Selecting Sustainable Light Sources for Human-Centric Street Lighting and an International Comparison of Graz and Houston

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Abstract

A recent analysis by McKinsey & Company and the International Energy Agency declared that lighting retrofits are the most cost-efficient way to combat climate change, save on power bills, and control expenses. (Baillie) While street light upgrades and retrofits appear to be an obvious economic solution, many human factors remain largely unaddressed. Evidence shows that there are visual and non-visual characteristics of lighting that have a negative impact on our circadian, neuroendocrine, and neurobehavioral systems.

The purpose of my research is to: 1) determine which factors should be considered for the implementation of sustainable human-centric street lighting, 2) evaluate currently available street lighting technologies, 3) discuss the street lighting needs of Graz and Houston, and 4) propose methods to improve the sustainability and human factors involved with street lighting in Graz and Houston.

Research was conducted during a nine month period from June, 2015 to February, 2016. This consisted of four phases: 1) a semester long project dedicated to the Outdoor Lighting Design Competition sponsored by XtraLight Manufacturing Company, 2) a three month internship at XtraLight Manufacturing Company in Houston, Texas, 3) one week of on-site observation at American Testing and Assessment Laboratories, a photometric laboratory also located in Houston, Texas and, 4) five months of studying in Graz, Austria.

I have determined the following characteristics of lighting to be the most influential on human health: timing and duration, spatial distribution, correlated color temperature (CCT), spectrum, color rendering index (CRI), luminance, illuminance, glare, and light pollution.

Recommendations for Graz and Houston include taking a more strategic approach to implementation of street lighting by 1) considering the rapid advancement of OLED technology, 2) evaluating the benefit of using LEDs with a lower CCT in residential areas, 3) invest in renewable energy sources and 4) considering economic solutions such as relocating luminaires to implement new technology in desired locations.

Contents

1 Introduction

1.1 Purpose of Study

The subject of this research paper was inspired by an outdoor lighting design competition sponsored by XtraLight Manufacturing Company in Houston, Texas. The company challenged Industrial Design students to design modern street light luminaires to house LedLinX, their patented modular LED panel system. My proposal took first place in the competition allowing me to continue developing the design and begin manufacturing a limited quantity of luminaires during my summer internship with the company. I am inspired by the technology behind their products and the potential for LEDs to reduce the environmental impact of existing luminaires. The purpose of my research is to: 1) determine which factors should be considered for the implementation of sustainable human-centric street lighting, 2) evaluate currently available street lighting technologies, 3) discuss the street lighting needs of Graz and Houston, and 4) propose methods to improve the sustainability and human factors involved with street lighting in Graz and Houston.

1.2 Significance

As the global climate continues to degrade, sustainability is becoming an increasingly prominent topic. This environmental crisis is due significantly to the fact that our main sources of electricity are being generated from nonrenewable fossil fuels. A recent analysis by McKinsey & Company and the International Energy Agency declared that lighting retrofits are the most cost-efficient way to combat climate change, save on power bills, and control expenses. (Baillie) Artificial lighting has allowed our society to extend the productive day, this shift towards 24-hour days leaves us increasingly dependent on artificial lighting. Steadily growing energy demands make it more important than ever to reevaluate our energy consumption. In an estimate made by Philips Electronics Company, Europe could save EUR 3 billion in annual energy costs by upgrading streetlights to modern technology, this is equivalent to 45 million barrels of oil or 11 million tons of emitted CO2. (Philips Lighting) While the energy required to operate inefficient street lighting contributes to global warming, poor air quality, and high electricity bills, there are several other issues involved with the light produced. Artificial light has been known to affect the navigation of birds and insects, migration, feeding, communication, and mating behaviors in animals. For humans, artificial lighting can shift our biological clock, cause migraines, and even contribute to mental illness.

1.3 Methodology

Research was conducted during a nine month period from June, 2015 to February, 2016. This consisted of four phases: 1) a semester long project dedicated to the Outdoor Lighting Design Competition sponsored by XtraLight Manufacturing Company, 2) a three month internship at XtraLight Manufacturing Company in Houston, Texas, 3) one week of on-site observation at American Testing and Assessment Laboratories, a photometric laboratory also located in Houston, Texas and, 4) five months of studying in Graz, Austria.

During the Fall Semester of 2014 at the University of Houston I was involved in a semester-long Industrial Design project led by Professor Jeff Feng that focused on outdoor luminaire design. Prior to the semester, Professor Jeff Feng and XtraLight CEO, Jerry Carroom collaborated to develop a student lighting design competition. This provided an introduction into lighting design requirements and the technology behind LEDs.

My street light design was awarded first place, this meant that it would be manufactured and installed on campus at the University of Houston, Texas in the United States. This project allowed me to work as an Engineering Intern at XtraLight Manufacturing Company in my hometown of Houston, Texas from June to August of 2015. During this time I further developed my street light design to comply with the company's manufacturing limitations and meet the campus lighting requirements where the luminaire was intended to be installed. In addition I worked alongside XtraLight's Engineers to develop area and street light luminaire concepts. This position provided further insight into the design considerations for outdoor luminaires including national standards, ratings, tests, and manufacturing. I also used this time to continue observation of Houston's communities and their existing luminaires.

Next, I observed luminaire testing procedures at American Testing and Assessment Laboratories (ATAL), a testing facility fully accredited by the National Voluntary Laboratory Accreditation Program (NVLAP). Scientists at ATAL used apparatus including the Type C- Goniophotometer, and the Integrating Sphere to collect precise measurements. ATAL's capabilities include measuring Light Distribution, Lumens, Power, Efficacy, Zonal Lumens, Total Harmonic Distortion, creating IES Files, measuring CCT, CRI, Ra, and R9, x ,y ,u ,v ,u1 ,v1 , Duv, CIE+ISTMT, Electrical: AC/DC Input/ Output Power, Voltage, Current, Efficiency, Total Harmonic Distortion, and Power Factor. They also tested in-Situ Temperature Measurement, Power, LED Case Temperature, and Driver TC Temperature. (American Testing and Assessment Laboratory)

During my five months in Graz, Austria I observed the cultural, social, and economic differences between Graz and Houston. I spoke with locals and other foreign exchange students about lifestyle, crime rates, and environmental deterioration due to excessive greenhouse gas emissions.

1.4 Scope and Limitations

The purpose of my research is to: 1) determine which factors should be considered for the implementation of sustainable human-centric street lighting, 2) evaluate currently available street lighting technologies, 3) discuss the street lighting needs of Graz and Houston, and 4) propose methods to improve the sustainability and human factors involved with street lighting in Graz and Houston.

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The beginning of my studies took place in Houston, Texas in the United States where I had access to street light specifications and worked alongside a network of knowledgeable people in the industry. My time spent in Graz proved to be more difficult for conducting research. My largest obstacle in Graz was language followed closely by lack of available resources. While in Graz I had additional obligations with school and residency that limited my availability.

2 Presentation and Analysis of Data

2.1 Sustainable Street Lighting Design Considerations

The factors considered by municipalities for the decision to upgrade or retrofit street lighting vary based on community needs. Through an analysis of several case studies concerning the upgrading of street lights I have identified these common goals:

- Reducing overall costs.
- Reducing environmental impact.
- Complying with technical standards and government mandate.
- Addressing human-centric design and community concerns.

Less common objectives include improving lighting levels, achieving product standardization, and improving the community's image.

2.1.1 Cost

Replacing or retrofitting dated street lighting technology poses high initial costs that often deter municipalities from future savings. The evidence behind upgrading to more efficient lighting technology's ability to reduce power consumption is undisputable. According to the IES, updating street lighting is a low risk investment, often with a return up to 60% per year. They were able to determine this through calculations that include costs of energy, maintenance, material, labor, external costs such as meeting environmental standards, risk and liability costs, new construction or replacement / retrofitting costs, environmental costs (hazardous materials) end of life disposal, and avoided costs such as the downsizing of a purchase. (IES RP-31-14 Recommended Pactice for the Economic Analysis of Lighting 4-5)

The IES simplifies the economic analysis of lighting for municipalities by classifying two main categories of techniques, first level and second level analysis. In their guidelines they state that first level analysis is simple but can be misleading due to potential inaccuracies, and it is generally only used when considering smaller purchases. This method considers: the cost of the light, the simple payback, and the simple rate of return. A more thorough method, second level analysis, considers**:** lifecycle cost/ benefit analysis, savings investment ratio, internal rate of return, and net present value. (IES RP-31-14 Recommended Pactice for the Economic Analysis of Lighting)

There is a large potential for energy savings through the use of controls. The IES suggests that photoelectric controls such as switches, dimmers, timers, and photocells can be implemented to reduce energy consumption and improve user satisfaction. (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting) Although implementing additional technology can reduce costs in the long run, it adds to the upfront costs of luminaires. Financial assistance is often available for municipalities looking to upgrade or retrofit street lighting. Grah LED suggests that this can be achieved through public private partnerships, carbon trading, and revolving renovation funds. (Grah LED Lighting Learning Center)

2.1.2 Environmental Impact

Much like the methods used for calculating costs (first level and second level analysis,) there are multiple techniques for the evaluation of a product's environmental impact that provide varying levels of accuracy. Many buyers will typically only focus on the environmental impact caused by the energy consumption of a lighting source by citing the efficacy (lm/W). However similar, efficacy is not the same as efficiency, which is the ratio of total energy in to useful energy out. Before a street light is operational it goes through several energy-intensive processes that should be considered when calculating the environmental impact.

Life Cycle Assessment (LCA) is a more inclusive analysis and has been used in many industries since the early 1990s to calculate the environmental impact of a product by analyzing the entire lifecycle, from production to disposal. Calculations include factors such as product efficiency, the use of hazardous materials, product lifespan, and maintenance. (Douglas Hartley)

A study conducted by Students at the University of Pittsburgh indicates that the most significant reduction of CO_2 emissions can actually be achieved through changing the source of electricity. “When 100% wind energy is used, the impact of the manufacturing of the bulb and housing is expected to be higher than the lifetime electricity use.” (Douglas Hartley)

2.1.3 Technical Standards and Government Mandates

Europe’s main reference for technical street lighting standards comes from The International Commission on Illumination (CIE). The United States implements standards from the Illuminating Engineering Society (IES.) (Davenport) Technical standards establish requirements involving manufacturing, technical criteria, testing methods, and practices. Following these standards is not always necessary however they can help a product receive certifications that verify that the product meets the criteria for specific applications. These certifications come from standardized tests outlined by accredited organizations that can only be administered at accredited light testing facilities such as American Testing and Assessment Laboratories (ATAL) located in Houston, TX.

Governments are able to require municipalities to follow specified criteria like in the city of Los Angeles, California. After the successful implementation of LED retrofits in Los Angeles, the Bureau implemented a new policy that required all new retrofit projects use LEDs, or in some cases induction lighting as a standard practice. (Good Practices in City Energy Efficiency) Policies like these force old technology to be phased out in lieu of a more efficient and environmentally friendly future. Non-profit organizations such as The Climate Group are making an impact by encouraging more leaders to implement policies and incentives for reducing energy consumption in the public sector. (No Need To Wait: Accelerating Adoption of LED Street Lighting)

2.1.4 Human Factors

The majority of lighting research is focused on understanding the effects of light on our vision but more recently there have been rising concerns over the effects of lighting on human health, most notably the effect on circadian rhythm. As the use of artificial light sources becomes more popular we see increasing evidence of its impact in nature. Research shows that artificial lighting has also affected the navigation of birds and insects, migration, feeding, communication, and mating behavior in animals. A frequently cited example of the negative impacts of artificial lighting concerns sea turtle hatchlings. After emerging from their nests, their natural instinct drives them towards the reflections of moonlight on the water. This natural light typically guides the hatchlings into the ocean, however the optical radiation produced by electrical lighting has been blamed for drawing them inland, towards highways and communities. Local codes have been implemented in areas of concern that use shielded light sources or amber lighting in attempt to avoid interfering with wildlife. (IES RP-33-14 Lighting For Exterior Environments) If artificial lighting is making such a large impact on wildlife, what is it doing to us?

Standards published by the Illuminating Engineering Society (IES) concerning impact of light on human health suggest that there are certain key visual and non-visual lighting characteristics that affect our Circadian, Neuroendocrine, and Neurobehavioral Systems. These are: quantity, electromagnetic spectrum, timing, duration, spatial distribution, and adaptation. (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses) Other sources suggest there are even more characteristics of artificial light that affect humans. I have determined the following characteristics of street lighting to be the most influential for humans:

- Timing and Duration
- Spatial Distribution
- Correlated Color Temperature (CCT)
- Electromagnetic Spectrum
- Color Rendering Index (CRI)
- Luminance and Illuminance
- Backlight, Uplight, and Glare

2.1.4.1 An overview of Circadian Rhythm

The National Sleep Foundation describes the circadian system as our body's "internal clock". Circadian rhythm is a roughly 24-hour biological cycle that regulates our sleeping and eating patterns, it can affect digestion, hormone production, body temperature, and other parts of our bodies. The circadian system uses external cues such as sunlight to stay in rhythm with the 24 hour day allowing us to adjust to foreign time zones and seasonal light fluctuations. (Sleep and the Circadian System) The circadian system is composed of the suprachiasmatic nuclei (SCN), pineal gland, retina, and retinohypothalamic tract. (Richardson) Retinal photoreceptors convey optical radiation in neural signals that are sent to the SCN, resetting the 24 hour light-dark cycle. (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses) The pineal gland produces a hormone called melatonin which is responsible for making us feel tired. Optical radiation negatively affects the amount of melatonin produced. During the early hours of the morning melatonin levels will drop, in the evening production should increase in preparation for sleep. (WebMD)

2.1.4.2 An Overview of Photoreceptors

Human eyesight uses a series of photoreceptors located in the retina called rods and cones, these send information along an optic nerve to our brain. Standards published by the Illuminating Engineering Society (IES) state that in areas with high illuminance we use photopic vision, this utilizes the cones in our eyes and results in more accurate color perception. In dark environments scotopic vision engages the rods in our eyes which lack the ability to distinguish color. For dimly lit environments our eyes use a combination of rods and cones, this is called mesopic vision. (IES RP-33-14 Lighting For Exterior Environments)

Night driving requires mesopic vision however The Illuminating Engineering Society of North America (IESNA) currently uses photopic measurement criteria for evaluating street lights. This causes discrepancy in defining the lighting needs of an area. While the evaluation is currently under review many people are making calculations for LEDs using both photopic and scotopic vision. (Grah LED Lighting Learning Center)

2.1.4.3 Timing and Duration

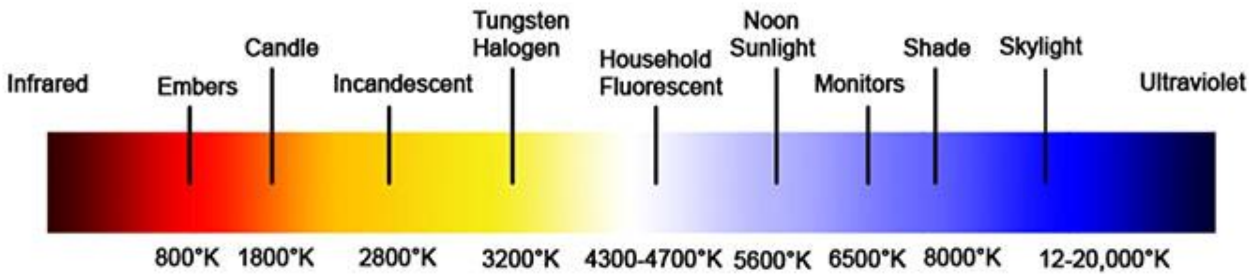
Timing and duration are crucial in determining the shift of circadian-phase resetting. Exposure to optical radiation will result in either a phase delay or phase advance depending on the time and length of the exposure, scientists have developed a “Phase Response Curve (PRC)” as a visual representation of the change in direction and magnitude of the phase response curve. IES standards interpret data to suggest that “the degree of phase shift increases exponentially with optical radiation exposure duration, and that the first half of the exposure induces a disproportional higher effect than the latter half.” (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses)

2.1.4.4 Spatial Distribution

Spatial distribution refers not only to the distance between light sources but also to the relation of the light source to the light receptors in the human eye. According to the IES, a collection of non-visual light receptors is spread “nearly uniformly across the retina in a net like distribution.” This information would imply that the direction of incoming light is insignificant, however, studies have shown that melatonin production is suppressed more efficiently when optical radiation enters the visual field from above. (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses)

2.1.4.5 Correlated Color Temperature (CCT)

The Correlated Color Temperature is determined by comparing the color of light to the color of a theoretical black-body heated to a temperature measured in degrees of Kelvin (K °). Lighting is often described as being warm (yellow) or cool (blue). Philips explains “warm light is around 2700K, moving to neutral white at around 4000K, and to cool white, at 5000K or more.” (Philips Lighting) Although CCT is not directly related to spectra, it is possible to have lights with the equal CCT made up of different combinations of wavelengths. (Brigagliano)



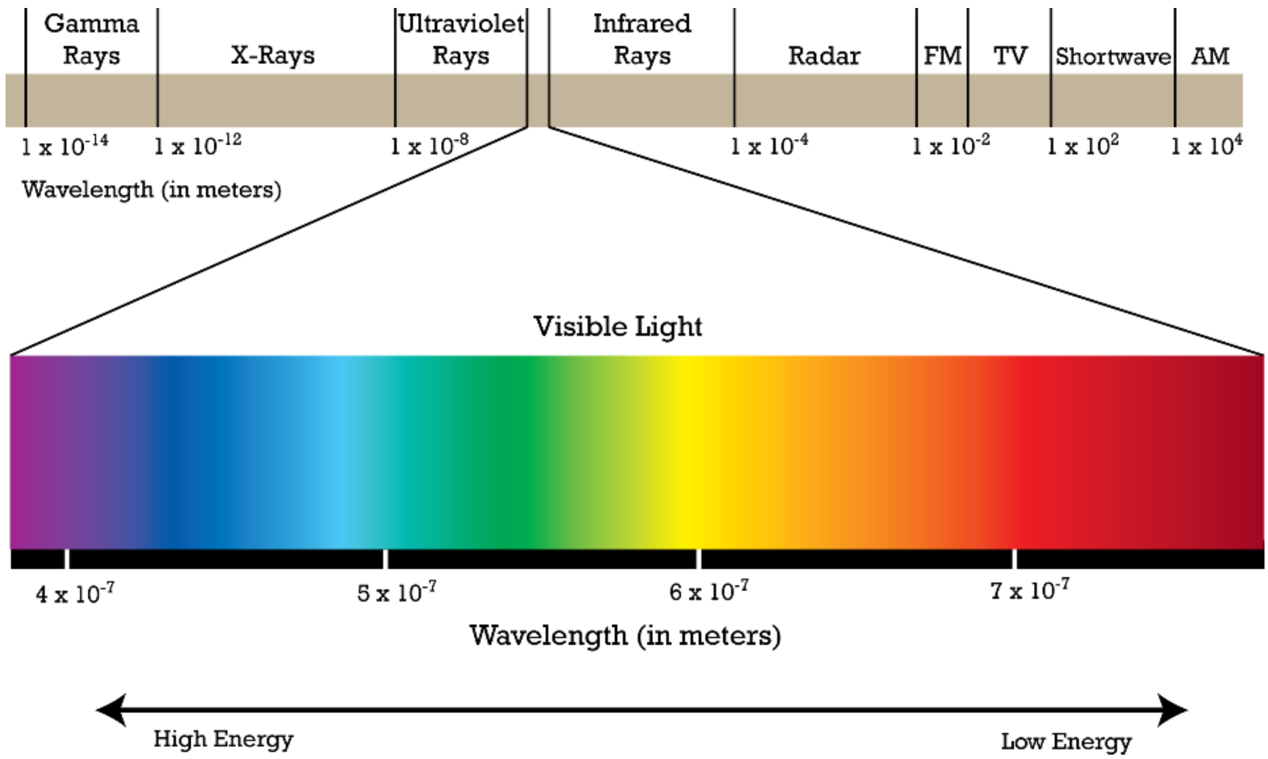
(Lowel EDU A Lighting Resource Center)

Color temperature has been found to directly affect the circadian system of humans, interfering with hormone secretion. The change in hormone levels affects alertness, sleepiness, mood, and stress levels. Street lighting not only increases the safety for drivers, but also cyclists and pedestrians. Studies have shown that the CCT of a light source can also affect the perceived brightness. It is possible to engage additional rods in the eyes with a blueish-white light source, a CCT of 5000K to 6500K. Theoretically, by engaging scotopic vision, streetscapes could appear brighter at the same luminance level. (Brigagliano)

According to Grah Lighting, the CCT of street lighting directly correlates with the driver’s ability to see. Grah Lighting reports that “White light sources have been shown to double driver peripheral vision and increase driver brake reaction time at least 25%.” (Grah LED Lighting Learning Center)

2.1.4.6 Electromagnetic Spectrum

The electromagnetic spectrum includes the range of frequencies of electromagnetic radiation from gamma rays to the longest, radio waves. The visible spectrum includes frequencies that are visible to the human eye. Lighting above the visual spectrum is referred to as ultraviolet light and lighting below the visual spectrum is Infrared. (Lowel EDU A Lighting Resource Center)



The diagram above represents the electromagnetic spectrum (Electromagnetic Spectrum)

According to the IES, our sensitivity peaks in short wavelengths section of the visible spectrum. Recent studies observing the impact of light on animals suggest that "melanopsin and classical photopigments participate in the circadian phototransduction of various species…" (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses)

Lighting for People suggests that “Light sources limiting blue wavelength emission and having strong green wavelength emission should be developed for outdoor lighting. According to current scientific knowledge this type of spectral content would limit the impact on our circadian systems, enhance mesopic vision, and limit glare. Furthermore it would produce less sky glow and attract fewer insects that blue rich light sources.” (Schlangen, Lang and Le)

Today more than ever we need to address the needs of senior citizens as the average age of the population is increasing. According to Lighting for People “In terms of spectra elderly would benefit from limitations in blue emissions at night. Research points out that blue-rich light results in the aggravation of night-time driving conditions for elderly people due to the yellowing of the lenses of the eye with age.” (Schlangen, Lang and Le)

2.1.4.7 Color Rendering Index (CRI)

When light hits an object most colors are absorbed, the colors that are reflected produce the perceived color of the object. The Color Rendering Index is used to assign a value to our perception of color. CRI is a measurement of the degree of color shift that objects undergo when illuminated. It can have a value up to 100 which is considered the closest to natural daylight resulting in the best color rendering. CRI is not affected by the Correlated Color Temperature (CCT).

The IES explains that scotopic vision occurs at luminance levels of 10^-4 to 10^-6 cd/m^2. In these dark environments, the rods in our eyes are solely responsible for our visual experience. Because rods lack the photo-pigments necessary for color vision it is important to provide ample amounts of lighting with a sufficient CRI in dark environments where color perception is necessary. According to the IES, urban environments typically emit enough ambient light to prevent scotopic vision. (IES RP-33-14 Lighting For Exterior Environments) Hartley points out that municipalities generally place lights with a high CRI in historical areas and high traffic roadways while lighting with lower CRI values are installed in low traffic areas. (Douglas Hartley)

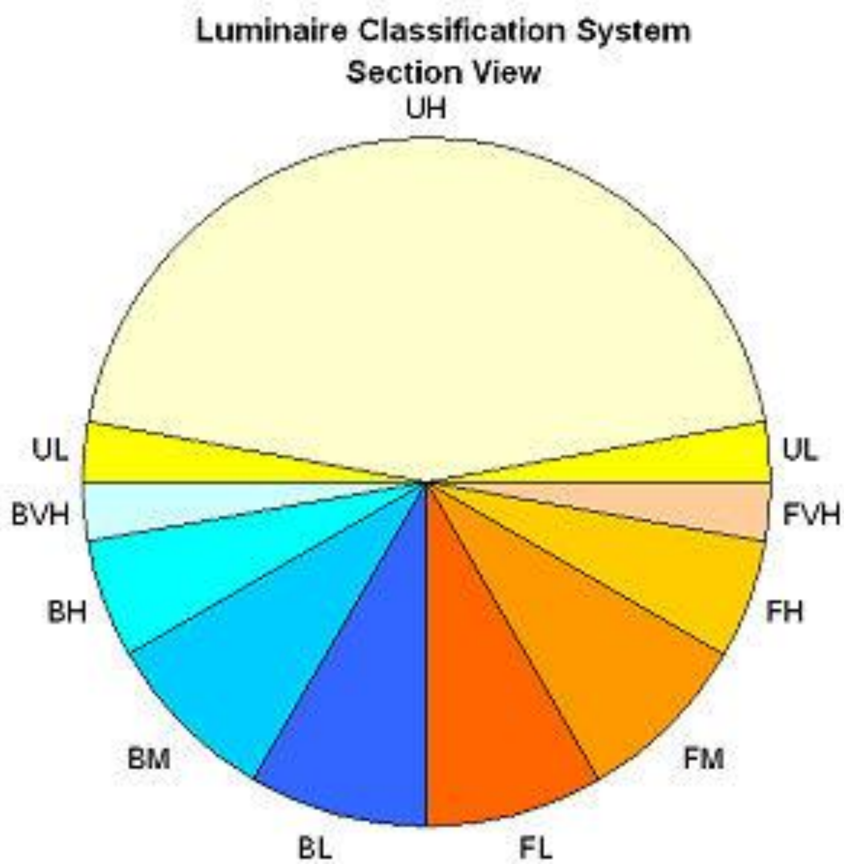
2.1.4.8 Luminance and Illuminance

Illuminance is a measurement of incident light, it is measured in lux or footcandles. This is the measurement used to determine lighting requirements in different areas. On the other hand, luminance relates to the quantity of light reflected or emitted towards an observer, or, the apparent brightness. (What is Luminance)

Cited in IES standards, resent tests indicate that exposure to lighting with Illuminance between 1 lux and 5 lux at specific monochromatic wavelengths is capable of suppressing melatonin production in healthy humans. The abovementioned standards from IES explain that this sensitivity is much higher than indicated in previous studies. (IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses)

2.1.4.9 Light Pollution, Sky Glow, Backlight, Uplight, and Glare

The Luminaire Classification System Rating (LCS) is used by the International Dark-Sky Association (IDA) and Illuminating Engineering Society (IES) as a classification for lighting zones. These ratings are based on zonal lumen limits (see image below). The LCS rating is often referred to as the BUG system, BUG is an acronym for Backlight, Uplight, and Glare. Backlight consists of the light directed behind the luminaire, Uplight is the light directed above the horizontal plane of the luminaire, and Glare is the light emitted at angles known to cause glare. (International Dark-Sky Association)



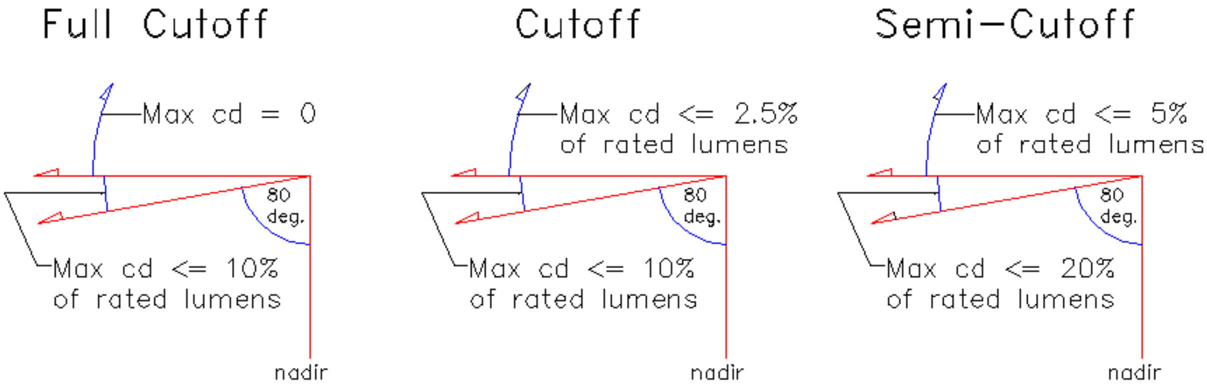
The Luminaire Classification System Section View provided by IES displays the zones referenced in LCS and BUG ratings. These zones are comprised of three main categories; Forward Light (FVH, FH, FM and FL), Backlight (BL, BM, BH and BVH) and Up Light (UL and UH.) The subcategories are used to provide more thorough analysis of light distribution.

Uplight is the main contributor to light pollution and sky glow. In the IES standards, light pollution is defined as unnecessary or wasted light that degrades the natural nighttime luminous environment or impacts humans and other species. Sky glow is a term used to describe light reflected by particles in the atmosphere that are responsible for obstructing our vision of the night sky. While sky glow can occur naturally, it is largely a byproduct of light pollution. (IES RP-33-14 Lighting For Exterior Environments) According to the Tucson, Arizona–based International Dark-Sky Association (IDA), the sky glow of Los Angeles is visible from an airplane 200 miles away. (Chepesiuk)

Glare is responsible for the unpleasant visual sensation caused by bright lighting. There are no units for the measurement of glare due to its subjective nature. The Lighting Research Center states that glare can be classified as causing disability or discomfort depending on the sensitivity of the observer. Disability glare is defined by reducing visibility and discomfort glare refers to lighting that causes annoyance or pain. As we age our eyes become more sensitive to glare. (Lighting Research Center)

The Illuminating Engineering Society of North America (IESNA) classifies luminaires based on the amount of light dispersed over the horizontal line of the luminaire as non-cutoff, semi cutoff,

cutoff, and full cutoff.



- Non cutoff fixtures distribute their light in all directions creating excessive light pollution and glare. Non cutoff fixtures are not used for roadway lighting.
- Cutoff fixtures allow less than 2.5% of the light to leave above 90 degrees. The cutoff lights have a wider spread of light than full-cutoffs, and they generate less glare than semi cutoffs.
- Semi Cutoff fixtures allow for less than 5% of the light to be emitted above 90 degrees. The cobra head is a popular version of a semi cutoff street light fixture.
- A full cutoff fixture does not allow any light to escape above 90 degrees, eliminating light pollution

(Grah LED Lighting Learning Center)

2.2 Street Lighting Technology

2.2.1 Lighting Systems

A lighting system includes all of the equipment necessary for the lighting source to function. Most high performance light sources such as solid state lighting and fluorescent lamps will require additional control equipment to provide the proper conditions to receive the intended life and output ratings. (Astrodynetdi) Although not essential, it is becoming more popular to implement controls for energy management and user satisfaction. Lighting controls include everything from simple switches, dimmers, and timers to photocells. These allow systems to be controlled manually or to function automatically. (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

2.2.2 Light Sources

2.2.2.1 Standard Incandescent Filament and Tungsten-Halogen Lamps

Standard incandescent lamps produce light using a tungsten filament inside of a glass bulb that contains an inert gas or a vacuum. These lamps are not efficient compared to commercially available alternatives.

Cost

- Incandescent lamps have the lowest initial costs.

(Grah LED Lighting Learning Center)

Lifetime

- 1,000 to 5,000 hours

(Grah LED Lighting Learning Center)

- Longer life Incandescent lamps are less energy efficient than lamps of equal wattage.
- Tungsten-Halogen lamps have a longer life than standard incandescent lamps.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Efficacy

- 11 to 15 lm/W
- Standard Incandescent lamps convert only 10% of the energy consumed into light, the rest escapes as heat.

(Grah LED Lighting Learning Center)

- Neodymium lamps have lower efficacy than standard incandescent lamps.
- Tungsten-Halogen lamps have higher efficacy than standard incandescent lamps.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Illuminance

- Neodymium lamps produce less light than standard incandescent lamps.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CCT

- Standard Incandescent lamp is approximately 2,800K.
- Tungsten-Halogen lamp is approximately 3,000 K.
- Neodymium lamps absorb red and yellow light, changing the CCT.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CRI

- Standard Incandescent and Tungsten-Halogen lamps are at or near 100.
- Neodymium lamps absorb red and yellow light, changing the CRI.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Other Parameters:

- Standard Incandescent and Tungsten-Halogen lamps start instantly.
- Both have a stable CCT and CRI throughout their lives.
- Both offer full-range dimming.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

- Most common in areas prone to street light damage due to the low cost of replacement lamps.

(Grah LED Lighting Learning Center)

2.2.2.2 Solid State Lighting

Light Emitting Diodes (LEDs) currently make up approximately 2% of the global lighting market. It has been projected to represent 30% by 2015 and 80% by 2020. (Rogers) As with LEDs, Organic Light Emitting Diode (OLED) technology is progressing rapidly and offers a promising future for lighting technology.

IES standards define an LED as “a low voltage constant current driven diode which emits light.”

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)   OLEDs emit light through a process called electrophosphorescence, this process involves two to three layers of organic matter layered between an anode and a cathode that are charged with an electric current. (Freudenrich)

According to the US Department of Energy “The Current OLED panel’s efficiency is almost half that of LED packages, at one third of the lifetime. OLED’s luminaire price is more than 50 times that of LED lamps on a dollars per kilolumen basis.” (US Department of Energy, April 2012)

Cost

- Initial LED costs are high but they pay for themselves with reduced energy and maintenance requirements.

(Grah LED Lighting Learning Center)

- OLED technology is still new so the price is high. Panels can currently only be purchased on three continents. As with LEDs, the technology is progressing rapidly and the price is expected to decrease substantially.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Lifetime

- LED luminaries have a lifetime between 50,000 and 100,000 hours. They are considered to reach the end of their lifetime when they emit 70% of their initial light output. LEDs do not burn out like incandescent bulbs, they only dim.

(Grah LED Lighting Learning Center)

- Poor thermal management can drastically reduce the lifetime of an LED.

  LEDs and Lumen maintenance are generally unaffected by frequent switching and cycling, however this may affect the driver and control circuits in the luminaire.

- OLED lifetimes have not been validated, however they are said to be approaching the limit required for most indoor applications.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Efficacy

- LEDs have 70 to 150 lm/W

(Grah LED Lighting Learning Center)

- LED technology has recently surpassed the efficacy of compact fluorescent lamps.
- Recent OLED prototypes were said to reach 50 lm/W.

  (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Illuminance

- OLED prototypes have "low light output."
- (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Spectrum

- White light emitted by an RGB LED with the same color temperature as white light emitted from a phosphorus LED will not have equal spectral distributions.

  (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CCT

- LEDs have a CCT from 3,200 to 6,400K.

(Grah LED Lighting Learning Center)

- LEDs can achieve a wide range of colors through phosphor conversion and by combining single color dies.
- Dimming RGB LEDs can result in light color change
- OLEDs emit a warm light, usually below 4000K.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CRI

- LEDs have a high CRI from 85 to 90.

(Grah LED Lighting Learning Center)

Other Parameters:

- LEDs can be either DC or AC driven with a power rating range of <1 watt to >10 watts.
- Dimmable from 100% to 1%
- Phase dimmer controls found in incandescent light systems can cause flicker with LEDs.
- Require good electrical and thermal management
- Performance is sensitive to operating temperature.
- OLEDs are less than one micrometer thick and can be implanted in glass, and formed into flexible materials.
- The OLED light source does not have to be hidden from view.
- OLEDs have an angular light distribution so optics may be needed to focus the beam.
- OLEDs are extremely sensitive to water contact

  (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)
- LEDs do not have any warm up time.

(Grah LED Lighting Learning Center)

2.2.2.3 Fluorescent Lamps

Fluorescent lamps contain a low pressure mercury vapor and an inert gas for starting. When voltage is applied an arc forms between two electrodes, this generates mostly ultraviolet radiation that excites the phosphors that coat the inside surface of the lamp's glass. Fluorescent Lamps include: Full Wattage Linear T12, Reduced Wattage Linear T12, Slimline, High Output, Very High Output, T8, T5, T5 High Output, Compact Fluorescent (CFL), Induction Fluorescent, High Intensity Discharge (HID), High Pressure Sodium (HPS), Mercury Vapor, Quartz Metal Halide, Ceramic Metal Halide, etc. (IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Cost

- Instant start ballasts are normally less expensive but shorten the lifetime of the lamp.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Lifetime

- Mercury Vapor: 12,000 to 24,000 hours
- Metal Halide: 10,000 to 15,000 hours
- High Pressure Sodium: 12,000 to 24,000 hours
- Compact Fluorescent: 12,000 to 20,000 hours

- Induction: 60,000 to 100,000 hours

(Grah LED Lighting Learning Center)

- Instant start lamps use a “cold mode” startup method where a high voltage sends electrons crashing into electrode at high velocities. This method may lead to a reduced lamp life.
- Reducing power to a fluorescent lamp does not guarantee a longer life like with incandescent lamps.
- Well-designed dimming ballast will not reduce the lamp life.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

- The lifespan of a CFL is reduced due to frequent cycling of the lamp

(Grah LED Lighting Learning Center)

Efficacy

- Mercury Vapor: 13 to 48 lm/W
- Metal Halide: 60 to 100 lm/W
- High Pressure Sodium: 45 to 130 lm/W
- Compact Fluorescent: 50 to 72 lm/W
- Induction: 70 to 90 lm/W

(Grah LED Lighting Learning Center)

- Dependent on the lamp system’s Ballast. Electronic ballasts provide improved efficacy.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

Illuminance

- Dependent on the lamp system's Ballast Factor (BF), a higher BF produces more light, similarly a lower BF produces less light.
- Performance is negatively affected by high or low ambient temperatures.
- Special lamp-ballast systems and luminaire designs allow for a wider range of operating temperatures.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CCT

- Mercury Vapor: 4,000 K
- Metal Halide: 3,000 to 4,300K
- High Pressure Sodium: 2,000K
- Compact Fluorescent: 2,700 to 6,200 K
- Induction: 2,700 to 6,500 K

(Grah LED Lighting Learning Center)

- Available in a wide range of CCTs depending on the phosphor coating the lamp.
- CFL CCT is approximately 3,000K.
- Fluorescents are available in a wide range of colors from cool white to a warm incandescent-like color. They also come in saturated colors such as blue, green, and gold.
- Linear fluorescent lamps exhibit almost no color change when dimmed.
- Compact fluorescents experience color shift at the lowest light levels when dimmed.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

CRI

- Mercury Vapor: 15 to 55
- Metal Halide: 80
- High Pressure Sodium: 25
- Compact Fluorescent: 85
- Induction: 80

(Grah LED Lighting Learning Center)

- Available in a wide range of CRI ratings depending on the phosphor coating the lamp.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

- CFL CRI is approximately 85.

(Grah LED Lighting Learning Center)

Other Parameters:

- Commonly available in linear, circular, and U-shaped lamps.
- Requires a ballast to limit current.
- Unless started in the abovementioned "cold mode," fluorescent lamps have a delay of a few seconds until they reach full brightness.
- Not recommended to be paired with motion sensors unless there is an instant start ballast.
- Instant start lamps are not recommended for dimming.
- Startup time is negatively affected by low ambient temperatures.
- Ballasts can create an audible noise due to vibration.

(IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting)

- Diffused non-directional lighting.
- Contain the harmful substance, mercury.
- Should be mounted between 20 and 30ft above the street.
- CFLs produce less light in cold weather and occasionally fail to start.
- Induction Fluorescent contain lead.

(Grah LED Lighting Learning Center)

3 Analysis of Graz and Houston

3.1 Graz

3.1.1 Overview

- Graz is filled with well-preserved history and modern design.
- 34 Museums
- 50% of Graz is green
- Awarded the "Europe Capital of Culture" award in 2013.

(About Graz)

3.1.2 Demographics

- 271,998 Residents
- Austria's second largest city
- 8 institutions of higher education – over 50,000 students

(About Graz)

- Nearly 20% of the population is between 20 and 30 years old.

(Abgestimmte Erwerbsstatistik 2012 -Demographische Daten, Wanderung)

3.1.3 Street Lighting

The City of Graz has about 24,000 street lights, prior to the "Green Light Graz" initiative it cost around Euro 1.17 million to power the lights for one year. The initiative modernized existing lighting systems, many of which were installed in the 60's. During the first implementation of the program, 720 lights were retrofitted to use energy-efficient high pressure sodium vapor lamps. Since then, Graz has modernized approximately 18,000 lights. The initiative has implemented LED luminaires on side streets and has begun adapting control systems in low-traffic areas. Energy savings surpassed predictions, since 2011 Graz has saved Euro 67,200 / year. Additionally Graz has reduced CO2 Emissions by 500,000 kg/ year. (Green Light Graz 2010)

3.2 Houston

3.2.3 Overview

- Cultural value include: sports, food, art, theater, shopping.
- Fourth largest museum district in the country
- 650+ Urban Green spaces

(Loftus-Farren)

3.2.2 Demographics

- One of the youngest populations in the country due to the influx of immigrants.

- 2,162,000 residents make Houston the fourth largest city in the U.S. and the largest in Texas. Houston is growing rapidly, between 2011 and 2013, Houston gained more than 34,000 residents.

(World Population Review)

3.2.3 Street Lighting

In May, 2014, the City of Houston announced a five year plan to retrofit over 165,000 street lights. By upgrading to LEDs the city is predicted to reduce energy consumption by 52% or 54.6 million kWh saving approximately $2.7 million per year. The city is expected to reduce greenhouse gasses by 4%, or 355,000 tons over the 12 year life of the project. (Harc)

3.3 Cross-Cultural Analysis

During my time in Graz I was able to gain a glimpse into cultural values, attitudes, and customs. I believe the most influential cultural aspects on street lighting are: attitude towards environment, crime rates, driving requirements, public transportation, and nightlife.

Austrians are very proud of where they live, this is evident in the way they take care of public spaces and also in their cultural celebrations. Almost every Texan exhibits a similar pride, unfortunately, Houstonians don’t always show our pride through caring for the environment. Campaigns have adopted catchy slogans such as “Don’t mess with Texas” to educate about the impact of littering. Additionally Houston has an astonishing crime rate, ranking higher than the national average in murders, rapes, robberies, assaults, burglaries, thefts, auto thefts, and arson. (Crime rate in Houston..) According to the Erasmus Student Network, crime rates are very low in

Austria. Violent crimes are very rare but petty crimes, such as pickpocketing are more common. (Safety)

The concept of sustainability seems to be very popular throughout Europe, rather than ignoring climate change, citizens take responsibility and make strides towards becoming sustainable. For example, it is standard for people to sort their trash for recycling. While this means having five bins: biological waste, paper, metal, plastic and packaging, and finally dry waste; Europeans are generally happy to do their part. In contrast, only about 14% of Houston's residents recycle. According to the writers at Co.Exist, this could be partially due to the lack of recycling services available to residents, the lack of education, and the absence of mandatory recycling laws. (Schwartz)

It is very difficult to navigate Houston without a vehicle, public transportation is available but comparatively small to the city. The overall opinion of Houston's Metro is very poor due to the cleanliness, safety, and delays. Based on personal experience living in Graz without a vehicle I enjoy the safety and reliability of the public transportation. Graz is much smaller than Houston so even without public transportation, everything is within walking distance. This has shown to be beneficial for keeping intoxicated people from driving. The stigma of drunk driving in Graz is much worse than in Houston. This could be partially due to the high price of a driver's license in European countries, or the fact that it is easily avoided through the use of public transportation.

Houston's nightlife ends around 2:00 am, when the last round of drinks is served and everyone is asked to leave. In Graz, bars and clubs are open until 5:00 am and there are no open container laws. Residents of Graz may be out later than Houstonians but that they do not require the high illumination typical of Houston.

3.4 Recommendations

Municipalities should think more strategically about the future of street lighting technology and the growth and advancements of their cities. They need to not only consider the cost of the luminaire and its efficiency, but expand into the impact on humans and wildlife.

1.) Graz and Houston should consider the rapid advancement in OLED technology for areas with high foot traffic and visual appeal. This includes areas with cultural importance and historical significance.

   - The high angular light distribution would spread light effectively illuminating roadways, paths, and architectural details.
   - OLED panels do not need to be hidden from sight.
   - Thin flexible panels allow for creativity in design.
   - OLEDs emit warmer light that contains less of the blue tones responsible for affecting circadian rhythm.
   - There is potential to integrate LEDs and OLEDs where high luminous levels are required.
   - Graz: Hauptbahnhoff, Congress, Jakominiplatz.
   - Houston: Museum District, Rice Village, Westheimer.

2.) In residential areas that require the light output of LEDs, municipalities should consider LEDs with a lower CCT.

- Lower CCT level LEDs emit a more yellow toned light and have less of an impact on circadian rhythm.
- Although less efficient than high CCT LEDS with a bluish light, these LEDs are still more efficient than competing technologies with similar outputs.

3.) Cities should simultaneously invest in renewable energy.

- In most cases, the majority of a luminaire's CO_2 emissions come from electricity input during use.
- "When 100% wind energy is used, the impact of the manufacturing of the bulb and housing is expected to be higher than the lifetime electricity use." (Douglas Hartley)

4.) Cities should consider multiple options while waiting for a development of technology.

- Installing more efficient luminaires as place holders until the desired technology is available.
- Relocating the replaced luminaires to locations with less efficient technology. This would allow for new technology to be implemented in the most suitable areas. Additionally it would remove luminaires based on efficiency rather than location.
- Once technologies like LEDs reach 70% of their initial power output, they are considered to be at the end of their usable life, however they still emit light.

These fixtures should be analyzed to see if they are suitable for lower light areas, need to be recycled, or can be retrofitted and reused.

4 Conclusion

The processes of updating and/or retrofitting street lights are low risk investments with high returns that minimize environmental impact. It is necessary to take a strategic approach to the future of street lighting and its impact on the growth and advancements of our cities. Globally, governments are beginning to take action by restricting the manufacturing and installation of inefficient technologies. It is in the best interest of municipalities to find a low cost alternative to inefficient street lighting however many times this means they will prioritize budget over user-satisfaction.

Recently there have been several concerns about the impact of artificial light on humans and other species that share our environment. Street lights, especially luminaires using light emitting diodes (LEDs), have a received a bad reputation for causing circadian phase shifts and effecting hormone production in humans. A human-centric lighting solution requires a deep understanding of both the visual and the non-visual effects from lighting.

Human eyesight uses a series of photoreceptors located in the retina called rods and cones. Scotopic vision engages the rods in our eyes for sight in darker environments, Photopic vision engages cones in daylight conditions, and mesopic vision engages both rods and cones for low light conditions. The cones in our eyes must be engaged in order to accurately perceive colors.

Hartley points out that lights with a high CRI engage the cones in our eyes and are typically used in historic areas and roadways that accommodate large amounts of traffic. (Douglas Hartley)

The visual and non-visual characteristics of lighting that impact human satisfaction and well-being are timing and duration, spatial distribution, correlated color temperature (CCT), spectrum, color rendering index (CRI), luminance and illuminance, and light pollution.

Lighting systems consist of several components necessary for the function of the lights however additional lighting controls such as simple switches, timers, photocells and dimmers can be implemented to increase human satisfaction and reduce energy consumption. By optimizing ballasts, drivers, heat dissipation and controls you can significantly affect the luminaire efficiency, light output, and lifetime of a lamp however, not all lighting technologies are compatible with these controls and they increase the cost of the luminaire.

There are three main families of lighting sources, standard filament and tungsten-halogen lamps, solid state lighting, and fluorescent lamps. Recently LED technology has been progressing rapidly, today LED street light luminaires are still relatively expensive but drastically reduce CO_2 emissions and save on electricity costs. Several cities are upgrading and retrofitting luminaires to LEDs, a decision mainly driven by the financial benefits.

Graz, Austria and Houston, Texas, USA are both implementing programs to upgrade inefficient street lighting technology. Although there is a significant difference in population size, the two cities have a lot in common. Graz and Houston both have younger populations with an active nightlife scene. However, Graz has a more effective public transportation system and less lenience for drunk drivers so they have less night time vehicular traffic along with less alcohol related traffic incidents. These factors play a large role in lighting requirements for vehicular safety in the two cities.

Recommendations for the area include taking a more strategic approach to implementation of street lighting by 1) considering the rapid advancement of OLED technology, 2) evaluating the benefit of using LEDs with a lower CCT in residential areas, 3) invest in renewable energy sources and 4) considering economic solutions such as relocating luminaires to implement new technology in desired locations.

References

Abgestimmte Erwerbsstatistik 2012 -Demographische Daten, Wanderung. Graz: Statistik Austria, 2012. <http://www.statistik.at/blickgem/ae4/g60101.pdf>.

American Testing and Assessment Laboratory. 5 July 2015. <http://ata-labs.com/services/>.

Astrodynetdi. 2015. 10 July 2015. <http://www.astrodynetdi.com/power_supplies/guides/led-drivers/faq/>.

Baillie, Doug. *Facility Executive*. April 2013. June 2015. <http://facilityexecutive.com/2013/04/lighting-trends-lighting-decisions/>.

Brigagliano, James. *Solar Lighting: Making Steps Off-Grid towards a Sustainable Future*. November 2010. November 2015. <http://ce.construction.com/article.php?L=223&C=712&P=7>.

Chepesiuk, Ron. *Missing the Dark: Health Effects of Light Pollution*. January 2009. 25 September 2015. <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2627884/>.

Crime rate in Houston.. 3 November 2015. 2015. <http://www.city-data.com/crime/crime-Houston-Texas.html>.

Davenport, Thomas L.R. "Street Lighting Design in LightTools." 2012. <http://optics.synopsys.com/lighttools/pdfs/LightTools_SLD_whitepaper.pdf>.

Douglas Hartley, Cassie Jurgens, and Eric Zatcoff. *Life Cycle Assessment of Streetlight Technologies*. University of Pittsburgh. Pittsburgh, 2009. <http://www.pitt.edu/news2010/streetlight_report.pdf>.

Electromagnetic Spectrum. n.d. <http://www.pion.cz/en/article/electromagnetic-spectrum>.

Freudenrich, Craig. *howstuffworks Tech*. n.d. 14 August 2015. <http://electronics.howstuffworks.com/oled2.htm>.

Good Practices in City Energy Efficiency. Los Angeles: Energy Efficient Cities Initiative, 2011. <https://www.esmap.org/sites/esmap.org/files/LosAngeles_LED_final_edited_11-9-11.pdf>.

Grah LED Lighting Learning Center. 1 September 2015. <http://www.grahlighting.eu/en/learning-centre/financial-instruments>.

Graz Tourism. 2015. 13 October 2015. <http://www.graztourismus.at/en/good-to-know/about-graz>.

"Green Light Graz 2010." n.d. <http://www.grazer-ea.at/cms/upload/news/greenlight/infofolder_greenlight_graz_2010.pdf>.

Harc. 5 June 2014. 2 October 2015.

IES. "Design Guide for Sustainable Lighting: An Introduction to the Environmental Impacts of Lighting." Design Guide. n.d. Document.

IES DG-10-12 Design Guide For Choosing Light Sources for General Lighting. IES, n.d.

IES. "IES RP-16-10 Nomenclature and Definitions for Illuminating Engineering) ." Standards. n.d.

IES RP-31-14 Recommended Pactice for the Economic Analysis of Lighting. Illuminating Engineering Society, n.d.

"IES RP-33-14 Lighting For Exterior Environments." n.d.

"IES TM-18-08 An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses." n.d.

International Dark-Sky Association. "Specifier Bulletin for Dark Sky Applications." 2009.

Lighting Research Center. March 2003. July 2015. <http://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightpollution/glare.asp#>.

Loftus-Farren, Zoe. *Earth Island Journal*. 10 March 2014. November 2015. <http://www.earthisland.org/journal/index.php/elist/eListRead/led_streetlights_save_energy_but_could_have_some_serious_side_effects/>.

Lowel EDU A Lighting Resource Center. 2010. June 2015. <http://lowel.tiffen.com/edu/color_temperature_and_rendering_demystified.html>.

Luc Schlangen and Dieter Lang, LE Philipp Novotny and Herbert Plischke, MUAS Karin Smolders and Domien Beersma, RUG. "Lighting For Health and Well-Being in Education, Work Places, Nursing Homes, Domestic Application, and Smart Cities Katharina Wulff and Russell Foster, UOXF Christian Cajochen, UNIBAS/UPK Heli Nikunen, Leena Tähkämö, Pramod Bhusal, Liisa Halonen, AALTO." 2014. <http://lightingforpeople.eu/wp-content/uploads/2014/02/SSLerate-3.2-3.4-v4.pdf>.

"No Need To Wait: Accelerating Adoption of LED Street Lighting." n.d. <http://www.theclimategroup.org/_assets/files/LED-Consultation-Handout.pdf>.

Philips Lighting. n.d. June 2015. <http://www.lighting.philips.com/main/support/support/faqs/white-light-and-colour/what-does-cct-mean.html>.

Richardson, Gary S. "The Human Circadian System in Normal and Disordered Sleep." *Physicians Postgraduate Press, Inc.* (2005). <http://www.psychiatrist.com/PCC/article/Pages/2005/v07s02/v66s0901.aspx>.

Rogers, Matt. "Energy = Innovation." 2012.

Safety. n.d. 8 June 2015. <http://unigraz.esnaustria.org/safety >.

Schlangen, Luc, Dieter Lang and Novotny Philipp Le. "Lighting for Health and Well-Being in Education, Work Places, Nursing Homes, Domestic Applications, and Smart Cities." 2014. 15 October 2015.

Schwartz, Ariel. *Houston's Plan to Make Landfills Extinct*. n.d. 16 June 2015. <http://www.fastcoexist.com/1681448/houstons-plan-to-make-landfills-extinct>.

Sleep and the Circadian System. n.d. 20 March 2016. <https://sleepfoundation.org/sleep-news/sleep-and-the-circadian-system>.

WebMD. 2005-2016. 20 March 2016. <http://www.webmd.com/sleep-disorders/tc/melatonin-overview>.

What is Luminance. n.d. 2015. <http://www.ransen.com/photometric/What-Is-Luminance.htm>.

World Population Review. 2015. US Census. 3 August 2015.