The Problems of Artificial Light at Night, is a Solution at Hand?

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Abstract

Since the introduction of street lights the world has embraced outdoor lighting and all the advantages that it confers. However this has come at a cost to our community and ecosystem, with most of the world's population now living under light polluted skies.

Not only are astronomers increasingly hampered by the encroachment of light pollution into their domain, but the effects of night lighting extends past light pollution, to include negative health effects on the community at large, as well as negative impact on other species. Additionally outdoor lighting is a massive consumer of energy, and contributes significantly to the greenhouse gas burden of the planet.

A solution for many of these problems is at hand. Over the last five years Light Emitting Diodes (LED's) have emerged as the cheap efficient outdoor lighting source of the future.

The aim of this paper is to look at how outdoor lighting works, the negative impacts of outdoor lighting, and in particular, street lighting, and how a well designed LED street lighting plan could simultaneously address all the issues. It also reveals how a poorly designed LED outdoor lighting system could make the problems worse.

With the advent of LED street lighting technology, there is now a once in a lifetime opportunity to correct all the problems we have created to date, and still enjoy all the benefits that outdoor lighting confers.

Introduction

Artificial lighting has been one of the great innovations of mankind and has positively enhanced our quality of life. The advent of outdoor and street lighting in particular has fundamentally changed the nightscape.

Street lights were first introduced in Wabash County, Indiana in 1879 (Indiana Historical Bureau, 2013). Within two years other major cities in the United States were doing the same, and our way of life was changed forever as we enjoyed all the benefits of the "night life."

Unfortunately, like so many technological advances, there has been a downside with a significant cost to our community and ecosystem. Astronomers were the first to notice the adverse effects of light pollution with the increasing difficulty in visualizing and photographing feint celestial objects (Riegel, 1973). Forty years on, it is estimated that 80% of the world's population live under light polluted skies. In the USA and Europe, this figure is estimated to be 99% (Falchi et al., 2016). Depending on the geographic region, the use of artificial light at night is increasing at a rate of up to 20% per annum, (Hölker et al., 2010).

It is now apparent that the adverse effects of night lighting have extended well past just the effect of light pollution. Possible negative health effects are emerging from exposure to artificial light at night, particularly blue rich light, including circadian rhythm disruption, increases in cancer rates, heart disease, diabetes and obesity (Falchi et al., 2011) (Navara and Nelson, 2007). Lighting also impacts on our health indirectly due to the energy required to produce it. This impacts us through the atmospheric pollution of electricity generation and the greenhouse gases it produces, (Mills, 2002).

Artificial lighting at night, often abbreviated to "ALAN", negatively impacts numerous animal species. (Thomas et al., 2015), (Navara and Nelson, 2007).

Provision of outdoor lighting is a significant financial burden on its providers.

Artificial lighting at night is here to stay, but could we still provide quality lighting and simultaneously reduce the harmful effects?

To answer this question means reviewing the topic from three different viewpoints; the viewpoint of the user, the viewpoint of those negatively affected, and the viewpoint of the outdoor lighting provider. From the user's perspective we need to understand how we visually perceive the world, and how different forms of lighting are needed for different purposes. From the negatively affected, we need to know what are the harmful aspects of artificial lighting and the principles as to how this occurs and can be limited. From the provider's viewpoint we need to examine if we can simultaneously reap the benefits of lighting, reduce the harmful effects, and do it in a more cost effective manner.

With the dramatic advances in LED lighting technology in the past few years, it is inevitable that it will become the prime outdoor lighting mechanism of the future. By reviewing its characteristics, we can determine whether the change to LED's can solve any, all, or only some of the issues.

Methods

I have done a literature review covering the different aspects of the issue. This included, visual physiology, harmful effects of artificial lighting, physics and extent of light pollution, different lighting technologies, and major strategic reviews of urban lighting, by Australian government authorities.

The findings have then been collated from the three viewpoints above.

Results and Discussion

1. The viewpoint of the user

What are we trying to achieve with street lighting?

The object of street lighting is to perceive the world at night in a way that is conducive to pedestrian and vehicle safety, and to reduce hazards through removal of darkness(IPWEA, 2016 p.1). While the definition is simple, the way this happens is not so straightforward, and the nature of ideal lighting in any situation is largely determined by how we perceive and interpret light.

1.1 Human Visual Perception

Much of the description that follows is derived from Guyton and Hall's Textbook of Physiology, (Hall, 2011a)

The photoreceptors in the eye are the biological equivalent of the CCD chip in a camera. The photoreceptors are divided, based on their anatomical shape into rods and cones. In addition there are non-rod non-cone photoreceptors that serve other functions.

Cones are responsible for high acuity colour vision in high lighting conditions, while rods are responsible for monochromatic low acuity vision in low lighting conditions.

The acuity of cones is partly due to the density of cones, particularly in the central vision area called the fovea, and partly due to the fact that each cone activates one ganglion nerve cell that leads via the neural pathway to the optic cortex of the brain.

There are three populations of cones that combine to give us colour vision. "Red" cones (also known as "L" cones, as in long wavelength) have peak sensitivity around 580 nanometres. "Green" cones (also known as "M " cones for medium wavelength) have peak sensitivity around 520 nanometres and “Blue” cones (also known as “S” cones for short wavelength) have peak sensitivity around 420 nanometres. There are slight differences in the distribution of cones in the retina, particularly with a higher concentration of S cones in the central vision area known as the fovea.

Red and Green cones account for approximately 46% each of the total cone population while blue cones only account for the remaining 8%. Blue cones are thought to signal where to insert blue in the perceived image, but contribute little to visual acuity(Dick 2016). This may explain why increasing blue light past a certain point does not improve colour discrimination or object recognition.

There is possibly a slight variance between sexes for cone populations as red and green cones are X chromosome traits, which may explain why women prefer warmer street lighting to men,(Clanton, 2014). Perception of LED street lighting versus traditional lighting in people with colour blindness has not been studied.

Light that stimulates more than one class of cone will stimulate more cones per given area of retina and therefore achieve higher visual acuity. As a result visual acuity is better where light is not restricted to one specific wavelength as happens with Low Pressure sodium vapour lamps (at 589nm) and red LED lights (650nm). This is reflected in the colour-rendering index that compares perceived colour to that of normal daylight. Detailed image perception e.g. facial recognition is easier when the colour index of the light approaches 100, i.e. close to the daylight spectrum. This coincides with the wavelengths that excite all three cone types around wavelengths of 500nm.

Colour rendering index approaches 100 using LED lights with a correlated colour temperature of 3007K. Little is gained by using luminaires above this figure{Jin, 2015 #25}

Fifteen kinds of color pieces and L*a*b* values

Reference color	Color	L*	a*	b*
1	Deep green	39.19	-27.39	20.4
2	Blackish green	27.89	-10.24	4.02
3	Yellow	69.04	-5.24	62.51
4	Turquoise	66.36	-25.36	-6.34
5	Dark blue	60.95	-1.67	-20.05
6	Gold	55.29	18.62	57.81
7	Green	79.62	-28.94	62.44
8	Watermelon red	42.34	39.77	4.25
9	Red	30.04	44.8	14.38
10	Orange	40.71	37.26	44.37
11	Light purple	54.22	15.19	-20.18
12	Pink	66.55	17.06	-8.37
13	Sapphire	22.64	12.49	-35.85
14	White	73.2	-0.5	-6.22
15	Beige	72.05	0.19	5.51

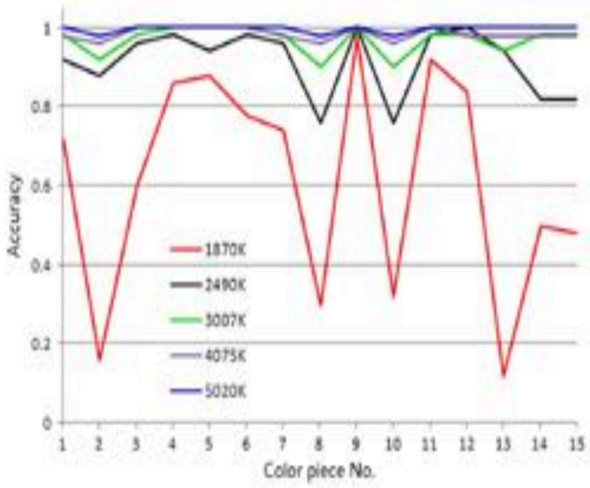

Figure 1.
Colour discrimination accuracy under LED's of five Colour Corrected Temperatures.{Jin, 2015 #25}

The rods, on the other hand, achieve higher sensitivity by having up to 10 rods stimulating each ganglion cell. Like a CCD chip, sensitivity is achieved at the expense of resolution. Figure 2 shows that rods are relatively insensitive to wavelengths longer than 580 nanometres (red and orange light).

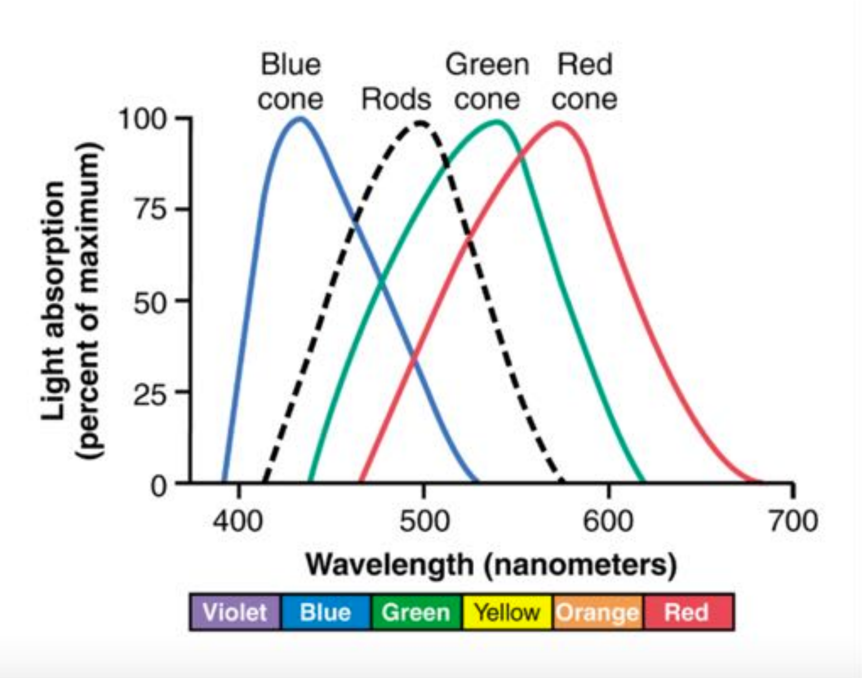

Figure 2
Relative Spectral Sensitivity of photoreceptors in the human eye
(Hall, 2011b)

Figure 3 is a semi logarithmic graph demonstrating the relative spectral sensitivity of rods versus cones. It can be seen that the sensitivity of the rods and cones are similar in orange and red wavelengths whereas rods are approximately 1,000 times as sensitive in green and blue wavelengths.

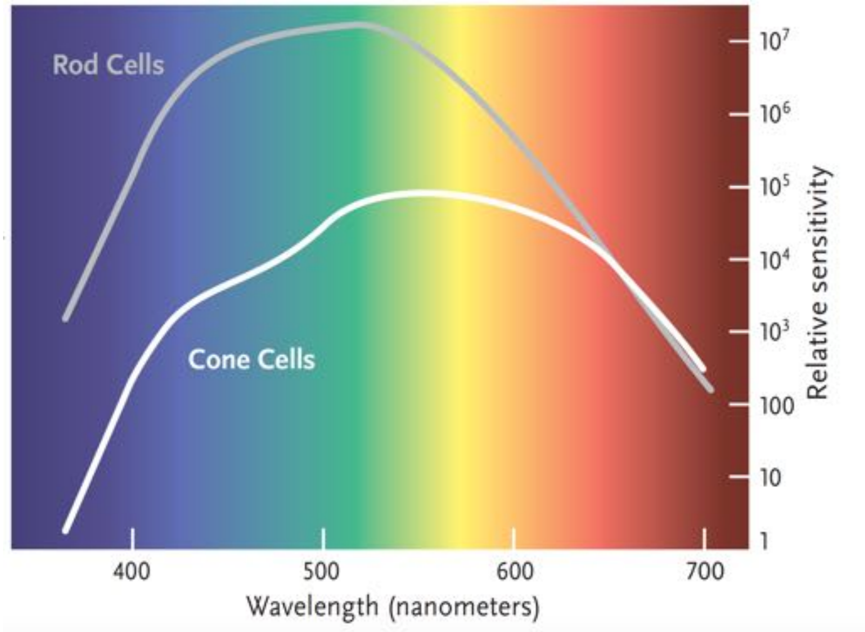

Figure 3
Relative spectral sensitivity of rods and cones in the human retina
(Dick, 2016)

Dark adaptation

The interaction of photons in rods and cones involves converting the chemical rhodopsin to metarhodopsin, which excites electrical changes in the rods. Metarhodopsin is slowly reconverted back to rhodopsin.

Intense stimulation of the receptor cell exhausts the supply of rhodopsin, a process called bleaching. This is the primary cause of decreased light sensitivity in bright light. From Figure 2 it can be seen that light with a wavelength of less than 580 nanometres, if sufficient to stimulate the cones will bleach out the rods.

Low light conditions allow a build up of rhodopsin, by a factor of 100 in cones and a factor of over 10,000 in rods. (See Figure3). This process takes up to 40 minutes for full re-adaptation after bright white light exposure.

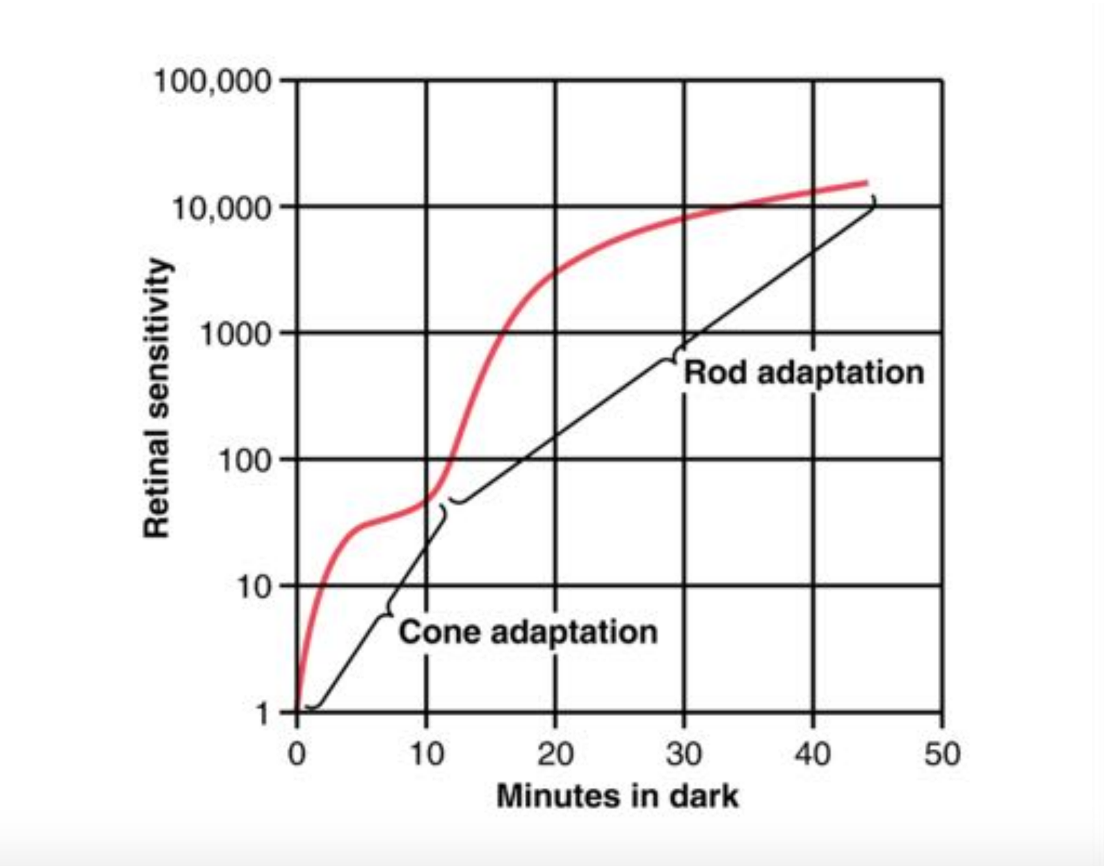

Figure 4.
Dark adaptation of the retina.
(Hall, 2011c)

Pupillary Constriction

The iris and pupil of the eye acts in the same way as the diaphragm in a camera. By decreasing the pupillary size in bright light. The constricted pupil can decrease light transmission to the inner eye by a factor of 30. The reflex is mediated by non-rod non-cone retinal photoreceptor cells that are maximally sensitive at 480nm (green blue) (Do and Yau, 2010).

From this physiology it follows that

- Light with a wavelength of shorter than 580 nanometres is associated with bleaching of rods and pupillary constriction.
- Light with a wavelength longer than 580 nm minimally impacts on dark sensitivity of rods.
- Light between 580 nm and 620 nanometres activates both red and green cones whereas light with a wavelength longer than 620 nanometres only activates red cones. Therefore the light between 580 and 620 nanometres results in a higher visual acuity. All three colour cones are stimulated at around 500nanometres, and highest visual acuity will therefore happen around this wavelength.
- Further in keeping with the aim of removing darkness, light with a wavelength shorter than 580 nanometres contributes to night blindness and therefore dark regions between artificially lit areas.

Conclusion

Different wavelengths of light are required for different purposes.

High visual acuity and colour perception happen in bluer light, while a “sweet spot” for night lighting that preserves night vision, while providing maximal visual acuity through stimulation of both Red and Green Cones exists around wavelengths of 580-620 nanometres.

2. The Negative effects of Artificial Lighting at night

Artificial light at night has negative effects on our health and safety, other species, and the visual environment.

2.1 Artificial lighting at night and health

Numerous studies now show a negative health impact to artificial light at night.
Much of the research relates to the suppression of the release of the hormone melatonin in the pineal gland of the brain. Melatonin is primarily involved in the control of circadian rhythm. It also has other effects on control of numerous other hormones, and our immune system,(Navara and Nelson, 2007).

Melatonin suppression occurs primarily at the blue end of the spectrum, via the non-rod non-cone photoreceptor cells. Exposure to light at a wavelength of 460 nanometres suppresses melatonin while light at 550 nanometres does not suppress melatonin, (Falchi et al., 2011). The intensity of the light required to suppress melatonin production continues to decrease as research continues. Just 0.1 lux (equivalent to the light of the full moon) is sufficient to suppress melatonin secretion, (Pauley, 2004). This is below the intensity level received from typical streetlights.

Disease processes now associated with melatonin suppression include sleep disturbance, coronary heart disease, diabetes, and obesity(Falchi et al., 2011). There is also limited evidence that shift workers with chronic circadian disruption and melatonin suppression have a slight increase in breast, colorectal, and prostate cancer(Greene, 2012), (Pauley, 2004), but some believe the research is suggestive only and remains inconclusive(Yong and Nasterlack, 2012). Chronic excessive blue light exposure is also related to retinal damage and an increased incidence of permanent visual impairment due to retinal damage from macular degeneration (Algvere et al., 2006).

The American Medical Association reviewed the data and, based on the above health concerns, recommends that street and outdoor lighting should be shielded, dimmed, and, where appropriate, limited to a 3000K correlated colour temperature (Stevens and Motta, 2016).

Mercury toxicity is another health concern with streetlight production.
39% of Australian streetlights are Mercury vapour lamps, and on average each contains 50mg mercury. Nationwide this amounts to 90kg, (IPWEA, 2016 p.15). Mercury is very toxic in humans down at concentrations of two parts per billion, and health effects include, neurotoxicity, heart, kidney and respiratory disease, (Nabi, 2014). Due to the pollution concerns, production of mercury vapour lamps is being phased out worldwide.

LED lights contain no mercury.

2.2. Artificial lighting and Greenhouse Gas Emission.

Artificial lighting at night also impacts our health due to its energy consumption through the burning of fossil fuels and production of greenhouse gases. Worldwide estimates of electricity consumption for lighting are approximate at best, with it being estimated in 1997 to be 2016 Terawatts, corresponding to carbon dioxide emissions of 1775 million tonnes,(Mills, 2002). The carbon dioxide emissions related to street lighting in Australia in 2016 is estimated to be 1.25 million tonnes in 2016, (IPWEA, 2016 p.53).

2.3. Artificial lighting at night, street crime and motor vehicle accidents.

Studies to date on the relationship of lighting at night, street crime, and motor vehicle accidents, are mixed and inconclusive, and often suffer from poor statistical analysis (Gibbons et al., 2014) p.4.

One study in 1999 showed driver reaction times were improved with bluer lighting but this was neither peer reviewed or published outside the Arizona Department of transport. See figure 4.

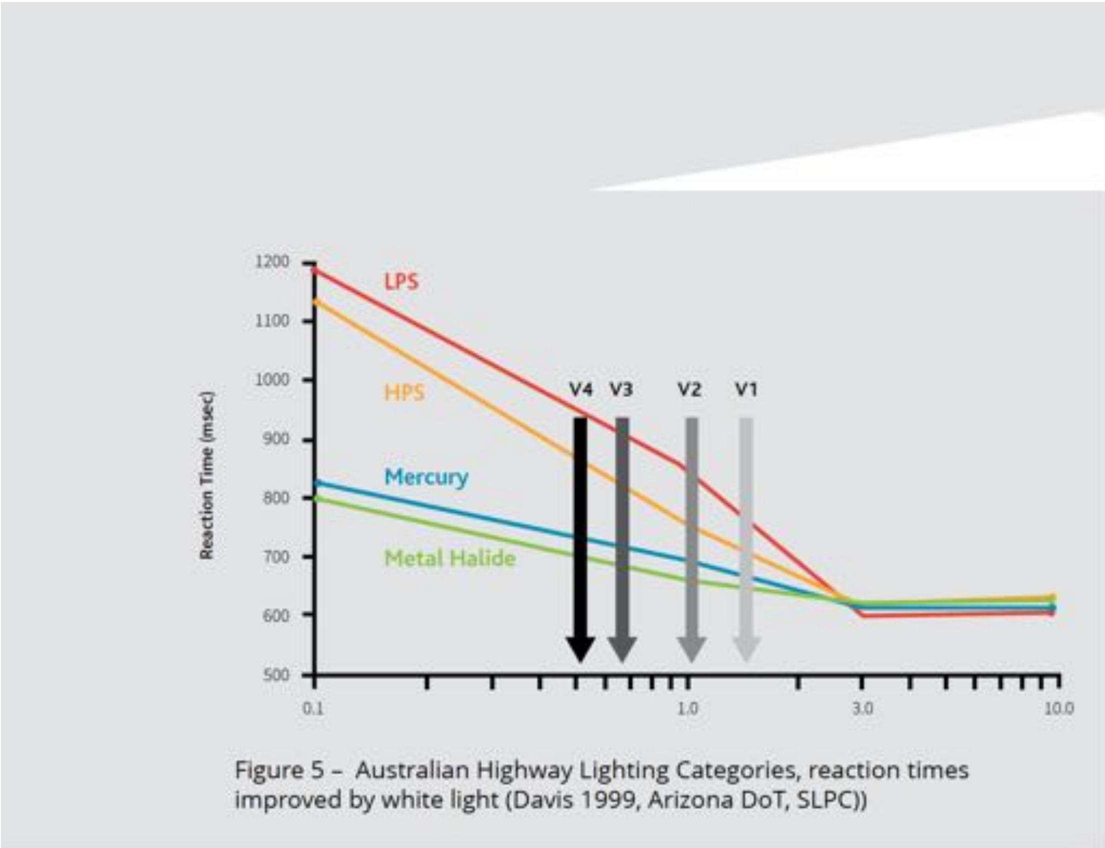

Figure 5
Driver Reaction time under different light sources.
(IPWEA, 2016 p.11).

Another small but elegant study showed pedestrian recognition by drivers may be impaired by blue poor (High pressure sodium) lighting in the presence of oncoming traffic, (Saraiji et al., 2016) but this has not been verified in further studies.

When normal scanning movements are accounted for in driver reaction, it was shown that spectral differences in lighting had little or no impact and argued that there was no justification using higher CCT lights to improve reaction times {Gibbons, 2015 #24}

The largest retrospective review to date, across England and Wales, found little or no evidence that decreased public lighting led to an increase in crime rates, or an increase in motor vehicle accidents(Steinbach et al., 2015).

With regards to street crime, one review showed a 20% reduction in street crime in well lit areas,(Farrington and Welsh, 2002), while a large trial of improved alley street lighting in Chicago demonstrated a 21% increase in crime after installation of additional lighting,(Morrow & Hutton, 2000).

The mixture of opinions as to how spectral differences affects street safety visual perception and crime rates, relates to the different endpoint in the research. If highest foveal visual acuity is the sole aim, then some results tend to favour a more blue rich light. LED streetlights at 4100k seem to be preferred,(Clanton, 2014) p.71. Whereas if a compromise between visual acuity and preservation of night vision and minimization of indirect health effects is the aim, the studies tend to favour a less blue rich light, in the region of 3000K.

2.4. Impact of artificial light at night on other species.

Artificial Lighting at night affects multiple other species, including insects, birds, fish, nocturnal foragers, and turtles. Effects range from interference with reproduction, migration, to foraging behaviour (Navara and Nelson, 2007). Artificial lighting at night disorientates newly hatched sea turtles, that mistake the lights for moonlight on the ocean (Tuxbury and Salmon, 2005). Even dung beetles rely on orientation to the moon, or in its absence, the Milky Way to navigate and avoid conflict with other beetles(Dacke, 2013).

2.5. Light pollution

2.5.1 Definitions

The following definitions assist in the discussion of light pollution, in conjunction with Figure 5.

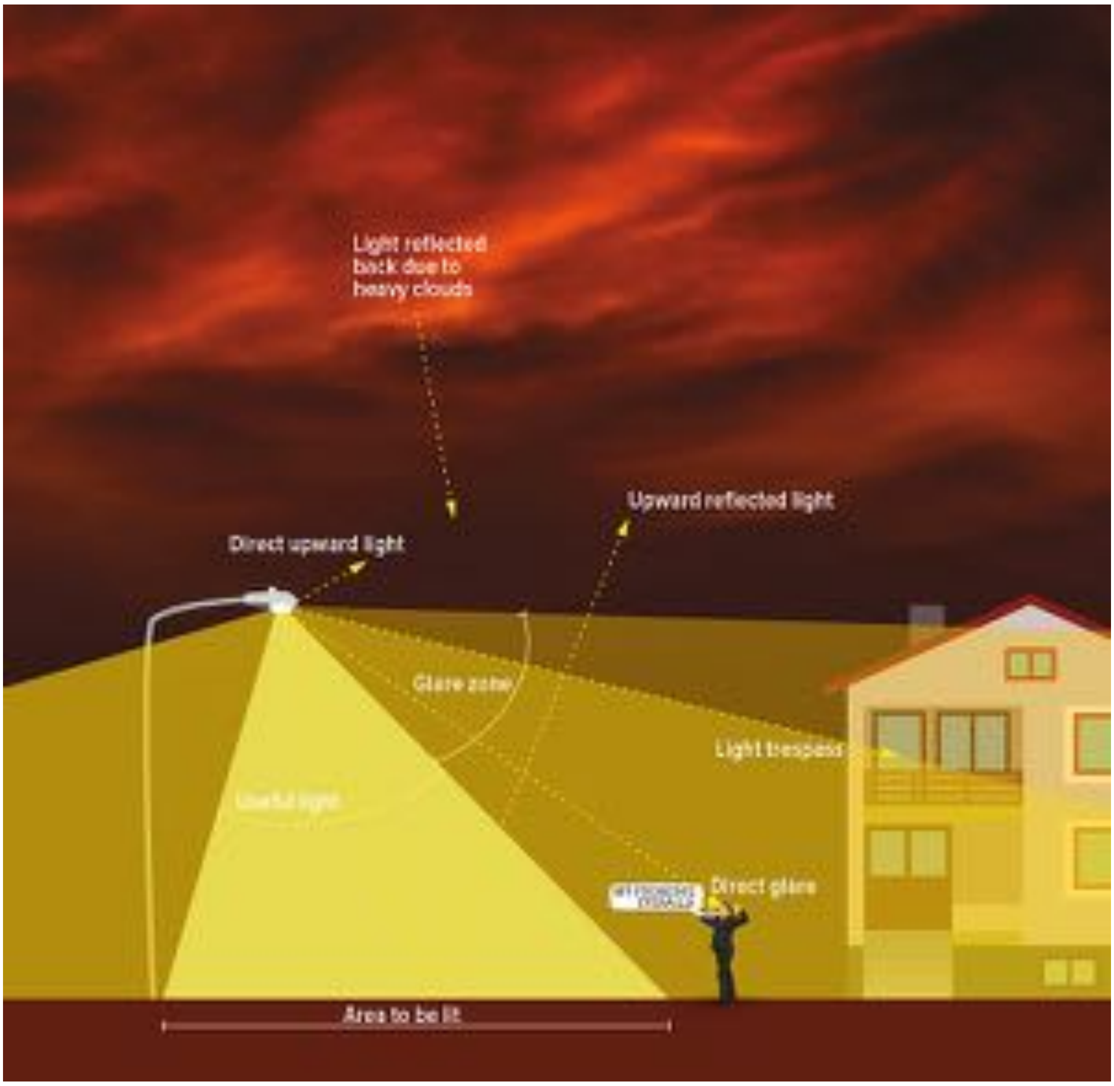

Figure 5. Sources of Light pollution.
(Pathberiya, 2013)

Looking at figure 5, from an astronomy viewpoint, unless the observing site is immediately adjacent to the light source, light trespass and glare are not the issue, rather it is both direct upward light and upward reflected light that creates secondary radiation, known as skyglow, that impairs observation even when some distance from the light source, such as a nearby population area.

Skyglow is defined as the diffuse luminance of the night sky.

Skyglow can be further divided into that which is naturally occurring and that which is induced by artificial (anthropogenic) lighting.

The naturally occurring sources of skyglow are
Starlight,
Moonlight,
Zodiacal light,
Auroral light.

Naturally occurring airglow is largely due to chemical processes, particularly with oxygen and sodium at an altitude of 80-100km altitude, (Cowley, 1998)

Anthropogenic skyglow is due to radiation interacting with atmospheric molecules, and atmospheric aerosols, which are predominately fine dust, sea salt, water droplets, and smoke (including car exhaust fumes).

Correlated Colour temperature (CCT) describes the spectral characteristics of artificial light is defined by comparison to the colour emitted by an ideal black body radiator at different temperatures, and is expressed in Kelvin.

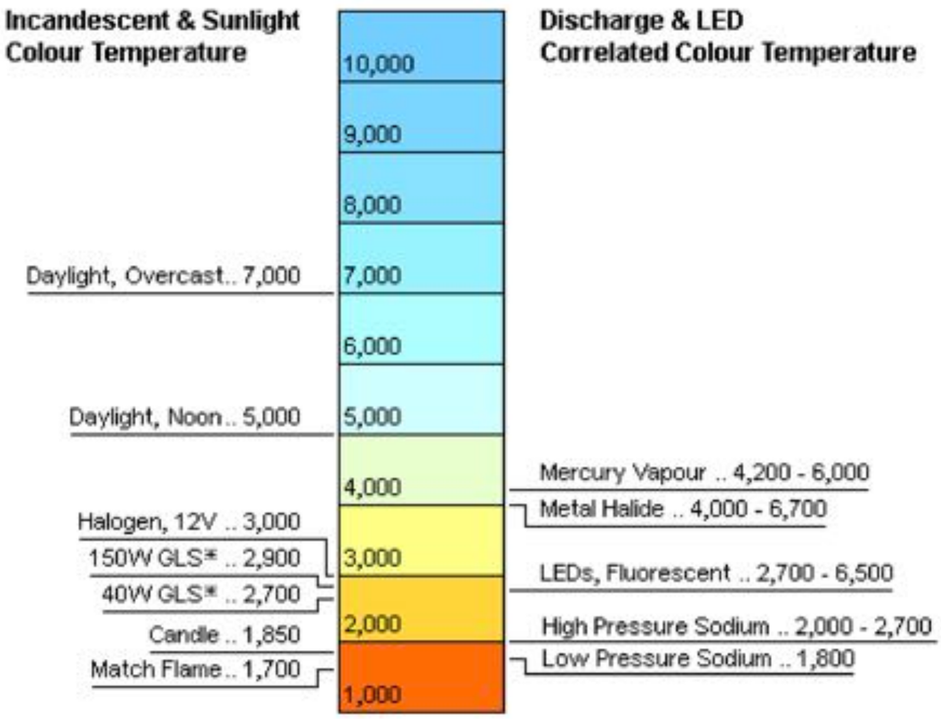

Figure 6
Correlated Colour Temperature
Elliott, R. 2013 <http://sound.whsites.net/lamps/lumen-lux-candela.html>

2.5.2. Factors contributing to Anthropogenic Skyglow

The International Dark-Sky Association (IDA) is the leading worldwide lobby group for policies and practices that decrease anthropogenic light pollution.
(< http:\darksky.org>).

IDA describes the three technical elements of combating light pollution and anthropogenic skyglow, in its study of blue rich white light, (IDA, 2010).

These are

a. Minimize blue emission frequencies. Use "warm-white" or Filtered LED's (Correlated colour temperature lower than 3,000K)
b. Choose fully shielded fixtures that emit no light upward.
c. Look for products with dimming capabilities.

Therefore we will examine how each of these factors contribute to skyglow

a. Impact of spectral output distribution of light on skyglow.

Light in a vacuum does not scatter (in spite of what you may see on Star Trek!). But light in the atmosphere does, due to interaction with the air molecules and aerosols.

Scattering by air molecules (Rayleigh scattering) is inversely proportional to the fourth power of the light's wavelength, while scattering by atmospheric aerosols (Mie scattering) is inversely proportional to the light's wavelength, (Garstang, 1986). The amount of scattering is determined by the density of the atmosphere and most occurs below 4,500 metres altitude. Light at 440nm scatters 2.5 times as much as light at 550nm,(Garstang, 1986).

This scattering also explains why, as light travels further through the atmosphere, in addition to the inverse square law of light intensity, it diminishes in intensity through loss of higher frequencies and therefore appears redder. (Luginbuhl 2014).

Light sources of calibrated equivalent brightness and design, but shorter wavelengths, will produce more skyglow, but this spectral effect decreases with distance, see Figure 7. The graph compares the light sources as a ratio to Low Pressure Sodium.

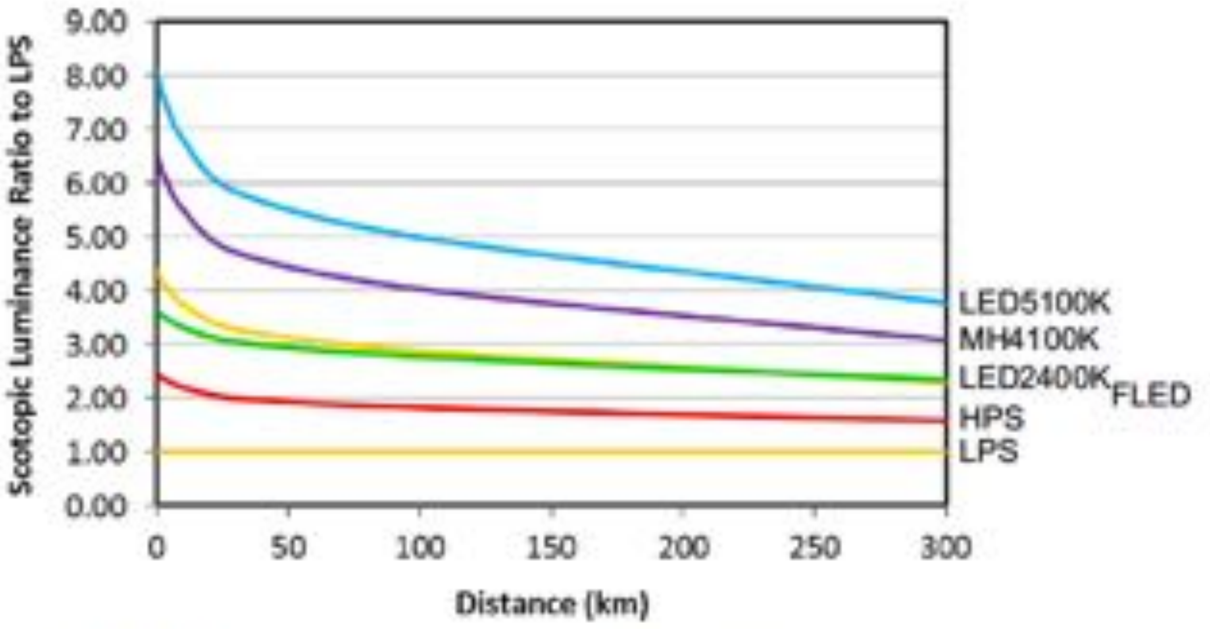

Figure 7. Relative skyglow levels as a function of wavelength and distance from light source.
(Luginbuhl et al., 2014)

LPS = reference light source= Low pressure Sodium
HPS = High Pressure sodium
LED 2400k = Light Emitting Diode with corrected colour temperature of 2400K
MH4= Metal Halide with corrected colour temperature of 4100K
LED 5100k = Light Emitting Diode with corrected colour temperature of 5100K

The spectral distribution of the light sources in Figure 7 is in figure 8.

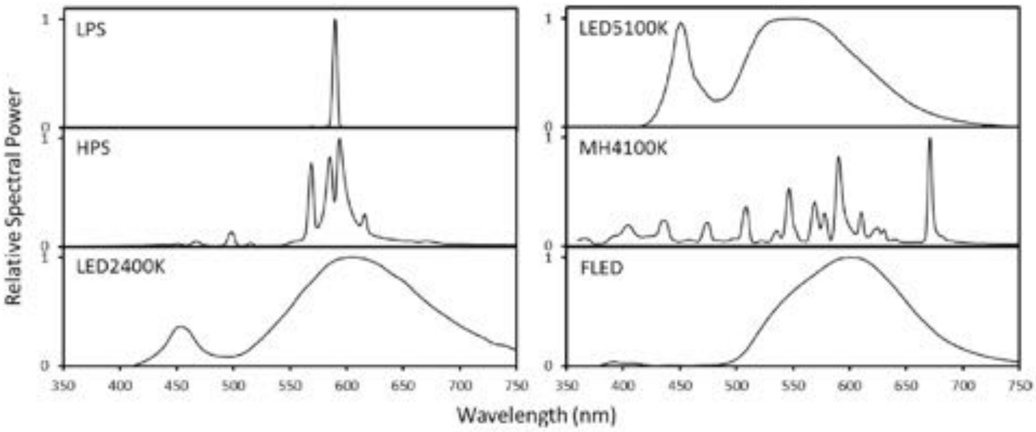

Fig. 1. Spectral power distribution of the six lamp types evaluated in this study. The lamp type abbreviations are explained in the text.

Figure 8. Spectral power distribution of the six lamps measured in Figure 5. (Luginbuhl et al., 2014)

Spectral Characteristics of different types of Streetlights.
(As demonstrated in the above spectral distribution graphs):

Low-pressure sodium lights have a single output frequency at 589 nanometres. While astronomers can easily filter out this frequency, while taking photographic images, the monochromatic nature of the light, makes object recognition difficult unless the object's colour is close to that of the light. Therefore they are only used for street lighting in critical areas, such as near astronomical observatories.

High pressure sodium lights comprise 31% of Australia's 2.3 million street lights,(IPWEA, 2016 p.49). They have a broader frequency distribution than low-pressure sodium, centred about the ideal night vision wavelengths of 580 – 620 nanometres. Object recognition is superior to low-pressure sodium luminaires.

Metal Halide lights which includes mercury vapour lamps, comprise 39% of Australia's street lights, (IPWEA, 2016 p.49). They have a distinctly blue green appearance and a spectral distribution from 350 to 680 nanometres.

LED lights comprise 6% of Australia's streetlights,(IPWEA, 2016 p.49). However it is unclear what the spectral distribution of already installed lights is. LED's are typically created based on a blue base LED (hence the spike at 460 nanometres) exciting phosphors to produce any desired corrected colour temperature. The light is also multi spectral, aiding in object recognition. The light may then be further filtered (FLED) to remove the blue colour spike.

Conversely a 5100K LED as used in the above study is more light polluting than any of the other old technology lights.

The colour spectrum of traditional street lighting has not been a significant factor in the selection of street lighting to date. More than half of Australian street lighting is by unshielded mercury vapour lights, the most blue rich, oldest technology and least efficient luminaire available,(IPWEA, 2016 p.2). Attempts to ascertain data on reasons behind this by the IPWEA (and myself), met with commercial–in-confidence issues.

Conclusion regarding spectral issues

With the advent of LED street lighting, spectral output is no longer a factor in the cost of lighting, it is technically just as easy and cheap to produce and run any correlated colour temperature of LED luminaire. So there should little financial incentive in choosing any particular colour temperature of the lighting. However LED lights can potentially be constructed with even higher kelvin rating than old technology lights, and therefore be more light polluting than older technology lighting. This presents a major threat to our environment if not recognized and avoided.

From the perspective of, efficacy, health effects, effects on other species, and skyglow, LED lighting with a correlated colour temperature of not greater than 3000K should be used. There is some evidence that bluer lighting up to 4100K may be safer in certain roadway conditions. Such lighting should only be used if further studies validate this hypothesis, and then only where necessary, and using the other two techniques to minimize light pollution, namely shielding and dimming.

b. Shielding

Shielding is the prevention of light leaving the luminaire in a direction above the horizontal.

The brightness of a light obeys an inverse square law with distance (Bennett et al., 2014 p. 518). However many such lights, will still have the potential to cause skyglow at a distance.

There are two types of light spread that contribute to light pollution as a result of inadequate shielding, (Falchi et al., 2016). The first is light emitted between 0 and 45 degrees above the horizontal plane. The lower the angle the further the light travels through the atmosphere, and hence the greater potential to interact with atmospheric molecules and scatter. It is therefore particularly critical to remove light emission between 0 and 5 degrees above the horizontal.

The second is light emitted between 0 and 10 degrees below the horizontal as this maximises the likelihood of specular reflection from asphalt, and concrete, which could lead to light pollution from upward reflected light. Therefore full shielding, to be effective must keep all light emitted to below 10 degrees below the horizontal.

This creates a paradox. The use of lower numbers of streetlights with wider beam spread may increase the likelihood of light pollution.

BUG rating

The Illuminating Engineering Society and International Dark-Sky Association jointly introduced the BUG rating to help quantify shielding quality in individual luminaires,(IDA/IES, 2011). BUG stands for backlight, uplight and glare. The principle criteria being light emitted 80-90 degrees from the nadir of the light.
The classification runs from G0, suitable near observatories, to G5 high glare,(Miller et al., 2013). See figure 9.

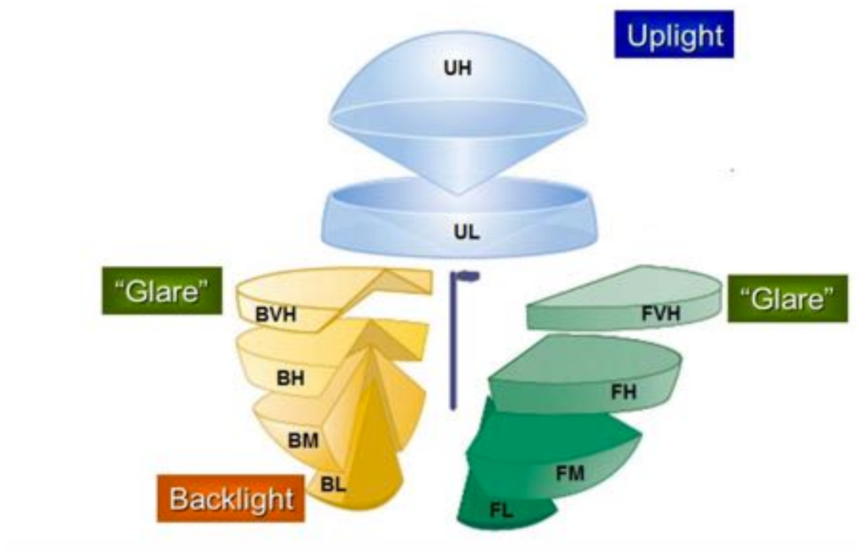

Figure 9
BUG scale of luminaires.
(Miller et al., 2013, IDA/IES, 2011)

The International Dark-Sky Association reviews individual luminaire data and supplies an "International Dark-Sky Association Seal of Approval" to lights that are at or below 3000k colour temperature and comply with or exceed the appropriate BUG rating.

Traditional lighting is largely unshielded and lighting suppliers have been reluctant to retro install shielding, in spite of the enormous amount of light that escapes upward, where it serves no purpose. The reason for this is unclear.

LED lighting is unique in that each individual diode is individually lensed. Therefore it is technically easy to focus the light to appropriate spread patterns.

While some light spill into the critical areas seems inevitable with more traditional lighting sources, there is no reason why this should happen at all with LED lights.

c. Dimming

Of all the ways modern man has devised to pollute the world, light pollution is unique in that turning lights down can immediately decrease the pollution, or immediately eliminated by turning lights off.

High pressure sodium and metal halide streetlights do not easily lend themselves to dimming. The nature of the arc created inside these lamps mean that these lights cannot simply be turned up or down. Varying the dimming, incurs fluctuating output for several minutes, possible complete loss of output and potentially significant decrease in bulb life, of 10-24,000 hours (Ji and Wolsey, 1994, Tähkämö and Halonen, 2015).

As most streetlights in Australia are rented off energy companies, there is little or no commercial incentive to employ dimming technology. Therefore the usual situation is that lights come on at full power at sunset and remain that way till sunrise, regardless of need. This is depicted in Figure 10.

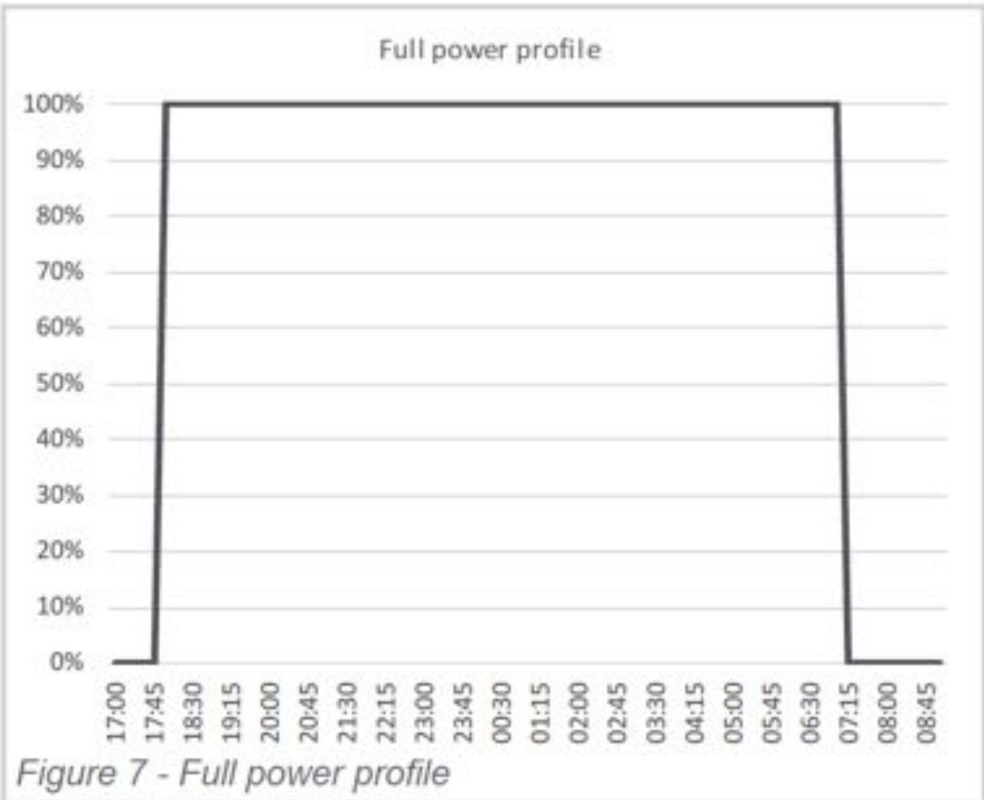

Figure 10.
Constant full power lighting profile
(Citelum, 2016)p.43

LED lights do not have these problems, they have instant start-up and, with appropriate circuitry they can be dimmed (LED Lamps Wiki 2017). Further, unlike more traditional luminaires, dimming prolongs the life of the luminaire. The life of LED luminaires is in fact so long that we do not know how long they will actually last, estimates are up to 50,000 hours (7-10 years)(IPWEA, 2016 p.34), and even longer with dimming. As a result, dimming opens up numerous possibilities that simultaneously decrease the need for unnecessary light and decrease energy consumption and cost. Commonly this strategy is called “smart lighting” or “intelligent lighting”.

One such lighting profile is the multi power profile where street lights are dimmed outside peak hours. This is demonstrated in Figure 11.

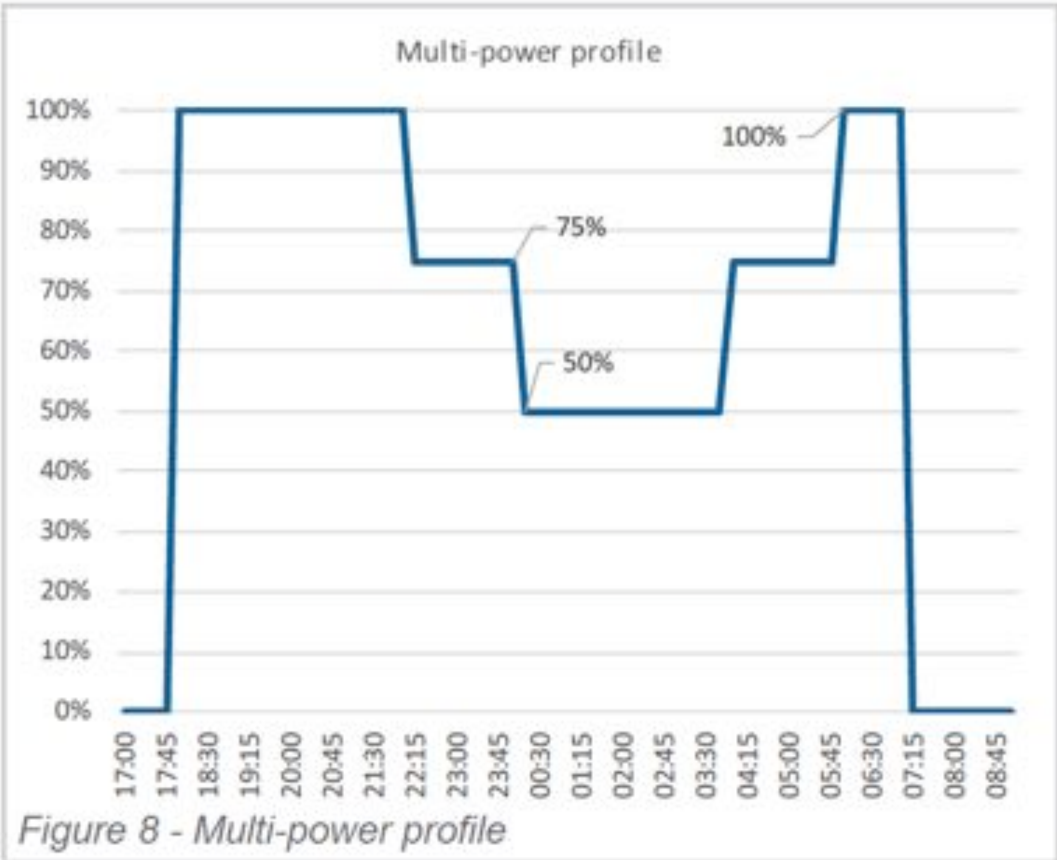

Figure 11.
Curfewing lights outside peak demand time.
(Citelum, 2016) p.43.

With the addition of motion sensors to each lighting pole, an even more efficient pattern known as Tri-power profiling, can be achieved with greater dimming and then brightening with detection of pedestrians or motor vehicles. This is demonstrated in Figure 12.

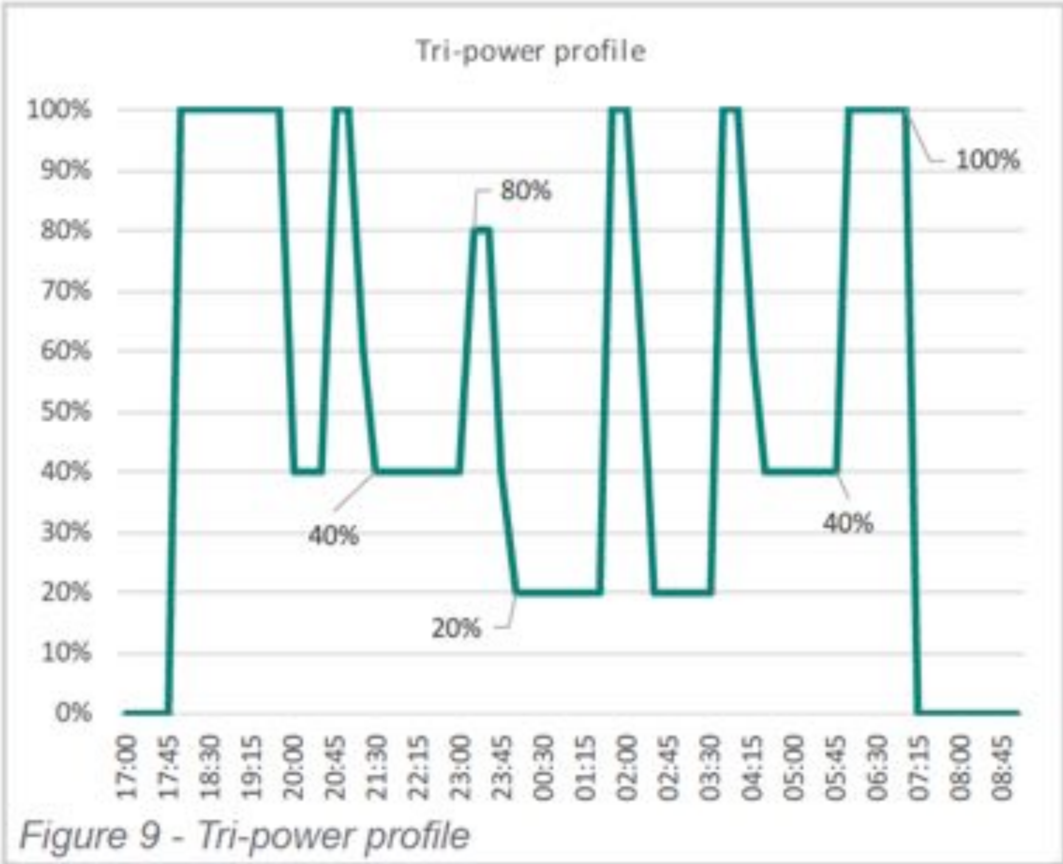

Figure 12.
Combination of curfewing and motion detection.
(Citelum, 2016 p.43).

While outlay is higher this system represents the greatest saving of energy and the greatest extent of light pollution reduction.

Control of tri-power profiling is achieved by either centrally controlled computers or by local Wi-Fi connection between adjoining nests of lights, allowing lights to anticipate the passage of pedestrians or motor vehicles through a region and supply more than just the luminaire in their immediate vicinity. A popular system at present is known as Zigbee (Kaleem et al., 2014).

Light pollution -Conclusion

Unlike more traditional outdoor and street lighting systems, LED lighting systems are far more able to comply with the three criteria set out by the International Dark-Sky Association, while simultaneously providing effective lighting and decreasing the negative health, climate, and other species impacts of artificial lighting at night.

3. The viewpoint of the Provider

LED lighting and its associated technologies can provide optimal quality lighting, with less environmental impact and less energy usage.

3.1 Background

It is reasonable to assume that end providers of outdoor lighting are motivated by both providing the most appropriate lighting systems and doing this at the least cost. From the above analysis it appears that end providers could achieve both aims through the installation of LED lighting.

However the cost effectiveness and versatility of LED lighting could, paradoxically make the situation worse for two reasons. Firstly the decreased cost, long term, due to decreased maintenance costs and electricity consumption could see an increased provision of outdoor lighting and subsequent light pollution. Secondly the ability of LED lights to be created with virtually any correlated colour temperature could see an increase in blue-rich light, if providers are not aware of, the downside of such lighting.

There needs to be a distinction made between the end provider of lighting and the supplier of lighting and electricity. The end provider e.g. local councils, will benefit from systems designed to minimize electricity consumption.

Conversely, the suppliers of the majority of Australian outdoor lighting systems to the providers, are electricity producers, and their business priority is to maximize the sale of their most profitable products, and electricity. It is not in their business interests to use more energy efficient systems, nor are they directly concerned with the negative impacts of lighting.

This would seem to be the case given that in Queensland, Western Australia, and Tasmania, in spite of the negative effects and inefficiencies of unshielded blue rich light being known for over ten years, authorities and suppliers of outdoor street lighting continue prefer to install mainly this type of lighting, (IPWEA, 2016 p.47), (Citelum, 2016 p.28).

It is unclear whether this is due to ignorance, or for commercial reasons. A personal attempt to clarify this with the various authorities has met with silence.

It therefore implies that end providers need to develop outdoor lighting master plans that are scientifically valid, and balance commercial interests with the health, safety and needs of the population and environment.

To date only one such master plan has been developed and approved in Australia. It is worth examining it, to see if it demonstrates the ability to provide more appropriate lighting at less cost.

3.2. Sunshine Coast Urban Master Lighting Plan

The Sunshine Coast Council, in South East Queensland, is the first regional council in Australia, and one of the first in the world, to develop and commence the rollout of an Urban Lighting Master plan based on smart technology LED street lighting,(Citelum, 2016).

Rather than stay with the traditional council practice of renting its 30,000 street lights from a major electricity supplier, (Energex), without any say in how the lighting is provided, it is replacing them with a grid of its own smart LED luminaires. This replacement has already commenced and is predicted to be complete by 2023.

3.2.1 Historical Background

Over the last few years the Sunshine Coast Council developed a new image. It resolved to become the "Low Carbon Capital of Queensland, " and the most sustainable region in Australia with the motto of "Vibrant, Green and Diverse."

The Sunshine Council spends 55% of its electricity budget on street lighting and 63% of this is on maintenance charges. It accounts for 10% of its entire budget,(Citelum, 2016),p11. It was deemed appropriate to see if a different approach was financially justified.

Into this philosophy was developed the need for a Sunshine Coast Urban Lighting Master Lighting Plan. International lighting consultants, Citelum, undertook this study,

This study mapped out the present street lighting structure of the Sunshine Coast, then predicted what would be the outcome of replacing each luminaire with newer technology luminaires, owned powered and maintained by the council, from the standpoint of cost and amenity.

In September 2016 the Sunshine Coast Council decided to adopt all the recommendations of the Sunshine Coast Urban Master Lighting Plan and further appointed Citelum to oversee its implementation. The first of the lights were installed in a new development in the region's south in February 2017.

The following analysis is based on the principles already discussed, to see whether this plan is scientifically valid, and therefore provides an appropriate template to be used by other regions to provide effective cost efficient lighting while simultaneously decreasing light pollution.

3.2.2 Lighting needs

The analysis included both a street-by-street and individual luminaire intensity mapping of the region. Additionally sequential aerial light pollution maps were secured. Areas of special need were identified and the plan requires the zoning of the region dependent on usage and faunal sensitivity, as per the International Dark-Sky Association guidelines(IDA/IES, 2011).

Input from Queensland Police was also received on high crime hazard areas requiring special attention.

Particular emphasis was made of the impact of artificial lighting at night on the local loggerhead Turtle nesting sites.

Spectral issues

The plan recognizes the negative health effects on humans and fauna effects of blue rich light.

Analysis of the present situation shows that 60% of the street lighting luminaires are mercury vapour lamps, which are the highest emitters of blue rich light.

The plan proposes to use only 3000K LED lights that have or comply with the International Dark-Sky Association Seal of Approval program. Considerable debate occurred with council as to whether 4000k lights had a place but eventually it was agreed to stay exclusively with 3000k (Carey, A . pers. Comm., 16th March 2017).

Shielding

None of the present luminaires on the Sunshine Coast are fully shielded.

60% of the region's streetlights are mercury vapour lights of the design seen in Figure 13.

Figure 13.
Unshielded Mercury vapour luminaire (Author's Personal Photo).

37% of the region's streetlights are unshielded high pressure sodium luminaires as per Figure 14.

Figure 14.
Unshielded high pressure Sodium Luminaire from 5 degrees above horizontal (Author's Personal Photo).

Given no attempt has been made to shield the present lighting; the considerable attention given in the master plan to only install fully shielded lights that comply with International Dark-Sky Association Seal of Approval guidelines, will significantly decrease light pollution, and wasted light.

Dimming

No dimming of any luminaire occurs at present.

The master plan requires both the use of local networks for dimming such as Zigbee and a central management system with every luminaire monitored and adjusted as per sensitivity zones and specific events e.g. beach lighting will be significantly curfewed during loggerhead turtle hatching season.

Energy expenditure and greenhouse gas emission.

It is predicted that once fully installed, electricity usage will fall by 45-55%.
This is in line with predictions made by the IPWEA report, (IPWEA, 2016 p.57).
This will mean the entire electricity requirement of the Sunshine Coast Council will be offset by its own 15 megawatt solar farm due to come online in August 2017.

Maintenance Costs

Unlike more traditional lighting, LED lights are many individual LED's in one luminaire. Failure of a luminaire is usually incremental rather than all-or nothing. Central monitoring can detect incremental loss, and can predict servicing weeks in advance, so decreasing servicing costs. Combined with the longer life span of LEDs, it is anticipated that each luminaire will require servicing less than once every ten years rather than once every six to twelve months as occurs at present. Considering maintenance represents 63% of present lighting costs, this should provide significant savings.

Criminal Hazard Reduction and Safety

The high hazard areas identified by the Queensland police can be addressed by the use of tri-power lighting profiles rather than increased lighting. Due to central collection of movement as well as lighting data from all street lamps, the movement patterns in high concern areas can be collected without the need for increased lighting.

Risks

The main risks with the approach to owning its own network is the large capital outlay and that LED lighting technology is progressing so fast that installed luminaires may rapidly become obsolescent and present difficulties with spare parts etc.

Other considerations

The Sunshine Coast Urban Master Lighting Plan does not have direct control over other lighting such as sporting venues. However the plan does include such issues and recognizes the need to address this as part of its light pollution minimization strategy.

The Sunshine Coast Council has no control over Department of Main Roads lighting, which may limit the effectiveness of its light pollution strategy in its region. This is well illustrated where the first tranche of lights were installed in Caloundra South in February 2017. Figure 15 and 16 shows the International

Dark-Sky Association compliant luminaire and the lighting effect. Magnitude 5 stars are still visible immediately after exposure to these lights and within 10 metres behind them. Figures 17 and 18 show the high intensity non compliant unshielded blue rich LED luminaires installed at the same time by the Department of Main roads on the approach route to this new suburb. The Southern Cross is barely visible after exposure to these lights ten metres outside their beam sprea

Figure 15.
International Dark-Sky Association Compliant LED luminaire as used in the Sunshine Coast Urban Lighting Master Plan. (Author's Personal Photo)

Figure 16
Luminaire lighting effect 3000K (Author's Personal Photo).

Figure 17.
Queensland Department of Main Roads unshielded blue rich LED lights installed February 2017 on Caloundra South access road. (Author's Personal Photo)

Figure 18.
Lighting effect (Author's Personal Photo)

Conclusion

The Sunshine Coast Urban Master Lighting Plan is based on a scientifically validated approach to all the issues of providing a better lighting network with high probability of substantially decreased light pollution and decreased long term cost.

It serves as a comprehensive and worthy document upon which other regions and authorities could base their own lighting master plans.

Conclusion and Recommendations

The clear advantages of LED lighting and associated technology means there will be a major change in how and who provides outdoor lighting in Australia over the next five to ten years.

If the principles outlined in this paper are followed we could see a substantial reduction in the negative impacts of outdoor lighting. If they are not, inappropriate LED lighting could make the situation substantially worse.

The recent experience in Australia has shown that outdoor lighting suppliers have not provided lighting based on what is efficient or best for the health, safety, and needs of the population or environment.

If we are to right the wrongs of the past it is essential that people with an understanding of these issues work to raise awareness of the problems and the solutions, with both the population at large and specifically with the key stakeholders.

Hopefully we can then maximize the likelihood that we do not have a brighter future.

References

ALGVERE, P. V., MARSHALL, J. & SEREGARD, S. 2006. *Age‐related maculopathy and the impact of blue light hazard.* Acta Ophthalmologica Scandinavica, 84, 4-15.

BENNETT, J. O., DONAHUE, M., SCHNEIDER, N. & VOIT, M. 2014. *The Cosmic Perspectiv.* Seventh Edition, Pearson New International Edition*.* Boston, Pearson.

CITELUM 2016. Sunshine Coast Council Urban Lighting Master Plan. version 2 revision 3 ed.

CLANTON, N. 2014. *Seattle LED Adaptive Lighting Study*. Report No. E14-286 Northwest Energy Efficiency Alliance. Published May 29, 2014.

COWLEY, L. 1998. *Atmospheric Optics* [Online]. Available: <http://www.atoptics.co.uk/highsky/airglow2.htm> Viewed May 4 2017.

DACKE, M., BAIRD, E., BYRNE, M., SCHOLTZ, C.H. AND WARRANT, E.J., . . . , 2013. Dung beetles use the Milky Way for orientation. *Current Biology,* 23, 298-300.

DICK, R. 2016. Is Red Light Really Best. *Sky and Telescope,* Vol 131, p.22-25.

DO, M. T. H. & YAU, K.-W. 2010. *Intrinsically photosensitive retinal ganglion cells.* Physiological reviews, 90, 1547-1581.

MORROW, E., HUTTON, S, 2000. *The Chicago Alley Lighting Project: Final Evaluation Report.* Illinois Criminal Justice Information Authority

FALCHI, F., CINZANO, P., DURISCOE, D., KYBA, C. C. M., ELVIDGE, C. D., BAUGH, K., PORTNOV, B. A., RYBNIKOVA, N. A. & FURGONI, R. 2016. *The new world atlas of artificial night sky brightness.* Science advances*,* 2, e1600377.

FALCHI, F., CINZANO, P., ELVIDGE, C. D., KEITH, D. M. & HAIM, A. 2011. *Limiting the impact of light pollution on human health, environment and stellar visibility.* Journal of Environmental Management, 92, pp.2714-2722.

FARRINGTON, D. P. & WELSH, B. C. 2002. *Effects of improved street lighting on crime: a systematic review*. Home Office London. Home Office Research Study 251

GARSTANG, R. H. 1986. *Model For Artificial Night-Sky Illumination.* Publications of the Astronomical Society of the Pacific. 98, 364-375.

GIBBONS, R., GUO, F., MEDINA, A., TERRY, T., DU, J., LUTKEVICH, P. & LI, Q. 2014. *Design criteria for adaptive roadway lighting*. Federal highway Administration, U.S. Department of Transportation. Publication No. FHWA-HRT-14-051

GREENE, M. W. 2012. *Circadian rhythms and tumor growth.* Cancer letters, 318, 115-123.

HALL, J. E. 2011a. Guyton and Hall Textbook of Medical Physiology. 12th edition ed.: Elsevier Publisher. Chapter 30 pp. 609-621

HALL, J. E. 2011b. Guyton and Hall Textbook of Medical Physiology 12th edition. Figure 50-8 pp. 614 Elsevier Publisher.

HALL, J. E. 2011c. Guyton and Hall Textbook of Medical Physiology 12th edition. Figure 50-9 pp. 614 Elsevier Publisher.

HÖLKER, F., MOSS, T., GRIEFAHN, B., KLOAS, W., VOIGT, C. C., HENCKEL, D., HÄNEL, A., KAPPELER, P. M., VÖLKER, S. & SCHWOPE, A. 2010. *The dark side of light: a transdisciplinary research agenda for light pollution policy.* Ecology and Society, Vol 15 Issue 4 p. 13

IDA 2010. *Visibility, environmental, and astronomical issues associated with blue-rich white outdoor lighting.* International Dark-Sky Association. *Tucson-Washington, DC*. <http://darksky.org/wp-content/uploads/bsk-pdf-manager/8_IDA-BLUE-RICH-LIGHT-WHITE-PAPER.PDF>

IDA/IES 2011. Model Lighting Ordinance. International Dark-Sky Association. <http://darksky.org/wp-content/uploads/bsk-pdf-manager/16_MLO_FINAL_JUNE2011.PDF>

Indiana Historical Bureau 2013. 85.1966.1 *First Electrically Lighted City Wabash County.* Created 12/17/2013. Viewed 10th May 2017. <https://www.in.gov/history/files/85.1966.1review.pdf>

IPWEA 2016. *Roadmap Street Lighting and Smart Controls (SLSC)*. Institute of Public Works and Engineering Australia, Australian Government Department Of The Environment And Energy. Released Dec 14, 2016. Sydney, Australia <http://www.slsc.org.au/slsc/slsc-programme/slsc-roadmap>

JI, Y. & WOLSEY, R. 1994. *Dimming systems for high-intensity discharge lamps.* Lighting Answers, Vol 1, 4, 1-8. <*www.lightingassociates.org/i/u/2127806/f/tech_sheets/Dimming_for_HID.pdf*>

KALEEM, Z., AHMAD, I. & LEE, C. *Smart and energy efficient led street light control system using ZigBee network.* Frontiers of Information Technology (FIT), 2014 12th International Conference on, 2014. IEEE, 361-365.

LED LAMPS 2017 Wiki 2017 Wiki article, 9th May 2017 viewed 10th May 2017 <https://en.wikipedia.org/wiki/LED_lamp>

LUGINBUHL, C. B., BOLEY, P. A. & DAVIS, D. R. 2014. *The impact of light source spectral power distribution on sky glow*. Journal of Quantitative Spectroscopy and Radiative Transfer, 139, 21-26.

MILLS, E. *Why we're here: the $230-billion global lighting energy bill.* Proceedings from the 5th European Conference on Energy Efficient Lighting, 2002 Nice, France.

NABI, S. 2014. *Toxic Effects of Mercury*, Springer Publisher .

NAVARA, K. J. & NELSON, R. J. 2007. *The dark side of light at night: physiological, epidemiological, and ecological consequences.* Journal of Pineal Research, 43, pp.215-224.

PATHBERIYA, S. 2013. *Lights out! Too many bulbs actually put us in the dark.(light pollution)*. Alternatives Journal, 39, 32.

PAULEY, S. M. 2004. *Lighting for the human circadian clock: recent research indicates that lighting has become a public health issue.* Medical hypotheses, 63, 588-596.

RIEGEL, K. W. 1973. *Light pollution*. Science advances, 179, pp. 1285-1291

SARAIJI, R., YOUNIS, D., MADI, M. T. & GIBBONS, R. B. 2016. *Pedestrian visibility at night: The effect of solid state streetlights.* Lighting Research and Technology, 48, 976-991.

STEINBACH, R., PERKINS, C., TOMPSON, L., JOHNSON, S., ARMSTRONG, B., GREEN, J., GRUNDY, C., WILKINSON, P. & EDWARDS, P. 2015. *The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis*. Journal Of Epidemiology And Community Health, 2015. Vol 69 pp.1118-1124.

STEVENS, R. & MOTTA, M. 2016. *Human and Environmental Effects of light Emitting Diode (LED) Community Lighting.* Report Of The Council On Science And Public Health, American Medical Association.
Report No. 2-A-16.

TÄHKÄMÖ, L. & HALONEN, L. 2015. *Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies*. Journal of Cleaner Productio., 93, 234-242.

THOMAS, J. R., JAMES, J., NEWMAN, R. C., RILEY, W. D., GRIFFITHS, S. W. & CABLE, J. 2015. *The impact of streetlights on an aquatic invasive species: Artificial light at night alters signal crayfish behaviour.* Applied Animal Behaviour Science. Vol 176, pp.143-149.

TUXBURY, S. M. & SALMON, M. 2005. *Competitive interactions between artificial lighting and natural cues during seafinding by hatchling marine turtles.* Biological Conservation*,* 121**,** 311-316.

YONG, M. & NASTERLACK, M. 2012. Shift Work and Cancer: State of Science and Practical Consequences. *Archives of Industrial Hygiene and Toxicology,* 63**,** 153-160.