Figure 58 - Current vs time and Voltage vs time graph for the three-phase rectifier and buck converter.

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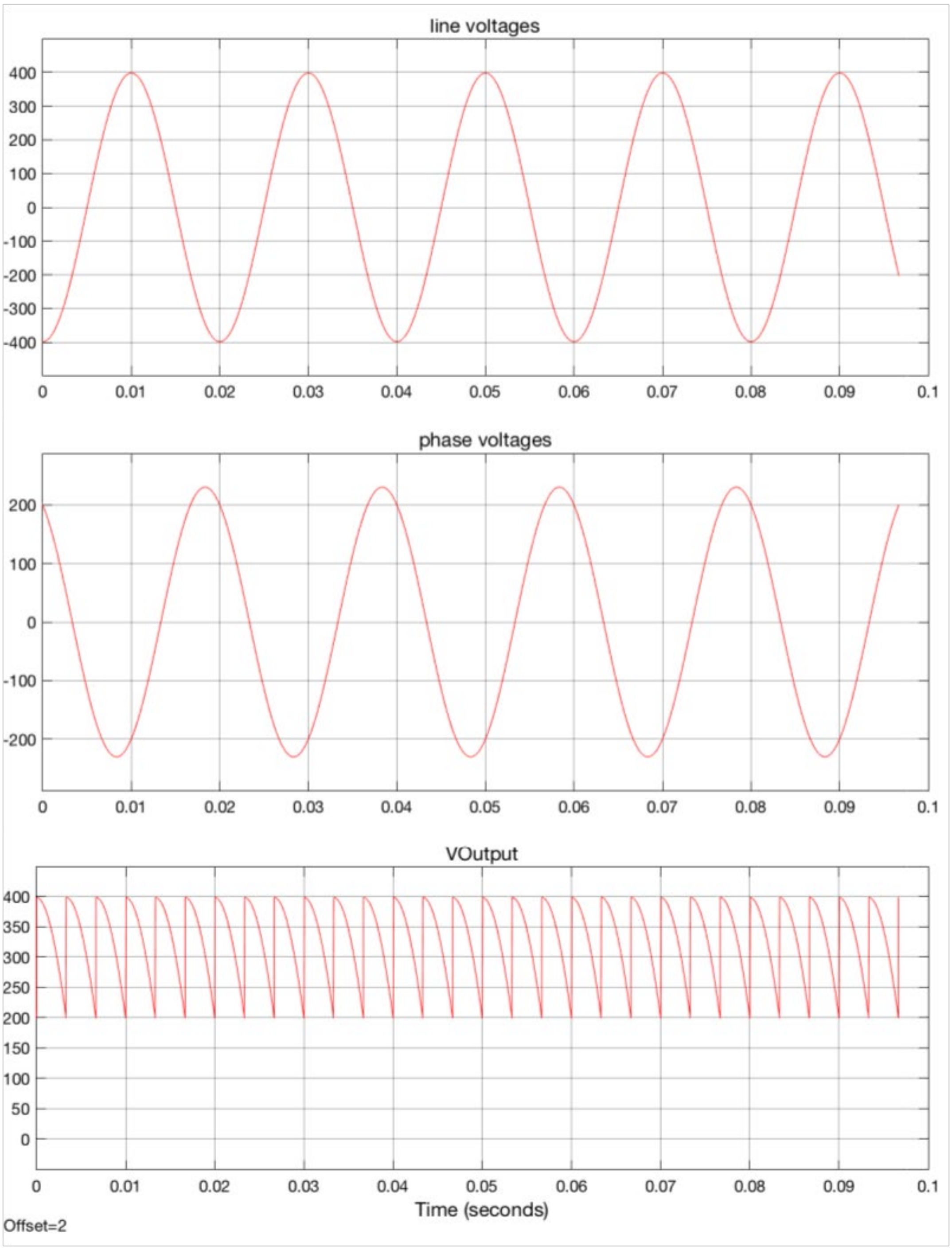

Figure 59 - Line to line, phase and output voltage of the three phase rectifier.

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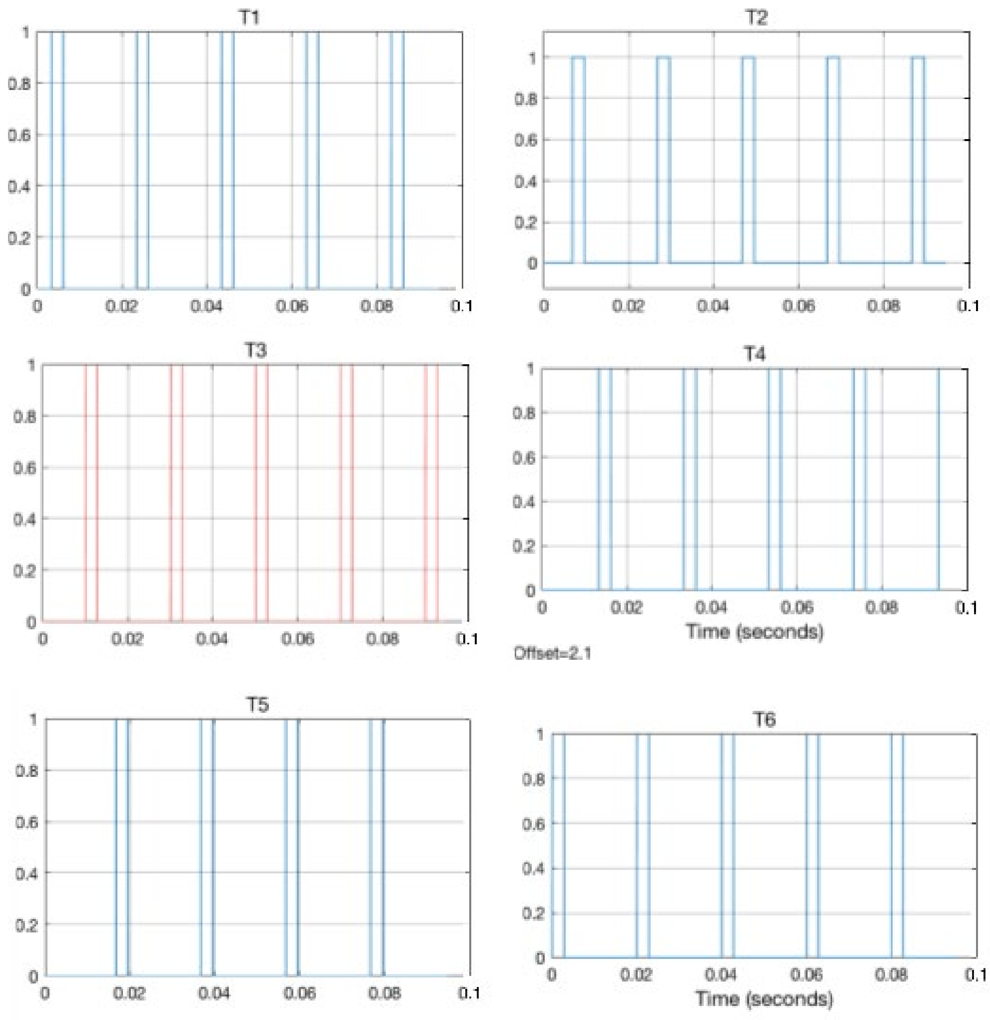

Figure 60 - Thyristor gate pulses for the three-phase rectifier with buck converter.

Calculation of Power Losses

The three main causes of power dissipation in a DC/DC converter are:

- Inductor conduction losses
- MOSFET conduction losses
- MOSFET switching losses

Firstly, the inductor conduction loss is given by:

$$P_L = I_{RMS-L}^2 \times R_{DCR}$$

Where R_{DCR} is the DC-Resistance of the inductor. The rms inductor current is given by:

$$I_{RMS-L}^2 = I_0^2 + \frac{\Delta I^2}{12}$$

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where ΔI = ripple current. Typically, ΔI is about 30% of the output current. Therefore, the inductor current can be calculated to be:

$$I_{RMS-L} = 1.00375 \times I_0$$

Because the ripple current contributes only 0.375% of I_{RMS-L} , it can be neglected. The power dissipated in the inductor now can be calculated as:

$$P_L = I_0^2 \times R_{DCR}$$

Next, for the MOSFET losses, the power dissipated in the **high-side** MOSFET is given by:

$$P_{Q1} = I_{RMS-Q1}^2 \times R_{DSON1}$$

Where R_{DSON1} is the on-time drain-to-source resistance of the high-side MOSFET. Substituting for I_{RMS-Q1}:

$$P_{Q1} = \frac{V_0}{V_{IN}} \times \left(I_0^2 + \frac{\Delta I^2}{12}\right) x\, R_{DSON1}$$

The power dissipated in the **low-side** MOSFET is given by:

$$P_{Q2} = I_{RMS-Q2}^2\, x\, R_{DSON2}$$

Where R_{DSON2} is the on time drain-to-source resistance of the low-side MOSFET. Substituting for I_{RMS-Q2}

$$P_{Q2} = \left(1 - \frac{V_0}{V_{IN}}\right) \times \left(I_0^2 + \frac{\Delta I^2}{12}\right) \times R_{SON2}$$

The total power dissipated in both MOSFET's is given by:

$$P_{FET} = P_{Q1} + P_{Q2}$$

Substituting for P_{Q1} and P_{Q2}:

$$P_{FET} = \left(I_0^2 + \frac{\Delta I^2}{12}\right) \left[\frac{V_0}{V_{IN}} \times (R_{SON1} - R_{SON2}) + R_{SON2}\right]$$

where $\Delta I = \frac{(V_{IN} - V_0) \times V_0}{L \times f \times V_{IN}}$ and where L = Inductance (H), f = Frequency (Hz), V_{in} = Input voltage (V), V_0 = Output voltage (V).

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For typical buck power supply designs, the inductor's ripple current, ΔI, is less than 30% of the total output

current, so the contribution of $\frac{\Delta I^2}{12}$ is negligible and can be dropped to get:

$$P_{FET} = I_0^2 \; x \left[\frac{V_0}{V_{IN}} \times (R_{SON1} - R_{SON2}) + R_{SON2}\right]$$

Note that when $R_{SON1} = R_{SON2}$, the power dissipated in the MOSFETs is independent of the output voltage. From Equation 19, the MOSFET conduction losses at any output voltage can be calculated. The other losses such as switching losses and inductor conduction losses are independent of output voltage and remain constant with changes in output voltage. Hence, P_D now can be computed as:

$$P_D = P_L + P_{FET} + Other\ Losses$$

The other losses include the MOSFET switching losses, quiescent current losses etc. If both the total power supply losses and power supply output power are known, the overall efficiency at any output voltage can be calculated with:

$$\eta = \frac{P_0}{P_0 + P_D}$$

Conclusions

Firstly, neural network analysis on LED lighting for lettuce was investigated. A series of data sets from various literature on lettuce growth using LEDs was collected and together with experimental data collected within the current study was normalised such that the data was maximally compatible. A deep neural network was then fit to the data using MATLAB to test performance. Fitting results show that there is a general tendency for the neural network to fit to the target data, with an R value of around 0.8 for all data sets and an error histogram which is significantly better than one which would represent random prediction data. There is however significant variation in the error, with some large errors in neural network predicted vs target data. This was thought to be due to the incoherence between the different studies in the literature. Not only were many of the studies looking at different varieties of lettuce, but they also had different experimental conditions and approaches beyond the lighting input data. As Ozawa *et al.* stated in their work comparing two studies with very similar conditions two years apart, there was significant different in output data even in identical lighting conditions for the same crop [60]. Overall, it seems that though neural networks could prove

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to be very useful for this application, the difficulty comes when collating data from different studies. If enough data on growth of a species under several LED light recipes was available from a single source with identical experimental conditions and procedure, fitting of data using neural networks could potentially give considerably better results.

Secondly, a model was built based on the 3 vertical tier LED lit strawberry growing facility at the University of Reading. A series of the following CEA power saving considerations were investigated in a simplified conservative approach to be combined and quantitatively analysed for energy saving potential:

1. Careful choice of the most efficient LED devices available for setup. For the UoR system used as a case study the newest Osram lights were compared to the currently used Sulis LED boards:

   Calculated Energy Saving: **14%**

2. Energy saving from appropriate choice of the spectral recipes based on the literature. A comparison of purely white Osram LED boards vs an optimal [62] red/blue/white mixture with the same PPFD output value gives:

   Calculated Energy Saving: **21%**

3. Calculations based on dimming LED boards during sunlight hours on clear days where appropriate for a 3-tiered greenhouse as at the UoR gives:

   Calculated Energy Saving: **8%**

4. DC rectifier use in place of AC could increase efficiency and would be less likely to break since fewer components and therefore increase average lifetime of modules.

   Estimated Energy Saving: **10%**

5. Operating LEDs at half the forward current increases power output efficiency and will also lower LED junction temperature and therefore increase lifetime, while making the modules more compact by reducing heatsink requirements; so higher investment of LED number is balanced by energy saving and increased time before replacement.

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Estimated Energy Saving: **6%**

6. Dynamic and model aided control of CEA light environment would allow efficient use of natural lighting to minimize energy use in supplementary artificial lights, as well as helping sole artificial lighting setups to grow plants.

These savings have been calculated to give a significant combined total estimated energy savings of approximately **47%** when compared with a system which doesn't employ any of the energy saving methods investigated. Costing analysis is ongoing.

Thirdly, the HOMER software was used with system input load requirements, energy cost tariffs and installation costs along with four different grid connected and off-grid supply setup regimes to investigate accurate geographical energy consumption and cost for electricity supply for the CEA system at UoR. Results show that a grid connected system with wind installed would be the cheapest and most environmentally sustainable option.

Finally, power distribution to lighting setup was considered. Arguments for DC grid supply in place of AC grid supply to LEDs were discussed, referring to existing literature on other DC grid application areas and electricity savings. Schematics of a DC based greenhouse system were discussed followed by modelling of both DC-DC buck converter and rectifier coupled with buck converter in MATLAB Simulink. Full efficiency and power loss calculations are currently in progress.

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