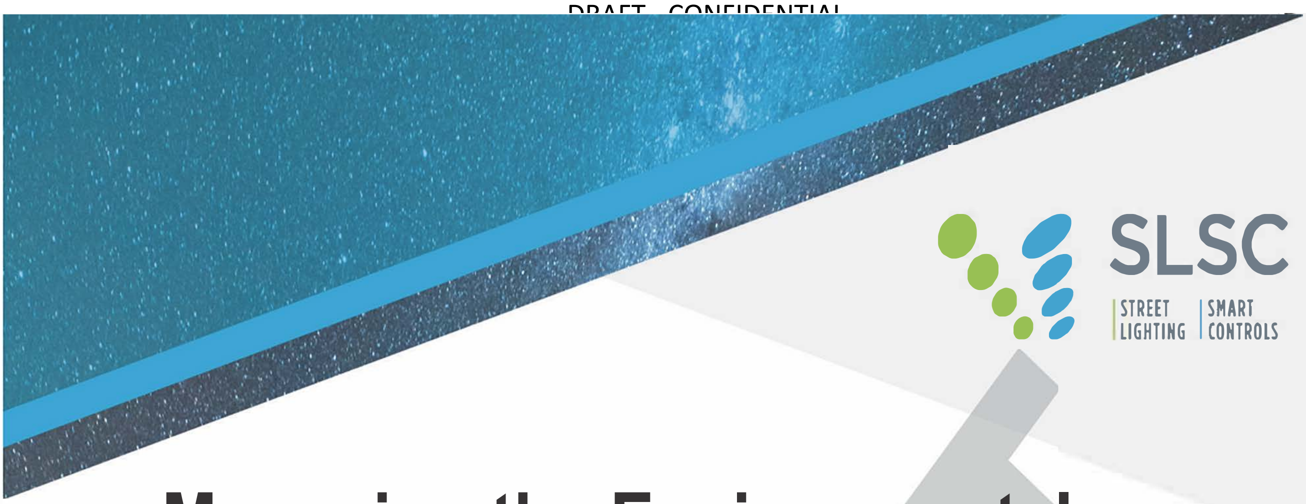
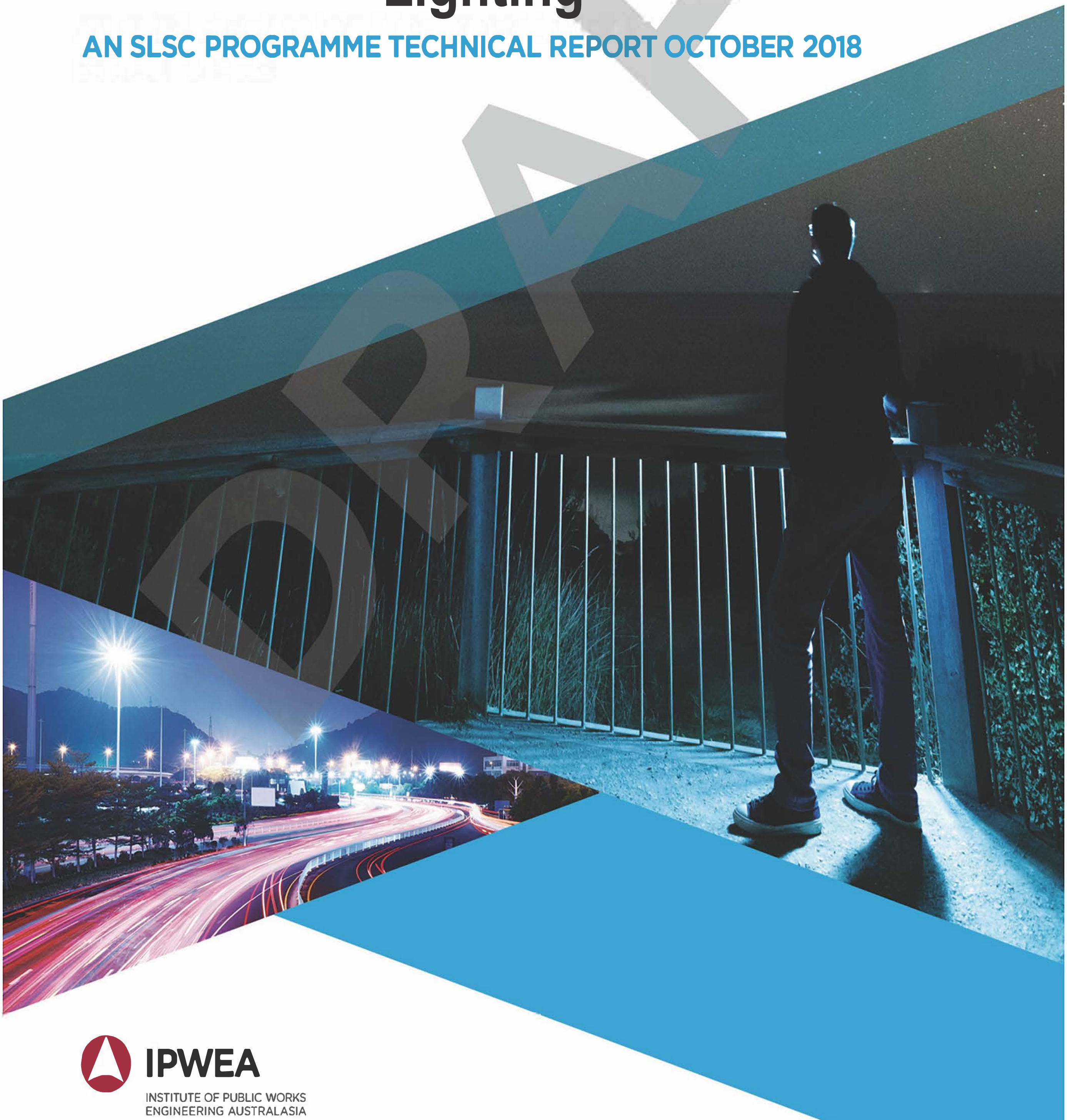


SLSC
STREET LIGHTING | SMART CONTROLS

Managing the Environmental and Health Effects of Public Lighting

AN SLSC PROGRAMME TECHNICAL REPORT OCTOBER 2018



IPWEA
INSTITUTE OF PUBLIC WORKS ENGINEERING AUSTRALASIA

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Authors

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Disclaimer: the contributions made by these organisations is greatly appreciated in advancing the body knowledge on this subject, but does not automatically imply that this report has been adopted, or endorsed by these organisations.

Executive Summary

The mass replacements of public lighting with LEDs, both planned and underway, creates a unique opportunity to consider and incorporate a wide range of new and emerging technical, social, and environmental issues which have not been previously accessible.

While international commentary has focused mainly on the correlated colour temperature of LEDs, understanding whether any potential harm is associated with public lighting and how best to mitigate it, requires full consideration of a broader array of topics.

As well as spectral power distribution and correlated colour temperature, other critically important topics for consideration include the intensity of the light, length of exposure, what other lighting is present, where lighting is directed, and what time of night the exposure is experienced.

For the first time, LEDs and smart controls provide the ability to vary almost all aspects of lighting and this fine control over light dosage has been overlooked as a major mitigator of any potential adverse impact lighting may have on health and the environment.

All types of lighting can create health and environmental problems if incorrectly or inappropriately deployed. But research has shown that white lighting used on vehicular roads results in shorter stopping distances than with yellow HPS lighting. This technical report concludes that the intelligent use of LEDs and smart controls can provide effective lighting solutions that substantially mitigate health and environmental concerns.

This report outlines the range of drivers of the potential positive and negative effects of lighting on humans, the wider ecosystem and observation of the night sky. It then summarises the range of advantages and disadvantages associated with blue-rich white lighting that must be weighed in the balance when making lighting decisions.

Despite the reality of compelling energy and operational advantages from the astute use of new technology the gains are not always reflected in commensurate cost savings to Australian councils. Institutional barriers to the adoption of updated technologies still exist, slowing the uptake of measures that can minimise adverse health and environmental effects of public lighting.

The report concludes with the following five IPWEA recommendations:

1. IPWEA continues to recommend that 2000K yellow HPS lighting be replaced with 4000K LEDs on main or arterial roads requiring Category V lighting as it is yet to be demonstrated that colour temperatures of 3000K or lower provide an equivalent improvement to driver reaction times and road safety. Nevertheless, IPWEA acknowledges that this topic is engendering intense international interest with on-going research which IPWEA is actively monitoring.
2. Where the lighting needs of pedestrians predominate on Category P roads and other public spaces lit with Category P lighting, IPWEA recommends the use of approximately 3000K lighting. This is likely to be preferred by many users and international consensus suggests these lower colour temperatures substantially mitigate a range of potential health and environmental concerns. However, few if any studies that suggest such risks, address the critical factor of light dose or exposure – which needs to be addressed before mitigation can be proved necessary. IPWEA acknowledges that lighting at colour temperatures of up to 4000K remains an option under AS/NZS 1158 for Category P lighting and may be appropriate in some circumstances.
3. In some specific environments (e.g. near astronomical observatories or near sensitive ecosystems) lighting with colour temperatures well below 3000K, or with very particular spectral power distributions, may be most appropriate.
4. Irrespective of the colour temperature of the LEDs being deployed, IPWEA recommends that most public lighting applications should include smart lighting controls and a Central Management System so that all luminaires can be controlled individually and *en masse* for the purposes of trimming excess light, dimming lighting when appropriate, and turning off lighting when not needed.

5. IPWEA recommends that MIESANZ or equivalent qualified lighting designers are appointed on all major lighting replacement programmes to ensure selection of appropriate luminaires and good photometric design that minimises glare, light spill and, upward waste light, and is fit for the environment for which it is intended.

1. Introduction

In a public private partnership with government, industry, and other peak bodies, the Institute of Public Works Engineering Australasia (IPWEA) has developed the Street Lighting and Smart Controls Programme (SLSC, www.slsc.org.au / www.slsc.org.nz) to provide high quality, impartial information, advice and assistance to all stakeholders with the goal of accelerating the rollout of LED street lighting and smart controls across Australia and New Zealand.

This technical report by IPWEA, is part of a series of Briefing Papers on issues of importance to the SLSC sector.

This technical report provides the exterior lighting industry and public works practitioners with guidance on how to manage the positive and potential negative issues arising from the application of lighting in public spaces.

This technical report contributes to that program and aims to clarify and balance a range of new and emerging topics in relation to the use of artificial light at night (often abbreviated to "ALAN").

It does not address economic and operational issues which have been adequately addressed elsewhere[1], but focuses on safety, health and environmental issues relating to light colour, dose (light intensity and duration) and the time of night of that dosage.

The issues involved relate to complex physics, biology, and physiology. This report references relevant and reputable published research and other science, and acts as a technical briefing report for the guidance of industry and government.

The purpose of this report is to inform professionals who are responsible for public lighting, whether they work in the exterior public lighting sector or in the public works engineering and asset management sectors. The report does not deal with interior lighting other than to contrast the comparative risks that humans face from interior lighting with those faced from exterior lighting.

From a historical perspective, the potentially positive and negative effects of blue-rich white lighting have become particularly important since Light Emitting Diode (LED) technology became commercially viable about 6-10 years ago. Before then, the most prevalent public lighting was 70+ year old white Mercury Vapour (MV) lighting technology, 60+ year old yellow High Pressure Sodium (HPS) lighting technology, and 30+ year old white Metal Halide (MH) lighting technology.

It is important to recognise that MH and MV white lighting has greater blue content than even 4000K LEDs, and these two types of lighting represent more than 40% of all street lighting currently used in Australia. Thus, LED lighting in these cases represents a *decrease* in blue-rich white light, even before accounting for the lower lumen output of LED design solutions, or from the use of controls. In this wider context, LED lighting has arguably been very unfairly maligned.

In most cases the change to LED lighting reduces energy consumption and maintenance by more than 50% over legacy technologies and so even if for economic reasons alone, LED lighting will continue to progressively replace all previous lighting technologies[2]. Nevertheless, LED lighting technology is improving at a far greater pace than any of its predecessor lighting technologies, bringing with it many opportunities to maximise the benefits and minimise any potential detriments of artificial lighting at night.

LED is a real revolution in lighting, and for asset managers working in exterior public lighting the mass replacements of public lighting, both planned and already underway, creates a need to become familiar with

[1] See IPWEA, 2016, *Street Lighting and Smart Controls (SLSC) Roadmap,* for Department of the Environment and Energy, Australian Government, by Strategic Lighting Partners and Next Energy.

[2] The exceptions are where in some places the lighting is owned by network companies and the tariff does not pass these savings through to the user.

a wide range of new technical, social, and environmental topics associated with LED lighting and smart controls. This disruptive change in technology has surpassed the ability of technical standards for product and design to keep pace. In Australia and New Zealand, there are major gaps in professional knowledge and guidance for the application of the latest lighting and control systems technologies. The IPWEA SLSC Programme is bridging these knowledge and guidance gaps.

Australia and New Zealand currently have some of the lowest illumination levels for street lighting in the developed world and are much lower than that of the USA or EU. A typical Australian residential road is lit to as little as 1/5th of the lighting level used on comparable residential roads in North America or Europe. Lighting levels on our main roads, while more comparable to overseas, are at the low end of international norms.

In Australia and New Zealand, the Technical Specification for road lighting luminaires, SA/SNZ TS1158.6:2015 Amd1:2018, states that the value of nominal Correlated Colour Temperature (CCT) for road lighting should be no greater than 4000K.

As at the date of this report, only about 15% of Australia's 2.5 million street luminaires have been converted to LEDs and less than 1% of LED luminaires installed in Australia have smart controls. There are around 1 million MV luminaires in Australia[3] that will need to be replaced under the requirements of the Minamata Convention (reduction of mercury) within the next three-four years and this lends urgency to the need for sound guidance in this area.

Despite the reality of compelling energy consumption savings and maintenance task reductions the economic advantages are not always reflected in commensurate cost savings to councils. Some DNSP asset ownership models and bundled tariff structures act as a barrier to the adoption of updated technologies that can minimise adverse effects of public lighting. As this report subject is the environmental and health effects of public lighting, analysing the important financial and institutional barriers is beyond the scope of the report. However, a general refocus of attention on institutional barriers to uptake in Australia is opportune and this report is a reminder that the drivers of constructive change are not exclusively financial, but also include environmental and health effects.

This Technical Report is a contribution by IPWEA to the Street Lighting and Smart Controls (SLSC) Programme to bridge the knowledge gaps that exist; to acknowledge the concerns in good faith of special interest advocacy groups; and to weigh the latest issues in the balance to help optimise overall outcomes for the industry, for our environment, and for our communities. One size or rule does not fit all circumstances and lighting design plays a critical role in getting the balance right between competing objectives.

2. Light

Light is the visible region of the electromagnetic radiation spectrum – the region in which humans can see. As with all electromagnetic radiation, light is made up of tiny bundles of energy called photons which combine the properties of both waves and particles. The 'colour' of visible light is determined by its wavelength or mix of wavelengths in nanometres (nm) as shown in Figure 1. For example, 450-495nm is perceived as blue[4] light whereas wavelengths of 620-750 nm are perceived as red. Visible light is a very tiny fraction of all electromagnetic radiation that is emitted. X-rays, radar, radio, TV and much more has the same wave and particle properties of light. It is important to note that different species perceive light differently, and the responsiveness of other species to individual wavelengths often differs markedly from humans. For example, some organisms can detect some parts of the ultra-violet and infra-red regions of the electromagnetic spectrum which are invisible to humans and thus is not referred to as "light".

Light is energy

Light is the only form of energy that humans can see – and then only when it is viewed directly from a source or indirectly when it interacts with a surface (such as buildings or roads) or airborne particles (like dust). Like

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3 IPWEA, 2016, Street Lighting and Smart Controls (SLSC) Roadmap, for Department of the Environment and Energy, Australian Government, by Strategic Lighting Partners and Next Energy.

4 Humboldt State University see http://gsp.humboldt.edu/olm_2015/Courses/GSP_216_Online/lesson1-2/spectrum.html

all forms of energy, it is measured in Joules for energy and Watts for power[5] or W/m^2 to measure the irradiance (or radiant power density) of light on a surface. When measuring non-visible electromagnetic radiation power in relation to the wavelength of the radiation, the measure is called radiometric spectral irradiance (or radiant power density and is measured in $W/m^2/nm$. This is relevant when the effect of lighting colour (wavelength) on non-human subjects (including turtles, birds and insects and light scattering in the sky) is discussed.

Photometry is the physics of light perceived by humans

Because the studied physics of light is generally about humans, the measurement of visible light has a correction factor applied to account for the variable sensitivity of the human eye to different colours. The measurement of light therefore separates in to two separate branches. *Radiometric* measurements are those used to measure electromagnetic radiation – whether visible or not, whereas *photometric* measurements are only used for the visible region of the electromagnetic spectrum. The *radiometric* spectral power density is used to measure the power of any electromagnetic wave relative to its wavelength. The equivalent *photometric* measure (i.e. calibrated to the average human eye) is the radiometric figure multiplied by a varying fraction depending on the typical human sensitivity to each wavelength and this turns the measurement into a photometric spectral power density. This measure is important to systematically treat the impacts of light correctly, especially blue-rich white light, as discussed later.

Virtually all lighting measurements – including intensity (candelas), flux (lumens), luminance (candela/metre squared) and illuminance (lux) - are made with this photometric correction factor. Thus, all measures of light intensity factor-in the human eye's colour response which is then called luminous flux in lumens, and one lm/m^2 is called a lux.

This variable responsiveness of the human eye in daylight has a mathematically described function which is illustrated as the white photometric line in Figure 1 and applied to all instruments and calculations in order to get numbers that correspond to what humans see. This is called the V(λ) (V Lambda) photopic function.

Human eyes use three types of cells in the retina resulting in wide variation in sensitivity to both colour and light intensity.

The lighting industry uses three curves:

- The photopic response for a bright day as described above – is used as the standard function;
- The black line in Figure 1 represents the eye's colour sensitivity in the dark and is called the scotopic response (known as V'(λ)); and
- NOT shown is the region that represents lighting levels in-between the two conditions called the mesopic response which approximates low level lighting in a residential street.

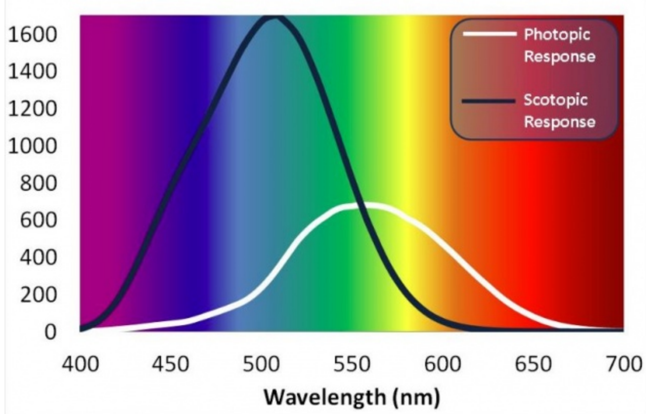

Figure 1 The black line shows the average human eye's response to very low light Scotopic response in lumens/Watt to colour and the white line shows its bright daylight photopic response (Source: Lux Review)

Biology, unlike Physics, is variable and imprecise

The physics of light is precise in its ability to accurately model and measure lighting intensity, duration and total dose, and the time at which the dose is received. In contrast, its detection by, and impact on, living biology including humans, is very imprecise.

Much of the science of how lighting affects humans or biology is the subject of significant ongoing research. Variations in sensitivity between humans, and across the wide range of situations in which they live make this branch of science challenging. For example, the photopic function V(λ) described above represents all of humanity, but may not accurately represent an individual's response due to differences in age, gender and

[5] A Watt is a Joule per second

possibly even ethnic origins. This is the first of many imprecise factors that apply in lighting's impact on biology which need to be recognised before conclusions are formed.

White Light

White light is the combination of all the colours "of the rainbow" which the eye's three types of retina cells sense. The signals from these cells are processed by parts of the brain cortex and combined to result in the human perception of colour. Thus, the perception of colour is determined by the spectral power distribution of the light emitted, the sensitivity of the retinal cells and the way the brain processes those signals.

Pure white light that could be described as "scientific white" is when all colours of the rainbow (i.e. wavelengths) are equally represented in the spectral power distribution. On a graph like Figure 1 this would be a straight line from violet all the way to dark red. The white lights occurring in the real world are nothing like this. They are mixtures of spectral power distributions that look white because our eyes and brains process these wavelengths to result in a perceived white. For example, a white Mercury Vapour lamp has a spectral power distribution shown in Figure 2[6] showing that most of its energy is in the invisible region and is one of the reasons MV technology is so inefficient. Furthermore, biological organisms that are sensitive to this infra-red region will be receiving significant energy that humans can't see.

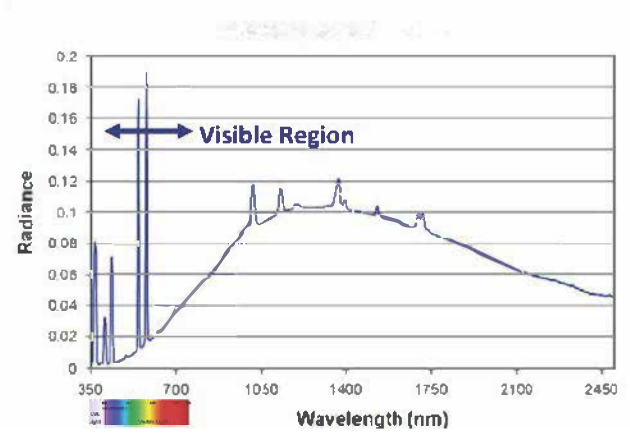

Figure 2 Mercury Vapour Radiance Spectrum (Source: NOAA)

6 Elvidge, C.,"Spectral Identification of Lighting Type and Character", National Oceanic and Atmospheric Administration, Boulder, Colorado · Earth Observation Group

In practical terms, industry and users have historically considered white light to range from approximately 2700K to 6500K[7] and have used loosely defined terms such as warm white, neutral white, cool white and daylight, however there is no formal standardisation of these descriptors.

The International Commission on Illumination (CIE[8]) has defined an x, y co-ordinate chromaticity system to describe colour regardless of its luminance. The CIE system also defines the "saturation" of that colour – or its "colourfulness" or "purity". The plot of all colours and saturations is shown in Figure 3[9]. Around the outside of the colour plot is shown the wavelength of "pure" or "saturated colours" and on the inside is a line representing white light generated by heating a "black body"[10].

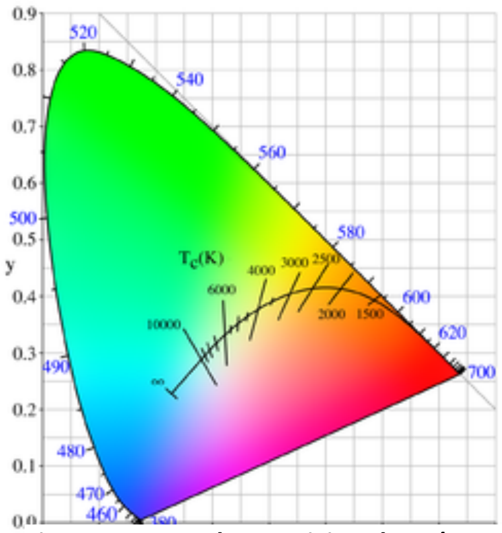

Figure 3 CIE Chromaticity Chart (Source: LEDs Magazine)

1850-1930K	Candle Flame
2000-3000K	Sun (Sunrise or Sunset)
2500-2900K	Tungsten light bulb
3000K	Tungsten Lamp 500W-1K
3200-3500K	Quartz Light
3200-7500K	Fluorescent Light
3275K	Tungsten Lamp 2K
3380K	Tungsten Lamp 5K, 10K
5000-5400K	Direct Sun (Noon)
5500-6500K	Daylight (Sun & Sky)
5500-6500K	Defused Sun (Cloudy/Hazy)
6000-7500K	Sky (Overcast)
6500K	RGB Monitor (White Point)
7000-8000K	Shade

Figure 4 Colour Temperature (Source: Mastin Labs)

The colour of the white light is directly related to the temperature of the body being heated in "Kelvin[11] (K) according to Planck's Law. For example, a tungsten filament heated to 2,700 Kelvin[11] will glow the same ("warm") white we have become used to as provided by the incandescent lamp. The higher the temperature, the more blue the colour as shown in Figure 3 and also in Figure 4 which tabulates the colour temperature of some common light sources together with a lay person's representation of the colour being described.

3. Drivers of the positive and negative effects of lighting on humans, ecology, and the night sky

This report restricts its discussion of artificial light at night to three areas:

- **Human** - the effects on humans;
- **Animals and plants** - the effects on mammals, insects, birds, and plants; and
- **Sky haze** caused by light scatter[12] (known as Rayleigh scattering or Mie scattering) on night sky darkness and star visibility.

The following is a summary explanation of some of the considerations and concepts in this context.

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7 Ohno, Y. Fein, M. Vision Experiment on Acceptable and Preferred White Light Chromaticity for Lighting, National Institute of Standards and Technology, Gaithersburg, MD USA, 2014.

8 The approved acronym CIE is for the initials of the French name of the organisation

9 LEDs Magazine, Volume 9, Issue 7, "Understand colour science to maximize success with LEDs – part 2"

10 Referred to as Planckian bodies because they behave according to Planck's law.

11 Add 273 to convert Kelvin units to degrees Celsius.

12 This is also the main vehicle for transporting lighting effects outside of the lighted area, such as for example, ALAN effects impacting species in a nearby national park

A. Spectral Power Distribution (SPD)

To appreciate the consequences of the complex science of light and colour, it is important to recognise that: "*colour is a function of the human visual system and is not an intrinsic property. Objects don't have a colour, they give off*[13] *light that appears to be a colour. Spectral power distributions exist in the physical world, but colour exists only in the mind of the beholder. Once the visual information leaves the eye, basic physics ends and neurocognition takes over*"[14].

Spectral Power Distribution (SPD) is more important than Correlated Colour Temperature (CCT or often abbreviated to "Colour Temperature") when analysing colour's impact on humans, animals, plants, and night sky interference. It is the wavelengths that impart the effects of the light rather than the perceived colour.

Colour temperature is widely used as a descriptor of white light colour appearance. It is literally the colour that a "black Planckian" body approximated by a piece of graphite would emit if heated up to the colour temperature being described and so does not adequately describe the spectral power density being emitted. Colour temperature should not be confused with colour or spectral power distribution. For example, CCT only describes the appearance of the light source to the human eye, but a large number of different spectral wavelength combinations can be used to make up the same colour temperature[15].

Significant research has taken place on the effects of blue-rich white light on humans and the ecology and substantial evidence exists that it can produce negative consequences. The science behind these effects is beyond the scope of this report, but the key driver for these potential negative consequences[16] is the spectral (i.e. colour) impact of artificial lighting on:

- Melatonin suppression in humans;
- Sensitivity of biological species, animals, insects and plants; and
- Spectral effects on night sky and star visibility.

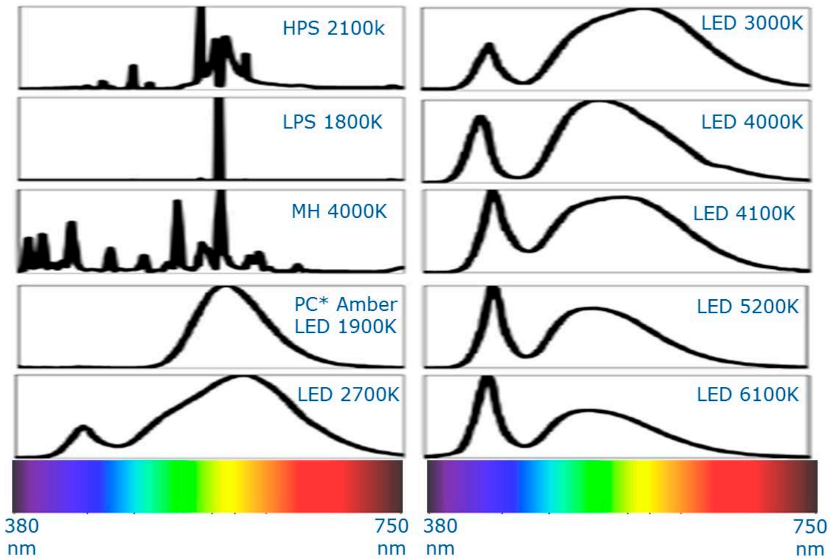

Figure 5 Representative Spectral Power Distributions (SPDs) of 10 different lights sources including three legacy High Intensity Discharge (HID) lamps and 7 LED light sources of differing Colour Temperature (Source: European Commission 2018[17]). NB "PC" stands for Phosphor Corrected"

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[13] Better wording might be "reflect" instead of "give off", but this is a quotation.

[14] Extracted from The Physics Hypertextbook.

[15] The reason for the term "correlated" is because the colour temperature only applies to the Planckian black body that lies on the curve in Figure 3 and any other colour below or above this line has to be correlated through a mathematical process back to the Planckian curve before it can be called "colour temperature".

[16] The Lighting Research Center in the U.S. has found that even relatively high levels of light require about 2 hours of exposure before melatonin suppression begins **Reference required**

[17] European Commission, JRC Technical Reports, Revision of the EU Green Public Procurement Criteria for Road Lighting, March 2018, Figure 19, p71

Therefore, the spectral power distribution of the widely varying products in the market is an important factor. **Figure 5** above shows 10 SPDs together with a colour spectra to show the contribution of each wavelength to the overall colour appearance.

Figure 5 illustrates the marked difference between the legacy HID lamps and the new LED technologies – both in colour temperature and spectral power distribution. **Error! Reference source not found.** below summarises the research that relates these spectral components to both the advantages and disadvantages provided by lighting at night.

However, as the Illuminating Engineering Society of North America identifies: "*What is often missed is that the total energy in a wavelength band is more critical than the height of the spectral peak. Specifically, it is the area under the curve (width x height) that we should be more concerned about. For example, if you define "blue content" as the fraction of light between 400 nm and 490 nm compared to light between 400 nm and 700 nm, then for the sources above* [two of them shown in Figure 6 below]*, the blue content of the LED is 16.6%, the fluorescent is 18.4%, and the HID is 24.0%.*"[18]

Another important issue is that most SPD graphs express the spectral power in *relative* terms such as shown in Figure 5 above. This makes comparison for the light sources within the study easy, but it is not useful for comparison with light sources from outside the study. The IES graph in Figure 6 below compares LED and Metal Halide light sources of 4000K at 150 Lux and shows clearly the difference in the SPDs at the interesting blue-rich part of the spectrum, mentioned above.

Figure 7 shows a similar non-relative irradiance comparison between LED and HPS light sources. The scientific approach to comparing the blue-rich energy emitted by white lights is to compare the proportion of the area under the SPD curves between 450 and 495 nanometres, with the total area of the visible part of the SPD curve in question. Thus Figure 7 shows that clearly LED lighting has a greater proportion of blue-rich energy emitted than does HPS, but the proportion of energy emitted is relatively small.

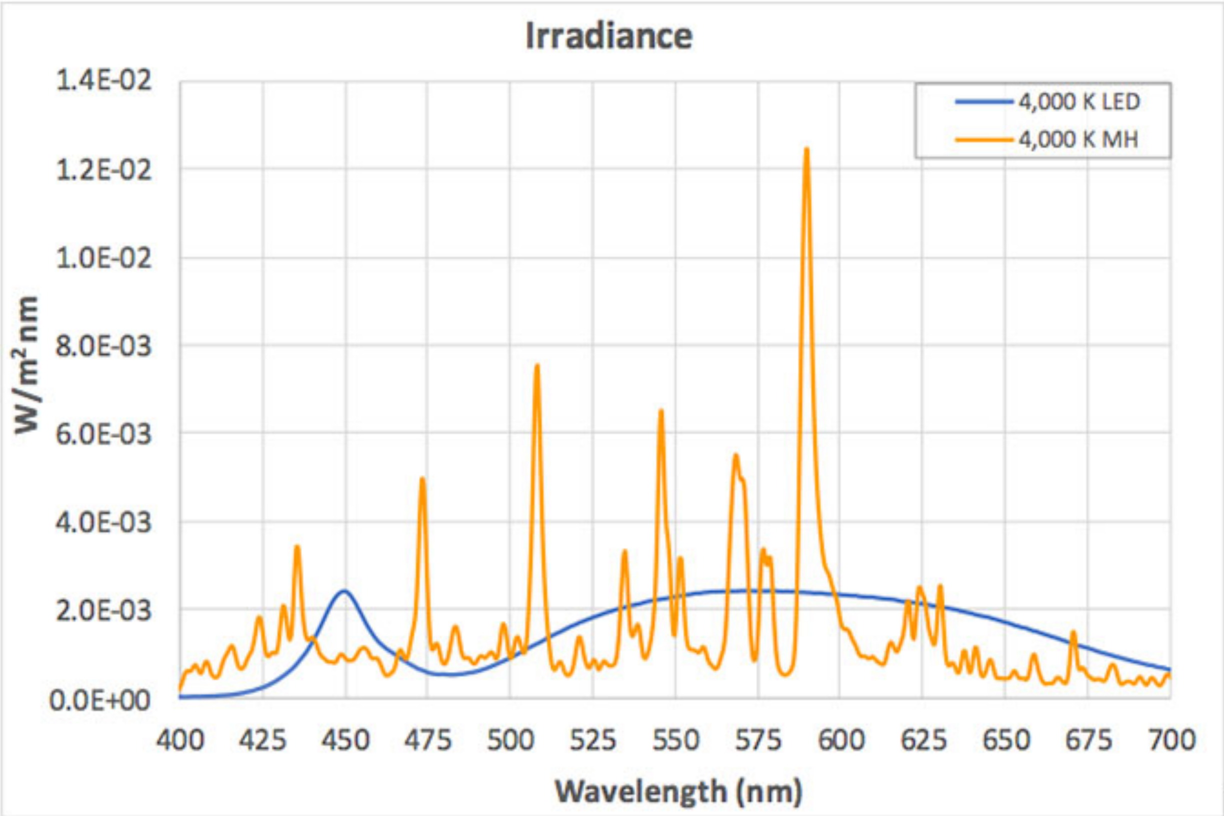

Figure 6 Irradiance comparison of a 4000K LED with a 4000K Metal Halide light source of the same 150 Lux illuminance (Source: IES)

[18] Eric Bretschneider Ph.D, Illuminating Engineering Society (of North America), Forum for Illumination Research, Engineering, and Science, weblink here.

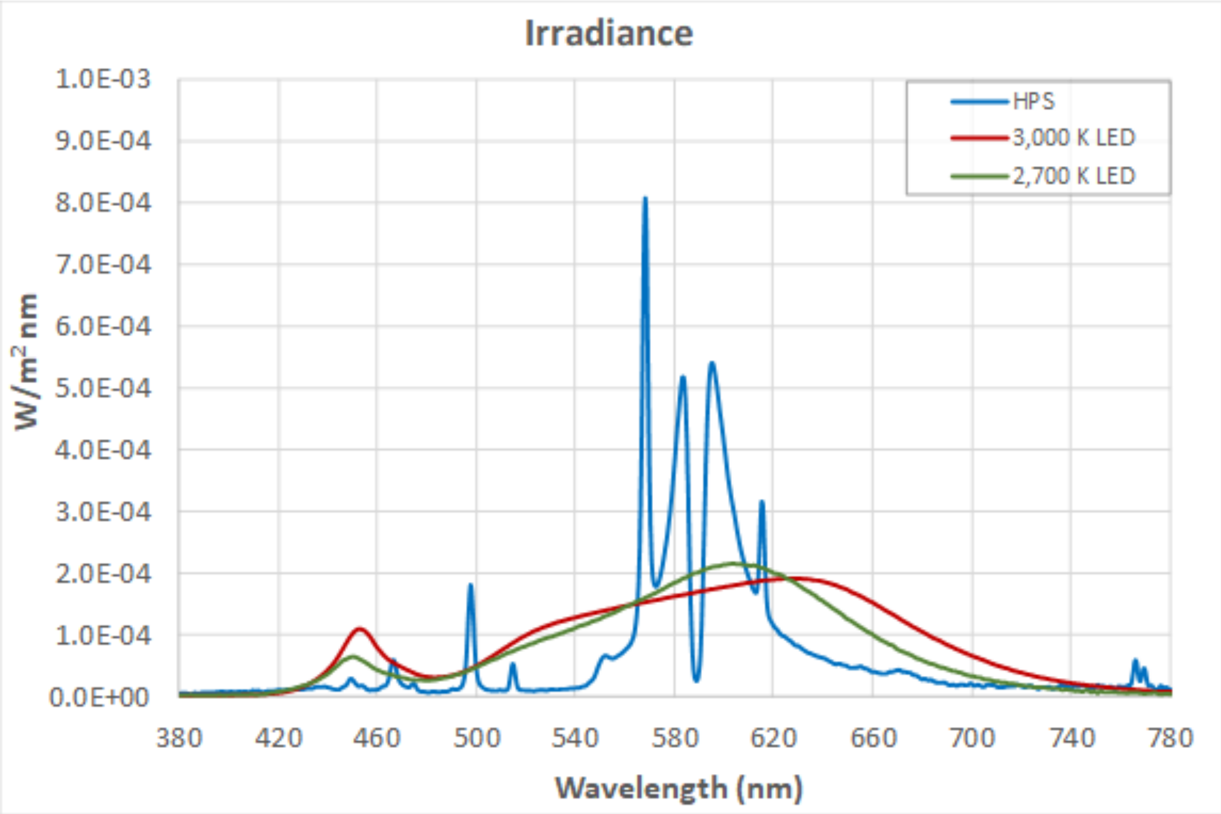

Figure 7 Spectral Power Distribution Comparison of LED and HPS luminaire at 10 Lux (Source: Eric Bretschneider PhD 2018[19])

B. Lighting Intensity

Significant research confirms the intuitive observation that an organism which is sensitive to light – be it human, animal or plant – will be sensitive to the *amount* of light energy that falls on it. Thus, dimming, or switching off blue-rich white light will reduce or eliminate potentially harmful melatonin suppression effects caused by that light. In simple terms, less light equals less impact.

The same conclusion holds for minimising the negative effects of street lighting on the night sky. As a US Department of Energy study on this subject says, "*The relationship between light output and sky glow is linear; increases or decreases in the luminaire output levels are matched one-for-one in the resulting contributions to sky glow from the street lighting system*."[20] In blunt terms, street lighting or any other lighting, will never *improve* night sky visibility. The excellent visibility of the night sky in remote regional areas of Australia clearly demonstrates this effect.

Error! Reference source not found.1 below identifies which advantages and disadvantages provided by public lighting are reduced or increased by decreasing lighting use.

C. Lighting Dose

Similarly, the duration that a subject is exposed to lighting of a specified intensity is a critically important factor in determining the light sensitive subject's response to that light. Multiplying this duration together by the light intensity provides a "dose" quantity that is a fundamental principle of both physics and biology. The dose received by a subject in all disciplines (including medicine) is a fundamental factor that determines how we are affected by radiation or light. This is why it was particularly surprising that the

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[19] Eric Bretschneider PhD, EB Designs & Technology LLC, Denton, TX 76210, USA.

[20] US Department of Energy, Energy Efficiency & Renewable Energy, An Investigation of LED Street Lighting's Impact on Sky Glow, April 2017, P32

American Medical Association's announcement in 2016 that suggested a maximum of 3000K colour temperature lighting should be used, completely ignored this very important dose factor[21].

As for lighting intensity, **Error! Reference source not found.**1 also identifies where dose has an impact.

D. Time of Day / Night

All organisms on this planet relevant to this report are synchronised to the solar cycles of the rotating earth and the resultant day/night and seasonal cycles. Their biological and biochemical states are therefore related to the position in that cycle and are affected by the time of exposure to light. With modern control systems, it is a simple process to fully programme dosage and time of day/night to precisely target illumination only where and when it is required. Up to recent times, there has been no compromise possible - public lighting was full-on for all the dark hours. Now control systems can alter each individual luminaire's settings to balance community, astronomical and ecological benefits against the detriments. The task to weigh up all the factors has become much more complex, but is now possible to establish and apply a net-benefit position as determined by the community concerned.

E. Luminaire Design and Orientation

With the mass adoption of LED technology, it has become more important than ever that luminaire design, site location and orientation avoids any light directed where it is not required. This will reduce glare which is key to good visibility. Where light does spill, this is regarded as light pollution and results in unintended and/or undesirable consequences. These include night sky and animal/bird interference, as well as light trespass into residential homes or other situations where the light is not required.

4. Potential Benefits from White Lighting

4.1. Transport Activities

The capability to travel safely at night by keeping drivers alert and obstructions and hazards visible.

As identified above the research indicates that Transport Safety is directly influenced by all of 3A to 3E in Section 3 above.

White lighting has both been demonstrated and is generally accepted, as being safer in vehicle traffic situations than yellow lighting.

This is due to the faster reaction times of humans in environments illuminated by white lighting in contrast to yellow HPS lighting and the correspondingly demonstrated reduced stopping distances for vehicles[22].

In 2017 there were 410 fatalities at night (36%) out of a total of 1,131 fatalities on Australian roads[23] but the proportion of travel taken at night is substantially less than 36% so the risks of death and injury at night are far higher than daytime. As Elvik et al[24] says;

> "*According to a study from the USA, about 25% of all traffic travels during the hours of darkness while 50% of all fatal accidents occur in darkness,"* and "*… road lighting reduces fatal accidents by 60% and injury and property-only accidents by around 15%*".

These are substantial safety benefits that are also affected by SPD (section 3A), light intensity (section 3B), lighting dose (section 3C), time of day (section 3D) especially as traffic volumes are highly dependent on this, and Luminaire design and orientation (section 3E).

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21 Kraus, L., Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting, American Medical Association. Action of the AMA House of Delegates 2016 Annual Meeting: Council on Science and Public Health Report 2 Recommendations Adopted and Remainder of Report Filed

22 Clanton, N. of Clanton & Associates & Gibbons, R. of Virginia Tech Transportation Institute (VTTI), 2014, Seattle LED Adaptive Lighting Study, Northwest Energy Efficiency Alliance, available from Researchgate here. Other studies by Clanton & Associates in San Diego, Anchorage and San Jose corroborated sorter stopping distances for white light, as also by the Arizona Department of Transportation, USA, May 2003 called "Roadway Lighting: An Investigation and Evaluation of Three Different Light Sources", Final Report 522,

23 Bureau of Infrastructure, Transport and Regional Economics (BITRE), 2018, Road trauma Australia 2017 statistical summary, p33

24 Elvik, R, Hoye, A, Vaa, T, and Sorensen M (2009), Handbook of Road Safety Measures, Institute, of Transport Economics, Oslo, Norway, Emerald Group Publishing Ltd, 2nd Edition, October 2009, Part II, Section 1 Table 1.0.1 page 145 – 155 & pp 272 – 281

4.2. Productivity & Entertainment

The capability to do productive and entertaining activities such as reading, physical work, sports, hobbies, increased use of public amenities/spaces; and time-shifting of human activities.

Less researched, but just as evident is that lighting for productivity and entertainment is directly influenced by all of sections 3A to 3E above.

High illumination levels with white light that depicts colours well are ideal for task lighting where detail or, for example, fast moving sporting activities requires human responsiveness and avoidance of errors or to attract a paying audience[25].

Other examples of highly valued activities that expose humans to blue-rich white lighting that are helpful, include the use of mobile phones, tablets, televisions, computers, and other monitors widely used in society for productivity and entertainment.

The SPDs, illumination levels, dosage, and time of day when these essential devices are used need to be weighed against any potential adverse health effects described in 4.1 above.

4.3. Security & Safety

The improvement in, or perception of better security and safety.

The ability to distinguish features and colours is important for people to feel secure. The better colour rendition properties of white lighting provides both safety and security benefits which translate into transport and pedestrian security and safety[26] as well as reduced damage to public infrastructure, and is a function of: (ref sections 3A to 3E above)

- lighting SPD;
- lighting intensity;
- appropriate lighting dose;
- time of night lighting; and
- good orientation & photometric design.

These are necessary conditions for people to both feel secure from unknown risks, and also for security camera surveillance.

4.4. Precisely Controlled Lighting

LED luminaires in conjunction with smart controls provide precise tailoring of the lighting service to community needs for normal and emergency services; traffic management, community safety, and amenity.

Being effectively a point source, optical control of where LED light is emitted is much greater than for legacy technologies.

Furthermore, when LED luminaires are fitted with smart controls managed by a Central Management System (CMS) public lighting can be controlled to precisely deliver all of the parameters from sections 3B to 3E and sometime in the near future, are also likely to be able to control the colour temperature of the LED luminaire (section 3A) as well. Thus, this benefit facilitates the delivery of all the benefits in this section[27].

4.5. Enabling Smart City Infrastructure

Public lighting with CMS control systems provides the enabling physical infrastructure for a very large number of smart and connected city services through its prevalence, being up high, and being supplied with 24 hour electricity.

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[25] For example, an IESANZ lighting prize winner involved a horse racing track where the light levels were increased only for the specific periods where each race was being filmed for broadcast

[26]

[27] Model Public Lighting Controls Specification V1, July 2017, Institute of Public Works Engineering Australasia (IPWEA), available from http://www.slsc.org.au/slsc/slsc-programme/model-specifications

A change to critical infrastructure is usually a once-only generational opportunity and must be taken carefully and with well-informed scientific input that balances the advantages against the disadvantages very carefully as the net result will stay with the community for decades.

5. Potential Adverse Effects of White Lighting

5.1. Sleep & Health

Excessive amounts of blue rich white light or duration of light may contribute to health issues and sleep disruption.

As identified above the research indicates that sleep and health problems are affected directly by all of sections 3A to 3E above.

While the effects of blue-rich white light supressing melatonin are well researched and documented[28], what is not so well understood and factored into public concerns is that all such melatonin suppression effects are dependent on: (ref sections 3A to 3D above)

- lighting SPD;
- lighting intensity;
- lighting dose (noting the relatively short durations that people are under public lighting and their relatively significant distances from the light source, results in low doses), and
- the time of day (night).

For example, some researchers have noted that the blue-rich white light dose received by even stationary people under street lights are an order of magnitude or more less than that experienced by people reading on their mobile phones or tablets in bed at night [29].

Before negative conclusions can be drawn, it is important to:

a) measure dose, SPD, timing of dose, and

b) use the relatively inexpensive controls systems to dim or switch-off lighting at off-peak times when higher light levels are not required.

5.2. Dark Sky Interference

Light pollution interferes with the dark sky (for professional and recreational astronomical activities).

As identified above the research indicates that Dark Sky interference is directly influenced by all of sections 3A to 3E above.

A report by the US Department of Energy which investigated LED Street Lighting's Impact on Sky Glow found that:

"The three main characteristics of luminaires that influence sky glow are SPD, total light output, and light distribution (and, most importantly, the amount emitted as uplight above the horizontal plane).

Each of these characteristics can be varied during at least the initial selection of products and should therefore be carefully evaluated as part of the system design. In addition, street lighting is only one of many sources of light at night in urban areas."

The findings in this study consequently represent only the estimated contributions to sky glow from the street lighting system under the conditions considered and may not even address the primary sources of sky glow contribution in locations like large urban areas."[30]

Properly designed and installed full-cut off LED luminaires direct very small amounts of light upwards (generally, below 1%).

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28 AMA Press Release, June 14, 2016 about this here and the Board of the Illuminating Engineering Society response here and background here.

29 Kinzey, B. Pacific Northwest National Laboratory, Portland Oregon, USA, IES Street and Area Lighting Conference September 17-21, 2016, Page 14

30 U.S. DOE Solid-State Lighting study: An Investigation of LED Street Lighting's Impact on Sky Glow, 2017, p38

In contrast, legacy HPS, MV, MH, CFL and T5LFL luminaires with bowl-type visor optics beam between 3% to 6% of luminous output directly up into the night sky.

This is easily observed from an aeroplane window at night, where the pin-pricks of directly visible legacy HPS or MV luminaires are observable everywhere, whereas with controlled optic LED lighting there are no pin-pricks, but only the reflection of the light off the road surface.

5.3. Environment

Artificial light interferes with the ecology of some types of species, including turtles, birds, plants, and insects[31].

As identified above the research indicates that fauna and flora are directly influenced by all of sections 3A to 3E above.

Like humans, photosynthesis and other process in plants[32] and the biology of animals possess a circadian clock that regulates their activities and physiology[33].

Also like humans, these mechanisms are related to colour (SPD, section 3A), light intensity (section 3B), dosage (section 3C), time of day (section 3D), and photometric distribution of the luminaire (section 3E).

5.4. Wastage caused by Legacy Lighting

Failing to replace obsolete legacy technologies with LEDs due to concerns about potential harm from blue-rich white light wastes energy, will continue to generate higher levels of upward waste light, incur higher maintenance costs, and may result in heavy metal pollutants (such as mercury) being released to the environment.

Lighting wastage is not only governed by SPD or operating time of day/night, but it is also a function of light intensity and the length of time a luminaire is operating unnecessarily.

Fortunately, wastage is easily minimised through the use of modern LED luminaires with good optical control but perhaps most significantly by the use of intelligent individual luminaire controls or CMS controls as outlined in A4 and Appendix 1 (Section 8).

5.5. Poor Lighting Design

Excessive glare from poorly designed installations make visibility difficult and uncomfortable - particularly for the aged or visually impaired.

Poor lighting design is a catch-all that applies to all 5 factors in sections 3A to 3E above and of course applies to all lighting technologies, not just LED. Poor lighting design may put the wrong light (colour spectra, intensity) in the wrong place, at the wrong time. Eliminating poor design will maximise benefits and minimise disadvantages.

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31 "ALAN affects behaviour, foraging, reproduction, communication, breeding cycles and the habitat of many nocturnal species, including invertebrates, amphibians, birds, bats, turtles, fish and reptiles. On the other hand, the impact of ALAN on flora is less documented; a review on the topic is reported by Briggs. Exposure to artificial light prevents many trees from adjusting to seasonal variations. The presence of ALAN stimulates photosynthesis at a time when photosynthesis does not normally occur." Aube´ M, Roby J, Kocifaj M (2013) Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility. PLoS ONE 8(7): e67798. doi:10.1371/journal.pone"

32 Sweeney, B.M., Biological clocks in plants. Annual Review of Plant Physiology, 1963. 14(1): p. 411-440

33 Cashmore, A.R., et al., Cryptochromes: blue light receptors for plants and animals. Science, 1999. 284(5415): p. 760-765.

6. Discussion

It is clear that public lighting has come through a LED technology revolution which has provided many benefits, but there is now a greater requirement to balance these against increased awareness of the potential detriments that come with some of these benefits.

The need for professional engineering and lighting design

The research is clear that blue-rich white lighting is both beneficial to humans in some situations and adverse to humans and other forms of life, in others. The observability of the night sky is also diminished by excessive and uncontrolled blue-rich white light. But as in all situations, there is a trade-off of positive and negative effects. Furthermore, LED lighting has justifiably attracted attention to these positive and negative effects, but care is required especially because many legacy technologies exhibit the same or worse characteristics. For example, Mercury Vapour, Metal Halide and 4000K CFL and T5 LFL luminaires making up more than 40% of all Australia's street lighting have similar or greater blue-white SPD impact than LED. In the case of MH luminaires their SPD's result in a 112% greater (harmful) melatonin suppression index (MSI) than 2700K LED delivering the same illuminance[34].

The accommodation of these advantages and adverse impacts needs to be carefully and rationally considered. It is a project specific trade-off which needs the application of engineering principles and design application arising from well-established science, together with an understanding of all the costs of applying– or not applying this technology as an integrated system.

Metrology standards for blue-rich white light

One of the many organisations that are making contributions in this area is the International Commission on Illumination (CIE). The CIE is the peak international standards body for the science of illumination and is currently developing International Standard "CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light"[35]. This standard aims to set the requirements to identify and measure the response of humans to blue-rich white light which is referred to as the "melanopic" content of light.

This standard is a draft (currently in a consultation stage) that defines age related sensitivity to the melanopic content of light. This identifies very considerable reductions in melanopic sensitivity with age. This is one of many illustrations that demonstrate the application complexities– even before the critical issues of dose is considered.

LED lighting is not the enemy

The harmful consequences of drawing narrow or hasty conclusions was made by Dr Jim Brodrick[36] of the US Department of Energy who stated[37]:

> "*Some media coverage of concerns about blue light, light at night, and dark-sky issues can give the impression that LEDs are the enemy, when in fact they're a critical part of the solution, which the American Medical Association (AMA) acknowledges. It's important to remember that these issues have been around for decades, long before the emergence of LED technology. The key takeaway from the AMA's guidance is the importance of properly matching lighting products with the given application, no matter what technology is used. More than any other technology, LEDs offer the capability to provide, for each application, the right amount of light, with the right spectrum, where you need it, when you need it*."

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34 Aube´ M, Roby J, Kocifaj M (2013) Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility. PLoS ONE 8(7): e67798. doi:10.1371/journal.pone.0067798. Table 2, p6. Calculated from LED with an MSI of 0.285 and Metal Halide an MSI of 0.624. The obsolete Mercury Vapour technology it is not mentioned in this paper.

35 Draft International Standard CIE DIS 026/E:2018: CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light.

36 Solid-State Lighting Technology Manager in the Building Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

37 SSL Postings, June 21, 2016, US Department of Energy.

Is there a need for lighting after midnight to before dawn?

In 2015 an important and substantial public lighting research project was undertaken by the London School of Hygiene and Tropical Medicine[38] (LSHTM). This confirmed an important conclusion from a study of 62 of the 174 City and District Councils in England and Wales who switched off, and/or dimmed, their public lighting:

"… provide no evidence that switch off, part-night lighting, dimming, or white light adaptations to street lighting were associated with night-time traffic collisions. The results also provide no evidence that these lighting strategies are associated with an increase in crime at an area level. Results suggest that in the aggregate, dimming and white light regimes were associated with reductions in crime, though estimates were imprecise."

This vitally important conclusion was misinterpreted by several scientists who were investigating the effects of road lighting on night sky pollution to identify that road lighting had no useful road safety or crime mitigating effect. This is of course completely incorrect because all Councils who either dim or switch off their road lighting only do so at times long after evening peak traffic flows have subsided, mainly after midnight. Furthermore, other research conducted widely across the transport sector is highly conclusive that road lighting reduces crashes at peak night traffic times. What this important LSHTM paper does confirm is that (for the UK), is that there is no safety or crime mitigating need to light roads after midnight or before the dawn peak traffic periods, particularly in rural regions.

Choices of 2000K, 3000K or 4000K?

This choice reflects an evolution in lighting. Yellow 2000K High Pressure Sodium (HPS) lamps superseded very inefficient white Mercury Vapour luminaries in most places in the world about 40 – 60 years ago. Commercial availability of very energy efficient and high colour rendering performance white light 4000K LEDs started in about 2008. Since then, recognition of their functional advantages from a transport and road safety perspective over low colour rendering performance 2000K yellow HPS has been enthusiastic.

With yellow HPS lighting it is almost impossible to discern colours of objects at night[39] and US research shows that reaction times are longer (and thus stopping distances larger) under 2000K yellow light than with 3500K or 4000K LED lighting**Error! Bookmark not defined.**. Conversely, 4000K LED lighting also suffers from colder appearance and has greater (potentially harmful) blue light percentage and melanopic disruption potential (scientifically described as Melatonin Supression Index or MSI) and consequently there has been some public and interest group push-back[40].

IPWEA understands that new road safety research is being conducted which shows that 4000K is safer than 3000K especially for high speed roads where driver reaction times need to be faster to be safer.

Lighting Dose

US research found from 30 sets of sample measurements taken independently that the illumination from LED street lights was less than 1/200th that of a typical evening smart phone or tablet use**Error! Bookmark not defined.** (Note that US light levels for street lighting are general much higher than those for Australia) As with most forms of radiation (and discussed earlier in the paper), the potential for harm is directly proportional to dosage or exposure (intensity and duration). With street lighting, the intensity is low because of the distance from footpaths to street light luminaires, and the duration is short, because humans do not usually stare at or stand directly under street lights for protracted periods of time.

Lower colour temperatures may necessitate designs with more light

In a statement on this subject from the US Department of Energy[41] which makes the important points that blue light content, the need for proper control of glare, and the need to limit spill light are not new issues or unique to LEDs.

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38 Steinbach R, Edwards, P., et al, "The Effect of Reduced Street Lighting on Road Casualties and Crime in England and Wales: Controlled Interrupted Time Series Analysis", Department of Population Health, London School of Hygiene and Tropical Medicine. J Epidemiology Community Health 2015; 0:1–7 doi:10.1136/jech-2015-206012, 3 June 2015

39 Referred to as "colour rendering"

40 Some examples of web-links: Rome, Davis California, and Brisbane, Australia

41 of 21 June 2016 on its SSL Postings

It also notes that while using light with low colour temperatures may be useful to mitigate some impacts, this may also reduce the effectiveness of public lighting. To achieve the same safety levels, lighting designs using low colour temperatures may therefore require, *"…designs with more lumens which may completely negate the effects of reducing the relative amount of blue light emission."*

As the US DOE suggests, the 'raw' melanopic content produced by a light source is only one contributor to any ensuing environmental or health impacts actually realised. Focusing exclusively on a single measure ignores the various means of controlling or offsetting the increased harmful melanopic content of white light sources, and particularly those that are enabled by LED technology such as more precise photometric distribution and switching and dimming capability.

The importance of road reflectance and design and installation

Typically, the light reflected off surfaces of Australian roads is about 7% of incoming light[42]. It therefore takes a reduction of about 14 lumens from the luminaire to match the sky glow reduction from 1 lumen of eliminated direct uplight – this 14:1 ratio is why a focus on uplight reduction is very effective in reducing sky glow impacts.

7. IPWEA SLSC Conclusions & Recommendations

Conclusions:

These conclusions arise from the report above which references authoritative research:

1. The cooler (i.e. bluer) the white light (higher CCT), the better it is at keeping humans alert for intensive activities such as driving;
2. The warmer (i.e. yellower) the white light (lower CCT), the better it is at allowing humans to sleep; reduces the risks of possible health problems; reduces disturbance to the ecology; and minimises disturbance to the visibility of the night sky;
3. Until LED luminaires were widely adopted, most of the world's road lighting was yellow High Pressure Sodium (in NZ >90% and AU >30%) with colour temperatures of between 1800K and 2000K;
4. Now that LEDs are being adopted worldwide, main road transport authorities responsible for roads with Category V lighting have shown a strong preference for 4000K lighting based on faster driver reaction times;
5. By restricting LED luminaire operation to times of peak road or foot traffic and dimming or switching off after these times, a balance of health, environment and night sky outcomes can be achieved to the satisfaction of the particular community involved;
6. With modern LED luminaires it is relatively easy to ensure good lighting design outcomes that avoid glare and light spill and produce minimal direct upward waste light;
7. The extra cost of this good lighting design is very moderate in the context of overall project costs and is a 20 year investment in community safety, aesthetics and the environment;
8. For some specialised applications the use of yellow monochromatic light may be justified. The specific application sometimes presents special requirements that outweigh everything else, for example near observatories or turtle-nesting grounds. The relevant local authority must be sensitive to these issues and weigh the needs accordingly. The resulting lighting quality for humans may be poor and/or the lighting scheme may be inefficient, but these parameters are being sacrificed at those locations to achieve these other regionally important objectives. These decisions should be locally determined in each case and should not be generally applied. The local authority must achieve the best balance among objectives that are often competing.

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[42] AS/NZS 1158.2:2018 Appendix D provides road reflective factor tables. R3(Dry) is the default Australian road surface design specification. This is Qo=0.07. Qo is the average luminance coefficient of the road surface. ie a measure of the diffuse reflection from a road surface.

Recommendations:

1. IPWEA continues to recommend that 2000K yellow HPS lighting be replaced with 4000K LEDs on main or arterial roads requiring Category V lighting as it is yet to be demonstrated that colour temperatures of 3000K or less provide an equivalent improvement to driver reaction times and road safety. Nevertheless, IPWEA acknowledges that this topic is engendering intense international interest with on-going research which IPWEA is actively monitoring.
2. Where the lighting needs of pedestrians predominate on Category P roads and other public spaces, IPWEA recommends the use of approximately 3000K lighting. This is likely to be preferred by many users and international consensus suggests these lower colour temperatures help to mitigate a range of potential health and environmental concerns. However, few if any studies that suggest such risks, address the critical factor of light dose or exposure – which needs to be addressed before mitigation can be proved necessary. IPWEA acknowledges that lighting at colour temperatures of up to 4000K remains an option under AS/NZS 1158 for Category P lighting and may be appropriate in some circumstances.
3. In some specific environments (e.g. near astronomical observatories or near sensitive ecosystems) lighting with colour temperatures well below 3000K, or with very particular spectral power distributions, may be most appropriate.
4. Irrespective of the colour temperature of the LEDs being deployed, IPWEA recommends that most public lighting applications should include smart lighting controls and a Central Management System so that all luminaires can be controlled individually and *en masse* for the purposes of trimming excess light, dimming lighting when appropriate, and switching off lighting when not needed.
5. IPWEA recommends that MIESANZ or equivalent qualified lighting designers are appointed on all major lighting replacement programmes to ensure selection of appropriate luminaires and good photometric design that minimises glare, light spill and, upward waste light, and is fit for the environment for which it is intended.

Appendix 1 – Smart public lighting controls and Central Management Systems (CMSs) ***(Note; this section to be included as a breakout box at appropriate location)***

Smart public lighting controls overseen by a Central Management System (CMS) allow lighting asset owners or managers to collect, analyse and use substantial amounts of information not available currently, greatly improving asset management. Information is gathered from each individual luminaire, and used by the CMS to provide performance enhancing functions, including:

- **Switch, dim and brighten lighting levels** according to ambient light, programming, schedules, calendars or real-time signals;
- **Collect and aggregate energy consumption** data with high accuracy for the user or to a third-party billing system;
- **Collect and analyse Inventory information** on luminaire or field device location with selectability on maps, descriptions, colour coded assets and street level views of asset locations;
- **Provide data analytics** and system power characteristics on any particular luminaire and generally displaying the history of any collected data on any field device;
- **Monitor operational hours** and condition of luminaires and control electronics for predictive maintenance purposes and for warranty enforcement;
- **Identify luminaire and electrical failures**, anomalies and other failures - on maps for the whole city and for a particular geographical section on road maps and satellite maps;

- **Collect data from field devices** and supply to the user or to third party software such as Asset Management Systems (AMS), Energy Billing Systems or Geographical Information Systems (GIS), and;
- **Sense and detect a wide variety of traffic, environmental** and other parameters from the street that could interact with luminaires to adjust light levels, or to provide the city with information to help improve services, comfort and safety in the city[43].

[43] Model Public Lighting Controls Specification, Street Lighting and Smart Controls (SLSC) Programme of the Institute of Public Works Engineering Austrasia (IPWEA), July 2017.