# Design optimisation of LED luminaires for horticultural lighting

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**Abstract of the master's thesis**

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**Abstract**

This thesis studies the design aspects of LED luminaires for horticultural lighting. Key aspects in LED luminaire design for horticulture were found to be light output, energy efficiency, spectrum and thermal management. Those were discussed. A survey for Finnish greenhouse growers on their currently used luminaires and expectations for future LEDs was performed. The survey also inquired the main obstacle the growers see in replacing their conventional luminaires with LEDs. The survey revealed that the growers expect longer lifetimes, better reliability, lower prices and increased yields in addition to increased energy efficiency. Biggest challenge of LEDs was found to be the initial costs. Conventional light sources and currently available LED luminaires are also presented and compared. Life cycle costs calculations between HPS and LED luminaires are performed. Usage of connected lighting in horticulture is discussed. LEDs have the potential to replace the conventional light sources, such as HPS in plant growth. However, certain key aspects, such as energy efficiency must be developed. Currently the life cycle costs of LED luminaires and HPS lamps are approximately equal. The optimal lighting strategies for different crops must be researched to further enhance the potential of LED luminaires.

**Keywords** light emitting diodes , horticulture , luminaire design

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Työssä tutkittiin LED-valaisimien suunnittelua puutarhaviljelyyn. LED-valaisimien suunnittelussa avainasemassa havaittiin olevan valontuotto, energiatehokkuus, spektri ja lämmönhallinta. Edellä mainittuja suunnittelunäkökulmia tarkasteltiin työssä. Työtä varten tehtiin kysely suomalaisille viherkasvattajille heidän käyttämistään valaisinratkaisuista, heidän odotuksistaan tulevaisuuden LED-valaisimilta, sekä haasteista LED-valaisimiin siirtymisessä. Kyselystä kävi ilmi, että kasvattajat odottavat LED-valaisimilta pidempiä käyttöikiä, parempaa luotettavuutta, matalampia hintoja, sekä parempaa sadontuottoa että energiatehokkuutta. Suurin haaste valaisinvaihdoksessa nykyisistä valaisimista LED-valaisimiiin on kasvattajien mukaan korkeat hankintakustannukset. Lisäksi työssä esiteltiin ja vertaillaan nykyisin käytössä olevia kasvatuslamppuja, sekä LED-valaisimia. Elinkaarikustannuslaskelmat tehtiin suurpainenatrium- ja LED-valaisimille. Työssä esitellään myös valaistusautomaation käyttöä puutarhaviljelyvalaisussa. LED-valaisimilla on potentiaalia korvata tavanomaiset valaimiset puutarhaviljelyssä, mutta muutamia keskeisiä ominaisuuksia, kuten energiatehokuutta, tulee parantaa. Tällä hetkellä LED- ja suurpainenatrium-valaisimien elinkaarikustannukset ovat likimain yhtä suuret. LED-kasvatusvalaisimia voidaan parantaa kehittämällä ja optimoimalla valaistusstrategioita eri kasveille.

**Avainsanat** LED, puutarhaviljely, valaisinsuunnittelu

# Preface

I want to thank my family and friends for their support during my studies. I also want to thank my instructor Paulo Pinho for guidance and supervising my thesis. Kiitos.

Helsinki, 18.7.2018

Pirkka Palmumäki

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# List of symbols and abbreviations

## Symbols

| | |
|---|---|
| $c$ | speed of light in vacuum $\approx 3 \times 10^8$ [m/s] |
| $C_i$ | price of investment |
| $C_{op,o}$ | operating costs of old device |
| $C_{op,new}$ | operating costs of old device |
| d | day |
| $d$ | distance |
| $E$ | energy |
| $E_g$ | band gap energy |
| $E(\alpha)$ | angular irradiance |
| $f$ | frequency |
| h | hour |
| $h$ | Planck's constant $\approx 6,626 \times 10^{-34}$ [Js] |
| i | rate of interest |
| $I(\alpha)$ | angular radiant intensity |
| $I_{max}$ | maximum radiant intensity |
| K | kelvin |
| lm | lumen |
| ln | natural logarithm |
| m | meter |
| mol | mole |
| nm | nanometer |
| $R_{thBA}$ | thermal resistance of the external cooling solution |
| $R_{thJA}$ | thermal resistance between junction and ambient air |
| $R_{thJS}$ | thermal resistance from junction to soldering point |
| $R_{thSB}$ | thermal resistance of the substrate |
| s | second |
| $s$ | height |
| T | temperature |
| $T_a$ | ambient temperature |
| $T_j$ | junction temperature |
| $t_p$ | photoperiod |
| V | voltage |
| $\mathrm{V}_0$ | built-in voltage |
| W | watt |
| y | year |
| $Q$ | total power dissipation of the junction |
| $\lambda$ | wavelength |
| $\lambda_{peak}$ | peak wavelength |
| $\mu$ | micro |

## Abbreviations

| | |
|---|---|
| ATP | adenosine triphosphate |
| $C_6H_{12}O_6$ | glucose |
| CAD | computer-aided design |
| CLS | connected lighting system |
| $CO_2$ | carbondioxide |
| CCT | correlated colour temperature |
| DALI | digital addressable lighting interface |
| DPB | discounted payback time |
| DLI | daily light integral |
| G3P | glyceraldehyde 3-phosphate |
| $H_2O$ | water |
| $H^+$ | hydrogen ion |
| HPS | high-pressure sodium-vapor |
| HVAC | heating, ventilation and air conditioning |
| HID | high intensity discharge |
| $L_{70}$ | lumen deprecation |
| LCA | life cycle assessment |
| LCC | life cycle cost |
| LED | light emitting diode |
| LEE | luminous extraction efficiency |
| LUE | light use efficiency |
| NADPH | nicotinamide adenine dinucleotide phosphate |
| $O_2$ | oxygen |
| PAR | photosynthetically active radiation |
| $PAR_L$ | PAR at plant canopy |
| $PAR_P$ | PAR emitted from luminaire |
| PGA | 3-phosphoglycerate |
| PPF | photosynthetic photon flux |
| PPFD | photosynthetic photon flux density |
| Pr | red absorbing form of phytochrome |
| Prf | far red absorbing form of phytochrome |
| PSI | photosystem I |
| PSII | photosystem II |
| PWM | pulse width modulation |
| RGB | Red-Green-Blue |
| RuBisCo | ribulose-1,5-bisphosphate carboxylase/oxygenase |
| RuBP | ribulose-1,5-bisphosphate |
| SMD | surface mount device |
| TEC | thermo electric cooler |
| UV | ultraviolet |

# 1 Introduction

The environmental factors, such as temperature and the amount of light are not optimal for year-round plant growth in Finland. Due to long, cold and dark winters, artificial environments (e.g. greenhouses) are needed to ensure the adequacy of food plants. [1] Natural sunlight is the main source of light in greenhouses, but because of the lack of sunlight during winter months, supplemental light is required. [2]

Finnish greenhouse growers have been using mainly high pressure sodium lamps as their main source of supplemental light. [2][3] There has been promising studies on the possilibity of using light emitting diode (i.e. LED) luminaires in plant growth, however, further research is still required. [4] In the year 2017 there were 389 hectares of greenhouse growing area in Finland and almost 90 million kilograms of vegetables produced. [1] Hence, there exists a massive potential for LED luiminaires.

In the past years, LEDs have become widely popular in lighting solutions in almost all application areas mainly due to their small size and high energy efficiency and controllability compared to conventional luminaires. However, most of the LED luminaires have been designed to match and comfort the human vision (e.g. in offices and homes). [5] Thus, horticultural applications have not been the main target of development in the transformation from traditional lamp-based system to LED-based lighting systems. Therefore, additional studies of LED luminaires for horticultural use are needed.

Plants do not utilise light the same fashion as humans, thus they require different characteristics, such as spectrum and light output, from the light sources. Therefore, the LED luminaire design aspects for horticultural use differ from conventional luminaires. In addition, high prices of LED technology and the lack of knowledge of plant photobiology has also been one of the reasons for the slow development of horticultural LED luminaires. [2]

This thesis aims to study the design and related optimisation aspects of LED luminaires for horticultural lighting. In addition, this thesis aims to gather information from Finnish greenhouse growers about the currently used lighting solutions and about the expectations the growers have for the future horticultural LED luminaires. They survey also inquired the growers about the main challenges on switching from conventional luminaires to LED luminaires.

In chapter 2 the influence of light on plant growth presented. It is an important topic to understand when designing luminaires for horticultural use. In chapter 3 light emitting diodes and their working principle are introduced among with some of their key characteristics, such as lifetime and energy efficiency. Chapter 4 introduces and compares conventional luminaires used in horticultural lighting with contemporary horticultural LED luminaires. A survey for Finnish greenhouse growers was performed for this thesis. The survey aims to acquire information from the growers about the current state of their lighting solutions and about their expectations from the future LED luminaires. The survey is presented and discussed in chapter 5. Connected lighting in horticulture is discussed in chapter 6. In the chapter, the potential usage of lighting automation and currently available protocols to control horticultural LED luminaires are presented. In addition, a few lighting control systems available on the market are introduced. Finally, in chapter 7 the design aspects of LED luminaires for horticultural lighting are discussed. The design aspects are studied via literature research and using the survey data. The survey data gathered from the growers is used to outline the studied luminaire design aspects. Discussion about the thesis is performed in chapter 8. In chapter 9, conclusions from the thesis and future study aspects are discussed. A summary of the thesis is presented in final chapter 10.

# 2 Influence of light on plant growth

This chapter briefly introduces to plant photobiology and how light affects the plant growth and development. The utilisation of sunlight, photoreceptors, photosynthesis and photomorphogenesis are discussed. Later in the section measurements of the radiant energy among with quantification of light are presented.

The Sun emits a continuous spectrum of electromagnetic radiation from ultraviolet wavelengths to infrared wavelengths. The effects of the atmosphere prevent a major portion of the radiation from reaching the Earth. However, wavelengths from 300–1000 nm pass the atmosphere and reach the surface of the Earth. [7] The before mentioned band of wavelengths is significant to life processes and photosynthesis, since only the wavelengths within it have influence in the life processes. [7]

The visible light wavelengths between 400–700 nm are primarily utilised in the process of photosynthesis. [8] The energies of the wavelengths beyond 1000 nm are not energetic enough to cause photochemical change and the wavelengths below 300 nm are destructive to biological photoreceptors. [7] Light propagates as waves but interacts with matter as particles. Light consists of photons, and the energy of a photon is directly related to its frequency, thus inversely proportional to its wavelength according to the Planck-Einstein equation [7]:

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

## 2.1 Photosynthesis and photoreceptors

Photosynthesis is a biological process in which photosynthetic organisms (such as plants, algae and bacteria) capture and convert solar radiation into chemical energy. The chemical energy is stored in organic carbon compounds, which can later be utilised by the plant cells. During photosynthesis, the photosynthetic organism absorbs light and transforms atmospheric carbon dioxide and water into oxygen and carbohydrates. [9] An example of a photosynthetic reaction, where glucose and molecular oxygen are produced, is described by the following chemical equation. [9]

$$6\mathrm{CO}_2 + 6\mathrm{H}_2\mathrm{O} \overset{energy}{\longrightarrow} \mathrm{C}_6\mathrm{H}_{12}\mathrm{O}_6 + 6\mathrm{O}_2 \tag{2}$$

where $\mathrm{CO}_2$ = carbon dioxide
$\mathrm{H}_2\mathrm{O}$ = water
$\mathrm{C}_6\mathrm{H}_{12}\mathrm{O}_6$ = glucose
$\mathrm{O}_2$ = oxygen

Glucose and other by-products are used in the plant growth. In green plants the light is absorbed by pigment molecules, such as chlorophylls a and b, and carotenoids. The relative absorption spectra of the pigments is shown in figure 1. The photosynthesis takes place in parts of the chloroplasts (stroma and thylakoid membranes). [10] Photosynthesis can be divided into two parts: light reactions and dark reactions. [9]

The light reactions take place in the thylakoid membranes. The chlorophyll *a* among the other pigment molecules in the thylakoid membrane absorb the radiant energy, which is then transferred into reaction-centres (photosystems) PSII (i.e. photosystem II) and PSI (i.e. photosystem I). The photosystems produce NADPH (i.e. nicotinamide adenine dinucleotide phosphate), oxygen and $H^+$-ions. The protons in the stroma go through ATP synthase, which produces a phosphate called ATP (i.e. adenosine triphosphate). [10] The beforementioned processes are called light reactions [8]. The ATP and NDAPH are then used in the dark reactions to convert $CO_2$ into carbohydrates inside the stroma. [8]

The dark reactions consist of a three-step process called Calvin cycle. [8] The three steps are carbon fixation, carbon reduction and RuBP regeneration. In the first step of the cycle, an enzyme called RuBisCo (i.e. ribulose-1,5-bisphosphate carboxylase/oxygenase) is used to combine 5-carbon compound RuBP (i.e. ribulose 1,5-bisphosphate) and carbon dioxide into a (unstable) 6-carbon sugar. The unstable sugar splits into two 3-carbon molecules PGA (i.e. 3-phosphoglycerate), which is reduced to G3P (i.e. glyceraldehyde 3-phosphate) in the carbon reduction step. NADPH and ATP provide energy in the step. Portion of the G3P is used to produce glucose or fructose. In the last step of the cycle, the remaining G3P is used to regenerate RuBP starting the cycle from the first step. [9] The whole photosynthetic process is shown simplified in the following figure 2.

Photoreceptors in plants are responsible for absorbing the radiant energy, which is used in production of biomass and provision of information. Phytochrome is a pigment, which absorbs red (655 – 665 nm) and far-red wavelengths (725 – 735 nm). [12] It is a photochromic pigment meaning it exists in two forms. One form is called Pr and the other is called Pfr. The first, Pr, absorbs red light and the latter absorbs far-red light. The forms are interconvertible by appropriate radiation. The far-red form Pfr can be converted into the red light form Pr by exposing it to red-light and visa versa. [12] The red light and far-red light ratio affects germination, flowering and de-etiolation. Brief exposure to red light initiates the beforementioned and exposure to far-red light inhibits these effects [12].

Blue/UV-A (ultraviolet) light receptors are called cryptochromes. Blue light

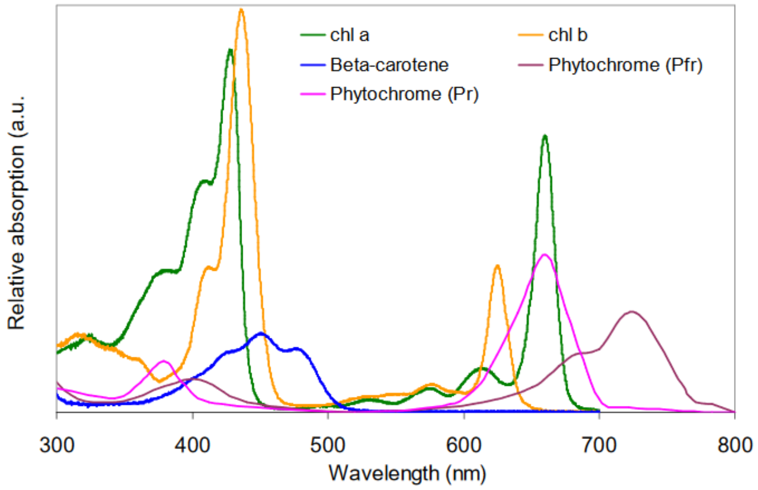

Figure 1: Absorption spectra of photosynthetic pigments [11]

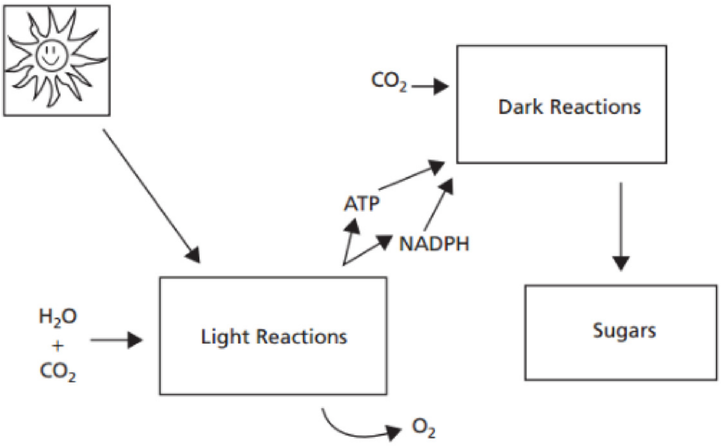

Figure 2: Simplified overview of the photosynthetic process [9]

photoreceptors cause the bending of the plant towards (or away from) light. The adjustment of orientation due to light is called phototropism. [12] The cryptochrome photoreceptors engage in various different functions, such as monitoring the quality, quantity, direction and periodicity of the light [11].

Chlorophylls are major photosynthetic receptor pigments, which are located in plants' chloroplasts. [7][11] In plants, the chlorophyll a is the main photosynthetic pigment. [9] Chlorophylls a and b absorb light mostly in the blue and red regions with peaks at 625–675 nm and 425–475nm. [11] The absorption spectrum of chlorophylls a and b are presented in the figure 1. In addition, there also exists accessory, or auxiliary, pigments called carotenoids, which do not directly contribute in the photosynthesis, but they have the ability to provide energy to chlorophyll a. [11][9]

The absorption spectrum of carotenoids is also presented in the figure 1.

## 2.2 Photomorphogenesis

Light is essential for photosynthesis and it is also critical for plant growth and development. Photomorphogenesis means plant growth and development mediated by light. [7] It is how plants react to changing environment and modify their growth by optimal use of available light. Plants are unable to change their location and must thus resort to other means in order to adapt to the changing environment. As with the photosynthesis, the most important cue is light. Plants absorb the light via photoreceptors. Blue and red light are the most important colours (wavelengths) affecting plants' photomorphogenesis. [12]

## 2.3 Photoreceptor photosystems

Photosynthetic and photomorphogenetic photoreceptors can be divided into three different photosystems: photosynthetic responsible for photosynthesis, phytochromatic responsible for red and far red absorption and cryptochromatic system responsible for blue light absorption. [7][11]

The photosynthetic photosystem absorbs the radiant energy and transforms it into biochemical energy, which is then used in plant growth and development. [7] The photoreceptor pigments in the photosynthetic photosystem are chlorophylls and carotenoids. [11]

The cryptochrome and phytochrome photosystems process information provided by the light environment. The response varies between organisms, since the same environmental signal may result in a different behaviour in different plants. [7] The photoreceptor pigments in the phytochromatic photosystem are Pr and Pfr and blue and UV-A sensitive pigments are found in cryptochrome photosystem. [11]

## 2.4 Photosynthetic light measures

Electromagnetic radiation propagates as waves and interacts with matter like particles. The single unit (i.e. quantum) of electromagnetic radiation is called a photon. The energy of a photon was described earlier in the equation 1. The amount of photochemical change is in direct relationship with photon fluence rate, which means the number of photons per unit time per area [7]. Electromagnetic radiation, thus radiant energy, can be measured in a multiple of ways. However, not all of the metrics available are suitable for measuring the radiant energy utilised by the flora. Light can be measured using photometry, radiometry and quantum measurements

[7]. The photometric measurement instruments, which measure lumens rather than energy (photons), are constructed to match the sensitivity of the human eye, and thus, are not an appropriate method for studying the effects of light on plants. [7] Radiometric methods measure the radiant energy over time and are useful for measuring especially the total photosynthetically active radiation (PAR, wavelengths 400–700 nm). Since the radiometric measurements measure the total radiant energy, those do not distinguish the energies between different wavelengths. [7]

As mentioned before, the photochemical change in plants is directly related to the number of photons falling on the leaves per unit time per are, which can be measured using quantum methods. A quantum sensor can measure the amount of photons and is therefore the most useful method for studying the photobiological effects. [7] A special meter called PAR meter can be used to measure the number of photons between 400 nm and 700 nm wavelength band. It measures the photosynthetic photon flux density (PPFD), which among a few other quantities, will be explained next.

The measures Photosynthetic Photon Flux and Density and Daily Light Integral with corresponding abbreviations PPF, PPFD, DLI will be used in this thesis to compare horticultural luminaires. The reason these measures are used instead of lumens is because plants absorb radiation in photons as was previously explained. Thus, the measures, such as lumens or lux, used to measure human vision are not applicable in the sense plants perceive the world.

Photosynthetically active radiation (i.e. PAR) is the term used for the band of wavelengths from 400–700 nm. These wavelengths are essential for photosynthesis. [7] Daily light integral (DLI) describes the total amount of photons in PAR wavelengths occurring on a surface in a day (24 hours). The unit for DLI is $\mu\text{mol}/m^2d$. [13] DLI can be especially useful in greenhouse lighting automation. In order to reach a target amount of light in a day for plants, the DLI can be used as the input parameter to control the luminaires in some lighting control systems. [14]

As mentioned before, the amount of photochemical change is in direct relationship with photon fluence rate (i.e. the number of photons per unit time per area). A single $mol$ of light equals to $6,023 \times 10^{23}$ photons. [7] Photosynthetic photon flux (PPF) is the amount of photosynthetically active radiation (PAR) emitted from a light source ($\mu$mol/s). Photosynthetic photon flux density (PPFD) is the amount of photosynthetically active radiation (PAR) occurring on a surface ($\mu\text{mol}/\text{s}m^2$). [13] Manufacturers may inform the PPFD of their luminaires without revealing the dimensions (i.e. measurement settings) used to measure it and this may make the comparison of different luminaires problematic.

# 3 Light emitting diodes

Light emitting diodes are widely used in many fields and applications. LEDs can be used for example in street lighting, traffic lights and in digital displays. They are widely used due to their low power consumption, long lifetime and small size. LEDs can reach a lifetime up to 50000 hours. [15] They can be manufactured in many sizes and many shapes, such as, round and rectangular to fit a wide range of applications.

This chapter presents the main technical characteristics of light emitting diodes, which are relevant and important for the discussion of the design aspects of LED luminaires. The LED luminaire design aspects will be discussed in chapter 7. First, the principles of light generation are discussed, which will give the reader an idea of how LEDs differ from conventional, thermal radiation based light sources. Later in the chapter the working principle and internal structure among with a few other key characteristics are presented.

## 3.1 General principles of light generation

Light is always produced from physical matter. Light can be produced in many different ways. However, artificial light generation can be distinguished into two main categories – thermal emission and luminescence. Visible light can also be generated by using phosphor materials and ultraviolet light source. [15][16] Thermal radiation and luminescence are presented next. The latter, luminescence or more precisely electro-luminescence is the phenomenon utilised in LED light generation.

In thermal radiation, the electromagnetic emission is generated from the thermal motion of the atoms, molecules and ions in the matter. The emissions occur at all wavelengths; thus, the spectral distribution is continuous. [16] All matter at all temperatures ($T > 0$K) emit electromagnetic radiation. If the temperature rises over 1000K the radiation becomes visible. The intensity and colour changes if the temperature rises. The colour will shift towards white light. [16] For instance, an incandescent lamp is based on thermal radiation.

In luminescence, the electromagnetic radiation is spontaneously emitted. An atom, ion or other subatomic particle falls from higher energy state to lower energy state and the energy difference is emitted as a photon. [16] Unlike the spectrum in thermal radiation, the spectrum of luminescence is not continuous. The emission only happens at certain wavelengths. Luminescence in lamps usually happen in solid materials or in gases. There are several types of luminescence, such as photoluminescence and electro-luminescence. [16] Light generation in LEDs is based on electro-luminescence. In electro-luminescence the radiation is influenced by an electric field through the material. In the following section, the internal structure and working principle of LEDs will be discussed in more detail.

## 3.2 Internal structure and working principle

Light emitting diodes are two-lead semiconductor devices, which radiate light under appropriate conditions, when electricity is flown through it. [17] An LED consists of p-type semiconductor material and n-type semiconductor material layers. The positive p-type material contains positive charge carriers, holes, and the negative n-type contains negative charge carriers – electrons. [15][17] As the name suggests, the materials form a diode, which allows current flow only in one direction. The p-side is referred to as anode and the n-side as cathode [15]. An overview of the structure can be seen in the figure 3 [15].

LEDs operate in two main states: unbiased and biased states. Although both sides of the semiconductor structure are conductive, the junction between the layers is not. It is called the depletion zone and it is created under the unbiased state with no voltage applied across the device. [15] The unbiased state is determined by the built-in voltage $V_0$. The LED state can be biased by applying an appropriate forward voltage $V$ over the semiconductor device. [15][17] In forward bias mode, a positive terminal is connected to the p-type material and a negative terminal to the n-type material. [15] When a forward-bias voltage $V$ is applied over the LED, electrons (and holes) start to flow towards the depletion zone. Thus, the forward bias reduces the width of the depletion zone. Eventually the depletion zone becomes narrow enough for the electrons to tunnel across the junction and enter the p-type material. [15]

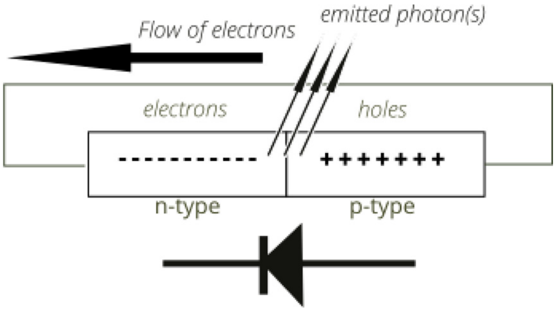

Figure 3: Forward biased light emitting diode

The holes and electrons can recombine at the p-n junction if they have the same momentum, and thus emit a photon. This phenomenon is called electro-luminescence. [17] The recombination can either be radiative as described or nonradiative. In nonradiative recombination no photon is emitted and the energy is relaxed to the semiconductor. This will result in self-heating of the semiconductor device. [18]

In radiative-recombination the electron falls from higher energy state to a lower energy state. The energy difference between the states is emitted as photon. [15] The energy of the photon depends on the energy bandgap $E_g$ (in electronvolts) of the p-n junction materials. [17] Forward biased LED overview can be seen in figure 3.

Not all of the energy is emitted as photons, since some of the energy is lost as heat. [18] The energy of the emitted photon is proportional to the frequency, and thus, inversely proportional to the wavelength, as shown by solving the Planck-Einstein equation (4). The dependence of the colour on the bandgap energy $E_g$ can be derived from the Planck-Einstein equation [17]. The energy of the emitted photon is given by,

$$E = hf = \frac{hc}{\lambda} \approx E_g \tag{3}$$

solving the equation for the wavelength $\lambda$ as follows that,

$$\frac{hc}{\lambda} \approx E_g \Longleftrightarrow \lambda = \frac{hc}{E_g} \tag{4}$$

The colour of the light emitted is related to the wavelength of the photon. Moreover, the wavelength depends on the band gap energy of the materials used to form the p-n junction or via doping the semiconductor materials. Thus, the colour and energy of the light emitted from the LED can be defined by using different materials to form the junction. [15] Being able to control the peak wavelength and therefore the colour of the light is important in plant growth, and thus an important design aspect for horticultural LED luminaires. As we saw in the previous section, plants react on certain wavelengths.

Doping a semiconductor material means adding impurities to a pure material (for example silicon). The electrical properties change and can be controlled via using the dopants. In LED production, impurity atoms (donors) are introduced to create n-type conductivity and acceptors are used to create p-type conductivity. [16] The colour of the light emitted can be tuned via using different dopant materials [15]. Table 1 lists a few combinations of doping materials and the peak wavelength the semiconductor alloy emits.

Table 1: Examples of alloy materials and resulting output wavelength [15]

| Material | Peak wavelength |
|---|---:|
| GaAsP/GaP | 635 mm |
| InGaAlP | 623 mm |
| SiC/GaN | 470 mm |

As was stated, the colour output of an LED depends on the semiconductor materials used. Consequently, colour variations can be achieved through the use of multiple LEDs, such as red, green and blue, packed into a single package. [15]

White light can be formed via multiple methods. For instance, via colour mixing: by packing red, green and blue LEDs in a single setup results in white light output. In addition, using yellow phosphor coating on a blue emitting LED can be used to achieve white light output. [15]

## 3.3 Lifetime

In the beginning of the section 3 it was briefly noted that the lifetime of LEDs can reach up to a hundred thousand hours. The lifetime of that magnitude is somewhat misleading. In fact, the lifetime of LEDs is currently under debate in order to define a standardised measurement method. [19] Currently, different methods are used to define LED lifetime. One method used is the lumen maintenance. It is used by many manufacturers to define the lifetimes of their luminaires. It is specified as the time in hours after which the light output has dropped a specific percentage from the initial value. Typically, $L_{70}$ (or L70) value is used. The L70 gives the time period after which the light output has decreased 30% from the intial. [20][19]

In terms of the L70 lumen maintenance rating, LED luminaires generally have a lifetime of about 25000-50000 hours. The actual operational lifetime of a LED luminaire may be longer. It depends on the photoperiods used. In horticultural lighting, a photoperiod is the number of hours the luminaire is operated in a 24-hour period. The magnitude of the luminaire operational lifetime is illustrated in figure 4. Plot in the graph is the lifetime in years versus photoperiod used. Equation (5) is used to calculate the actual operational lifetime in figure 4.

$$t = \frac{t_l}{t_p \cdot 365 \text{ d/y}} \tag{5}$$

where $t$ = actual operational lifetime
$t_l$ = luminaire lifetime in hours
$t_p$ = used photoperiod
$d$ = day
$y$ = year

where $t_p$ is the used photoperiod.

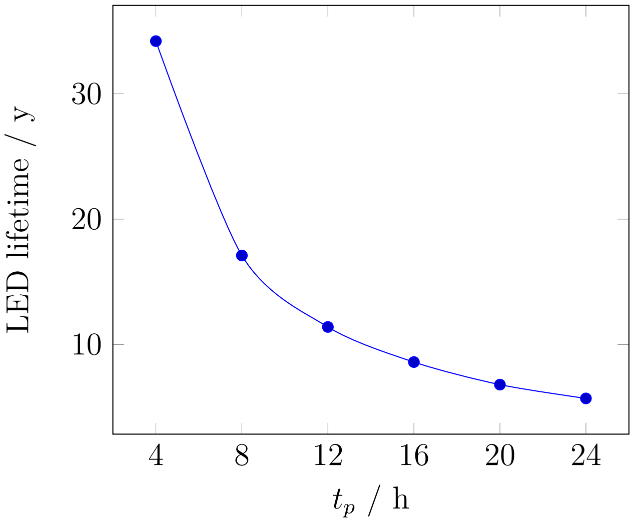

Figure 4: 50000 h lifetime versus photoperiod

The lifetime also depends on the currents the LED is driven. In other words, higher currents reduce the lifetime. In addition, higher temperatures do also affect the lifetime. [20] As was mentioned earlier, not all of the energy in the recombination is emitted as a photon. Thus, LEDs produce heat at the p-n -junction and thermal management is an essential design aspect of LEDs. [18] Since heat is not emitted as infrared radiation, cooling must be used to dissipate the junction heat. [21] Thermal design of LEDs is discussed further in section 7.

## 3.4 Energy efficiency

There are multiple different efficiency factors, which have an influence on the overall energy efficiency of an LED device. These factors are internal quantum efficiency ($\eta_i$), injection efficiency ($\eta_{inj}$), light extraction efficiency ($\eta_{lee}$), external quantum efficiency ($\eta_{ext}$), radiant efficiency ($\eta_e$) and luminous efficiency ($\eta_v$). [17]

Internal quantum efficiency is defined as the ratio between radiative recombination (i.e. electron-hole recombination pairs that emit photons) and total recombination rate. Injection efficiency is the fraction of the electrons entering the active region from the electrons passed through the device. [22][17]

External quantum efficiency is the ratio between emitted photons to the number of injected electrons. It can be calculated by a product of internal quantum efficiency, injection efficiency and light extraction efficiency with the following equality [17]:

$$\eta_{ext} = \eta_i \cdot \eta_{inj} \cdot \eta_{lee} \tag{6}$$

In LEDs, light is emitted from the active region, however, not all of the emitted photons can escape the semiconductor structure. The photons may be reflected back at the semiconductor-air interface due to total internal reflection. Light extraction efficiency (LEE) is defined as a ratio of the number of photons emitted into free space per second and number of photons emitted from active region per second. [23][24]

The substrate may reabsorb a portion of the emitted photons. Also, the p- and n-contacts can absorb photons, thus decrease LEE. The photons may also be absorbed by metallic contact surfaces. [23][24] Considering horticultural lighting, light extraction efficiency is important, since the quantity of light (i.e. number of photons emitted) is relevant to plant growth. [7] Thus, improving LEE would improve the overall light output of the LED, thus energy efficiency. It can be improved with various methods, such as using patterned substrate, which scatters the emitted photons, or highly reflective mirror layers. [23]

Radiant efficiency is the ratio between the radiant flux to electrical input power. In other words, the ability to convert electrical power into radiation. [17] Luminous efficacy describes the ratio between luminous flux and electrical power used (unit lm/W). [24] In other words, how effectively the light source converts electrical power into visible light. As was presented in section 2.4, lumens are not a usable quantity to be used in horticulture. However, in LED comparison it is usable. The theoretical limit for LED luminous efficacy is over 300 lm/W [23].

# 4 Currently used horticultural lighting solutions

An interview study by Anderson J. was performed in 2010. The results were that high-pressure sodium-vapor lamps (i.e. HPS) were the most popular solutions in greenhouses interviewed. A survey for this thesis was also performed. According to the survey results, HPS lamps are still the most used lighting solution in Finnish greenhouses. Although, LED luminaires are gaining interest.

This chapter introduces the lighting solutions currently used in horticulture. First the conventional luminaires are discussed, after which LED luminaires are presented.

## 4.1 Conventional lighting

As was previously mentioned, the study performed in 2010 found out that HPS lamps were primarily used for plant growth in the Finnish greenhouses. [3] Other discharge lamps, such as metal-halide and fluorescent lamps are also used in horticulture. [11] These lamp types will be introduced in next sections. The HPS lamps are discussed in more detail due to their popularity in horticultural lighting. [3]

### 4.1.1 High-pressure sodium-vapor lamps

High-pressure sodium-vapour lamps belong to the group of high intensity discharge lamps. The lamp consists of an arc tube inside a glass bulb, electrodes, getter and a ballast. The arc tube is usually filled with sodium, mercury and xenon. The HPS lamp produces light in the arc tube via excited sodium vapour. The ballast sends a high voltage pulse across the tube, which creates an arc through the xenon. The xenon heats up mercury and eventually the sodium is vaporised. The lamp does not ignite immediately. It takes some time for it to heat up and produce the desired light. Getters maintain the vacuum by binding oxygen and other residue gases, thus reducing heat loss. [16] A typical 400 W HPS lamp and its output spectral power distribution are presented in figure 5.

HPS lamps are used in greenhouses mostly as supplemental light sources due to their high radiant emissions, low prices and long lifetimes. [26] However, their spectrum is not optimal for plant growth. From figure 5 it can be seen that most of the HPS output light is within PAR wavelengths, however, tilting towards the red end. The low blue light emissions and low red/far-red ratio from HPS lamps induce unwanted characteristics in plants, such as stem and excessive leaf elongation. [26]

The spectrum of course is not adjustable, unlike in some of the modern LED luminaires. Technical specifications for two typical HPS lamps designed to plant

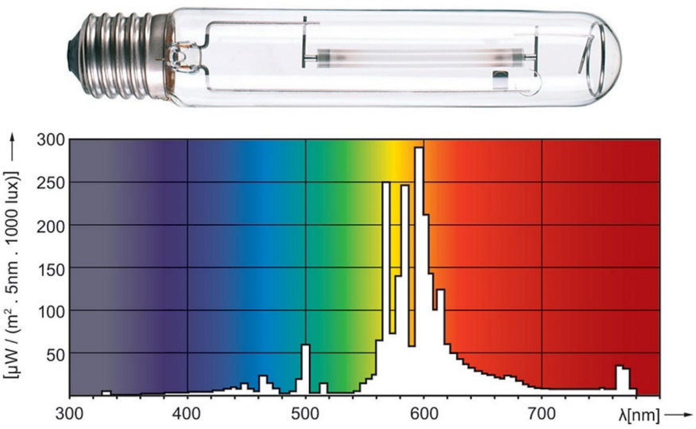

Figure 5: Typical spectral power distribution of a 400 W HPS lamp (top) [25]

growth are presented in table 2. The efficiency is given by the ratio between light output and power consumption.

Table 2: Specifications of two horticultural HPS lamps [27][28]

| | | |
|---|---:|---:|
| Power consumption | 430 W | 600 W |
| Light output | 695 $\mu$mol/s | 1100 $\mu$mol/s |
| Efficiency | 1,6 $\mu$mol/J | 1,8 $\mu$mol/J |
| Lifetime (L90) | 5000 h | 12000 h |

### 4.1.2 Metal-halide lamps

Metal-halide lamps are high intensity discharge gas lamps, which produce light by the excitation of metals in an arc. The lamp is composed of an arc tube and outer bulb. The arc tube contains mercury, a mixture of different metal halides and a small amount of noble gas, such as argon. Different halides can be used, but typically iodide is used. The outer bulb protects the arc tube and reduces heat loss of the lamp. [16] A typical tubular type metal halide lamp and a typical spectral power distribution are presented in figure 6.

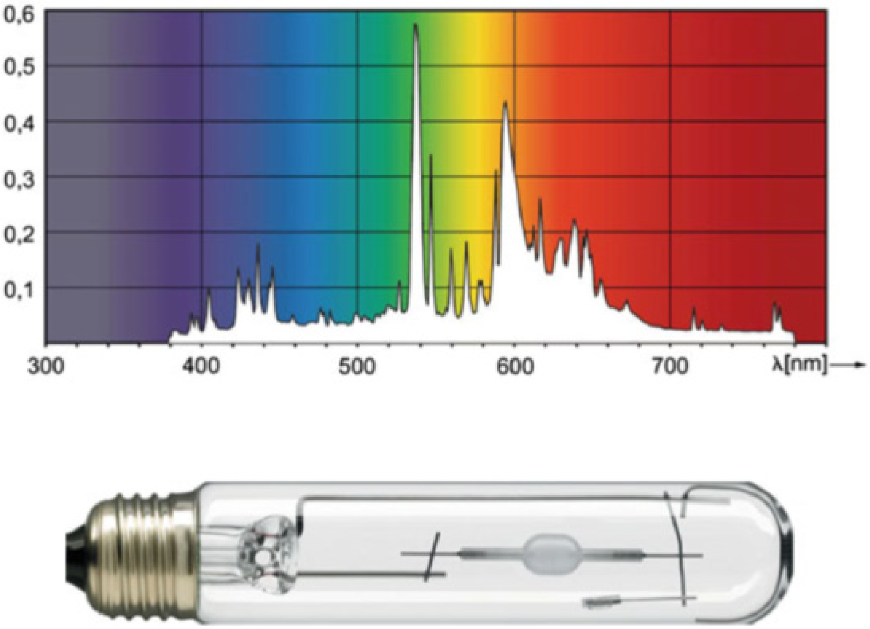

Figure 6: A typical metal halide lamp and output spectral power distribution [30]

### 4.1.3 Fluorescent lamps

Fluorescent lamps are low pressure mercury-vapor discharge lamps. The lamps consist of a discharge tube and electrodes in each end. The electrodes are wolfram-coated and emit electrons. The tube is filled with a noble gas, such as argon or krypton and it is internally coated with a fluorescent substance. Fluorescence is a material, which emits light when it is excited by UV radiation. The discharge tube also contains a tiny amount of mercury. [16][30] When a voltage is applied over the discharge tube electrodes, the gas atoms get excited. This results in energy emissions partially in visible spectrum and partially in UV radiation. The UV radiation excites the fluorescence, which then emits photons at visible wavelengths. The wavelengths depend on the fluorescent alloy. [30] There are many types of fluorescents lamps with different topology. However, the working principle is mutual. [16] An example of a fluorescent lamp and its output spectrum are presented in figure 7.

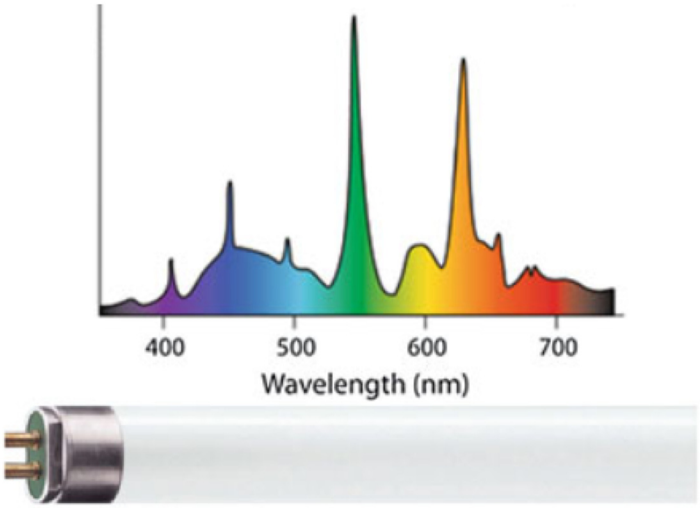

Figure 7: Linear tube fluorescent lamp and output spectral power distribution [30][31]

## 4.2 LED lighting

This section presents a few LED luminaires for horticultural applications. The luminaires have different design for different target application. Modular LED luminaires, vertical farming luminaires and greenhouse supplemental light luminaires are introduced.

### 4.2.1 Modular LED luminaires

Modular LED luminaires are LED luminaires, which can be connected by installing them in a chain. There is an interlighting and a toplighting module available on the market. The toplighting system is supposed to be used on top of the crop, whereas the interlighting system is supposed to be used within canopy of high wire plants. [32][33] An example of these two type of luminaires is shown in figure 8.

The modules can be controlled with a concept the manufacturer calls light recipes. The light recipes are different light scenarios (i.e. predetermined spectral conditions) for different crops. The light recipes allow modifying the spectrum – far red, red, white and blue – and individual light intensities. They are controlled with a software and according to to the manufacturer they provide flexibility and precision to plant growing. [34][32][33]

In chapter 2 it was explained how light influences plant growth. Different wavelengths affect the plants differently. Thus, using different light recipes, could result in crops with different characteristics, such as different taste or morphology. Also, the

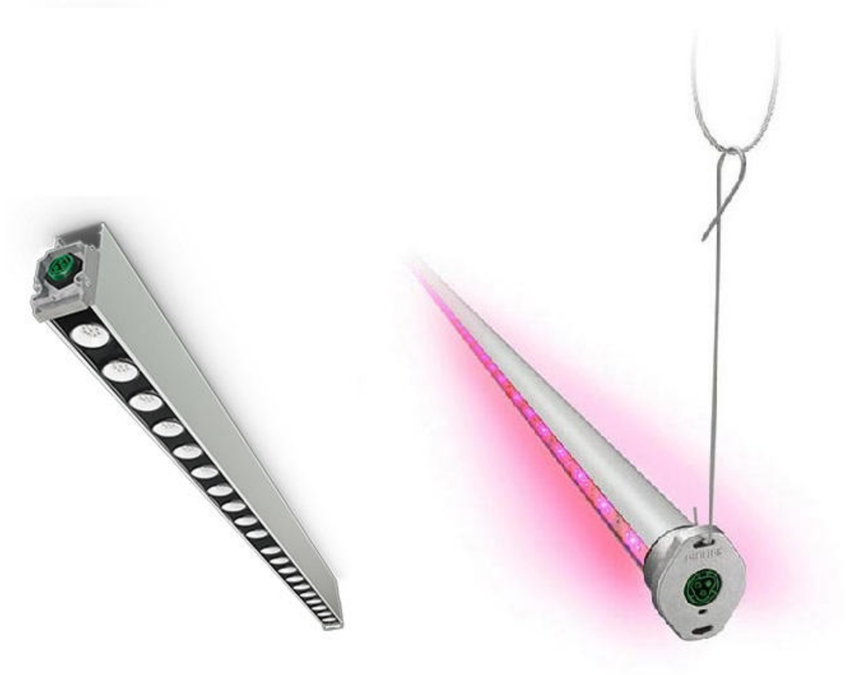

Figure 8: Toplighting (left and interlighting (right) modules [32][33]

light recipes enable the grower to utilise different spectrum and intensity settings for different phases of plant growth. [34] Nevertheless, the ability to alter the spectrum gives the grower (or researcher) a tremendous amount of control over the outcome.

Both LED modules are available as regular and as high light output systems. The main technical specifications for the modules are presented in tables 3 and 4. [32][33] The lifetime rating in the tables is the point in hours, where the light output has dropped to 90% of the initial output. The rating is based on lumen maintenance presented in section 7.6.

The manufacturer also states that the passively cooled modules produce much less heat than HPS lamps. [32] However, a research has found that the lack of heat from LEDs results in decreased yields compared to using HPS lighting. [4] The interlighting module is designed to be used within the canopy. The low heat emissions of the module allow the use of it as an interlighting within the canopy with HPS toplighting. Using LED interlighting with HPS toplighting has been found to increase crop yield and light use efficiency. [35][36]

Table 3: Toplighting module technical specification

| Model | Regular output | High output |
|---|---:|---:|
| Input voltage | 400 V | 400 V |
| Power consumption | 180–200 W | 175–200W |
| Light output | 380–440 $\mu$mol/s | 410–520 $\mu$mol/s |
| Efficiency | 2,1–2,3 $\mu$mol/J | 2,3–2,7 $\mu$mol/J |
| Lifetime | 25000 h | 25000 h |

Table 4: Interlighting 200 cm module technical specifications

| Model | Regular output | High output |
|---|---:|---:|
| Input voltage | 200–400 V | 200–400 V |
| Power consumption | 64 W | 81 W |
| Light output | 175 $\mu$mol/s | 240 $\mu$mol/s |
| Efficiency | 2,8 $\mu$mol/J | 3,0 $\mu$mol/J |
| Lifetime | 25000 h | 25000 h |

### 4.2.2 Vertical farming

Vertical farming is a concept in which multiple crop layers are piled on top of each other to form a vertical stack. It allows more efficient use of space. [37] A Finnish company has produced a vertical farming solution, which combines lighting, cooling and heat recovery. It uses water cooling as the LED thermal management, which according to the manufacturer, can prolong the LED lifetime. [37] Thermal management is an important design aspect of LED luminaires and reducing junction heat can improve LED lifetimes. [18]

The vertical farming system can be combined to a heat recovery system, which stores the heat for reuse. For instance, the recovered energy could be used to heat the growing space. The irrigation water, which is evaporated by the plants, is also gathered. Thus, the system can potentially save fresh water. The system is not a single luminaire, but a complete growing solution. [37]

The manufacturer offers an overhead (i.e. toplighting) luminaire for the system, which is presented in the figure 9. The producer claims that the fixture can be installed at the same height as HPS fixtures, thus providing a replacement for HPS based solutions. [37] However, the manufacturer provides no PPFD data, thus it is not possible to verify this claim without proper measurements. [37] The technical specifications for the luminaire are presented in table 5.

The lifetime in the table is the L90-number (refer to section 7.6 for L-number definition) and light output is informed as PPF. The power consumption is much higher compared to the previously presented LED module toplighting luminaire;

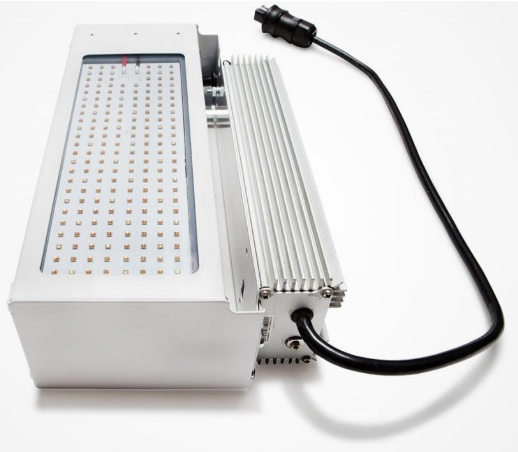

Figure 9: Overhead LED luminaire [37]

Table 5: Technical specifications of an overhead LED luminaire

| Model | Overhead |
|---|---|
| Input voltage | 90–305 V |
| Power consumption | 200 W |
| Light output | 400–500 $\mu$mol/s |
| Efficiency | 2,25 $\mu$mol/J – 2,5 $\mu$mol/J |
| Lifetime | 40000 h |

however, the light output is also considerably greater. The 40000-hour lifetime is also significantly higher. It may be a result of using the active water cooling.

Comparing the overhead LED luminaire to the 400 W HPS in table 2, the power consumption is 50% lower, but the light output of the LED overhead luminaire is just 30% lower. This results in the overhead LED luminaire being over 50% more efficient in terms of delivering photons. In addition, the lifetime is eight times the lifetime of the HPS. However, even though no price information is given for the overhead LED luminaire, it can be assumed that the price is significantly higher than the price of the HPS.

Designing the luminaires for vertical farming enables the grower to use the greenhouse space more efficiently by stacking the crops on a vertical pile. Thus, increasing the growing area without using more floor space. However, this is not possible for all plants, such as high wire plants (e.g. cucumber and tomato). Vertical farming can be constructed completely indoors. The natural sunlight is not used and therefore the luminaire form factor is not as crucial an issue as it is in greenhouses using sunlight.

Another LED luminaire designed for vertical farming is produced by a company from the USA. The manufacturer claims that it is suitable for vertical farming and especially designed for applications that require uniform PPFD. [13] The luminaire and the spectral power distribution are shown in figure 10. The company claims the spectrum is a full-cycle spectrum (i.e. the spectrum covers all PAR wavelengths), which ensures fast growth of plants. [13] From the figure 10 can be seen that the spectrum covers a wide range of wavelengths within the PAR range; however, no research results of yields are provided by the company to support the claims.

The specifications for the luminaire are presented in table 6. Comparing the lifetimes of the modular LEDs introduced in section 4.2.1 and the vertical farming luminaire presented earlier in this section, it can be seen that the luminaire's lifetime is about two times longer than of the LED modules and 35 % longer than the lifetime of the vertical farming overhead luminaire. In addition, the light output is highest of the presented luminaires, but the output efficiency per energy unit is at the same level with the others because of high power consumption. The light output level is about 40 % higher than the light output level of the 600 W HPS presented earlier.

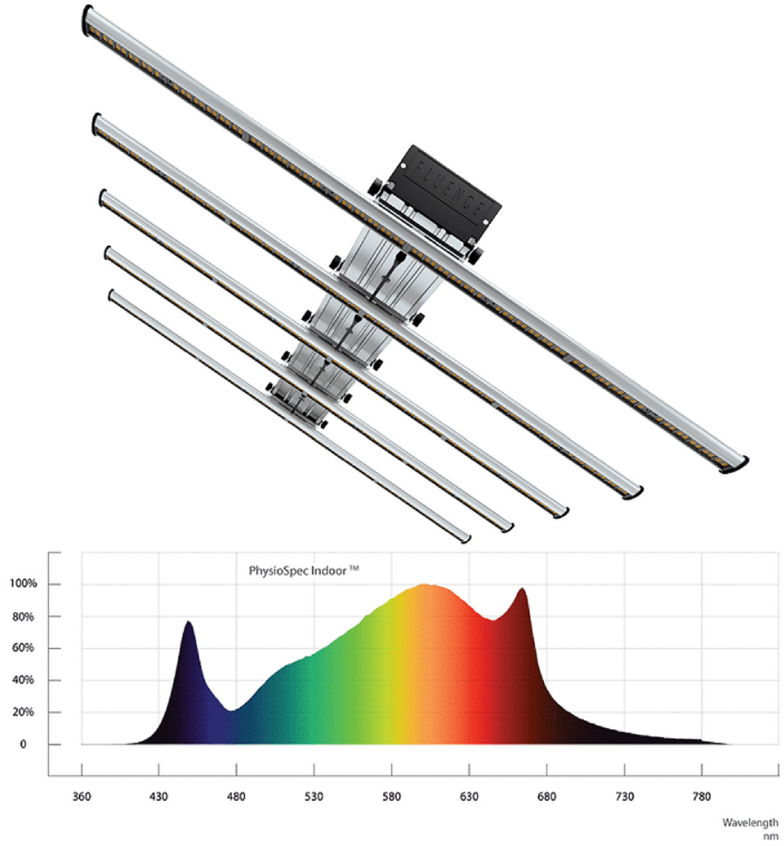

Figure 10: An LED luminaire for vertical farming and an example output spectrum power distribution of a vertical farming luminaire [13]

Table 6: Technical specifications for a vertical farming luminaire [13]

| | |
|---|---|
| Operating voltage | 100–277 V |
| Power consumption | 660 W |
| Light output | 1535 $\mu$mol/s |
| Efficiency | 2,3 $\mu$mol/J |
| Lifetime | 54000 h |

### 4.2.3 Greenhouse luminaires

Lumigrow combines LED lighting and cloud based controlling software into a single solution. [14] The company produces two models. The luminaires are fully LED based and according to manufacturer, they can produce more red and blue PAR per watt than any other adjustable luminaire on the market and gain up to 70% energy savings versus traditional HID (i.e. high intensity discharge) lighting [14]. The output spectrum, which cannot be modified unless the module is paired with the controlling system, is in %RGB – 75%-5%-20% [14]. The company does not provide any specific data nor spectral distribution chart, however.

The luminaires can be used individually or paired with the controlling software and a light sensor. The light sensor will be presented in section 6.2.2. A greenhouse luminaire is shown in the figure 11 and the technical specifications for both models are listed in table 7. [14] The manufacturer provides no lifetime data for their luminaires, thus the ratings are not presented in the specifications and therefore comparing the lifetime ratings is not possible.

Figure 11: A greenhouse LED luminaire [14]

Table 7: Specifications of two LED luminaire models

| | | |
|---|---|---|
| Operating voltage | 100–240 V | 100–240 V |
| Power consumption | 297 W | 595 W |
| Light output | 600 $\mu$mol/s | 1200 $\mu$mol/s |
| Efficiency | 2 $\mu$mol/J | 2 $\mu$mol/J |
| Lifetime | N/A | N/A |

An another LED luminaire designed for greenhouse supplemental light is presented in figure 12. The specifications for the luminaire are presented in the table 8. According to manufacturer, the LED luminaire is optimised for greenhouse use due to its sleek, narrow design, which allows great amount of sunlight for the plants. [13] The company also states that the luminaire is especially optimised for rolling tables. [13] The luminaire consists of over 1000 individual LEDs designed to produce light output to large areas, such as in greenhouses. [13]

Table 8: Technical specifications of a greenhouse supplemental light LED luminaire [13]

| | |
|---|---|
| Operating voltage | 100–277 V |
| Power consumption | 525 W |
| Light output | 1190 $\mu$mol/s |
| Efficiency | 2,3 $\mu$mol/J |
| Lifetime | 38000 h |

Figure 12: Greenhouse supplemental light LED luminaire [13]

The lifetime is informed as L90. It is a similar luminaire to the toplighting module presented in section 4.2.1, but with a slightly longer lifetime. It also has larger PPF, however, the energy consumption is also much higher. In terms of power consumption and light output, the LED luminaire is quite similar to the 600 W HPS introduced in table 2. The lifetime of the LED luminaire is only three times the lifetime of the HPS, thus the biggest differences are in the light output spectra.

The output spectra available for the luminaire are presented in figure 13. The spectral output cannot be controlled in real-time; however, the company offers the buyer an option to choose from the two spectral compositions presented in figure 13. The spectral composition on top is supposed to be used indoors and the one on the bottom is supposed to be used in greenhouses (i.e. supplemental light). [13] As presented in figure 13, both output spectra are in the PAR region and almost similar. However, the one, which is supposed to be used in indoor greenhouses (top in figure 13) has slightly more output power in the red and yellow regions and less output power in the blue peak.

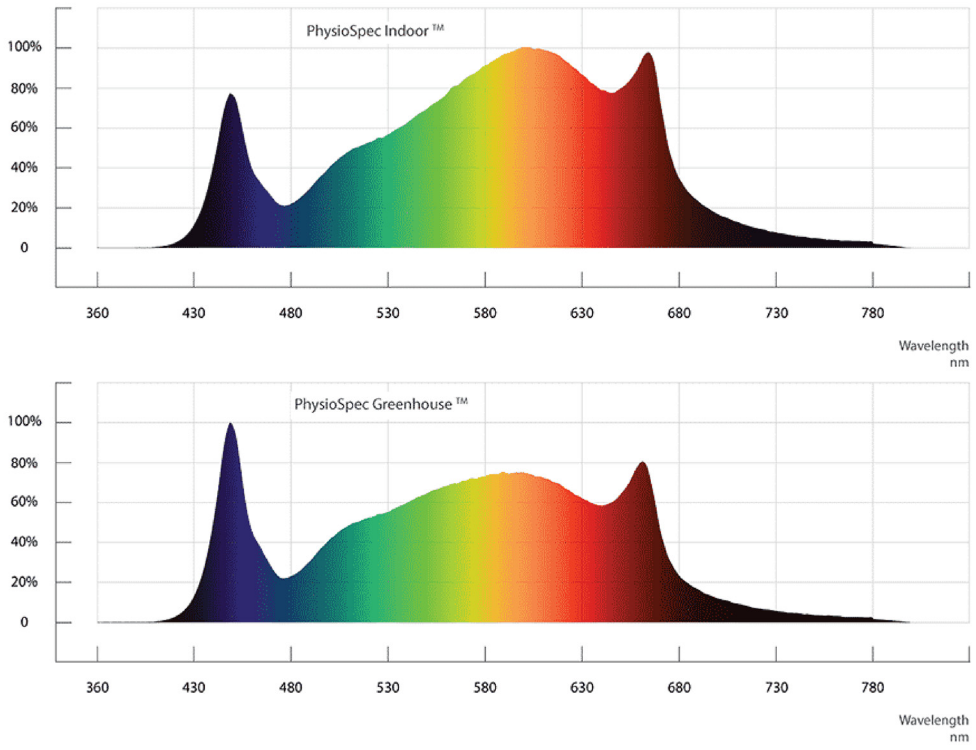

Figure 13: Available spectrums for the greenhouse luminaire [13]

This luminaire, like all the luminaires from the company, uses passive natural convection as the thermal management solution. [13] Therefore, no possible breaking moving parts of active cooling (e.g. fans or pumps) are present in the designs. This prevents overheating of the luminaire in case of a possible fan failure. Therefore, the lifetime is not dependent on the lifetime of the cooling solution. In addition, using passive cooling does not increase the power consumption; thus, increasing the energy efficiency of the luminaire.

A greenhouse supplemental light luminaire should be designed to block as little sunlight as possible. The dimensions for the luminaire should be minimised to allow sunlight penetration to the crop. The presented LED luminaires do not need additional reflectors unlike typical HPS lamps, thus the reflector does not cast a shadow. The shadow cast from the fixture is directly proportional to the luminaire dimensions. Thus, reducing the dimensions of the luminaire decreases the blockage of natural sunlight.

## 4.3 Summary

In this chapter conventional lamps and LED luminaires for horticultural applications were introduced and compared.

The market flourishes with different types of luminaires for different crops and requirements. The LED luminaires presented had either an adjustable spectrum or spectrum adjusted for specific plants. Although the presented list of luminaires is by no means comprehensive, it shows that there are a great number of options already available for different target applications. Moreover, the variety of luminaires on the market today is large and greenhouses around the world now have luminaire options to transition from the conventional light sources to LED-based systems.

Nonetheless, the ideal solution of luminaire depends on the application. In terms of design, for instance, greenhouse supplemental LED luminaires (e.g. the one shown in figure 12) can be designed to deliver a more collimated light than HPS lamps due to directionality of LED light output. The required photon beam varies between the applications. For example, in a large greenhouse, the lighting uniformity and even pattern from HPS lamps can be more optimal than a narrow beam from a LED luminaire [21].

As was shown in this chapter, the conventional lamps (i.e. HPS) and LED luminaires display quite a similar performance in terms of light output efficiency. Therefore, more development is required in the overall energy efficiency (i.e. light output per consumed energy unit) of horticultural LED luminaires for them to exceed the efficiencies of HPS lamps, and thus become more cost-efficient and intriguing an investment for the plant growers.

However, LED luminaires may be built to have a controllable spectrum and light output, which could be adjusted depending on the needs (i.e. crop type or growth phase). In addition, due to lower heat emissions, LED luminaires can be used within the canopy. Nevertheless, more research is needed on the photobiology to better tailor the spectra and light outputs for different plants. [31]

LED luminaires can basically be designed to have any form factor, whereas HPS luminaires typically rely on rectangular-shaped reflectors. For example, the LED luminaire in figure 12 has a bottom rectangular area of approximately 740 $cm^2$ [13]. For comparison, a 600 W HPS luminaire reflector bottom area can be 1026 $cm^2$. The data is from a luminaire reseller. Thus, it can be deduced that retrofitting an HPS luminaire with a similar form factor as LED luminaire, with similar light output performance, is possible. It can also be speculated that retrofitting an HPS lamp with a smaller form factor LED luminaire could be possible. The luminaire dimensions are important when using the luminaire as a supplemental lighting due to possible blockage of sunlight. [21] However, with collimating lenses, the light output distribution from LED luminaire can be made more focused, which can increase the photon capture by plant canopies [21][11].

# 5 Survey

A survey for Finnish greenhouse growers was performed for this thesis. It aims to acquire information about the currently used lighting solutions and about the possible transition from conventional lamp systems to LED based solutions in Finnish greenhouses. The expectations the greenhouse growers have for the future LED luminaires were also inquired. The survey was sent to a total of 36 members of the Kauppapuutarhaliitto ry, which participated in its *Puhtaasti kotimainen* project [38].

The growers were contacted via email. The survey was performed by sending a link to a web-based questionnaire. The survey was constructed using an online survey tool. It was sent to 32 growers from which a total of seven growers answered the survey. Therefore, the reply rate was approximately 22%. The survey questions, results and analysis are presented next.

## 5.1 Questions

The survey questions consisted of the following questions (translated, original questions in Finnish):

1. What kind of luminaires (lamp types) are you currently using?
2. Have you planned to replace your luminaires with LED based luminaires?
3. If you answered "no" in the previous question. Why have you not considered it?
4. If you have already replaced your luminaires with LEDs, what were the biggest motives?
5. If you have already replaced your luminaires with LEDs or you are planning to, what kind of expectations you have for the future LED luminaires for plant growth?
6. Which of the following are the biggest challenges considering switching to LED luminaires?
    - The overall costs
    - Performance
    - Lifetime/reliability
    - Other challenges, what?

## 5.2 Results

All respondents had considered moving into LED luminaires and some of them had already replaced a part of their luminaires with LEDs. However, all the growers were still using high-pressure sodium-vapor lamps. Three out of the seven respondents were already using LEDs among with HPS luminaires. According to them, the reasons for replacing legacy systems with LEDs were greater energy efficiency, increased quality (spectrum) of light and increased quality of seedlings.

The consensus among the growers was that the greatest obstacle in the transformation from the conventional luminaires to LED based luminaires was the immense initial acquisition cost. It was answered as the biggest obstacle by six respondents. In addition, lifetime and reliability were answered as a challenge by four respondents. Other issues mentioned were lack of knowledge on LEDs and possible increase in costs due to external heating. Performance of the LEDs, however, was not seen as an issue.

The survey also inquired growers' expectations for the future LED luminaires. The survey revealed that the growers expect longer lifetimes, better reliability, lower prices and increased yields in addition to lower energy consumption. Moreover, the respondents also underlined the importance of spectrum control.

## 5.3 Analysis

The survey sample size was small due to low reply rate. The reply rate might have been low because of the technical nature of the survey. The survey was only targeted at Finnish greenhouse growers. In Finland the need of supplementary lighting is high due to low amount of sunlight in winter months, hence if the survey was performed in a country with more sunlight, the results might have been different. Due to these, no generalisation can be made from the survey, but it does give some information about the expectations the Finnish growers have for future luminaires and the biggest obstacles they face in replacing the legacy systems with LEDs.

The biggest obstacles the survey revealed are presented in figure 14. It can be seen that the most important obstacle is the high cost of LED luminaires. Not only the luminaires are expensive, but the overall retrofitting may become expensive. The other obstacles also mentioned in the figure were electricity costs due to possible additional heating and lack of knowledge of LED lighting.

All the respondents answered that they are still using HPS based systems; however, had either partly replaced their luminaires with LEDs or had considered to. Although the sample size was small, it can be deduced from the survey that Finnish greenhouse growers are looking forward to modernising their current (HPS) systems to LED based systems once the obstacles have been overcome.

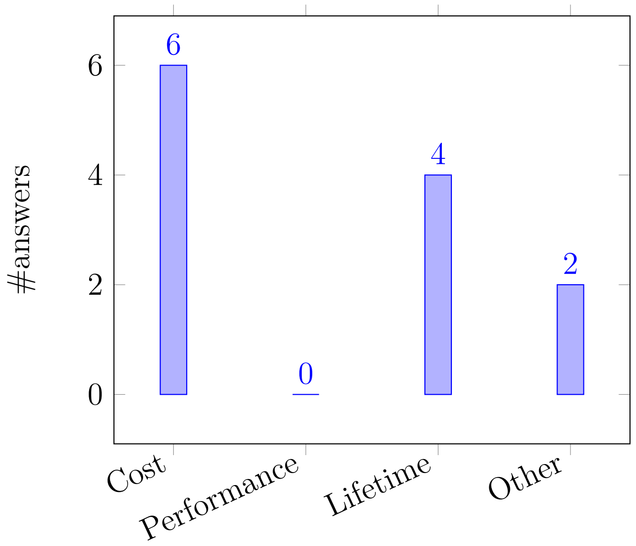

Figure 14: Main obstacles of replacing legacy luminaires with LEDs based on the survey results

It can be speculated that the high initial investment costs are the biggest obstacle in replacing the old lighting systems with LED systems. But as LEDs get more energy efficient, the life cycle costs will decrease (life cycle costs calculations are performed in section 7.8). However, LEDs produce much less heat, thus the growers must consider whether an external heating system is required. Although, the lack of heat produced could allow the grower to use vertical farming. However, vertical farming is not possible with high wire plants, such as tomatoes and cucumbers. In addition, the lack of external heat from the LEDs allows the growers to use LEDs as supplemental lighting closer to canopy (or within the canopy) without burning the plants.

Retrofitting conventional lighting systems in greenhouses is an expensive task and requires planning and consultation. In addition, if it is hard or even impossible to estimate the lifetime and thus, maintenance costs of the parts of the lighting system, it may not be an interesting choice for a greenhouse to replace its conventional lighting systems with the latest LED lighting technology, at least in the near future. On the other hand, if the growers do not see the benefits of LEDs over legacy system significant enough, they may still consider waiting for the future generation LED luminaires with improved properties (e.g. increased optical efficiency and increased lifetimes) or for the prices to decline significantly.

According to the answers, the growers expect longer lifetimes, better reliability, lower prices and increased yields in addition to lower energy consumption. The growers also expect control over the output spectrum. It can be assumed that the reason for the expectations of longer lifetimes and better reliability is the fact that most of the luminaires are not as simple to repair as the conventional lamps. Unlike the conventional lamp-based luminaires, the individual LEDs in a luminaire are typically not replaceable. Hence, in case of a catastrophic failure, the entire luminaire should be replaced, which is expensive. However, there is an initiative for modular LED luminaire interface standard called Zhaga. It is developed by Zhaga Consortium. The modular design would allow individual parts of the LED luminaires to be replaced not only by the original manufacturer, but by a part by any manufacturer supporting the standard interface. [39] Furthermore, the growers may not have strong, if any, technical background or knowledge on LEDs. Thus, they may be unaware of the lifetimes the luminaires currently have nor have knowledge on the latest development.

# 6 Connected lighting in horticulture

Different crops require different spectral compositions and light output levels. In addition, timing of light is important. For example, lettuce growth can be promoted by lighting at night. [31] LED luminaires may be designed to have control over the parameters (e.g. wavelength, light output and timing). To control these parameters, the luminaire should be designed to implement a control system or a communication protocol. The survey performed for this thesis also revealed that the growers would like to have the ability to control light output spectrum in LED luminaires.

Connecting and controlling horticultural LED luminaires with various environmental sensor devices, such as DLI sensors, could improve for example energy usage efficiency. For instance, supplemental lighting in a greenhouse increases the overall energy usage; however, by controlling the supplemental lighting with automation control algorithms could possibly result in improved energy usage and increased economic benefits [40]. Lighting automation is thus becoming increasingly important, since it can potentially save energy and increase profits.

Designing the luminaires to implement a standard communication protocol would allow third party manufacturers to produce control systems and interconnectable devices. There are currently multiple open standard communication protocols, which could be implemented in the LED luminaire designs. However, the lighting field still lacks a de-facto standard. In addition, there are proprietary lighting control systems for horticultural lighting automation on the market; however, most of them are not open for third party manufacturers.

Connected lighting system (i.e. CLS) means a network in which multiple luminaires and sensors collecting environmental information are interconnected and operate together. Connected lighting combines automation and lighting through various sensors or rules. For example, lighting automation has been used in building and office automation to save energy. This can be achieved through various sensors, such as daylight and presence sensors. The data acquired from the sensors is then used to control lighting.

Consequently, automation can also be utilised in horticulture (e.g. in greenhouses). Automation allows greenhouse growers to adjust their growth lights to environmental parameters, such as daylight and temperature. Thus, control the growing environment in a specific manner. In addition, other components, such as HVAC (heating, ventilation and air conditioning) and $CO_2$ sensors could possibly be installed in the control system.

This chapter introduces some of the currently available communication protocols and lighting control systems, which could be utilised in greenhouse environments to control horticultural LED luminaires.

## 6.1 Standard protocols

There are control protocols, such as DALI, ZigBee and KNX, which are either dedicated to lighting control or which can be utilised in lighting automation. The before mentioned protocols are not designed for horticultural use but could be utilised to control horticultural LED luminaires. The following sections discuss these protocols and the possibility of utilising them in connected lighting systems.

### 6.1.1 DALI

Digital Addressable Lighting Interface (i.e. DALI) is a wired digital lighting control protocol for communication between electronic lighting devices. It was developed to replace the 0–10 V analog control. It is a standardised protocol defined by the international standard IEC 62386. [42]

In a DALI system each individual device has its own address and can be controlled separately. The ability to send the commands to every device (i.e. broadcast) in the network or only to selected groups is also possible. DALI supports serial and star network topologies, and any combination of those. The protocol enables two-way communication between devices, thus the status of a device can be queried. System power and data is carried by the same wire. [42] DALI-2 will have the ability to control the colour of an LED lamp or luminaires; however, only correlated colour temperature (i.e. CCT). [42]

DALI has long been used in office and building automation. However, it could be used in greenhouse automation. It does not by the standard support wireless communication, such as Bluetooth, and requires the use of control cables. Thus, the installation may become complex. However, wired control can provide better reliability than wireless protocols, such as ZigBee. Although DALI can be used to control LED luminaires, the lack of appropriate horticultural sensor equipment, such as DLI sensors, could restrict its wider use in greenhouses and in horticultural applications.

A DALI compatible LED luminaire would have to be designed to include input and output ports for the DALI control cables. In addition, additional electronic components could be needed. These could result in increased overall luminaire dimensions. It could be a problem due to possible sun blocking and shadow casting, if the luminaire is used as a supplemental lighting. Nonetheless, the additional electrical components would increase the overall luminaire costs.

### 6.1.2 ZigBee

ZigBee is an IEEE 802.154.2-based communication protocol developed by the ZigBee Alliance group. It is a wireless protocol with low energy consumption and low data rate. ZigBee is used in many fields, such as in home and building automation, and industrial controls. [43] The protocol allows different devices, such as sensors, to communicate together. Thus, it can be used to create a connected lighting system.

ZigBee supports star, mesh and tree topologies. Star topology is the same simple topology Wi-Fi uses. The star network is controlled by a single ZigBee controller device. In mesh network the nodes connect directly to as many other nodes as possible. This increases the signal coverage. Tree network combines mesh and star networks. The star network devices are connected to a router, which transmit data and control messages using a hierarchical routing strategy. [43]

ZigBee is used in some home automation control systems, such as Philips Hue lighting control system. Consequently, the protocol could be implemented in greenhouse lighting automation, however, the reliability of the wireless protocol and the scalability could be an issue to the growers due to limited wireless coverage distance. Nevertheless, ZigBee could be implemented in smaller size greenhouses.

In fact, a non-commercial control system controlling temperature, humidity and soil moisture of a greenhouse has been made with ZigBee. [44] Although, the system was not designed to control lighting, the ZigBee network could be accompanied with a light sensor to measure and adjust lighting.

ZigBee is a wireless communication protocol, thus implementing the protocol requires wireless modules and antennae. This requires additional electronics, which could increase the required luminaire dimensions, and thus lead into sun blocking problems if the luminaire is used as a supplemental light. A ZigBee module includes a computing chip, which produces heat and consumes power. The additional heat increases luminaire temperatures and should be compensated with thermal management. However, the heat produced by a tiny chip may be insignificant in relation to other parts of the luminaire. The power consumption of the chip may also be insignificant.

### 6.1.3 KNX

KNX is a communication protocol standardised and defined by the international standard ISO/IEC 14543. It is used in building automation. It can be used to control lighting, heating and other functions, such as ventilation and irrigation. KNX protocol supports wired communication through twisted pair and power line. In addition, it supports wireless communication through radio frequency and Ethernet/Wi-Fi. [45]

In addition, the KNX devices, such as sensors, are able to communicate ad hoc. It means that the devices can communicate directly to each other and no centralised device of communication is required. [45]

Although the protocol is designed to and mainly used in building automation, it supports the control of many of the functions, which could be beneficial if implemented in greenhouses. Moreover, KNX is an open standard, which means that the growers would not be bound to a single manufacturer. This enables safer long-term planning and could guarantee safety for investments.

Furthermore, the KNX devices are able to simultaneously communicate wirelessly or through wires, thus simplifying the installations and increasing scalability. Moreover, the ability to communicate over the internet protocol could be utilised in data processing. For instance, it could be used to send the collected sensor information to be processed by a dedicated server. This could be especially useful in large scale greenhouses or in research.

Similar to ZigBee, implementing the KNX protocol requires either input and output ports or wireless module electronics, antennae and other system chip modules. This requires additional electronics, which could increase the required luminaire dimensions, temperatures and power consumption.

## 6.2 Proprietary lighting control systems

This section discusses connected lighting systems already available on the market. The discussed systems are closed source (i.e. proprietary), which means they do not support devices by other manufacturers nor is their specifications or application programming interfaces open.

### 6.2.1 Priva greenhouse controls and GrowWise

Priva is a system, which connects various sensor devices to create a complete control system. The system includes process control, climate control, light and $CO_2$ conditions control among with an ability to control plant irrigation automatically. [46]

Priva claims to be an all in one solution, from which the greenhouse growers could really benefit. However, since no data on the actual performance is provided, more studies and research are needed before the Priva system would be intriguing to the growers.

Philips has launched its digital lighting automation system called GrowWise Control System. According to the manufacturer, it is supposed to be a digital hardware platform to replace the old analog system. [47] Also according to the manufacturer, the control system will enable the user to create its own customised time-based light spectra. [47] The system controls deep red, blue, white and far red. In addition, it controls the light duration and intensity. The system is digital and according to the manufacturer, it can also be integrated into a climate or auxiliary computer. [47] However, the manufacturer provides no data or specifications for the GrowWise system, thus comparing it with the other systems or protocols is not possible.

### 6.2.2 smartPAR

LumiGrow has developed a lighting control system, which combines LED lighting and cloud-based controlling software into a single lighting system solution. [14] The system is operated via a cloud based application, through which paired LEDs can be controlled. [14] The system can be combined and used with the luminaires presented in section 4.2.3.

With the software it is possible to set up lighting zones, manage lighting automation (schedules), control intensity of the light and modify spectrum (i.e. ratios of red, blue, and white light emitted). Moreover, it allows control of photoperiod – the amount of light the crop is exposed to in a 24-hour period. It also enables the users to monitor energy usage and luminaire operational state. The control software works in cloud, thus on phones, tablets and computers without additional remote controls. [14]

Currently there is only one sensor module available to the system. It is a light sensor module, which measures daylight and controls the luminaires according to a plan set by the grower to meet the desired DLI. The manufacturer promises that the sensor connected to the system ensures ideal lighting conditions in any weather and despite of lack of natural sunlight. [14] However, there is no data nor research provided by the manufacturer. In small greenhouses one sensor could be adequate, but a large-scale greenhouse might require more than one sensor. The system is not open, thus only the devices from the manufacturer can be utilised with it. Therefore, there is not guarantee that there will be additional sensors in the future.

An illustration and connecting of the sensor is presented in figure 15. The sensor operates by constantly measuring the light levels in the greenhouse and automatically controlling the light levels of luminaires to reach the set DLI target. [14]

Figure 15: A DLI sensor module with an LED luminaire [14]

## 6.3 Summary

This chapter presented lighting automation systems and communication protocols, which could be used to create a CLS. However, there are more parameters to a greenhouse plant growth than just light. Plant growth depends on other parameters, such as temperature and humidity. Therefore, a complete greenhouse connected lighting automation system should offer control over other parameters in addition to lighting. There is atleast one complete system on the market, which claims to combine all the necessary sensors [46].

Currently there are also other lighting control systems (e.g. smartPAR), which simply control lighting, but lack other sensors and controls. For instance, smartPAR does not support devices, such as sensors and luminaires, made by third party manufacturers. Hence, there is no guaranteed support for the products nor a guarantee for further development of new products from the manufacturer. Thus, investing in such system may not be reasonable for a greenhouse grower in long-term due to these uncertainty factors.

There are communication protocols on the market, such as DALI, Zigbee and KNX, which could be utilised in horticultural luminaires to allow communication between luminaires and sensor devices. However, implementing the protocols requires additional electrics (e.g. wireless modules or input/output ports), which may result in negative outcomes, such as increased luminaire dimensions and temperatures. The additional electrical chips required for the communication consume power, and thus increase the overall energy consumption and luminaire cost. In addition, the additional electrical components could possibly decrease the systems' overall reliability and thus its lifetime. Moreover, the increased energy consumption and luminaire cost may increase the life cycle costs and payback times. However, the possible benefits from utilising lighting automation could overcome the increased operational costs in terms of improved yields.

Nevertheless, lighting controls beyond simple ON/OFF or timer are already available on the market and could be utilised in greenhouses. Some of them are designed for horticultural use and some are designed for building automation. However, the lighting field still lacks an open standard protocol dedicated to horticultural automation. Further development is therefore still needed. In addition, more research is necessary on the controlling strategies of greenhouse automation. They may become an important factor in the future [48]. For example, Pinho et al. concluded that outcome fresh biomass in lettuce grown under ON/OFF-strategy and dynamic lighting control were the same per energy unit consumed [49]. However, through optimisation of control strategies, a better energy efficiency could be achieved and therefore a better yield per consumed energy unit. [49]

# 7 LED luminaire design

This chapter presents important design aspects of LED luminaires for horticultural applications – plant growth in particular. The grower survey in chapter 5 revealed that growers expect adjustable spectrum and high energy efficiency from the future LED luminaires. In addition, as an obstacle to replacing the legacy luminaires with LEDs, lifetime and reliability were mentioned as key elements. Therefore, these aforementioned are presented in this section among with a few other essential design aspects.

## 7.1 Design process

Designing luminaires always requires the recognition of the target application. Application specific characteristics must be met with the design. For example, using luminous efficacy as one of the key design aspects is sufficient for human centric interior lighting, however, using it as a key for designing luminaires for horticultural applications is not recommended, due to the way plants perceive and utilise light.

LED luminaires have been designed mainly to serve the human vision (e.g. for home or office). Therefore, also the horticultural luminaires have been typically designed to replace the conventional lamps, such as HPS. [5] LED luminaires have a tremendous advantages over traditional HID lamps, such as spectrum control and lower heat emissions.

For horticultural applications, the target crop must be defined. The spectral composition and environmental variables can then be set accordingly. For instance, lettuce growers may not want flowering lettuces, but fast growing and high-biomass plants. Thus, certain plant processes, such as flowering, should be prohibited via luminaire output spectrum design. This can be achieved by tailoring the luminaire output spectrum. [41]

In horticultural applications it is also important to recognise the required luminaire design for different growing environment. There is different criteria for designing a luminaire for vertical farming and for greenhouse supplemental lighting. For example, for the vertical farming, it may not be important to minimise the luminaire dimensions. However, for greenhouse supplemental lighting luminaire, the dimensions are important due to possible shadow casting. On the other hand, the performance to cost ratio should also be optimised for the target application. For instance, in a greenhouse, the value of increased yields (e.g. fresh biomass) due to using supplemental lighting should be at at least equal to the additional operational costs of the supplemental lighting [31].

In the luminaire design process, lighting design tools, such as DiaLux can be used to simulate and calculate the output light levels on surfaces. In addition, mathematical models and tools (e.g. Matlab and Comsol Multiphysics) can be used to simulate and estimate the light outputs and thermal design. The luminaire designs can be modelled with a computer-aided design software (i.e. CAD). [50]

## 7.2 Light output

As was mentioned in chapter 2, the amount of photochemical change in a plant is equivalent to the amount of photons absorbed by the plant, thus photosynthetic photon flux output is a significant aspect in luminaire design. In fact, it can be considered as the most important aspect. Moreover, the photosynthetic photon density PPFD should be measured to match the requirements. [21] The more photons per square meter, the more potential photochemical change. However, the absorption is plant specific, and thus the spectrum should also be optimised. [41]

In addition, calculating the required light output (i.e. irradiance) to acquire the desired PPF output is important in the design process. [11] The number of individual LEDs required for the luminaire can thus be estimated. The desired PPF can be calculated at crop level by assuming the LED as a point source [11] (i.e. its largest dimension is small compared to the distance between the light source and target [16]). Thus, the photon flux at distance $d$ can be calculated as follows [11].

The angular radiant intensity at an angle $\alpha$ between the source and vertical plane is given by

$$I(\alpha) = I_{max} \cos(\alpha) \tag{7}$$

where $I_{max}$ is the maximum radiant intensity. Angular irradiance $E(\alpha)$ at distance $d$ from the LED source is given by

$$E(\alpha) = \frac{I_{max}}{d^2} \cos(\alpha) \tag{8}$$

The the photon flux of an LED source with peak wavelength $\lambda_{peak}$ (in meters) can be calculated as follows [11]

$$E_p(\alpha) = \frac{\lambda_{peak} \cdot I_{max}}{N_A \cdot h \cdot c \cdot d^2} \cdot \cos(\alpha) \tag{9}$$

where $N_A$ = Avogadro's number
$h$ = Planck's constant
$c$ = speed of light

The light output of an LED luminaire may be increased by increasing the amount of individual LEDs in the luminaire (i.e. LED density) or increasing the total light output of a single LED. [15] Increasing the LED density will result in higher light output. However, the overall luminaire price will increase due to more electrical parts used. Consequently, the increased power consumption will increase the operation costs and thermal load. Nonetheless, increasing the light output per LED would result in a fewer LEDs per luminaire. Therefore, calculating the amount of light and optimising the amount LEDs is an essential part of luminaire design.

There exists a problem in increasing the light output, however. Driving an LED with a higher current density will result in a lower energy efficiency due to current droop (i.e. reduction in the internal quantum efficiency). [5][18] Research on eliminating the current droop is currently being conducted. [5] Nevertheless, in LED luminaire design, the desired amount of light output should be calculated and optimised for the target application (i.e. crop type) and power consumption to achieve desired energy efficiency.

PPF levels can be adjusted either by controlling the current or with pulse width modulation (i.e. PWM). PWM means modulating the frequency at which an LED is switched on and off. Duty cycle (i.e. the time the LED is on in the ON/OFF cycle) can be decreased and thus the PPF output levels are decreased. However, the effects of using PWM to control PPF levels in plant growth are yet relatively unknown. [31]

## 7.3 Light distribution

The typical light output pattern of an LED on a horizontal plane is circular symmetrical. [51] Secondary optics can be used to direct the emitted light and enhance the photosynthetic usage efficiency. Without proper optics, a portion of the light is wasted, since it is not captured by the target plants. [51][11] Figure 16 illustrates a circular symmetrical pattern (left) and a rectangular pattern (right), which can be achieved by using proper secondary optics [51]. For instance, the illustrated rectangular pattern could be used in a narrow greenhouse growing area.

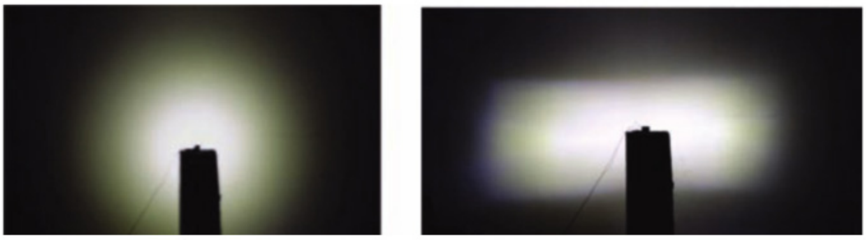

Figure 16: Circular and rectangular output patterns [51]

Thus, using proper secondary optics, the light output patterns could be optimised for the target application. Furthermore, it has been shown that using special collimating lenses as secondary optics, a certain level of photon flux can be achieved with fewer total amount of LEDs in a luminaire [11]. In addition, it has been shown that focusing photons on specific areas can be beneficial to photon capture by plant canopies [21].

## 7.4 Energy efficiency

Using LED luminaires for plant growth either as a supplemental lighting or as the only light source (e.g. indoor plan growth or vertical farming) means increased power consumption and cost of production. Energy efficiency is therefore an important design aspect, which should be considered in the design process. For luminaire comparison, a great measure for energy efficiency in plant growth is the ratio between output photons and energy input ($\mu$mol/J). [31]

The survey in section 5 revealed the growers expect the LED luminaires to be more energy efficient in the future. In addition, the biggest challenge in replacing the conventional HPS systems with LED luminaires was the high initial acquisition cost. Increased energy efficiency also means savings due to lower energy consumption. Since increased energy efficiency means more photon output per joule, the growers would receive more light output with lower costs, thus reducing the life cycle costs. In conclusion, the payback time of LED systems would become shorter due to cost savings in energy consumption and switching to LED based systems would also become more intriguing an investment for the greenhouse growers.

Using proper LED driver increases the overall energy efficiency. The optical efficiency (i.e. electricity converted into light) is only one part of the energy efficiency. The overall energy efficiency of the luminaires may be defined as the ratio between the input electrical power and the optical power. It defines how efficiently the luminaire converts electrical power into PAR range radiation. Therefore, a high-efficiency LED driver should be used to increase the overall energy efficiency. [11] There are multiple types of LED drivers on the market and a suitable driver should be chosen for the target application needs and requirements. [15] For example, the driver could be chosen based on the energy efficiency and reliability. In addition, if pulse width modulation (i.e. PWM) is wanted, the driver should have PWM circuitry [15]. Energy efficiency can also be improved by using high efficient LEDs. [52] Using optimal spectral composition can improve the energy efficiency too.

In addition to electrical efficiency, lighting efficiency can be defined in multiple ways, such as biomass produced per consumed energy unit or photons received by the plant. The first, energy to biomass conversion is sometimes referred to as lighting use efficiency (i.e. LUE), and the latter is the ratio of PAR received at plant canopy (i.e. $\mathrm{PAR}_P$) and PAR emitted from the luminaire (i.e. $\mathrm{PAR}_L$). [52]

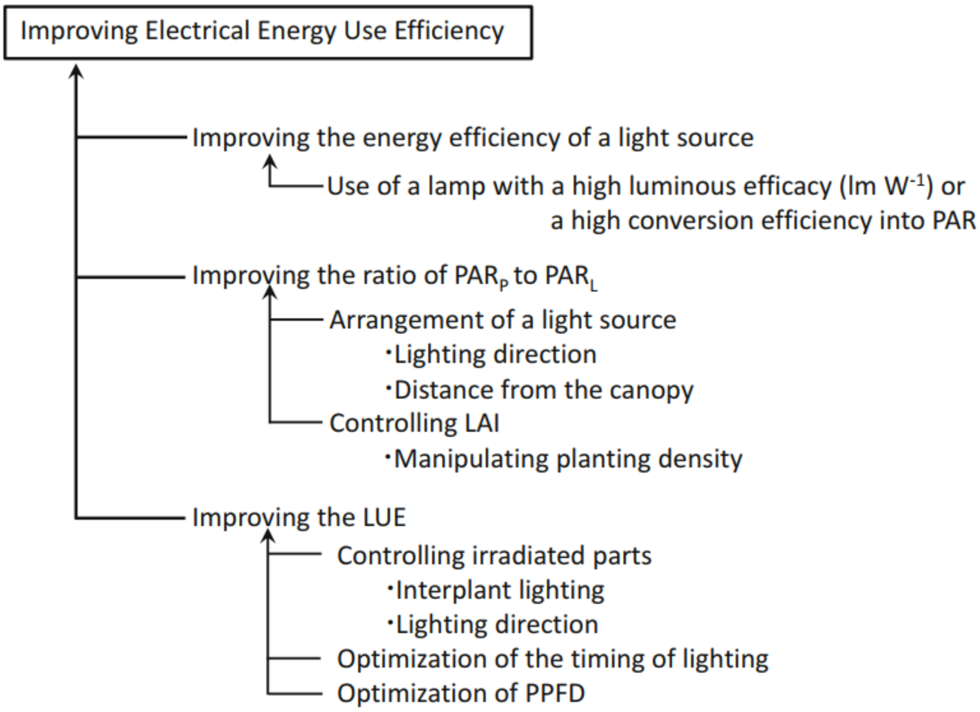

Figure 17: Factors affecting energy efficiency in horticultural luminaires [52]

Lighting efficiency can be improved in multiple different ways. In addition to using high efficient LEDs, the efficiency can be improved by improving LUE and $\mathrm{PAR}_P$ to $\mathrm{PAR}_L$ ratio. $\mathrm{PAR}_P$ to $\mathrm{PAR}_L$ ratio may be increased by reflectors or by minimising the canopy-luminaire distance. Thus, less photons emitted by the luminaire are wasted outside the canopy. LUE can be increased by controlling the irradiated parts of the canopy and direction of the lighting. LUE depends on the plant, and thus it can be further improved by optimising the timing of lighting and PPFD based on the target plant. [52] Figure 17 displays the factors, which can be optimised in order to improve lighting efficiency. [52]

## 7.5 Spectrum

The survey in section 5 revealed that the growers wish to have control over the spectrum to meet the requirements different crops have. In horticultural applications, the spectrum is an essential factor, since plants absorb and react differently to different spectral compositions. [7][26] The spectral composition is important to target application. For instance, a supplemental light luminaire requires different spectral composition than for example a vertical farming luminaire. Nevertheless, different growth phases and different plants require different wavelengths for optimal growth. In addition, the nutritional value and taste can be modified by using different wavelengths of light. [31] For example, using 440 nm blue light LEDs (30 $\mu$mol/$sm^2$) in combination with 640 nm red light LEDs (270 $\mu$mol/$sm^2$) increased the concentration of flavonoids in red leaf lettuce. [35]

As presented in section 4.2, the manufacturers are currently producing spectrum-adjustable luminaires. Real-time spectrum adjustments are not possible with older lamp types, such as HPS lamps, due to the fact that they emit light according to the characteristics defined in the manufacturing process. Furthermore, the individual wavelengths are not controllable, which is possible in LED luminaires consisting of many individual light sources (i.e. individual LEDs). Dynamically adjustable spectrum provides versatility, which means that a single luminaire could be used for multiple different crop types or target applications. In addition, one luminaire could be used for different growth phases if required.

By using different spectral compositions, and thus different ratios of certain wavelengths, the plant growth can be controlled. As mentioned before, also the plant characteristics can be adjusted via light quality. [41][35] However, the optimal spectrum for different crops are still an open question in research and the mechanisms controlling the plants' responses are still not fully understood. [26][35] Nevertheless, the target crop type should be recognised and the output spectrum in the luminaire should be adjusted to match its requirements.

The output spectrum can be constructed by using multiple LEDs with different peak wavelengths in a configuration, thus constructing a single distribution unit. The output spectrum can therefore be controlled. [53] The spectrum can be controlled by controlling the output intensities of the LEDs (e.g. with PWM or current-control [52]). Figure 18 demonstrates four of these distribution units using five different LEDs each. The density (r in the figure 18) of the LEDs in a distribution unit effects the output light uniformity [53]. However, using more wavelengths increases luminaire power consumption.

In luminaires designed for research (i.e. studying the interactions between certain wavelengths and plants), a dynamically controllable output spectrum can be highly valuable. A better understanding of the interactions and thus optimising the spectrum could benefit the growers. [5][6] For a research luminaire, the energy efficiency may not be such an important issue. Thus, a linear current-controlled power supplies can be used to create spectrally adjustable luminaires. [11]

The figure 19 illustrates the external quantum efficiencies of current modern LEDs

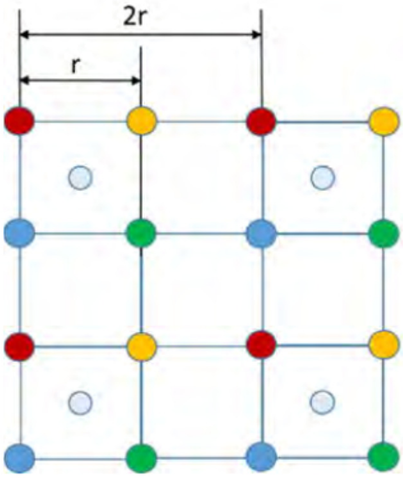

Figure 18: Four distribution units each consisting of five individual LEDs [53]

[5]. EQE is the ratio between emitted photons to the number of injected electrons (refer to section 3.4). In order to increase energy efficiency of all spectral components (and thus horticultural luminaires), research should be done to increase the EQEs of these and other wavelengths. This is important, since it reduces luminaire operating costs, and thus life cycle costs.

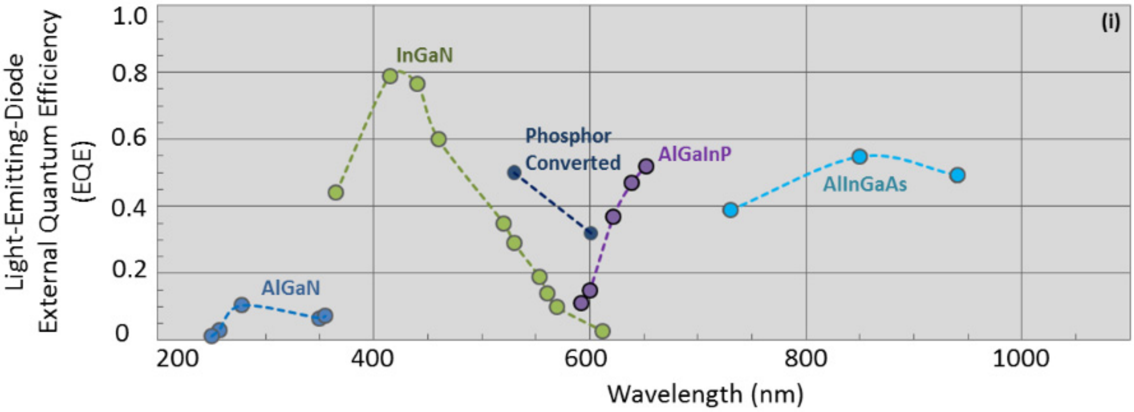

Figure 19: EQE of current LEDs at several wavelenghts [5]

Optimal light parameters (i.e. spectral composition and light output) for different horticultural plants and developmental stages is still an open question [31]. Chlorophylls primarily absorb blue and red wavelengths and in fact, red and blue LEDs provide the highest photon output per energy unit. However, other wavelengths are also utilised by the plants. [31] One of the major challenges related to the design of multi-wavelength LED luminaires is the spectral composition. The optimal choice of output wavelengths and the ratio of colours, which are suitable for the application and target cultivars is an open question. In addition to the spectral composition, the amount of light output (i.e. PPF) has an effect on plant growth too, and should be adjusted based on the target crop. [31]

As was previously introduced in section 7.2, PWM can be used to control PPF levels from an LED. There is a problem in this approach in multi-wavelength luminaires, however. It has been studied that using PWM with multiple wavelengths can result in negative effects in plants due to the light outputs being in different phase. Therefore, if PWM is used in a multi-wavelength setup, the timing to avoid phase differences is crucial. [31]

As was mentioned in section 3.2, white light can be generated using blue LED with a phosphor coating or mixing colours. [54] The emitted spectrum from phosphor coating can be defined by using different type and amount of phosphor coating. However, using phosphor conversion decreases the LED light output efficiency. [31] The LED light output efficiency ($\mu$mol/J) of colour mixing is currently higher than of phosphor conversion [54].

## 7.6 Lifetime, reliability and failure methods

Conventional non-LED based lighting systems are lamp-based that is, they are composed of individual replaceable lamps and other system components, such as ballasts and luminaire housing. Those systems tend to fail due to what is called a catastrophic failure. Catastrophic failure happens when a lamp disintegrates. In the lamp-based systems, the lamps' lifetime is usually far less than the system components' lifetime and the lamps tend to fail first, hence it has been adequate to only consider the lifetime of the lamp when assigning lifetime ratings. It has been a custom that the manufactures use measurements and statistical models to provide a lifetime rating based on the time at which 50% of the lamps of a sample group have failed. [19][20]

Testing and rating LED based systems' lifetime differs from the aforementioned. Instead of being lamp-based, they can be equipped, for example with fully integrated luminaires or lamps with internal or external driver. [19] A lifetime estimation for LEDs can be performed with a model called Arrhenius model [18]. Many different aspects affect the performance and cause failure of an LED based systems. For instance, thermal management, which will be discussed in section 7.7.

The failure of any of the systems' components may result in a product failure. However, as was previously mentioned, LED systems do not usually fail due to a catastrophic failure. They may fail due to what is called parametric failure. It means that the LED system discontinues to produce an acceptable quantity or quality of light output. Lumen degradation (i.e. decreasing of the luminaire light output) or colour shift are consequences of parametric failure. [19][5] Both have tremendous impact on the LED system, but do not qualify as catastrophic failure and are not as noticeable, since neither of them dismantles the system, but both affect the systems' performance.

Lumen maintenance has been used to represent the luminaire lifetime rating. The rating is usually specified as $L_{70}$ value (dimension hours). [19] The value is the time (in hours) when the light output has dropped 30% from the initial value. [19] Because the LED lifetimes are usually such long, it is difficult to directly measure them. However, standard test protocols (e.g. IES LM-80 & TM-21) for measuring and projecting LED package lumen maintenance exists. [5][20] These test protocols can be used to project the luminaire lifetime and thus provide the lifetime ratings.

The LED package is not the only component in the luminaire, which can cause a failure. Although, contemporary LED packages usually outlive the other luminaire components, the LED luminaires include a significant amount of other components, which can break and lead into failure. For example, thermal management components and optics may degrade over time due to various reasons. [19][20] This means that the system's actual lifetime is not only dependent on the LED package and the other parts must be considered also. In addition, extending LED luminaire lifetimes will improve the luminaire life cycle costs. [20]

## 7.7 Thermal management

Thermal management in general has been briefly noted in the thesis previously. LEDs produce heat at the p-n -junction, thus thermal management is a fundamental LED luminaire design aspect. Excess heat has negative effect on the performance, energy efficiency and lifetime of an LED. In addition, light output levels decrease, and colours shift due to temperature rise. [19][18]

Considering LED luminaire design, it is essential to design and apply proper thermal management. As was mentioned before, increased temperatures negatively affect several key parameters. [18] For horticultural applications (e.g. plant growth), spectrum and the amount of light output are essential aspects. Furthermore, reduced lifetimes and energy efficiency increase the life cycle costs and payback periods. Therefore, a cooling solution to minimise these negative effects is essential.

The thermal design should also be balanced with the requirements (e.g. form factor, weight and power consumption) set by the luminaire target application. In addition, the overall cost of the cooling solution must be considered. [18]

The heat losses are mainly produced in the active layer. The photons, which are emitted but do not exit the semiconductor, are reabsorbed and thus increase the LED temperature. In addition, the nonradiative recombinations at the active layer cause temperature increase. [18] There are methods to increase the number of photons, which exit the semiconductor (i.e. increase the light extraction efficiency) [23], but the methods are beyond the scope of this thesis. The aim of this thesis is to study the design of LED luminaires, thus the semiconductor level thermal management is not discussed further; however, the mechanism of heat generation and source of heat are important to understand.

Thermal management can generally be executed either passively or actively. [51] Passive cooling relies on conduction. In other words, there are no externally powered components, such as fans, present in the luminaire. Active cooling relies on external devices, such as fans or circulating water pumps. [51] Thermal management devices increase the luminaire cost, and thus optimising the required cooling solution to match the system is necessary. [18] Thermal resistance can be utilised to optimise the required thermal management. [51][11]

Thermal resistance is defined as the ratio between temperature difference of a component and its heating power (i.e. the electrical power not converted into photons). [51] It can be used to determine the required external cooling [11]. The total thermal resistance between the pn junction and ambient air is given by [51][18]

$$R_{thJA} = \frac{T_j - T_a}{Q} \tag{10}$$

where $R_{thJA}$ = thermal resistance between junction and ambient air
$T_j$ = junction temperature
$T_a$ = ambient temperature
$Q$ = total power dissipation of the junction

Thermal resistances in series can be summed together similar fashion to the electrical resistances. [51] A simplified thermal resistance model of an LED with an external heating sink attached is presented in figure 20 [11].

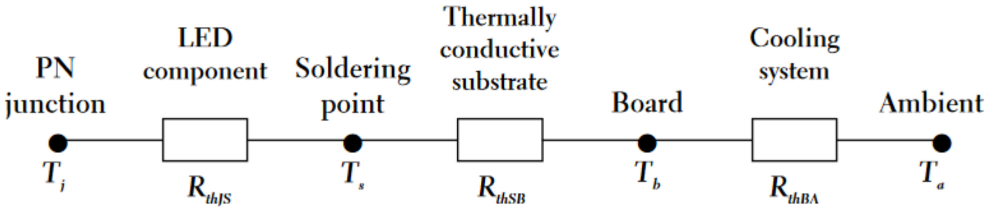

Figure 20: Simplified model of an LED with external cooling solution [11]

Where $R_{thJS}$ is the thermal resistance from junction to soldering point and $R_{thSB}$

is the thermal resistance of the substrate. The total thermal resistance of the system (i.e. between junction and ambient), $R_{thJA}$, is the sum of all thermal resistances $\sum R_i$. The thermal resistance of the external cooling solution $R_{thBA}$ is therefore given by

$$R_{thBA} = R_{thJA} - \sum R_i = R_{thJA} - R_{thJS} - R_{thSB} \tag{11}$$

Substituting the equation (10) to the equation (11), the required thermal resistance of an external cooling system is given by

$$R_{thBA} = \frac{T_j - T_a}{Q} - R_{thJS} - R_{thSB} \tag{12}$$

Passive cooling is usually constructed using heat sinks. Typically, aluminium or copper is used to construct a heat sink, because of their significant heat transfer capacity. The heat sink is attached to the heat generation source. It operates by conducting the heat from the component and then releasing it into surrounding air. Heat sinks can be constructed with a fin array to maximise the surfaces area, thus providing higher heat dissipation. In addition, either heat pipes or heat spreaders can be used. [18][51] Certain thermal compounds (i.e. thermal grease) can be used between the heat source and heat sinks to further increase the heat conduction. [18]

Heat spreaders are used to distribute the excess heat to a wider area, thus enhancing the heat dissipation. They can also be used in-between heat sinks and the component. Heat pipes are hollow tubes filled with liquid. The pipes are installed between the heat source and a heat exchanger, such as the previously discussed heat sink. [18] The liquid inside the pipe circulates through the pipe via capillary action. [51]

Passive thermal management has a few advantages over active cooling. The fact that passive cooling contains no external electrical devices, such as fans, also means it is not dependent on the operational status of those. In other words, failure of the external devices has no effect on the passive thermal management solutions. In addition, without proper maintenance, cooling fans may gather debris and dirt, hence compromising its operation. Furthermore, using external, auxiliary powered devices increases the overall power consumption of the system and may decrease the energy efficiency. The increased power consumption will lead into increased life cycle costs and payback times. These will be presented in section 7.8.

Active cooling systems rely on external devices and energy to increase the heat transfer. For example, forced air through cooling fans and pumped liquid can be used. [18] Cooling fans can be applied over a heat source (or heat sink) in order to enhance the heat dissipation. The external fan increases the airflow from the heat source, thus increasing the heat dissipation. [51][18] The fans could be controlled externally based on temperature information from sensors. However, this could lead into more complex luminaires, and hence increase the operational and acquisition costs. Nevertheless, it could be used to detect a possible failure of a cooling device, hence increasing system reliability. A typical cooling fan is displayed in figure 21.

Figure 21: Typical axial fan used in LED cooling [18]

Pumping liquid in a closed loop piping allows effective heat removal from the heat source. The liquid absorbs the generated heat, which is then transferred into heat exchanger. [51] This solution could be used in applications, where the relatively large number of external devices are not an issue. For example, the vertical farming system presented in section 4.2 uses circulating water in pipes to cool the luminaires.

## 7.8 Life cycle costs

This section compares the life cycle cost (i.e. LCC) of conventional and LED horticultural luminaires. The luminaires from chapter 4 are used in the calculations and are selected based on their light output (i.e. PPF). HPS lamps are used as the conventional lamp type in the LCC, because according to a previous study by J. Anderson [3] and the survey performed for this thesis, they are widely used in greenhouses. The aim of the LCC analysis is to evaluate if it is cost-wise reasonable for the greenhouse growers to consider replacing their legacy lighting with LED luminaires.

The analysis includes only monetary flows, thus other aspects, such as design, maintenance and end-of-life costs are omitted. Both lighting systems require design and maintenance, but those are in this analysis estimated equal, and hence omitted. In addition, both luminaires must be recycled, and thus the end-of-life costs can be considered equal. Therefore, they are omitted from the LCC calculations. The present value method is used to calculate the LCC as follows [56]:

$$LCC = I_0 + \frac{(1+i)^n - 1}{i(1+i)^n} \cdot C \tag{13}$$

where $I_0$ = initial investments (year 0)
$i$ = rate of interest
$n$ = total number of years
$C$ = annual operating costs

The annual operating costs $C$ per luminaire is calculated as as follows:

$$C = P \cdot t \cdot \epsilon \tag{14}$$

where $P$ = power
$t$ = usage in hours
$\epsilon$ = electricity price.

The table 9 provides the life cycle costs for 400 W and 600 W HPS luminaires and two LED luminaires. Rate of interest used is 4% and photoperiod is assumed as 10 hours, thus 3650 hours a year. Electricity price used in the calculations is 15c/kWh.

The LED luminaires chosen for the comparison are the modular LED toplighting and interlighting high modules from section 4.2.1 (with 400 W HPS) and the supplemental greenhouse luminaire presented in figure 12 (with 600 W HPS). The LED luminaires were chosen to match the light outputs of the 400 W and 600 W HPS luminaires presented in table 2. The luminaire prices are from luminaire resellers. The initial investment in HPS LCC calculations consists of the number of lamps (i.e. units) needed to fulfil the LED luminaire lifetime plus the price of the HPS luminaire. Years (n) are calculated from the LED luminaire lifetimes divided by the yearly usage.

Table 9: Life cycle costs of LED and HPS luminaires

| Type | Supplemental LED | modular LEDs | 400 W HPS | 600 W HPS |
|---|---|---|---|---|
| Power | 525 W | 281 W | 430 W | 600 W |
| Light output (PPF) | 1190 $\mu$mol/s | 760 $\mu$mol/s | 695 $\mu$mol/s | 1100 $\mu$mol/s |
| Lifetime (L90) | 38000 h | 25000 h | 5000 h | 12000 |
| No of units | 1 | 2 | 5 | 3 |
| Initial costs (EUR) | 765 | 679 | 350 | 300 |
| LCC (EUR) | 3096 | 1602 | 1763 | 2964 |

The discounted payback time (i.e. DPB), which takes into account the time value of money, is given by the following equation [56]

$$DPB = \frac{-\ln(1 - \frac{iC_i}{C_{op,o} - C_{op,n}})}{\ln(1+i)} \tag{15}$$

where $i$ = rate of interest
$C_i$ = price of the investment
$C_{op,o}$ = operating costs of old
$C_{op,n}$ = operating costs of new

The operating costs can be calculated with equation (14). For example, the luminaires are operated ten hours a day, thus 3650 hours annually. The electricity price is 15c/kWh and the rate of interest is 4%. If the 400 W HPS lamp and modular LEDs from table 9 are considered, the discounted payback time is 10,3 years. Considering switching from a 600 W HPS luminaire to a supplemental greenhouse LED luminaire, the DPB is 34,9 years.

Life cycle costs are a quick measure for the viability of an investment. Total life cycle costs are a sum of initial investment costs, operating costs and residual value (i.e. resell value and recycle costs). [56] Considering LED luminaire design, all three aspects may be optimised. Luminaire design has no effect on electricity price but increasing the overall energy efficiency decreases the operational costs, and thus decrease the life cycle costs. In addition, the payback times decrease with the operational energy usage difference between old and new device. The initial investment costs in LCC can be decreased by minimising the luminaire costs. The luminaire costs can be minimised for example by using cheaper materials in the luminaire; however, this usually affects operational reliability. From figure 9 can be seen that the life cycle costs of LED luminaires and HPS luminaires are relatively similar.

The following simplistic model can be used to obtain a perspective of the payback periods. The model is very simple and does not take into account many important parameters, such as HVAC costs and maintenance. Therefore, the model is not an accurate estimate of the payback period but merely an upper limit. The model assumes that the grower has already acquired and is using an existing non-LED based lighting system.

If only the payback period due to energy savings between the luminaires is considered, the payback period can be calculated the following way. The power consumption of each luminaire is based on the amount of power needed to acquire the same PPF output. The simple model for payback period (in years) $t$ then becomes:

$$t = \frac{S}{\Delta P \cdot \epsilon}, \tag{16}$$

where $t$ = payback period
$S$ = new luminaire price
$\Delta P$ = the annual difference in power consumption
$\epsilon$ = the electricity price per kWh

Obviously, the payback period should not exceed the lifetime of the LED luminaire. The upper limit for the LED luminaire price can be solved from equation (16) as follows:

$$\text{Price}_{NEW} \leq t \cdot \Delta P \cdot \epsilon + \text{Price}_{OLD} \tag{17}$$

This model does not take into account the possibility of increased yields, thus profits from using LED luminaires. In addition, the heating costs most likely increase and thus increase the overall costs.

For example, switching from a single 400 W lamp to modular toplighting high and interlighting regular luminaires. The two LED luminaires produce the same amount of PPF output (695 $\mu mol/s$) as the HPS, but use less power. The maximum price of the replacing system could be 560 euros, if the paypack period is assumed as 25000 h (i.e. the lifetime of the LED luminaire) and photoperiod as 10 h.

## 7.9 Other factors

Other factors, not discussed in the previous sections, should also be considered in the LED luminaire design. For example, casing: especially in greenhouse, the humidity levels may rise to such levels that the luminaire casing must be designed to such that the ingress protection (IP) is significant enough to withstand the environmental conditions. In addition, electrical safety standards should be taken into account. With proper casing, optical and thermal properties of an LED can be improved [51].

Depending on the target application, the form factor can become quite an important design aspect. Thus, it should be designed accordingly. For example, a luminaire designed to be used as a supplemental light to natural sunlight, should block as little sunlight as possible. [21] Since LED luminaires can basically be constructed in any form imaginable, they even be integrated within building structures (e.g. greenhouse supports). [21]

In addition to form factor, it is essential for the luminaire to produce even and uniform lighting. If for example, in a greenhouse the lighting is uneven, the crops may have areas, which differ in development. Thus, parts of the crop may be ready to harvest before other parts. In a large-scale greenhouse, this could become a serious issue and should be considered in the luminaire design. These can be overcome with proper design of secondary optics [11].

Conventional light sources, such as HPSs, can produce shadows due to singular narrow light cone. However, enlarging the illumination emission area on the luminaire (i.e. spreading the individual light sources on a larger surface are) can prevent casting of shadows within the canopy. The extremely small size of light emitting diodes allows the spreading of the light sources densely across the whole luminaire area, thus increasing the light incidence angles and possibly reducing shadows casted within the canopy. In addition, the freedom of form factor allows designing the luminaires in such fashion that the point like light sources (i.e. individual LEDs) are spread on a wide area. Thus, the light arrives at the crop from multiple different angles of incidence. Figure 22 illustrates the before mentioned light cones.

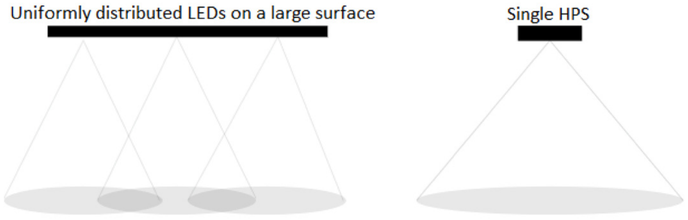

Figure 22: Light cone intersection of LED and HPS

Measuring the PPFD of the luminaire and installing the luminaire to a specific height in order to provide the plants with required amout of photons is important design and installation aspect. [57] In addition, if the crop under the fixture is narrow, using broad light beams may result in high amount of wasted light. [21] Light can be directed towards the crop by using collimating lenses as secondary optics, but it may result in loss of energy efficiency and increase the luminaire costs. [11]

When heat sinks, and other cooling solutions are applied on the luminaire, the weight also increases. [18] Therefore, sufficient luminaire attachments (i.e. docking) in case of mechanical failure should be considered. In addition, all materials used (e.g. cooling solution) in the luminaire will affect the end-of-life costs, thus increasing the life cycle costs. [18] Also, the environmental effects of the used materials should be taken into account and evaluated and the potential environmental impacts of the entire luminaire life cycle (i.e. the life cycle assessment) can be estimated using the ISO 14040 standard. [56]

Luminaire aesthetics (i.e. the exterior looks) may not directly contribute to the performance of an LED luminaire, but could be beneficial in product marketing. However, in some cases there might be some limitations to the luminaire looks. For instance, if the luminaire is required to blend into the surroundings.

Finally, in addition to the luminaire design, light planning is also a critical step. The behaviour and light output of multiple luminaires can be approximated by using a lighting simulation software, such as DiaLux.

## 7.10 Summary

This chapter discussed the key aspects in horticultural LED luminaire design. The design process for horticultural LED luminaires was first discussed.

Light output of LED luminaires was also presented. The amount of photochemical change is equivalent to the photons absorbed by a plant, and thus light output can be considered as the most important aspect in luminaire optimisation. Calculations for required light output to achieve desired PPF was presented. Light distribution and energy efficiency were discussed. Light distribution can be optimised using secondary optics. LED luminaire energy and lighting efficiency can be improved by multiple ways, such as using an energy efficient driver or increasing lighting use efficiency.

The grower survey performed for this thesis revealed that Finnish greenhouse growers expect the future LED luminaires to have controllable spectrum. A method of constructing spectrum was presented in this chapter. Adjustable spectrum can be constructed using LEDs with different wavelengths and controlling their intensities. Lifetime, reliability and LED failure methods were also discussed in this chapter. It was shown that LEDs usually fail due to parametric failure. It was discussed that lumen maintenance has been used to provide LED luminaire lifetime ratings.

Thermal management for horticultural LED luminaires was introduced in this chapter. It is an important design aspect, since excess heat has negative effects on the performance and lifetime of an LED. Generally, there are two methods to execute thermal management: passive and active cooling. LCC calculations between HPS and LED horticultural luminaires were performed in this chapter. The results from the LCC calculations were that similar optical performance (PPF output) HPS and LED luminaires have similar life cycle costs. Other factors, such as casing and mechanical structure also was discussed.

# 8 Discussion

The survey answers revealed that the growers expect the LED luminaires to be more energy efficient and have longer lifetimes in the future. Furthermore, the biggest obstacle in replacing the old HPS systems was the high initial acquisition cost.

Increasing the energy efficiency would decrease the life cycle costs and decrease payback times. Since increased energy efficiency means more photon output per joule, the growers would receive light output with lower cost per photon. The initial acquisition costs of LED luminaires is currently higher than the price of HPS luminaires. Thus, the initial costs should be compensated with high energy efficiency and more beneficial functions, such as adjustable spectrum. Also extending the luminaire lifetimes for example via better thermal management would fulfil the growers expectations and compensate for the immense initial costs.

Moreover, if the spectrum is adjustable, the luminaire is thus more versatile. According to the survey, the high initial costs were the main challenge the growers had. Thus, the versatility of the luminaires could interest the growers, since a single luminaire can be reused for different crop needs and growth strategies. Furthermore, specific spectrum control or even instant control of ON/OFF is not possible with conventional luminaires, such as HPS. However, the features are possible with LED luminaires. Thus, developing optimal lighting strategies could also make LED luminaires more intriguing an investment for the growers; since, optimal lighting strategies could further enhance fresh biomass production and yields.

It can be assumed that the change process from conventional luminaires into LEDs will still take time, because for the greenhouse growers, it becomes a question of investment and money. Rather, the growers may want to wait for the LED luminaires to either provide them with something significantly beneficial over legacy luminaires (e.g. better energy efficiency and more scientifically proven results in terms of performance) or significantly lower prices. Currently, the life cycle costs and benefits from the LEDs may not be great enough for the growers to fully begin the transition.

# 9 Conclusions and future aspects

This thesis studied the design optimisation of LED luminaires. It shows that LED luminaires have the potential to be used in horticultural applications and can replace the conventional light sources, such as HPS lamps in greenhouses. However, few key aspects, which were discussed in thesis (e.g. energy efficiency) must be developed design wise in order that LED luminaires would completely surpass legacy luminaires in terms of overall performance, usability and life cycle costs. In the luminaire design this means using developing more energy efficient LEDs, optics and identifying the target application. In addition to the luminaire design, the photobiology (i.e. the influence of light on plant growth) must also be researched to further enhance the luminaires.

LED luminaires already have capabilities, which are absent from the conventional light sources. For example, adjustable spectrum, instant on/off control, long lifetimes and the fact that switching the luminaires on/off does not affect the lifetimes. However, as the survey for greenhouses growers for this thesis revealed, acquisition price is the main obstacle to overcome before LED luminaires surpass the legacy lighting.

In terms of life cycle costs, the LED luminaires do not provide the growers with much higher value for their money than HPS lamps. Retrofitting the LED luminaires could be expensive and thus not intriguing for an established grower. However, for a new greenhouse, choosing LED luminaires over conventional options could be more interesting. The payback times grow quite lengthy due to the high power consumption of LED luminaires. However, the payback model introduced in section 7.8 does not take into account the possibility of increased yields or quality of crops resulting from using LEDs. Thus, possible increase in profits due to using LEDs are not taken into account.

During making thesis an idea of combining artificial intelligence with plant growing arouse. In other words, using AI to determine the growth phase and use different spectrum during different growth phases. The phase could be easy to recognise in rolling table growth due to linearity, however, in a non-rolling zone-based table growth it might not be such an effortless task. The idea is to use machine vision to recognize the plant growth phase. Thus, the spectrum could be automatically adjusted by the phase the plant is in.

Another future study idea that arouse is adjusting the control systems according to real-time measurements from the actual plants. I think an interesting study topic in the future would be Li-Fi (light fidelity). It is a technique were LEDs are used to transfer data in visible light spectrum. This could in theory be applied to horticultural applications, such as communication between the luminaires and sensors.

One of the respondents to the survey answered that creating a so-called interruption light with LEDs is something they are looking forward to. The interruption light means exposing the plants to a certain wavelength (usually during night time – outside of the photoperiod) to inhibit certain behaviour or change of growth phase of the plants. For instance, a brief usage of a certain wavelength could interrupt strawberries from exiting vegetative phase. This could be achieved using LEDs and automation.

Control strategies of automation in lighting control for better yields per energy unit is also an interesting topic of study and will likely be important in the future.

# 10 Summary

Most of the year the environmental factors, such as temperature and the amount of light are not optimal for plant growth in Finland. Due to long, cold and dark winters, artificial lighting is needed to ensure the required amount of light. Finnish greenhouse growers have been using mainly high-pressure sodium-vapour lamps as their main source of supplemental light. There has been a lot of promising studies and research conducted on the possibility of LED luminaires replacing the conventional luminaires in plant growth. Furthermore, there is massive potential of using LEDs in horticultural applications.

The aim of this thesis was to study the design optimisation of LED luminaires in horticultural lighting. A survey for Finnish greenhouse growers was also performed. The survey aimed to acquire information from the growers about the current state of their lighting solutions and about their expectations from the future LED luminaires. The survey results were presented and analysed. The study on the design of LED luminaires for horticultural lighting was done via literature research and using the survey data as a guideline.

The survey answers revealed that Finnish greenhouse growers were still using mainly HPS lamps as their supplemental light. However, the growers are looking forward to replacing their legacy luminaires with modern LEDs. However, before that certain challenges should first be overcome. The growers stated that the most important obstacle was the high initial costs. Also, lifetime was of concern.

Key design aspects for horticultural LED luminaires were found to be light output, energy efficiency, spectrum and thermal management. These aspects were discussed in this thesis. Lifetime and reliability were also discussed among with other factors, such as luminaire form, installation and light distribution uniformity.

The thesis also presented conventional luminaires and current state-of-the-art LED luminaires for horticultural use. Life cycle cost calculations were performed between LED luminaires and HPS luminaires used in plant growth. In addition, the potential usage of lighting automation was discussed. A few currently available protocols and lighting control systems to control horticultural LED luminaires were presented.

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