A RATIONALE FOR THE MANDATORY LIMITATION OF OUTDOOR LIGHTING

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Abstract

The great value of artificial outdoor lighting has largely obscured the social, ecological and environmental problems resulting from present lighting practice. Exponential growth of outdoor lighting has been observed in many countries. It is unsustainable and greatly at odds with the need to reduce greenhouse gas emissions. Artificial skyglow resulting largely from wasteful lighting design and overuse of lighting is increasingly hampering astronomical research, recreation and education and destroying indigenous cultural heritage. Stray light entering bedrooms at night disturbs sleep and contributes to sleepiness and fatigue, known factors in traffic and industrial accidents. Exposure to artificial light at night is a substantial risk factor for prostate and breast cancers, and it appears to be a contributing factor in the obesity epidemic. Outdoor lighting does not inhibit crime but increases it. Even faint light pollution can degrade habitat and affect the food chain over large areas. Drastic reductions in outdoor ambient light levels from all sources, in some indoor lighting and in the associated energy use are justified and will require legislation to be achieved. Present lighting practice needs to be completely rethought. Architecture and urban design need to change course accordingly.

Document Version 2.5.1, 4 April 2009. Check for later versions at the website of the Astronomical Society of Victoria Inc: http://www.asv.org.au or at the website of Dr Jan Hollan, http://amper.ped.muni.cz/bajc/ .

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PREFACE

Version 1.0 of this document was presented at the *22nd National Australian Convention of Amateur Astronomers* at Mornington, Victoria, Australia, in April 2006. Version 2.1 was kindly presented for the author by Dr Jan Hollan of Brno, Czechia at the *7th European Symposium for the Protection of the Night Sky - Light Pollution and Global Warming* in Bled, Slovenia, 5-6 October 2007.

Version 2.0 had an executive summary added, along with some important material for guidance of authorities who understand the pressing need to make an early start on reducing greenhouse gas emissions while reducing the cost and improving the quality of outdoor lighting. Version 2.2 included material specifically relating to illuminated advertising signs and was submitted to the Victorian Government's Advisory Committee on Advertising Signs in December 2007.

Subsequent versions include new and additional information on greenhouse gas targets and seriously adverse health effects of light exposure at night, on ecological light pollution and on reducing greenhouse gas emissions associated with street lighting. Some of this material was added as a result of enquiries in 2008 from the UK Royal Commission on Environmental Pollution about impacts of artificial light on human health and wellbeing. Information about the adverse effects of artificial skyglow on remnant indigenous cultural heritage was added when the document was submitted as public comment on lighting of a proposed desalination plant for Victoria.

Version 2.5 was submitted to a Victorian planning panel and advisory committee hearing on height limits for city buildings: it includes new information on tall buildings as disproportionate emitters of light pollution, applies new evidence linking prostate cancer with bright lighting, and contains a new appendix on the spectral properties and relative performance of common types of lamp.

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EXECUTIVE SUMMARY

The Growth of Outdoor Artificial Lighting

Electric lighting has become ubiquitous since its large-scale commercial introduction in the late 19th century. In countless ways it has added to the quality of life by allowing daytime activities to be extended into the natural dark hours. Nonetheless it has become increasingly apparent in recent times that large changes in the natural environment can rarely be made with impunity. This is particularly so in the case of artificial light outdoors at night, where the light flux can often be as much as a million times brighter than the natural value. Small areas might be lit to such levels here and there on the globe without much effect, but the situation has now progressed well beyond this stage in many countries. In short, often we now have far too much artificial light for our own good.

So far, the main barriers to having even more and brighter lighting at night have been its capital and operating costs. In deciding to introduce or increase outdoor lighting, the obvious benefits have hitherto been weighed almost solely against the direct costs involved. Along with others of its kind, this document indicates that the many non-monetary costs associated with artificial outdoor lighting have not been given due consideration. It will also become increasingly necessary in future to arrange overcompensating reductions in existing lighting before new or brighter lighting can be installed.

Greenhouse Gas Emissions Associated with Outdoor Lighting

Satellite imagery of Earth at night confirms marked worldwide trends for more and brighter artificial lighting. Town and city lighting is generally becoming brighter and extending further into the surrounding countryside. Ground-based measures confirm that total outdoor light flux in many countries is tending to increase exponentially, which is unsustainable. As this quantity is indicative of the growth in greenhouse gas emissions (GGEs) associated with providing this flux, this is a powerful reason to reduce outdoor lighting. In the developed countries that have or should have signed and ratified the Kyoto Protocol, in respect to outdoor lighting there are two parts to the required reductions: firstly to cut lighting energy use, as a proportion of all fossil-fuelled energy use, back to the agreed national targets for 2008 to 2012, and then to make timely reductions towards the 2020 and 2050 global targets yet to be set. The 2050 target appears likely to be no more than 40% of the 1990 aggregate, and may have to be much smaller given the rapidity and magnitude of climate changes already being observed. Furthermore, convergence of per capita fossil energy use to equality between developing and developed nations appears likely to require further large cuts in per capita usage for developed nations.

At Melbourne, for example, the measured growth in artificial skyglow from 1990 to 2010 will be about 36 times the maximum growth that could have been expected if lighting energy usage had complied with the Kyoto Protocol maximum growth of 8% that was over-generously allowed for Australia. In other words, artificial skyglow has become about 3.9 times brighter than in 1990. Indications are that lighting growth elsewhere in

Australia has been comparably excessive. Compliance of the lighting sector with the Protocol by 2010 would thus require as much as 97% of the increase in installed lighting since 1990, or its equivalent, to be removed. For other countries with more rational targets (ie reductions rather than growth in GGEs) under the Protocol, the figure will generally be over 100% if lighting energy usage has increased over 1990 levels. Offsets applicable from increases in use of renewable energy would reduce the excess, as would overall improvements in luminous efficacy of lighting; however, resulting improvements in the numbers are likely to be relatively small. Neither the lighting industry nor the governments involved appear to have grasped the stark reality of the problem.

While anthropogenic GGEs continue at excessive levels, no foreseeable improvements in energy efficacy or renewable energy supplies will allow more than minor mitigation of the problem in the short to medium term. Large cuts in total fossil-fuel energy use therefore appear to be essential. All lighting must share fully in meeting this burden or some other energy use sector will have to bear additional cuts. Street lighting curfews can play a useful part, for example.

Adverse Effects of Artificial Light at Night on Humans and Other Living Things

Quite small amounts of stray artificial light entering bedrooms at night can interfere with sleep. Sleep disturbances and deficits from this and other causes tend to increase industrial and traffic accidents next day. Insufficient sleep may be a factor in the obesity epidemic. Artificial light exposure before sleep and especially in the small hours can interfere with the body's endocrine system, particularly the melatonin cycle. Melatonin normally helps to protect the body against diseases including breast and other cancers. The World Health Organisation has accepted that shift work increases the risk of such cancers in humans, probably through interference with the melatonin cycle.

Bright light exposure in the evening, as with sports lighting and bright public lighting, is known to reduce the amount of circulating melatonin. A national epidemiological study published in 2008 indicates that breast cancer incidence, but not lung cancer incidence, increases significantly with the brightness of outdoor ambient artificial light in populated areas at night. A similar study of global data published in early 2009 described an even larger effect on prostate cancer. Few if any present lighting standards take any account of these effects, which is deplorable. The amount of stray artificial light allowed at windows of habitable rooms in internationally specified city lighting zones is as much as a hundred times brighter than the brightest moonlight. Other environmental and economic issues give many people little choice but to live in high-rise apartment buildings that are typically bathed in levels of outdoor ambient light flux at night that are toxic, at least in chronic exposures.

Adverse effects of artificial light exposure at night apply to most living things. Laboratory and field observations of these effects indicate that light levels just above, if not in, the natural moonlight range can affect the melatonin cycle. But much smaller amounts of artificial light can affect predator-prey relationships differentially, which in turn affect the food chain. Such risks to biodiversity begin to take effect as ambient artificial light levels become brighter than overcast starlight. This is increasingly the case in populated areas of the global land mass and adjacent coastal waters. Habitat degradation, including the effects of light pollution, is an important factor in the present world biodiversity crisis.

Specifications for allowable levels of ambient artificial light at night urgently need to incorporate the large reductions recommended in this report. They also need to take into account that many of the adverse biological affects are maximal for blue light, so that lamps and other light sources that emit copious amounts or proportions of blue light into the outdoor night environment need to be fitted with blue-absorbing filters or taken permanently out of service. This applies particularly to metal halide and other lamps with high mercury content, which are often used for commercial and industrial lighting, sports lighting, billboard illumination, decorative lighting and road lighting.

Outdoor Lighting and Crime

Often when reductions in outdoor ambient light flux at night are proposed for valid environmental and health reasons, strident objections are raised with claims that crime will increase. While there is no doubt that people do feel safer at night when there is plenty of light, the presence of glare reduces this effect. Furthermore, despite the successful efforts of a few scientists to have their unwittingly biased pro-lighting results published and accepted, there is no reliable scientific evidence that lighting reduces actual crime. On the contrary, there is reliable evidence that artificial light at night instead tends to increase the actual crime rate- each tenfold increase in light produces a crime rate increase of several percent. Regardless, present national lighting standards still tend to specify lighting levels on the basis of perceived or known risk of crime, thereby helping to perpetuate the myth of lighting for security while actually facilitating crime at night.

Perception of facial features is improved by bright lighting with good colour rendition. Such lighting has been promoted for crime prevention as assisting pedestrians to identify potential assailants. This ignores the arguably greater value for criminals in selecting easy targets and making faster getaways.

Street lighting curfews generally result in no effect or a reduction in crime, regardless of contrary propaganda by vested interests.

Lighting and Accidents

Objections to lighting reductions are also made in the belief that traffic accidents would increase. This ignores the claims of the car window tinting industry that tinting has no effect on the rate of traffic accidents, an argument accepted rather uncritically by politicians in allowing tinting to continue.

Statistical evidence has long been used to indicate that road lighting reduces accidents at night by about 30%, but the effect has recently been re-evaluated in the UK and found to be considerably smaller. Substantial reductions in road lighting specifications have now been instituted there. To the extent that this will reduce interference with sleep, it will reduce accidents from consequent drowsy driving.

City lights might look pretty to airline passengers but what they and the flight crew are seeing is unused waste light that is known to increase the risk of mid-air collisions because it reduces the conspicuity of aircraft navigation lights and safety beacons on high structures. The problem is greatest in built-up areas, which also have a higher probability of consequent injuries and property damage from falling wreckage.

Adverse Effects of Light Pollution on Astronomy, Stargazing and Cultural Heritage

Artificial skyglow caused by light pollution is becoming an ever more serious hindrance to astronomical research. It also handicaps amateur and educational astronomy and scuttles the aesthetic pleasure of seeing the pristine night sky. By blotting out the stars and constellations, artificial skyglow also helps to extinguish residual indigenous culture, given the close connection between features of the night sky and the creation myths that still govern social behaviour of some native peoples. For reasons such as these, UNESCO issued a strongly worded declaration in 2007 on the need to defend the night sky from light pollution.

Most artificial skyglow is not an inevitable consequence of development and prosperity. Much of it could be eliminated at its source simply by stopping unused waste light from traveling at or just above the horizontal. Better, by redirecting this light down to where it is needed, required lamp wattages can be reduced. Wattage can also be reduced by accepting the yellow-orange tints of low- or high-pressure sodium lighting instead of the blue-rich (and therefore more toxic) output of the less electrically efficient mercury vapour lamps, fluorescent lamps and metal halide discharge lamps. Short wavelength components of the light have the greatest effects in producing skyglow, hindering sleep and diminishing melatonin levels.

Mandatory Limits and Caps are Necessary for Outdoor Ambient Light Levels at Night

Overall, the case is strong that outdoor artificial light levels are often excessive as a consequence of individual and corporate ignorance, carelessness, selfishness and greed. In the developed nations and many of the developing nations, large reductions in the total ambient outdoor light flux are both necessary and achievable while decreasing actual crime, glare, greenhouse gas emissions and adverse health and ecological effects. Voluntary reductions and self-regulation have certainly not worked in the past, particularly in commercial pursuits such as illumination of outdoor advertising signs and floodlighting of business premises. There appears to be sufficient cause for most if not all illuminated advertising and decorative lighting to be banned. Substantial mandatory reductions in fossil-fueled energy use for lighting with annually reducing caps need to be introduced as a matter of urgency. It is possible for governments to do this in a way that will also save considerable amounts of public and private money while reducing crime, reducing accidents, improving health and reducing environmental and ecological problems involving artificial skyglow.

Adverse effects of artificial light spill into bedrooms at night are serious enough to warrant strict control. A universal maximum limit of 0.1 lux is proposed for spill in the plane of windows of habitable rooms and at property boundaries for all areas covered by existing lighting zones, even in city centres where 25 lux is the present limit. This might not be welcome news for everyone, but the case for making this change is based on a wealth of reliable scientific evidence relating to greenhouse gas emissions, risk of prostate, breast and some other cancers, biodiversity conservation, actual crime reduction, astronomy, indigenous cultural heritage, and reduction of drowsy driving and driver distraction. Large reductions are required in existing urban outdoor light flux, with full cutoff shielding of all lights that are retained as essential, and filtration blocking of all short wavelength visible light in excess of that emitted by a high pressure sodium lamp of similar light output.

Land development and renewal projects typically result in increased light pollution. Planning permission for such projects should be denied, especially in developed countries, unless outdoor lighting associated with the project is minimal, full cutoff, blue-poor, and by means of audited offsets from reduction of existing lighting on the site and elsewhere, represents no increase or preferably a genuine reduction in total emitted light pollution of the municipality or region.

Buildings that give largely unobstructed views from their upper levels can be potent sources of light pollution unless effective measures are taken to prevent the escape of internal light at night, and unless illuminated signs and logos and decorative external lighting are permanently prohibited apart from some minimal exemptions identifying companies open for business at the specific location. Planning permission for tall buildings in general should not be granted unless such measures and restrictions are fully incorporated and permanently enforced.

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1. INTRODUCTION

Although the widespread application of artificial lighting has transformed civilisation and enhanced the quality of life, these benefits have been accompanied by the largely hidden costs of substantial ecological and environmental degradation and undesirable social and health consequences.

Light pollution is now a widely accepted term for any unwanted or nuisance (trespass) artificial light that has adverse effects (eg Wikipedia Light Pollution 2009). Many of the problems caused by light pollution could be overcome by using minimal light for the circumstances and confining the light to where it is needed. These are necessary but not sufficient conditions for sustainable, safe and responsible outdoor lighting. Organisations concerned with light pollution have concentrated their efforts largely on campaigns for mandatory shielding of all outdoor light sources to block the direct emission of light at or above the horizontal. Although this is a useful goal and a necessary part of dealing with unwanted artificial skyglow, it is far from sufficient to overcome the total problem, which is much larger. Some light pollution organisations have chosen to work in harmony with the lighting profession in the hope of progress through consensus, but this has come at the cost of little or no action on the major part of the light pollution problem, viz the overuse and accelerating proliferation of outdoor lighting.

New and updated information on light pollution and its adverse effects is presented here. Although some of the evidence available to the writer tends to reflect the situation in Australia, the problems described and their solutions tend to be universal. Permanent solutions will require legally enforced national and regional maxima on the amount of outdoor artificial light, capped at well below present values. The increasingly urgent need to reduce greenhouse gas emissions (GGEs) would appear to justify restrictive caps on energy used to produce outdoor lighting, reducing over time in step with internationally agreed reductions in total GGEs on a national basis.

2. BENEFITS OF OUTDOOR LIGHTING

Outdoor artificial lighting provides many benefits:

- It generally improves visibility at night.
- Improved visibility facilitates mobility and travel in dim or dark conditions.
- Outdoor work and recreation can be continued through the natural dark hours.
- It decreases the fear of crime at night.
- Bright lighting helps attract customers to shops, and gives an impression of prosperity.
- Road lighting probably has a small direct effect in reducing traffic accidents at night.[1]

[1] However, the vehicle window tinting industry has been successful in convincing politicians that reducing the amount of light reaching the driver's eyes at night has no adverse effects on road safety! Beyer and Ker (2009) carried out a meta-analysis on 16 trials of the effect of road lighting on traffic accidents. They found that the

- Extensive use of electric light at night helps to raise the base (night) load on the electricity supply system, thereby facilitating performance improvement of fossil-fueled power stations in the system (an economic and greenhouse gas issue).

Satellite imagery of Earth at night indicates marked worldwide trends for more and brighter artificial lighting (Cinzano, Falchi and Elvidge 2001). City lighting is generally becoming brighter and extending further into the surrounding countryside (eg CPRE 2003). At present, attempts to reduce existing lighting or to restrict new lighting have to be justified against the potential reduction or loss of benefits such as those listed.

This document shows that outdoor lighting also brings with it many substantial disbenefits (adverse effects) that have not hitherto been given adequate consideration in deciding where and how much artificial lighting is to be installed and how much spill light is tolerable. Spill light is light emitted by a light source in directions other than towards the area where the light is required. In general, spill light is waste light that has not been used. It is usually avoidable by the use of correctly designed luminaires (light fittings). An unavoidable component of waste light is made up of light after it has usefully illuminated some surface or other.

3. ARTIFICIAL SKYGLOW

3.1 ENERGY LOSS AND SKYGLOW

From ground level, the night sky in its pristine state is not completely dark. Some of its light comes from the stars, some from sunlight scattered by space dust in the plane of the solar system, and some from atmospheric gases subject to radiation and particle fluxes mostly from the sun. This is called natural skyglow. Since the late 19th century, the night sky above artificially lit areas has become increasingly bright, in step with the increasing amount of waste artificial light traversing the atmosphere. A generally small proportion of this light is scattered back towards Earth's surface by air molecules and suspended particles of the atmospheric aerosol. This brightens the night sky and tends to make faint objects in space harder to see and photograph. This light pollution (or strictly, its outcome) is called artificial skyglow. As this report indicates in following chapters, artificial skyglow is much more than a problem just for the world's relatively small number of amateur and professional astronomers, and much more than a problem for the astronomy facet of education world-wide (eg Walker 2008). As will be seen from

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methodological quality of the trials was generally poor and judged the risk of bias in these studies to be high. Although such difficulties appear sufficient to prevent the drawing of reliable conclusions, they did find that street lighting may prevent road traffic crashes, injuries and fatalities. Conclusions like this have been reached before from individual studies such as the 16 examined, but typically the studies have been done or paid for by parties with potential conflicts of interest, eg people or companies involved in the lighting, power, vehicles and roads industries. Recent government research in the UK has resulted in a large reduction in the number of roads for which road lighting is justified as an accident prevention measure: see Section 5.1 below for more information on this.

following parts of this report, light pollution and skyglow affect almost everyone to some extent, sometimes quite seriously.

Typically, artificial skyglow results from unused and used light traveling at or above the horizontal and coming from outdoor light fittings (luminaires), traffic lights, from windows, skylights and transilluminated signs, and from illuminated surfaces such as roads, building walls, roofs, bridges, monuments and billboards. Vehicle lights add to the problem. Artificial skyglow tends to be proportional to the total amount of artificial light outdoors, but skyglow above a city (or town) has a 'constant' of proportionality that can be quite different from that applying to the skyglow caused by that city in the surrounding countryside.

The total artificial light flux emitted by a city tends to be proportional to the product of two quantities, the number of light sources and their mean output of light. Typically, both of these quantities increase over time in individual cities, particularly when the economy is growing. This suggests exponential growth in the total flux. The same result can be reached by considering the typically increasing amount of light in use per person (eg Hänel 2001), coupled with population growth in cities.

Exponential growth in something produced from finite resources is generally unsustainable. Much of the world's outdoor lighting is powered by electricity generated using fossil fuels. In studying the outdoor lighting situation to guide corrective action, it would be useful to know the relationships between energy consumption for outdoor lighting, the outdoor light flux produced and the resulting amount of artificial skyglow. However, the simple proportionalities that might exist at a particular place or at a particular time tend to vary with time and place respectively, and it may be difficult to determine some of these variations with the accuracy desirable. Regardless, paucity of information is a weak argument for inaction or delay in dealing decisively with a problem that is as pressing as unsustainable energy use is.

The amount of visible light produced by a unit of electricity consumed by a lamp is called the luminous efficacy, and is usually expressed as lumen/watt. It depends on the type of lamp. For example, the successive replacement of incandescent lamps in streetlights by low pressure sodium lamps after World War 2 produced much more light for the electricity used, but the gains were then reduced when mercury vapour, fluorescent and high pressure sodium lamps were substituted for reasons thought then to outweigh the increased electricity use.

From 1950 to 1980 in the USA and to 1990 in Germany, the *estimated* outdoor light flux grew at an increasing rate (Hänel 2001), ie exponentially. Even if they exist, *actual* values are difficult to track down for individual countries or regions. One exception is for the town of Osnabrück, for example, where electricity usage for (street?) lighting was approximately constant from 1981 to 1997 while the luminous efficacy and the number of lamps there both increased by about 20% (Hänel 2001). This indicates an exponential increase of about 40% in the outdoor light flux, but this has not been checked by direct measurement (photometry).

Extensive data sets do exist for lighting-related quantities in England from as early as 1711 to the present (Pearson 2003). For example, usage of candle tallow and whale oil for lighting had an overall exponential growth between 1711 and 1900, although there were pronounced fluctuations. Coal gas usage for lighting grew more or less exponentially from 1800 to 1900 and thereafter declined as electricity used for lighting began its upwardly accelerating trend. This growth continued until about 1970 when it plateaued until the early 1990s, when it rose sharply to recover to its earlier upward trend. Underlying exponential trends in energy use for lighting are therefore not just a recent phenomenon.

Within the last ten years, metal halide lamps with a white or bluish-white output have been replacing or supplementing the more efficacious and less expensive high pressure sodium lamps, which have an orange-white output. This would tend to increase the rate of growth of electrical energy used for lighting more than the rate of growth of outdoor light flux. Again, detailed quantitative data about the actual situation appears to be sparse or not readily accessible, which does little credit to the bodies that have fostered and profited from this growth.

Towards the end of the 20th century, increasing protests by astronomers led to the introduction of various generally small reductions in the proportion of upward waste light permitted by national standards for public lighting. Accordingly, artificial skyglow should not have grown quite as fast as total outdoor light flux. Improving air quality would have added to this trend, although industrial growth could be expected to have had an opposing effect. Because short wavelength light tends to be scattered in the atmosphere more than light of longer wavelengths, there would have been an opposing trend for atmospheric light scatter to increase during these most recent decades, because white light from metal halide lamps and compact fluorescent lamps replaced or supplemented the orange-yellow- (ie blue-deficient) light from sodium lamps and incandescent lamps. (This issue is treated at length in the Appendix.) Therefore in the last few decades, as a first approximation the overall amount of artificial skyglow has probably remained more or less proportional to the amount of electricity used for outdoor lighting.

Although street lighting is a major contributor to ambient artificial outdoor light at night and hence to skyglow, account also needs to be taken of additional sources such as vehicle lights, traffic signals and signs, architectural floodlighting, illuminated billboards, and internal light escaping from commercial and residential windows. This was recognised by Oba, Kawakami, Iwata et al. (2005), who found that the respective amounts of light directly emitted above the horizontal from street lighting, from buildings and from illuminated billboards in Tokyo were comparable. It is shown on this basis in Section 3.3 below that if the total light emitted by street and public lighting is L, the total amount of light emitted from all sources in a city centre can be about 1.7 L, and the total upwards waste light (used plus unused) can be about 0.6 L.

These ratios of light flux are also reasonably good approximations to the ratios of energy used to generate the light. Thus the energy cost of producing the skyglow above a city can be about 70% more than the energy cost for street lighting, although some of this total is unavoidable as it includes used waste light (ie light that has been reflected by usefully illuminated terrain). As another indication of the problem, in the Australian state of Victoria the amount of energy lost by *avoidable* light pollution at present is comparable with the total generating capacity of one of Victoria's large operational wind farms. The Victorian Government has been advised of this on several occasions but has not publicly acknowledge this energy waste, let alone acted to reduce it.

Artificial skyglow is therefore not trivial either in the waste it represents or in its most obvious adverse effects. Most of it is avoidable by modifying lighting practices in line with present knowledge. Reducing or eliminating light pollution will generally save money as well as improving the environment.

3.2 Growth in Skyglow

The scarcity of quantitative historical data about the total artificial light flux in cities or countries and the corresponding electricity consumption is regrettable. The first global comparison between cities in respect of lighting, population and area[2] seems to have been made by Isobe and Hamamura (2000), who used satellite measures of upwelling visible and near infrared light from cities at night. Monitoring of such light by aircraft or spacecraft could be important in the control of energy use and waste by outdoor lighting. As this upwelling light is also the source of the scattered light that is artificial skyglow, monitoring of skyglow from the ground could provide a relatively inexpensive source of proxy data for ongoing monitoring of energy consumed by all sources of total outdoor light flux.

In natural cloudless dark sky conditions, about 2700 stars are visible to young adults with good eyesight and without optical aid in the hemisphere above. Artificial skyglow blots out the fainter stars: in Melbourne (total population 3.5 million, state capital of Victoria), for example, only 2% to 3% of the naturally visible stars per hemisphere can now be seen from the middle suburbs,[3] and it can even be lower than 1% when viewing from the city centre. Given the relationships between the number of stars visible or the threshold stellar magnitude and the background sky luminance,[4] eg Schaefer (1990), the apparent sky luminance can readily be derived from visual observations.

The sky luminance can also be observed directly with a precision photometer or with the much simpler and more affordable Unihedron Sky Quality Meter (SQM, http://unihedron.com/) that has become available in recent years. The SQM indicates total skyglow in the logarithmic units convenient for astronomers, stellar magnitudes per square arc second. Readings can readily be converted to the SI unit of luminance, candela per square metre (cd/m^2) or its convenient submultiple, mcd/m^2. The SQM website has a converter.

Skyglow growth curves like that in Figure 1 below are valuable as evidence to support the imposition of lighting caps and other corrective actions in connection with environmental requirements. The starting point in generating such a curve is preferably

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[2] The writer was able to find crime rate data for many of the US and English cities listed as well. Brighter cities tend to have reliably higher crime rates (Clark 2003).

[3] An indication of how much worse skyglow could become in Australian cities is given by the writer's casual observations in the last dozen years of the number of stars visible unaided in moonless and cloudless night skies above London (none), Los Angeles (none, but Jupiter seen), Cairo (6) and Kuala Lumpur (6 with 2 oktas of cloud).

[4] Brightness is a perceptual quantity. Its psychophysical correlates are luminous intensity for a point source or luminance for a surface. However, astronomers persist with using the terms 'brightness' and 'surface brightness' in physical, psychophysical and perceptual senses.

the value of the almost completely natural skyglow that existed just before the introduction of electric light, in 1880, say. At least two more points are needed for curve fitting, preferably well separated, and the more the better to overcome uncertainty caused by night to night variations in atmospheric characteristics and the proportion of lights switched on. It is important to try to include some values derived from star visibility decades ago. Subtract the known luminance of the natural clear moonless night sky (about 0.28 mcd/m^2, but it varies with the solar cycle) from each data point to get the artificial contribution and fit an exponential curve using a computer spreadsheet. Add 0.28 mcd/m^2 to the curve heights to get total skyglow. The resultant curve is only indicative of the underlying trend and ignores fluctuations imposed by events such as economic depressions and wars, but the alarmingly unsustainable growth typical of recent decades will be well shown.

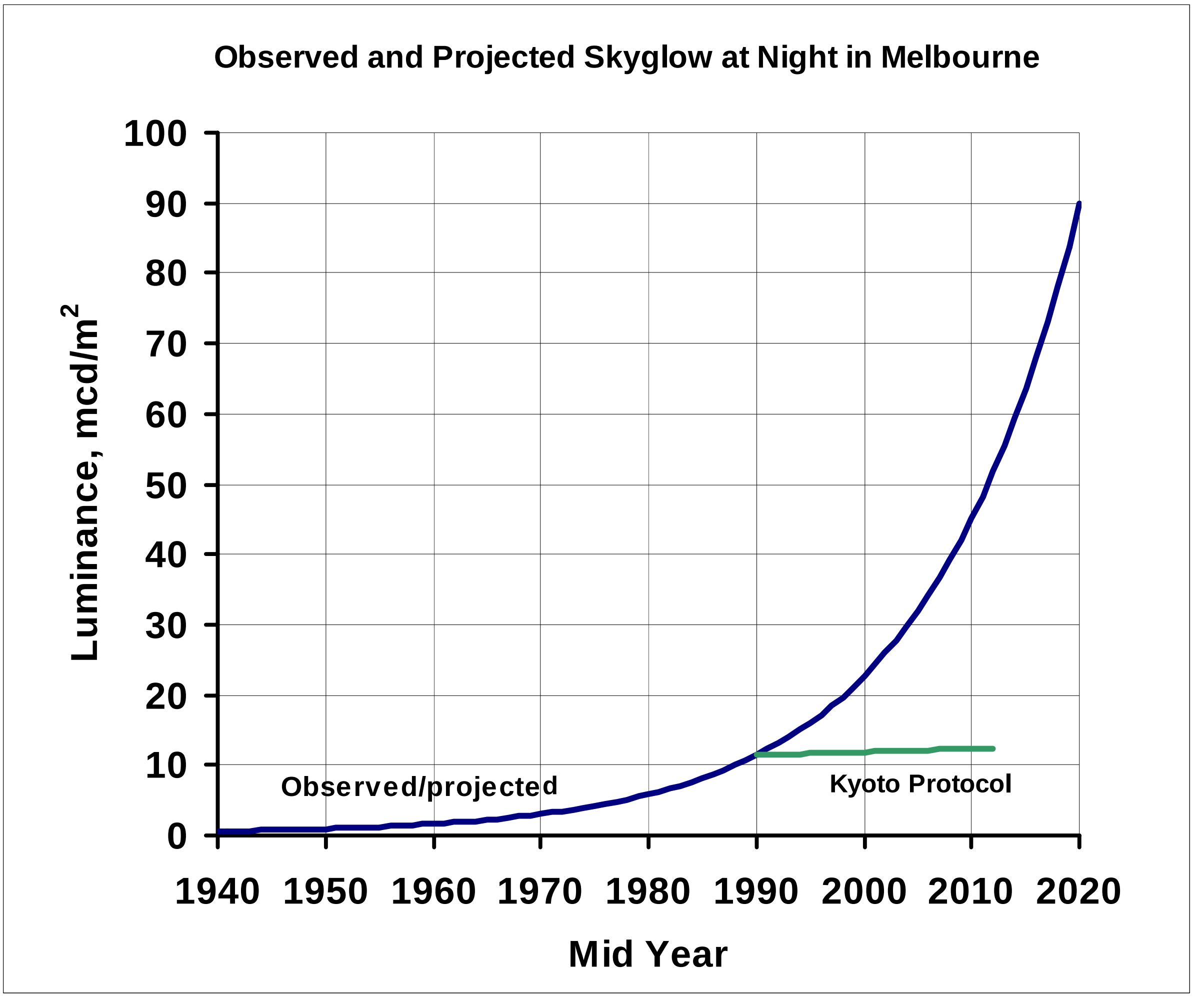

Figure 1. The blue curve is based on a smooth exponential fit to direct and scaled measurements and inferred observations of artificial skyglow over Melbourne from 1880 to 2010. It is shown here from 1940 (ignoring the wartime blackout) and extrapolated from 2010 to 2020. Its steady growth rate is 7.08% pa. The green curve shows the skyglow that would have occurred if lighting energy use had been restricted to the internationally agreed maximum growth in GGEs for Australia according to the Kyoto Protocol, starting from the blue curve value in the Protocol base year of 1990. The growth at 2010 since 1990 is

heading to be about 38 times the over-generous growth (8%, equivalent to about 0.4% pa) allowed for total Australian GGEs in the Protocol.

From Figure 1, the artificial component of Melbourne's skyglow appears to have doubled about every ten years, an increase of about 100% per decade or 7.08% pa. This can be compared with the exponential growth rates of 7% to 10% per annum in skyglow observed in Italy, ie 97% to 159% increase per decade (Cinzano 2002a), 6% pa or an increase of 72% per decade derived as typical for the USA by Cinzano (2002b), and 3% pa (34% increase per decade) in the UK (Clark 2003). Actual growth rates will fluctuate over time and depend on location, of course, but the smooth exponential approximation provides a good and conservative basis for comparison.

Figure 2. Melbourne's skyglow in 1990 as seen from Eltham, 20 km from the city centre, at midnight with the moon below the horizon. The photograph was taken by Dr T. J. Richards, Woodridge Observatory, Victoria, Australia. (Dr Richards has declined to claim copyright for this image but requests due acknowledgement if it is reproduced elsewhere.)

Figure 2 shows what Melbourne's light pollution looked like in 1990 on an occasion when the enormous amount of upwelling used and unused waste light was rendered starkly visible by a layer of high cirrus cloud. The situation was obviously bad in 1990. As Figure 1 indicates, the skyglow is nearly four times as bright now. Its horizontal extent has also increased substantially in that time.

3.3 Dealing with Artificial Skyglow

This analysis is an extension of that in Clark (2003). The purpose is to indicate how much reduction in skyglow would be possible by reducing various contributing sources measured by Oba el al. (2005). The total output light flux in lumens from streetlights and other public lighting luminaires is L; from vehicle lights, V; from transilluminated or floodlit signs and surfaces, A (for advertising); and internal light escaping from building windows, doorways and skylights, W.

The proportion of total light output of a streetlight that is unused, viz the upward waste light ratio (UWLR), is zero for full cutoff types,[5] and typically 15% for semi cutoff types, 25% for mercury vapour 'flower pots', and more than 50% for pole-top globes and circular wall packs. Assume for this example that UWLR for streetlights and other public lighting is 0.15, and that the same factor applies to vehicle lights. The UWLR for the remaining sources (advertising signs and windows) can reasonably be 0.5. Following Oba et al., the direct upward waste fluxes are set equal:

$$0.15\ L = 0.5\ A = 0.5\ W.$$

Thus, A = 0.3 L and W = 0.3 L. . This is appropriate for a city centre with many signs and lots of tall buildings having many windows. For suburban locations and country towns A and W would be relatively smaller. For completeness, vehicle lighting in the city centre is estimated by V = 0.1 L. The total ambient outdoor light flux T is given by

$$T = L + A + W + V.$$

In this city centre case,

$$T = (1 + 0.3 + 0.3 + 0.1)\ L, \text{ ie } 1.7\ L.$$

The total direct upward flux T_{DU} from these sources is

$$T_{DU} = 0.15\ L + 0.5\ A + 0.5\ W + 0.15\ V,$$
$$= (0.15 + 0.15 + 0.15 + 0.015), \text{ ie } 0.465\ L.$$

The total flux reflected upward from the built environment T_{RU} is the total downwards flux multiplied by the effective reflectance of the terrain, R_T:

$$T_{RU} = (0.85\ L + 0.5\ A + 0.5\ W + 0.85\ V)\ R_{T,}$$
$$= (0.85 + 0.15 + 0.15 + 0.085)\ L\ R_T, \text{ ie } 1.235\ L\ R_T.$$

The total upward flux is

$$T_U = T_{DU} + T_{RU}$$
$$= (0.465 + 1.235\ R_T)\ L.$$

But the total flux emitted by all sources, T, is 1.7 L. Therefore the fraction of total source flux that is directed upward, the Upward Fraction is

$$UF = T_U / T = 0.2735 + 0.7264\ R_T.$$

As a check, UF = 1 when $R_T = 1$. This indicates, correctly, that with perfectly reflecting terrain all source flux would eventually travel in directions at or above the horizontal.

A typical effective value for R_T in a city is about 0.1 if an arbitrary allowance is made for multiple reflections and light trapping by buildings. This indicates that 34.6% of the total

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[5] Lamps shielded *and installed* so that no geometrically direct rays from the face of the luminaire are emitted above the horizontal are called 'fully shielded' or 'full cutoff' (eg Paulin 2001; Keith 2005) (or sometimes 'aeroscreens', perpetuating the outdated belief that they are confined to the vicinity of airfields). Some countries specify such types by limiting the horizontal intensity in any azimuth to no more than (integer) 1 candela (cd) per 1000 lumen (1 klm) of the total output flux. The Illuminating Engineering Society of North American (IESNA) specifies an additional requirement for full cutoff luminaires: the light intensity is not to exceed 100 cd/klm at 80 degrees above the nadir (vertical down direction) in any azimuth. The practical effect of this is to limit glare at horizontal distances beyond about five times the mounting height.

light flux will end up in the sky and outer space. Of the Upward Fraction in this example, 0.274/0.346 or 79.2% consists of light directly radiated above the horizontal from all light sources including floodlit surfaces, ie light that does not usually reach the eyes of viewers, and is therefore unused light waste. The remainder of the Upward Fraction can be considered as used light waste. This is consistent with the impression that the light seen in city views from aircraft at night mostly comes directly from non-full-cutoff luminaires, unshielded lamps, sports lighting, undraped windows and brightly lit signs and surfaces rather than from illuminated roads, paths, fences, walls and vegetation.

If all direct upward unused waste light from road and pedestrian lighting were absorbed by a hypothetical instant installation of full cutoff shields, the first term in T_{DU} would become zero and the total flux T = 1.55 L, with L kept at its original value to facilitate comparison. Then T_U = 0.4385 L instead of 0.5885 L, a reduction of 25.5%. Note that this is a one-time improvement. If skyglow at the example city is increasing by say 7% a year, it would take just over three years for the skyglow reduction from introduction of full cutoff street lighting to be nullified.

In the case of a ‘dormitory suburb’ late at night with just street and path lighting on and producing 15% upward waste, instant full shielding of street and path lights would reduce skyglow by 64%. For a whole metropolis given instant full shielding on its street and path lights, the reduction in skyglow would thus be somewhere between 25.5% and 64%, probably closer to the former and likely to delay the overall growth of skyglow for maybe only five years. These examples are not overly sensitive to the choice of values such as the terrain reflectance (Clark 2003), but greater reflectance values would reduce the relative impact of full shielding.

The foregoing analysis suggests that the present strategy of the International Dark Sky Association (IDA) is nonoptimal. That strategy has been copied by many smaller groups with similar goals, making the outcome even worse. Much of the IDA effort in the twenty years of its existence has gone into trying to achieve zero upward waste light from outdoor luminaires, and it is still far from attaining that even in the US where its influence is greatest. Compared with the skyglow reduction from introducing full shielding on streetlights, at least in city centres there would be a 12% greater skyglow reduction by stopping all sign illumination instead, or by having blinds used at night on all external windows of internally lit rooms. It is recognised that pursuing the luminaire shielding issue might have greater political or educational payoff, however, as well as having a larger useful effect in suburban and rural areas.

The IDA’s remaining effort has gone into other worthwhile areas such as trying to keep illuminance maxima down to sensible values in lighting standards, having commercial lighting switched off after business hours, and writing a model lighting ordinance. It has attempted to do such things, with some success, by convincing the lighting industry to cooperate. Some IDA office bearers and members are lighting professionals with a genuine interest in so-called ‘sky friendly’ lighting. The downside of this strategy is that the IDA tends to avoid discussing or doing anything that could have the potential to alienate the lighting industry.

Since the IDA has been in existence, it has made some progress in the introduction of laws and standards to reduce upwards spill from outdoor luminaires. But while this has been happening, the overall trend in most countries has been the installation of more and brighter outdoor lighting; bigger city buildings with more glass walls, brighter internal lighting and no blinds; and more billboards, often bigger and brighter. In general, the total ambient outdoor artificial light flux generated by individual nations has been growing exponentially, often much faster than growth in the corresponding national gross domestic product, and both the extent and brightness of the accompanying artificial skyglow have been growing more or less in step with the total light flux.

Whatever gains have been made by IDA action in reducing upwards spill from outdoor lighting over the last two decades have been utterly swamped in that time by the increased skyglow resulting from growth in total outdoor light flux. What is desperately needed to solve the long-term problem of skyglow is to stop the total growth of lighting and turn it into a decline; absolutely nothing else will do. The IDA has made its choice: naturally it doesn't wish to be identified as the cause of a shrinking lighting industry because it could hardly expect cooperation from the industry in such circumstances. Unfortunately, the choice appears as tacit approval of the accelerating growth of outdoor light flux and artificial skyglow towards all-night artificial twilight, contrary to the IDA's *raison d'être*, to protect the night sky.

A permanent solution to the skyglow problem, at least in the developed countries, must involve reducing caps on total outdoor light flux or energy use for lighting or both. Self-regulation does not work any better than would voluntary speed limits on the roads, for example; it has to be the law and it has to be enforced. Restrictions on direct light emission above the horizontal, mandatory use of blinds or drapes to prevent the escape of internal light at night through residential, commercial and industrial windows, and severe restrictions on illumination of outdoor signs would all help to bring useful but one-time improvements, but their impacts in reducing skyglow and the accompanying energy wastage will tend to become relatively smaller as time goes on unless the overall growth is reversed as well.

3.4 SPATIAL DISTRIBUTION OF SKYGLOW

By using a Sky Quality Meter in conjunction with a Global Positioning System (GPS) receiver, it is now relatively easy to measure the distribution of skyglow across a city or region in little more than the time it takes to travel through the required distance. The major precaution necessary is to take the measurements from a position in which any potentially interfering artificial light source is close to the horizon and out of the sensor field or is at least shielded by a light pole, tree trunk or low building. Unlit sports fields are often the best available choice in populated areas as they also provide clearance from trees that tend to reach into the sensor field.

Figure 3 below was made with data from an SQM and a GPS in conjunction with a road map. Three of the measurements made are not shown: they were taken at or near intensely lit intersections or car parks and are clearly outliers with apparent sky luminances of up to 120 mcd/m^2. The most distant reading was made a month earlier than the other readings, and was close to the natural value.

The sharpness of the peak in Figure 3 suggests that much of the skyglow originates within or near the CBD, where there are many buildings and structures floodlit from below, despite a longstanding city lighting strategy that deprecates the practice. For example, the decorative twin slender concrete columns of the Bolte Bridge have near vertically aimed narrow-beam floodlighting that consumes about 90 kW. Crime-prone areas of the city have repeatedly been given more and brighter lighting but crime continues to grow there, consistent with the findings in Clark (2002, 2003). Large brilliantly lit billboards have been constructed near and even as an integral part of city tollways. Most of the lighting excesses are for commercial purposes.

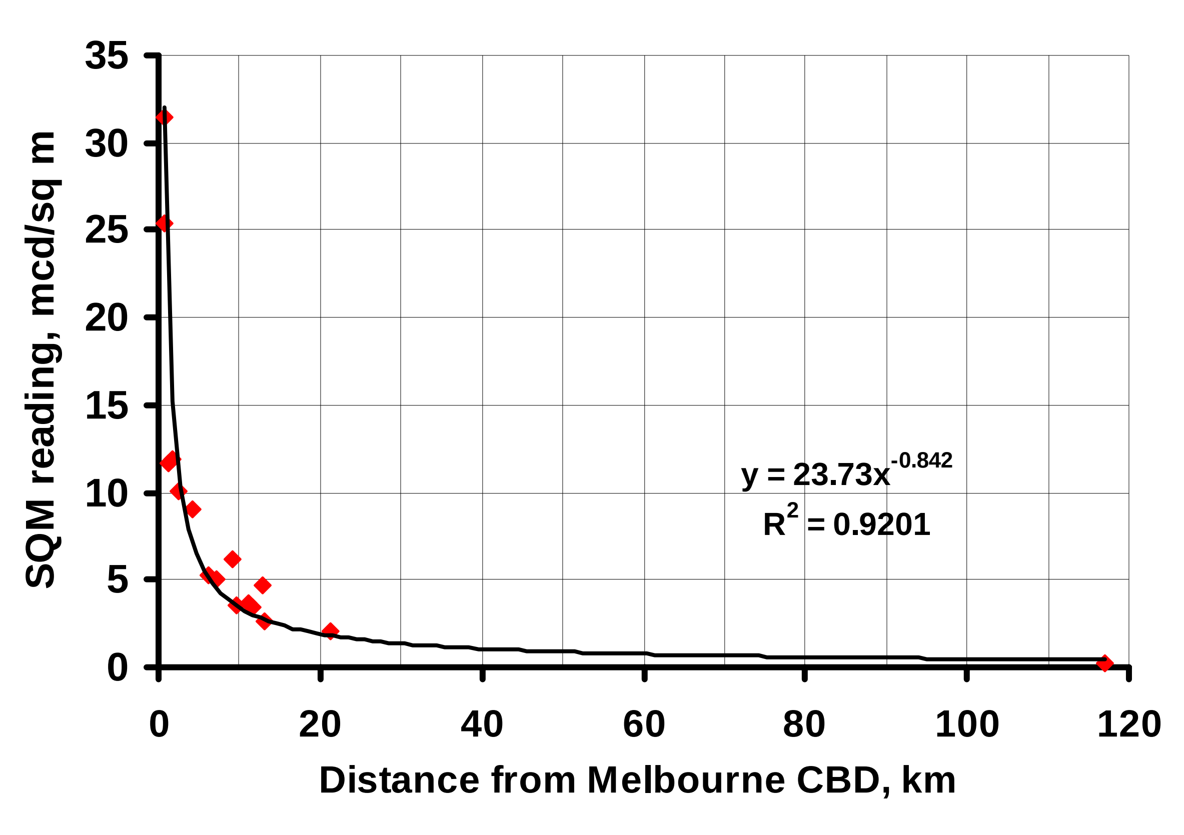


Figure 3. Total skyglow as a function of distance from the Melbourne central business district on 22 February 2006 with a moonless clear sky. The most distant reading was at the Leon Mow Dark Sky Site of the ASV near Heathcote in central Victoria. To give an idea of the units originally used in measuring the skyglow, 17, 19 and 21 stellar magnitudes per square arc second convert logarithmically to 17.1, 2.71 and 0.43 mcd/m^2 respectively.

Baddiley and Webster (2007) is a new analysis of the physical processes that give rise to artificial skyglow. It is based on distribution diagrams for different luminaire and lamp types and known scattering properties of the atmosphere in numerical modelling. The findings include the following:

> "Therefore any direct light travelling just above the horizontal is a major contributor to skyglow. Ground reflected light is typically a factor of 10 lower depending on ground reflectivity."
>
> "Light going straight up from towns has less effect on skyglow on clear nights in rural locations, than that travelling sideways. This is important as it can be easily prevented by using modern luminaires with well controlled upward light emissions."

> "… minimising light emitted from luminaires at or near the horizontal is of paramount importance."
> "Do we need the light or not?"

The importance of minimising spill light emitted in the few degrees just above the horizontal has been known from practical experience (eg in northern Italy) and understood for many years (Cinzano 2003, 2006). Hollan (2008) provided a useful explanation, rephrased here:

> The amount of scattering of a light beam in the atmosphere increases with its angular distance from the zenith. That is why shadows are at their darkest when the sun is high in the sky. Only about 8% of the light is scattered from a near-vertical beam. For a beam inclined at 30º to the horizontal, the atmospheric light path is twice as long and the loss from scattering is about 1- 0.92^2, or15%. For inclinations close to the horizontal, nearly all of the light is scattered because the light path is so much longer again. Sunlight becomes progressively weaker as well as redder as the sun sets, and shadows then are made even paler by the additional scattered light in the sky.
>
> At night, artificial light from a terrestrial source is subject to the same scattering processes. Most of the light travelling upwards at a steep angle leaves the atmosphere. The 8% or more that is scattered contributes to artificial skyglow. A greater proportion is scattered from beams at lower angles, increasing the skyglow. Practically all of the light will be scattered when the light is moving towards or just above the horizon. As this can be up to twelve times as much as the fraction lost from near-vertical beams, it is a much more potent source of artificial skyglow.

No account was taken of this strong angular dependence in the analysis included in Section 3.3 above, but the results there are not greatly affected. The same cannot be said for outdoor lighting standards that ignore this effect in defining the maximum upward waste light ratio of a luminaire. This ratio could be say 5%, which might appear to be acceptably small. But if most of this light is emitted at angles just above the horizontal, the luminaire could be several times more light polluting than if the waste were confined to steeper angles.

The Australian Standard for road and public lighting allows luminaires to emit a substantial amount of unused light into this environmentally damaging near-horizontal range. As road and public lighting is a major source of outdoor light flux in the middle and outer suburbs of Melbourne, this is one of the reasons why the curve in Figure 3 has such a long tail of values above the natural skyglow value. It extends well past the outer edge of the outer suburbs, typically 20 to 40 km or more from the CBD.

A related criticism can be aimed at initial attempts by lighting researchers to try to develop standard procedures for quantifying the total amount of spill light from buildings and surrounding land within a property boundary. An early example was for the lighting of a parking lot (Sundaram, Akashi and McColgan 2002). A notional box is imagined to have sides at the boundary and a flat top above the buildings or other structure. Computer software allows computation of the total light flux at each of the inside surfaces of the box, taking all existing or planned luminaires into account. The attempt to include light spill limits in lighting design is commendable. But at least in early attempts, the directions of beams after they had passed through the box appear to have been ignored, making it possible for the actual skyglow effect to be several times greater than expected. Effects related to the spectral power distributions of the light sources also appear to have been ignored. The Appendix indicates that a further substantial error could result as a consequence. As will become evident from the following Chapter 4, such shortcomings could be a matter of life and death for individuals living in the vicinity of lighting designs based on inadequate methodology. On the other hand, fixing the problems and taking account of new knowledge could be expected to lead the way to genuinely better and safer lighting.

3.5 OUTDOOR LIGHTING AND GREENHOUSE GAS EMISSIONS

Large-scale scientific research work fostered and coordinated by the United Nations and national peak science bodies has identified ongoing rapid climate change and global warming as highly likely to be mostly or fully caused by anthropogenic release of certain gases into the atmosphere. The gases include carbon dioxide, methane and others that transmit solar energy largely unhindered and tend to absorb the longer wavelength radiation emitted by Earth's surface. The main effects are to raise Earth's surface and atmospheric temperatures, ie the 'greenhouse effect', and to increase the variations that occur in weather. Another effect of rising atmospheric content of carbon dioxide is to increase the acidity of the oceans. The dynamics of this situation are that even if all fossil-fuel burning ceased overnight, ocean acidity will continue to grow for the next century, with the consequent likely extinction of many oceanic species.

One of the early outcomes of the UN action on climate change was the UN Framework Convention on Climate Change (FCCC). Signatory nations, which included Australia, accepted a legally binding obligation to reduce GGEs. The Kyoto protocol of 1997 set 1990 as the base year for assessing reductions, the end of the reductions period as 2008 and the reductions for most nations as five percent. At the last minute, Australia perversely negotiated an 8% emissions *increase* by 2010. This was reluctantly accepted by the other developed nations to avoid outright failure of the Protocol. Later, the Australian Government, along with the US Government, refused to ratify the Protocol.

Australia and the USA (along with some small rich nations) are the world's largest emitters of greenhouse gases on a per capita (ie per person) basis. The US and Australia have claimed that compliance with the Protocol would place them at an economic disadvantage compared with developing nations such as India and China. On the other hand, the developing nations maintain that the bulk of greenhouse gases in the atmosphere at present were put there by the developed nations over the past two centuries, and the Protocol falls well short of redressing this imbalance.

Concern in the Australian population about the Australian Government's failure to ratify the Kyoto Protocol was a factor in the change of government that took place in late 2007. Australia ratified the Protocol soon after.

Some of the developing nations have proposed that equitability would require GGE limits to be set on a per capita basis. Compliance with this is called 'convergence' (eg Garnaut 2008, pp 30-33). It would place severe burdens on the developed nations, but anything short of this hardly seems likely to provide a satisfactory long-term result. A current compromise being proposed by some developed nations is to work towards equal greenhouse intensities for nations, greenhouse intensity being the total emissions per nation divided by the nation's gross domestic product. This could be counterproductive by tending to retard the development of developing nations, an outcome that most nations appear unlikely to accept.

The world body that oversees and interprets global science on the greenhouse effect is the Intergovernmental Panel on Climate Change (IPCC). It is a joint panel of the World Meteorological Organization and the United Nations Environmental Program. The IPCC issues reports on its assessment of the observed extent of climate change, its predicted change and effects, its cause, and global measures required to reduce the effect of the identified anthropogenic contribution to climate change. Its Assessment Reports are becoming gloomier about the severity of the likely impacts of predicted effects of climate change and the consequent need for large early reductions in the global emission of greenhouse gases attributable to human activity.

The Fourth Assessment Report of the IPCC, *Climate Change 2007*, represents six years of research by over 2500 scientists from more than 130 countries. Nearly all of the IPCC scientist members supported the finding that decisive global action is required to reverse the rate of growth in the emission of greenhouse gases into the atmosphere. Delayed or incomplete action will greatly decrease Earth's capacity to support the human population and the diversity of all other living things. IPCC (2007) concluded that global GGEs will probably need to be reduced to 40% or less of 1990 levels by 2050 to avoid severe adverse effects from climate change. It does not appear likely that the supply of energy from renewable and nuclear fission sources and gains from increased energy efficacy will be sufficient to achieve this while total energy demand continues to increase. In other words, energy usage will have to be reduced.

Regardless of how reductions in GGEs are to be achieved, it is apparent that the desire of developing nations for equality in per capita access to energy and therefore their continued growth will place the developed nations under heavy pressure to reduce their own target GGEs to maybe 20% or less of 1990 levels by 2050, with intermediate binding targets of 25% to 40% reductions by 2020 as well. Even greater reductions may be justified, for example to just 10% by 2050, given the accelerating rate of climate change effects observed since the cutoff date for observations considered by the IPCC (Garnaut 2008).

Delay in starting the reduction process would increase the size of reductions required in later years. Reductions need to be implemented as soon as practicable with the early reductions being arithmetically the largest. At present it appears that the required reductions in fossil fuel burning can only be fully achieved by mandatory cuts to fossil fuel energy supply. For aviation in particular, there are few prospects for replacing fossil fuels. Therefore cuts in fossil fuel usage will need to be greater in other energy use sectors, such as land and sea transport, manufacturing, agriculture, commercial and residential. Outdoor lighting is part of each of these sectors. There would appear to be virtually no prospect that outdoor lighting will be allowed to continue on its present rapid expansion untouched.

Naturally, energy companies see such potential actions as a threat to their income and profits. Some have worked hard to try to discredit the science of the greenhouse effect and its consequences, and to have governments accept that economic prosperity would be severely reduced if the proposed substantial reductions in emissions were put into effect. The Australian and US governments in particular have followed these lines in attempts to avoid binding targets for emissions reductions. The 2007 change of government in Australia brought hopes of a more constructive Australian policy in which the economy would tend to be seen as dependent on the environment rather than specifying what environmental concessions can be made. Unfortunately, the achievements so far have fallen well short of the rhetoric. The more recent change of President in the USA has likewise raised hopes for a more rational approach, but the scientific reports continue to get worse and the scientific community is becoming increasingly concerned and angry about the lack of real progress by politicians world-wide.

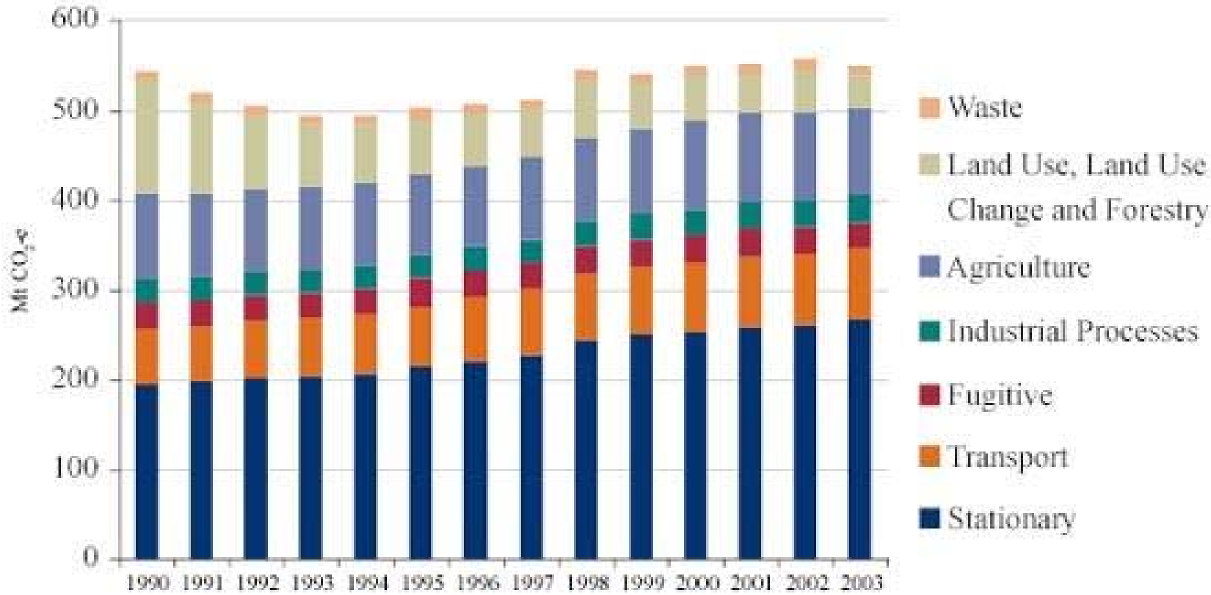
The economic issues still have to be faced, and the difficulties grew greatly with the onset of the 2008 global financial crisis.

The UK Government's independent Stern Review of the economics of climate change (Stern 2006) indicated that the economic costs of substantial emissions reduction are likely to be smaller than were previously assumed, and much smaller than the eventual costs of doing nothing. The regional situation was examined in Australia and two versions of a notable report have been issued by Garnaut (2008). They acknowledge that recent information about climate change has become more pessimistic and the need is stressed for drastic cuts in GGEs in Australia by 2020 and 2050 while the nation takes advantage of its natural resources to develop renewable energy sources and to assist other countries in the region to limit their GGEs also. However, Garnaut believed that Australia's 2020 reduction target should be limited unless international agreement ensures that other countries commit to large reductions. He also addressed the issue of compliance, noting that mandatory measures will be required rather than voluntary. For the same reason, 'mandatory limitations' has been part of the title of this document since its first issue in early 2006.

One of the ploys still being made by vested interests to argue for a reduced role of greenhouse gases in climate change is to point to evidence of climate forcing by solar activity or some other external action. Actually the apparent solar forcing is the opposite of what these interests have been claiming insofar as the indices of solar activity have been reducing while global warming has been increasing in recent years, while other possibilities are tentative at best (Lockwood and Fröhlich 2007). Regardless, as an example suppose that 10% of the observed rate of climate change is from some external cause such as solar forcing, cosmic rays, meteor infalls or whatever. For nations with the highest per capita GGEs, instead of needing to reduce emissions by say 80% of 1990 levels, it would have to be about 89% reduction in emissions for the total of greenhouse effect plus unchanged solar effect to reach the required reduction to 20% of the total 1990 base year emissions. The conclusion is that it would be prudent for the developed nations to aim for emission reductions even larger than those currently contemplated to allow for any unknown but probably small external forcing effect. Garnaut (2008) reached a comparable conclusion more succinctly.

Another tactic that tends to prolong the status quo for the lighting sector and some other energy use sectors in Australia and some other countries is to introduce the notion that the base year can be set at several years later than 1990 with little effect. This may have face validity in the USA, where GGEs in 1996 were apparently comparable with those in

1990. It is not true in the case of Australia, as shown in Figure 4. Despite this, the federal and state governments of Australia have encouraged local councils to manage GGEs in their municipalities according to the Cities for Climate Protection (CCP) program. The base year generally chosen for CCP assessments is 1996.



Source: Australian Greenhouse Office, 2006, http://www.greenhouse.gov.au/inventory/

Figure 4. Greenhouse gas emissions in Australia. The Australian stationary energy sector emissions for 1996 are about 18% higher than they were for the Kyoto Protocol base year of 1990. Compare this with the observed photometric increase in Melbourne's artificial skyglow in this period, 50%, an approximate indication of the corresponding increase in energy consumption then for outdoor lighting.

This has given rise to a widely circulated notion that compliance with the Kyoto Protocol can be achieved by similar limits on emissions relative to 1996 levels. But for Melbourne's outdoor lighting as indicated in Figure 1, it is apparent that this 1996 CCP baseline is about 50% higher than the 1990 Kyoto baseline, more than the increase for all GGEs over this period shown in Figure 4. Local councils in Melbourne have often used this 1996 base year in claiming successful voluntary compliance with the Kyoto Protocol when their growth in emissions, which typically has a large public lighting component, has actually been a blowout.[6]

[6] The present writer has alerted the Australian and Victorian governments to this problem on several occasions since 2004, but no serious response has been received and no attempt to correct the problem has been apparent. For example, when an earlier version of this document was sent to the Victorian Minister for the Environment one of his staff members responded with a do-nothing reply along the lines of 'thank you for your interest in this aspect of government policy'. Another ministerial staff member said that proposals for reductions in public lighting could not be considered as public amenity would be affected!

Although figures for annual increases in local government expenditure on lighting do not appear to be readily available, municipal council representatives at recent sustainable public lighting seminars in Victoria have described increases of up to 5% pa after allowing for inflation. The actual growth exceeds this, presumably because of lighting growth in new subdivisions in the outer suburbs and growth in non-council lighting such as commercial lighting and outdoor advertising signs. In Australia, any annual rate over 0.4% accelerates the gap between the Kyoto Protocol and what is actually happening. The proverbial *Fool's Paradise* comes to mind.

Light pollution reports by amateur astronomers in other large Australian cities and in rural areas indicate rapid growth much like that in Melbourne, so it appears that CCP procedures have unwittingly fostered unsustainable growth in energy use for public lighting in Australia.

Using country or remote sites for dark sky observations is a current work-around for city-dwelling amateur and professional astronomers in developed nations. But artificial skyglow from cities is now detectable over hundreds of kilometres away with inexpensive equipment. If the present unsustainable growth in outdoor lighting continues over the coming decades, many existing dark sky sites will be afflicted by skyglow as bright as that of suburbs at present. New observing sites will need to be established at locations several times further away from cities than the present distances. Amateurs would face unpalatable or prohibitive increases in travel time, costs and associated GGEs. Given that amateurs are contributing more than ever before to knowledge of the universe, hampering their scientific endeavours will come at a cost to humanity.

For the professional observatories at Siding Spring (which is in a sparsely populated inland part of the Australian state of New South Wales), the spread in skyglow from Sydney (the state capital) and nearer population centres poses an increasingly severe threat. Unless the growth in outdoor ambient light flux at night is stopped or reversed, in due course Siding Spring will inevitably experience the unacceptably bright skyglow levels that currently afflict Mount Stromlo Observatory near Canberra in the Australian Capital Territory. This kind of threat to professional astronomy appears to be happening in many other countries also. The costs of forced relocation to more remote sites would be worrying for the various national governments and organisations involved. Transport of goods and personnel could be increasingly discouraged by GGE controls. Again the handicapping of astronomical research needs to be considered seriously and avoided by decisive action to curb unnecessary outdoor light flux from all sources, given that astronomy is one of the prime wellsprings of scientific and technological progress.

4. REASONS TO LIMIT OUTDOOR LIGHT FLUX AT NIGHT

If the present trend for exponential growth of outdoor lighting in Australia continues, it is clear that the skyglow threat to astronomy will continue to worsen unhindered in the longer term even if light spill control measures such as those proposed by lighting organisations (eg ILE 2000) or the International Dark Sky Association (IDA 2008) are introduced and high levels of compliance are achieved. National and regional reducing caps on outdoor ambient light flux are required instead or preferably as well, but the astronomical problem by itself seems unlikely to be accepted by governments as sufficient reason for imposing drastic restrictions. But other reasons do exist to justify mandatory control of the amount of outdoor ambient artificial light at night, as distinct from control of the energy used or the greenhouse gases emitted to produce that light. The most compelling of these relate to health, wellbeing and the maintenance of biodiversity.

In evaluating the evidence, it is useful to have some idea of the lighting conditions that existed at night on Earth during the long time it has taken for evolution to result in the present array of life forms. In that time, it appears that day and night have almost always provided a strong lighting contrast from light to dark. The darkness is not absolute: starlight and natural skyglow provide dim illumination that many life forms can detect and use to advantage. For about half of the time at present the moon is in the night sky. Again this pattern has not changed much over many millennia, periodically providing a relatively large light increment that various life forms have evolved to use in the struggle for survival.

The lunar cycle provides about a nine times increase in natural night ambient outdoor illuminance from new moon to full moon, ie a range of nearly one $\log_{10}$ unit.[7] In the absence of light pollution, cloud can reduce the ambient illuminance by about one log unit at any phase of the cycle but the amplitude of the lunar modulation cycle in log units is more or less unaffected. In cities, light pollution typically increases the moonless clear night sky luminance by more than one log unit, and a corresponding increase takes place in the ambient illuminance. The lunar cycle amplitude with cloudless light polluted skies may thereby be reduced to about a fifth of a log unit or less. Cloud further diminishes the lunar modulation by decreasing the amount of moonlight and natural skylight reaching the ground while the ambient illuminance is increased by the greater proportion of upwelling artificial light that the cloud returns to the ground. The disruption of the natural lunar signal is further exacerbated by the relatively large variations in downwelling artificial light that accompany variations in cloud cover. The extent of this disruption as a consequence of burgeoning outdoor artificial light flux is unprecedented in all previous evolutionary history. Life forms that evolved a dependence on lunar phase may instead respond inappropriately to other light signals. Generally this could be thought likely to reduce survival probability of such species. In turn, this can affect the survival of dependent species, eg through the food chain.

It is now generally accepted that a high degree of conservation of biodiversity is essential for the long-term survival of humans. This is why the influence of artificial light on biodiversity is included in this chapter along with the more obvious topics of effects on health and wellbeing.

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[7] Light in ordinary units combines arithmetically. Living things tend to respond in proportion to the logarithm of the value in ordinary units, which is why logarithmic units are useful, both as absolute quantities and as increments and decrements.

4.1 OBTRUSIVE LIGHT AT BEDROOM WINDOWS

Quite small amounts of light at night can delay and disturb sleep.[8] The Australian Standard AS 4282-1997, *Control of the obtrusive effects of outdoor lighting*, sets the maximum outdoor artificial illuminance allowed in the plane of windows of habitable rooms at between 1 and 15 lux depending on the circumstances, despite citing a German study (Hartmann, Schinke, Wehmeyer and Weske 1984) in which complaints began when the illuminance at a window at night was as small as 0.06 lux (LNRW 2002).[9] In Appendix C of AS 4282 (1997), it is admitted that limits based on this and comparable investigations would be onerous to meet because existing lighting practices often produce much larger amounts of stray light. In common with other national lighting standards, the limiting values set were relaxed to values of between 1 to 15 lx, thereby requiring fewer and smaller departures from the status quo. Of course, the people who make such decisions are generally involved in the lighting industry and may have vested interests. Existing lighting practices thereby tend to be perpetuated in the face of contrary medical, behavioural and environmental evidence.

A piloted questionnaire survey of 1000 nationally representative subjects in Czechia by Forejt, Skočovský, Skotnica and Hollan (2004) concluded that for sleep to be undisturbed by lighting, the maximum external illuminance in the plane of bedroom windows should not exceed 0.1 lx, regardless of where the dwelling is located.[10] Hollan (2007) showed that this proposed requirement can be achieved even when the road surface adjacent to the window is artificially lit to as much as 2 lx, which is about eight times brighter than the brightest moonlight. Streetlights will generally need to have full cutoff characteristics in order to achieve the requirement.

Ad hoc observations by the writer and colleagues[11] using Sky Quality Meters in several suburban bedrooms, together with occupants' reports of spill light effects on sleep, definitely support this 0.1 lx maximum. Note that typical high quality conventional light meters have increments of 0.1 lx on their most sensitive range, so setting the limit at 0.2 lx instead could allow the actual exposure to be as much as 0.3 lx in practice, ie brighter than the light of a full moon, which would appear to be inadvisable.

Given the developments that are taking place in the UK in connection with light spill as a statutory nuisance, it is surprising that quantitative data about illuminances that have led

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[8] Note that the normal incidence illuminance produced by the full moon never exceeds 0.267 lux (eg Smith, Vingrys, Maddocks and Hely1994). Generally it does not exceed 0.2 lux in the vertical plane. For individual windows that can receive moonlight, values approaching 0.2 lux occur only for a few hours each month at most.

[9] The abbreviation for 'lux' is 'lx'. It is used in the remainder of this report.

[10] It is international practice for lighting standards to allow more stray light at windows in city lighting zones defined by the International Commission on Illumination (CIE) but this practice now appears to be so hazardous that a complete reform of lighting practices is required. Health and safety should not be compromised by allowing excessive light for any reason in the middle and inner zones of cities, particularly as present excesses are largely a product of careless, ignorant, wasteful and selfish lighting practices and indicative of glare.

[11] Particularly Geoff Dudley, Deputy Director of the Outdoor Lighting Improvement Section of the ASV.

to complaints are sparse- only a handful of individual cases could be collected in one recent attempt. The values ranged from 0.2 lx to 10 lx (Temple 2006, p 32).

Fimel (2007) suggested that attention to the interior design of a residence could reduce the effects of a given amount of stray light at the exterior of the building. Useful gains are certainly possible in this way but they should not be used to argue for increasing the allowable maxima for external illuminance. The worst case can readily arise through circumstances beyond the resident's control, viz direct illumination of a sleeper's face by external light passing directly through a window not fitted with drapes or curtains.

Ambulant recording of white and blue light exposure at the levels of present interest could be valuable in further quantifying the threat level posed inside residences by external stray light at night, but the technical difficulty of doing so is formidable. For example, a convenient and inconspicuous device by Hubalek, Zöschg and Schlerz (2006) with white and blue sensors is fine for daytime studies but unusable below about 10 lx. Clearly, sensitivities ten thousand times greater, ie down to 1 millilux (1 mlx), could be appropriate, especially when taking account of long-term cumulative effects of light exposure at night.

4.2 Lighting, Sleep Disturbance and Accidents

Sleep loss and sleep disturbance degrade wellbeing (Dement and Vaughan 1999) and can substantially increase the risk of road and industrial accidents in which daytime sleepiness and fatigue are factors (Dawson and Reid 1997; Stutts, Wilkins and Vaughn 1999; Williamson and Feyer 2000). In a study of drivers involved in motor vehicle crashes, 16 (55%) of a consecutive sample of 29 drivers had at least one sleep-related risk factor. This suggests that the number of sleep-related collisions is four times greater than those identified using current criteria of the Australian Transport Safety Bureau (Crummy, Cameron, Swann et al. 2007).

Lockley, Evans, Scheer et al. (2006) found that exposure to short-wavelength visible light increased alertness and vigilance in humans. Phipps-Nelson, Redman, Schlangen and Rajaratnam (2007) compared three kinds of nocturnal light exposure, all from 11-30 pm to 5-30 am, as a means of improving performance in a simulated truck night driving task. The exposures were <1.5 lx of 460 nm light, <1.5 lx of 640 nm light, and <1 lx of white light. Performance on a Psychomotor Vigilance Task was enhanced and delta and theta EEG activity was suppressed by the blue light exposure but not by other exposures. Therefore less than 1.5 lx of blue light is sufficient to keep humans alert during normal sleep time. Although not the purpose of the experiment, this means that such an exposure would hinder normal sleep at night, a key result in setting limits for stray light in bedrooms at night. As will become evident in the following section, such exposures are also a risk factor for breast and prostate cancers. And, as will be evident from results in the Appendix, high intensity discharge (HID) lamps used as motor vehicle headlamps are blue-rich light sources that are hazardous for this reason.

The use of heavy drapes or even blackout blinds to block excessive stray artificial light incident on bedroom windows is undesirable as such barriers also block the important beneficial waking effect of morning light for the bulk of the population (Forejt and Hollan 2004; Forejt, Skočovský, Skotnica and Hollan 2004). If governments are as serious as they claim to be about reducing road and industrial accidents, they should act to limit total artificial illuminance to 0.1 lx at windows of habitable rooms, regardless of rural, suburban or urban location and regardless of the source of the illumination. Current international guidelines on this matter are in urgent need of correction.

In the early days of orbital space flights, city residents were encouraged to turn all available lights on to greet the astronauts passing overhead. Fortunately, that rather childish response appears to be a thing of the past. But some airlines still dim the cabin lights to allow passengers a better view of city lights. What the flight crew as well as the passengers see is a tiny fraction of the upwelling waste light that causes artificial skyglow. City lights might look pretty from the air but they increase the risk of mid-air collisions because they reduce the conspicuity of aircraft navigation lights. This was a factor in a fatal mid-air collision near a suburban airport in Melbourne some years ago. The civil aviation authority was urged to take action against the wasteful and hazardous lighting at issue. The outcome was that the airfield lighting was made brighter! Not only did this exacerbate the risk of mid-air collisions but it likewise increased the risk of injuries and property damage from falling wreckage in the surrounding built-up area.

4.3 Light at Night, Obesity, Melatonin and Cancer

4.3.1 Artificial light at night

Wehr (1991) found that the durations of human melatonin secretion and sleep respond to changes in daylength. Light is the factor responsible. Melatonin is a powerful antioxidant and precursor of many important biochemicals (eg Jung and Ahmad 2006). Therefore it is hardly surprising that unnatural light exposure at night can have other serious adverse effects on health and wellbeing (Wiley and Formby 2000; Pauley 2004) in addition to those described in the preceding section.

Many mammal species exhibit a food craving known to be related to the extended duration of daylight during summer, leading to storage of body fat in preparation for the coming winter famine. Wiley and Formby (2000) suggested that the same mechanism can affect humans who are incompletely adapted to artificial light simulation of year-long summer light durations and not subject to a winter food shortage. This is their explanation of the increasing global incidence of obesity and obesity-related illnesses such as Type 2 diabetes. It is supported by laboratory trials (Spiegel, Tasali, Penev and Van Cauter 2004) in which human sleep curtailment resulted in decreased levels of the satiety hormone leptin, which is a response to a caloric shortage, and elevated levels of the hunger hormone ghrelin, which stimulates appetite. Speigel et al. noted that mean sleep duration in the US population had decreased by one to two hours over the past forty years. They did not mention the Wiley and Formby book.

A meta-analysis of cross-sectional studies from around the world indicated a doubled risk of obesity among short sleepers in children, adolescents and adults (Cappucio, Taggart, Kandala et al. 2007). The apparent link between inadequate sleep, obesity and associated diseases was given a positive review by Willyard (2008). Of course, there are many other effects at work, eg a longitudinal study of US children indicated that the number of hours spent watching television may be contributing to the increasing prevalence of overweight and obese children. The sedentary nature of watching and food advertising were considered to be reasons for the excessive weight (Danner 2008), but it is quite possible that the bright screen is increasing the apparent daylength after sunset, especially in winter. The Appendix indicates that television screens can be prolific sources of blue light. Extended viewing might also decrease time for sleeping.

Javaheri, Storfer-Isser, Rosen and Redline (2008) studied home sleep quality in 238 adolescents and found that systolic blood pressure was reliably elevated to or towards prehypertensive levels in subjects with short sleep duration and low sleep efficiency. The results suggest that the elevations are associated with recurrent arousals or awakenings from sleep. Note that Siegelová, Fišer, Brázdová, et al. (2004) had already reported reliable increases of clinical importance in systolic blood pressure of 9 adult subjects when their faces were exposed to illuminances as dim as 1 lx during sleep between midnight and 3 am. This provides a clue to the causal direction in the adolescent study, ie the disturbances increased blood pressure, not the other way around.

Like most living things, the human body produces the hormone-like substance melatonin in dark conditions at night. Exposure to light at night, especially in the small hours, can interfere with this process. In particularly careful laboratory experiments, as little as 0.4 photopic lux of blue light has been found to cause a half-saturation nocturnal melatonin response in humans (Glickman, Levin and Brainard 2002). In ordinary domestic situations, light exposures would be more likely to be polychromatic white rather than near-monochromatic blue.[12] Exposures of less than 100 lx of white light can have an appreciable effect on melatonin, depending on the visible short-wavelength spectral component of the light.[13] Evening exposure to 500 to 1500 lx for 1 to 2 hours is typical for sporting teams and many of the spectators in high-level competition and televised games at night. Such exposures can suppress melatonin levels by 40 to 60% (NAPBC 1997), even though they take place well before sleep and the dim-light onset of melatonin release.

[12] However, the ready availability of blue light-emitting diodes (LEDs) in recent years has resulted in their widespread use for decorative effects in consumer goods such as mobile telephones, audio players and computers. Measurements in the writer's home indicated that the eyes of users of such equipment can be illuminated by several lux of blue light. Blue light from mercury vapour lamps as well as from blue LEDs is also widely used for decorative lighting of buildings and structures.

[13] But in research funded by the lighting industry, it was found that 18 lx from blue LEDs was more effective at suppressing melatonin than 450 lx from mercury vapor lamps. Instead of finding out why their thresholds were well over an order of magnitude higher than those reported by others, the researchers concluded that white light used in buildings was much less effective at suppressing melatonin than was previously thought (LRC 2004)! Bullough, Bierman, Figueiro and Rea (2008) is a report of further work on the topic. Revell and Skene (2008) showed that a white lamp that had the same amount of blue light as a blue lamp actually produced a greater suppression of melatonin. In the absence of any effect of white light in increasing or decreasing the effect of short-wavelength visible light on melatonin suppression, it is clear that for a given amount of light, the use of blue-rich white lights such as mercury vapour lamps, cool-white fluorescent tubes, compact fluorescent lamps and metal halide lamps tends to be more hazardous at night than the use of incandescent bulbs and warm-white discharge lamps. See the Appendix for a quantitative treatment.

Dijk and Lockley (2002) reviewed the literature to portray the relationships between light exposure and the circadian rhythm[14] in humans. Light exposure during habitual sleeping time, especially in the first half, tends to delay the cycle, while bright exposure during the morning tends to advance it. Interference with the circadian rhythm by external factors leads to sleep disruptions and complaints. Gooley, Brainard, Rajaratnam et al. (2007) found that melatonin suppression and circadian phase delays in 46 humans were linearly related and dependent on photon density and wavelength of light irradiation for 6.5 hours during the early biological night. Blue light (λ~460 nm) had about twice the effect of green light (λ~555 nm), but the action spectrum described in the Appendix indicates this ratio as about 20. At least part of this discrepancy could be explained as a consequence of excessive bandwidth in the filters or monochromator used.

In interpreting the literature, there is a need to know whether the experiments reported refer to times at night when the eyes were open or shut. Naturally much more light is required to reach the retinal receptors if the eyes are shut, so the argument might be that stray light is of less consequence when the person is asleep. But it is common experience to be awake sometimes at night when trying to sleep and eyes are not always shut then. The need is to determine safe levels of stray light at night in the worst case, which is having eyes open and exposed to the light passing directly through the window. The safe level will be much smaller in this case than in the cases of eyes covered or closed. This smaller value is the one that should be used to determine the maximum allowable amount of stray light at windows of habitable rooms anywhere, regardless of time at night.

4.3.2 Light exposure at night and cancer

It has been known since the 1980s that melatonin is one of the body's most powerful agents for retarding the growth of breast cancer and other cancers (eg Jung and Ahmad 2006). Many laboratory and field studies have shown reliable positive connections between breast cancer incidence and light exposure at night (eg Davis, Mirick and Stevens 2001; Schernhammer and Hankinson 2005). Blask, Brainard, Dauchy et al. (2005) concluded (italics added):

> "Thus, strategies to preserve the integrity of the circadian melatonin signal (i.e., *avoidance of bright light at night*, intelligent lighting design, circadian-timed physiologic melatonin supplementation) coupled with modifications in nocturnal dietary fat intake may offer a unique approach to the prevention of breast cancer, and perhaps other melatonin-sensitive cancers, in our increasingly 24-hour society".

In the May 2006 issue of the prestigious journal *Cancer Causes and Control*, there were nine papers and reviews dealing with the relationship of breast cancer and other cancers to light exposure at night. All agreed that light exposure at night appears to be a substantial risk factor for breast cancer. Blue light of about 460 nm is particularly potent in affecting melanopsin, the primary circadian photopigment in rodents and primates (Glickman, Levin and Brainard 2002). Therefore the present tendency of replacing sodium lamps (which have a blue-deficient output) with metal halide lamps and fluorescent lamps (which generally have a blue-rich white output: see the Appendix) appears to be extremely ill-advised, quite apart from the substantial loss of luminous

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[14] 'Circadian' means 'about daily'. Circadian variables include body core temperature, plasma melatonin and wakefulness.

efficacy associated with the change (ie more electricity consumption for the same amount of visible light).

O'Leary, Schoenfeld, Stevens et al. (2006) (reviewed by Patel 2006) studied breast cancer incidence in Long Island women who worked evening or overnight shifts and a control group who did not work night shifts. They found a significantly reduced risk of breast cancer in the women who worked overnight shifts compared with women who never worked shifts. This is contrary to the results from many other studies of this sort. However, women who woke up during normal sleep hours and turned on lights twice a week or more often and twice a night or more often) had a significantly increased breast cancer risk. The authors concluded that further research is required to clarify these inconsistent findings.

Viswanathan, Hankinson and Schernhammer (2007) found that women working rotating night shifts for a long duration have a significantly increased risk of endometrial cancer, particularly if they are obese. They speculated that this increased risk is attributable to the effects of melatonin on hormonal and metabolic factors. This followed an earlier finding of increased risk of colorectal cancer in similar circumstances (Schernhammer, Laden, Speizer et al. 2003). Kubo, Ozasa, Mikami et al. (2006) found an increased risk of prostate cancer among rotating-shift workers.

In a through review of the journal literature related to light at night and cancer, Reiter, Dun-Xian, Korkmaz et al. (2007) pointed out that polluting the daily dark period with artificial light can no longer be regarded as inconsequential in terms of animal/human physiology. They conclude:

> "There is increasing epidemiological and experimental evidence that light at night has the capability of elevating cancer risk. This rise could be a result of a generalized disruption of circadian rhythms and/or a suppression of melatonin."

This is consistent with the earlier warning by Pauley (2004).

In another substantial review, Chen-Goodspeed and Lee (2007) found that recent studies suggested the role of the circadian clock could be a fundamental regulator for tumour suppression in humans.

On the basis of "limited evidence in humans for the carcinogenicity of shift-work that involves nightwork", and "sufficient evidence in experimental animals for the carcinogenicity of light during the daily dark period (biological night)", in December 2007 the International Agency for Research on Cancer Monograph Working Group of the World Health Organisation concluded that "shift-work that involves circadian disruption is probably carcinogenic to humans" (Straif, Baan, Grosse et al. 2007). WHO statements like this are necessarily conservative. The Danish Government has recently accepted the WHO finding and paid compensation to 40 women who developed breast cancer after working night shifts in state-sector jobs (The Age 2009).

In a landmark epidemiological study, Kloog, Haim, Stevens et al. (2008) found a positive association between night light intensity measured by satellite and breast cancer rates in females in 147 towns in Israel. Multiple regression analyses indicated that breast cancer rates were higher in the more brightly lit areas, which tended to be densely populated areas with high living standards. Conversely, abnormally low cancer incidence rates were found in low-income areas where outdoor and indoor artificial illumination tends to be dimmer than elsewhere for economic reasons. As a test of the method, female lung cancer incidence was also examined, the idea being that there was no known reason why this type of cancer would be affected to any extent by differences in amounts of light at night in different areas. Indeed, no reliable correlations were found for lung cancer incidence and amount of light at night. After adjusting for several variables such as ethnic makeup available at a population level, a strong positive association was revealed between light at night and breast cancer rate ($p < 0.05$) and this association strengthened ($p < 0.01$) when statistically significant factors were filtered out by stepwise regression analysis. The average artificial light exposure level was 9.1 times brighter than the minimum measured and corresponded to a female breast cancer rate 37% higher. From the dimmest to brightest areas, the rate was 73% higher.

Kloog et al. concluded that their study further strengthens previous findings of correlations between artificial light exposure at night and breast cancer in females. It is also consistent with the known impact of illumination on melatonin production and secretion by the pineal gland and the involvement of a variety of hormones in the development of breast cancer.

In round figures, the size of the effect observed by Kloog et al. can be summarised as 'ten times the ambient artificial light at night corresponds to a forty percent greater rate of breast cancer'.

Kloog, Haim, Stevens and Portnov (2009) is a further study along lines similar to the one in Israel. In this case they compared the incidence rates of three of the most common cancers (prostate, lung, and colon) in men residing in 164 different countries with the population-weighted light at night exposure and with several developmental and environmental indicators, including per capita income, percent urban population, and electricity consumption. They found a significant positive association between population exposure to light at night and incidence rates of prostate cancer, but no such association with lung cancer or colon cancer. The prostate cancer result is consistent with previous studies of circadian disruption and risk and with the suppression of melatonin and/or disruption of clock gene function by light exposure at night. Across the 164 countries, the risk of prostate cancer in countries with the highest light exposure at night was 110% higher than in the countries with the lowest exposure. This observed association is a necessary condition for a potentially large effect of environmental light exposure at night on risk of prostate cancer. However, the authors considered it is not a sufficient condition due to potential confounding by factors that increase the risk of prostate cancer and are also associated with light at night among the studied countries. Regardless, they stated:

> "There is, of course, the potential for confounding by known and unknown factors for which we could not adjust. However, for this to have occurred, the relative risk associated with the confounder would have to be very high, and the confounder would also have to be tightly correlated with LAN exposure in the localities studied…"

Of course, cautious interpretation of statistical analyses is important in framing conclusions on such matters. But these two papers by Kloog and colleagues build on substantial prior evidence of the serious consequences, including increased incidence and proliferation of some types of cancer, of experimental exposures to acute levels of exposure to light at night in humans and other mammals, and chronic environmental exposure of humans to generally sub-acute levels of light. Given that the Kloog et al. studies are about large and widespread human population samples in ordinary living and lighting conditions, they strengthen the existing evidence that associations between chronic light exposures at night and human breast and prostate cancer incidences are causal, whatever the mechanism(s) might be.

To summarise the evidence, exposure to artificial light at night can and does disrupt circadian rhythms and suppress the production of melatonin in humans and other mammals. There is laboratory evidence that such effects can and do increase the risks of initiation and growth of breast, prostate, endometrial and colorectal cancers. Epidemiological studies indicate reliable and substantial associations between the levels of chronic exposure to light at night and incidences of breast and prostate cancers in humans, although it is not established whether this is a result of circadian disruption, reduction of melatonin levels or some other factor related to light exposure or apparent daylength.

At the present stage of knowledge relating exposure to light at night and adverse effects on health, it is tempting to draw a parallel with earlier discoveries of factors with adverse health effects, eg ionising radiation, radioactivity, heavy metals, certain organic compounds, cigarette smoking and asbestos. In retrospect, the time lag in each case between initial demonstrations and general acceptance of the hazard seems to be inordinately long. In part, these delays resulted from protests, drawn-out court actions and biased scientific investigations by vested interests. In some cases, rearguard actions continued long after courts had started awarding damages for the illnesses. It is to be hoped in this instance that the appropriate responses will be put in place in a more timely fashion, unpalatable as many aspects will undoubtedly be.

4.3.3 Precautionary response

The strength of the evidence for a causal connection between per capita ambient light flux at night in towns and cities and the risk of breast and prostate cancer appears to be well beyond the level that might be regarded as sufficient to invoke the ‘precautionary principle’. This principle is included in Australian state and federal legislation relating to environment protection, and presumably in the environmental legislation of other countries. For example, the Victorian Environment Protection Act 1970 gives the following definition:

“1C. ***The precautionary principle***

> (1) If there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.
> (2) Decision making should be guided by--
> > (a) a careful evaluation to avoid serious or irreversible damage to the environment wherever practicable; and
> > (b) an assessment of the risk-weighted consequences of various options.”

The Act also links environmental damage with threats to public health. Therefore it would appear that the government should act quickly and decisively to protect its citizens from light exposure at night as an environmental risk factor for prostate and breast cancer.

4.3.4 A new dilemma about artificial lighting

Humans evolved in conditions of bright daylight and dark nights so it could be expected that exposure to daylight or skylight is not damaging for humans, although excessive exposure (eg from a day at the beach without shade or sunglasses) can result in sunburn of human skin and eyes by natural levels of erythemal ultraviolet radiation, while the intense visible light can produce a temporary reduction in subsequent dark adaptation (eg Clark 1971). Indeed, exposure to bright light in the morning is beneficial as it helps to dispel lingering sleepiness. Exposure during daylight hours to high natural levels of blue-rich visible light appears to carry none of the cancer risk that might attach to lesser exposures to artificial light in the evening or later.

Regardless, there is a known Blue Light Hazard, which relates to photochemical injury to the retina by light in the wavelength range from the ultraviolet to about 500 nm. One of its temporary effects is interference with dark adaptation. It is also implicated in some irreversible changes including exacerbation of age-related macular degeneration.

The Blue Light Hazard has been known for decades. Protection against it, short of the complete removal of short-wavelength visible light that would turn colour normals into the functional equivalent of tritan colour deficients (Clark 1968), was incorporated in the Australian Standards for sunglasses and industrial eye protection from the 1970s. There is plenty of information available about it in the popular and journal literature (eg Mainster and Sparrow 2003; Roberts 2005; Mogk and Mogk 2008; Siu, Morley and Coroneo 2008; Turner and Mainster 2008), but this is sometimes inaccurate in ascribing the effect to blue light only. Weale (2007) pointed out that this error arose from (in the present writer's words) confusion of the action spectrum at the cornea with the action spectrum at the retina. Regardless, the Blue Light Hazard action spectrum is definitely different from the action spectrum for melatonin suppression in the evening and night. The effects arise in quite different ways- the first involves photochemical damage to imaging light detectors and the second relates to normal non-imaging detection of light at abnormal times.

It is common, particularly in the interiors of large buildings, for artificial lighting to be required regardless of whether it is daytime or nighttime. Even when daylight is available indoors, artificial light may be required to supplement daylight. It is also common for indoor lighting, especially in commercial and industrial buildings, to have a colour temperature in the range of about 4000 K to 6500 K. This implies a relatively high content of short-wavelength visible light, and this tends to assist the achievement of reasonably efficacious conversion of electrical energy into light. It also gives occupants the daytime blue light exposure that appears to be useful if not essential for maintaining normal circadian rhythms. As indoor lighting is generally not as bright as the brightest daylight, there is little (but apparently not zero) risk of occupants experiencing adverse effects from the Blue Light Hazard if their exposure duration is less than say eight hours. But the risk might increase for longer exposures, such as for overtime or double shifts.

The situation can change markedly in the evening and at night, when melatonin suppression can be active in individuals with a normal circadian rhythm. The overall illuminance needs to be minimal, perhaps with local task lighting only as and when necessary. The relative proportion of melatonin-suppressing light also needs to be as low as is possible, and certainly not well above the proportion for which colour rendering is adequate. These properties are quite different from those of the artificial lighting appropriate for daytime use. Solutions such as separate day and night lighting systems, staggered bank switching or dimmable lamps may help but the capital cost may be daunting. Regardless, it might be less expensive than a single compensation payout for light-at-night induced cancer. Also, it is difficult to confine all internal light inside a building even if attempts are made with blinds or drapes on windows and skylights. If the internal light has the good properties described it will be less of a problem if and when it does escape.

If individual exposures of occupants to artificial light at night are routinely repeated and long, as in night shifts, the managers of the operation would appear to have a duty of care to assist individuals to have appropriately dark conditions before and during their subsequent sleeping time. Requirements for non-injurious lighting conditions and maintenance of circadian rhythms may already be implied by OH&S legislation requiring workplaces to be safe, but explicit mention of requirements would seem better.

The problems of catering for a mix of staff and customers in a retail environment might appear to be more difficult, but the lighting would need to be made appropriate for staff as those most at risk. Retailers might complain that bright light is necessary to attract customers, but typical levels at present are a relatively recent attainment through competitive ‘ramping’. Any such argument must be firmly rejected and mandatory upper limits put in place to ensure that no retailer is disadvantaged more than any other by this health-related change.

4.4 Broader Ecological Issues of Artificial Light at Night

In a recent thorough review of the topic, Navara and Nelson (2007) stated that urban light pollution and shiftwork contribute to the increasing prevalence of exposure of humans and other living things to artificial light at night, resulting in significant social, ecological, behavioural and health consequences that are only now becoming apparent. Artificial light exposure at night has demonstrated adverse effects on most living things, not just on humans, and because light pollution can be bright enough to be sensed many kilometres from the source lighting its adverse effects may cover very large areas.

Changes imposed on normal circadian light cycles lead to widespread repercussions in many species (eg Longcore and Rich 2004). The effects both on individuals and populations are of increasing concern, and need to be understood in the context of biodiversity conservation in order to determine the extent to which artificial light at night needs to be limited in quantity, quality and distribution. Most of the problems arise from light sources that are rich in blue light, such as mercury vapour lamps, fluorescent and induction lamps, metal halide and most other high intensity discharge lamps, and white and blue LEDs.

There are many websites and webpages that give details of scientific studies of adverse ecological effects of artificial light at night, eg Skykeepers (2009).

Some examples of the many ecological studies are described in the following sections.

4.4.1 Insects

In addition to endocrine disruption, there are many other adverse ecological effects of artificial light at night (eg Rich and Longcore 2005; Navara and Nelson 2007). Some relate to a tendency of many kinds of living things to move or orient themselves towards or away from a source of light. This is clearly beneficial in cases such as plants turning their leaves edge-on to the high sun when there is a need to minimise water loss. The consequences of unnatural light exposure at night may be quite adverse, however. A pertinent example is the attraction of some species of insects to outdoor artificial light sources, with consequences of increased mortality from incineration, dehydration, exhaustion and predation following entrapment, along with interference with reproductive behaviour (eg Frank 2005): light sources compete with pheromone plumes in providing guidance but lead to places less appropriate for mating and egg laying. In the case of fireflies attracted to the vicinity of artificial light sources, glare tends to prevent them from responding to light emitted by potential mates. A laboratory study indicated that the *Heliothis zea* moth will not mate unless the illuminance is less than about 0.05 lux, which corresponds to first and last quarter moonlight (Frank 2005).

Another indication that insects can be sensitive to low light levels was found in experiments on the nocturnal activity of fruit flies in artificial moonlight (Kempinger, Dittmann, Rieger and Helfrich-Förster 2009).

The British populations of two thirds of 337 macro-moth species declined substantially over a recent 35 year period. This has important and worrying implications for species such as insectivorous birds and bats, and suggests as-yet undetected declines may be widespread among temperate-zone insects (Conrad, Warren, Fox et al. 2006). It is also a problem for plants pollinated by the declining species, for the species that feed on those plants and so on.

Horváth, Kriska, Malik and Robertson (2008) found that many animals are able to detect polarisation in light. Flying aquatic insects use this to detect the presence of water surfaces, which polarise skylight reflected at angles well away from the vertical. Unfortunately, man-made objects such as cars and buildings with dark shiny surfaces also polarise light and can emit light signals that are falsely encoded for insects. Insects seeking a place to feed or breed are killed or disabled on impact. If they survive, they may starve or lay eggs where they cannot develop. The authors termed the misleading reflections 'polarised light pollution', and expressed concern at the mortality, disruption of the food chain, alteration of ecological interactions, and the downwards pressure this form of light pollution[15] places on biodiversity. To avoid this serious problem, they suggested solutions such as:

- select building materials that do not polarise reflected light,
- put white curtains behind windows,
- avoid putting large buildings within insect flight distance of inland water.

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[15] This is the only example of something termed light pollution known to the writer in which the light may be of natural origin, eg sunlight, daylight or moonlight. As such, it appears to lie outside the usual definitions of light pollution. Regardless, the effect is real enough and serious enough to warrant active corrective or preventative measures.

Other factors in insect population declines include habitat destruction by land clearing and development, and habitat degradation by agricultural pesticides, industrial toxins, climate change and artificial light. Of these, artificial light is one of the easiest to deal with and doing so can actually save money.

4.4.2 Animal migrations

Birds that fly at night and are attracted by artificial lights have increased mortality from collision with illuminated towers and high buildings (eg Ogden 1996; Shire, Brown and Winegrad 2000), and from exhaustion and predation following entrapment into circling around upwardly aimed floodlight beams, illuminated structures and large light-emitting buildings. Hundreds of millions of birds are killed annually in the US alone in these ways, and victims certainly include endangered species. Exposure to artificial light at night may adversely affect bird reproductive and other behaviour (eg Pollard 2007; Walker 2008). Artificial lighting can also disrupt bird migration by interfering with the night sky patterns used by birds as one of their methods of navigation (eg Fornasari 2002). These effects all tend to diminish populations.

From Navara and Nelson (2007):

> "Exposure to sky glow and artificial lighting that is currently common can have severe effects on the migratory patterns of animals... Changes in the timing and/or efficiency of migration and general orientation can be detrimental in terms of both survival and reproduction. Even low levels of artificial lighting effectively mimic the natural influences of the lunar cycle. Urban sky glow causes sky brightening long distances from the original lighting source, potentially affecting migrating individuals kilometers away… Such large-scale changes could have drastic ecological impacts".

Spatial concentration of birds and insects can affect predator-prey balances. If unnatural and sufficiently widespread and marked, as can be the case with attraction to outdoor light sources, this effect may inhibit breeding of the target species and thereby also put downward pressure on their population and consequently on other populations.

4.4.3 Aquatic and marine species

Many aquatic and marine animals undergo a ‘diel’ (daily) vertical migration that depends on the light-dark cycle. As illuminance decreases with depth, it is as though these species vary their depth to keep their light exposure within a dim range.[16] Therefore it was of interest to study whether light pollution affected the depth at which the evening ascent stopped for a particular species. Accordingly, aquatic ecologists measured illuminances and spectral irradiances at the surfaces of five lakes along a rural to urban gradient at new moon times. The innermost lake, Jamaica Pond in Boston, MA, USA had an illuminance equivalent to that from a full moon. The illuminance at the other lakes decreased with increasing distance from the city. At the most distant lake, Mirror

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[16] Actually, photometric quantities such as illuminance relate only to a standardised light sensor representing the human eye. Spectroradiometric units such as W/m^2 for a given small interval in wavelength are less convenient but more appropriate when some other kind of biological ‘light’ detector is involved.

Lake in central New Hampshire, the illuminance was only about 1% of that at Jamaica Pond.

At one of the intermediate lakes, Lake Waban, 16 km from Boston, the nightly vertical migration of the freshwater zooplankton *Daphnia* was reliably 2 m higher in amplitude and 10 to 20% greater in numbers when exposed to a simulated natural light level by the use of black plastic enclosures transmitting 4%, compared with observations in clear plastics control enclosures allowing the usual level of ambient artificial plus natural light at night. Suppression of vertical migration of such lake grazers and consequent reduction of their consumption of algae may contribute to enhanced concentrations of algae both in urban lakes and coastal waters (algal bloom), a condition that often results in deterioration of water quality (low dissolved oxygen, toxicity and odour problems) (Moore, Pierce, Kvalvik and Lim 2001, Pierce and Moore 2002).

Similarly, Gal, Loew, Rudstam and Mohammadian (1999) found that for *Mysis relicta,* mysid shrimps of the Laurentian Great Lakes, the presence of a small amount of artificial light at night introduced an upper limit to the vertical distribution indicated by sonography. This behaviour is considered to be for predator avoidance. Knowledge of this phototaxis was applied in a project to use cold deep water in Lake Cayuga as a substitute for refrigeration in providing cooling for nearby Cornell University buildings. Measurements indicated that *M. relicta* and a related species would avoid water where the illuminance was greater than about 0.0001 lx (0.1 mlx, 100 µlx) or considerably less. Trials with small incandescent lamps in the dark depths of the lake produced pronounced exclusion zones, confirming that the shrimps could detect and actively avoid even fainter light. An 8-W lamp at the cooling water intake was bright enough to avoid entrainment of the shrimps (CUFS 2006). In the present context, the importance of the observations is that artificial illumination as dim as 0.1 mlx or less affects the behaviour of some species. Given that fish were seen to be attracted to the lamp rather than being repelled by it, the differential in induced behaviour must influence predation in the lake and thereby affect the food chain. This is a biodiversity conservation issue.

There are many other examples of artificial light effects on marine life, eg Rich and Longcore (2005). Outdoor lighting of populated areas near coastlines certainly can have adverse effects on the biota of sand dunes, beaches and the adjacent waters.

4.4.4 Endangered species

The International Union for Conservation of Nature is the world's oldest and largest global environmental network. In October 2008 it announced that the world's mammals were in an extinction crisis, with almost one in every four species at risk of disappearing forever. Data shortages obscure the actual situation, which could be worse, at more than one in three. Many non-mammal species are also under threat, to the extent that the overall situation is described as a global biodiversity crisis (IUCN 2008).

The main reasons for the crisis include habitat destruction and degradation. The preceding sections in this chapter indicate that light pollution is certainly a non-trivial factor in the latter.

4.4.5 Urban zoos and domestic pets

Many cities have zoos in their urban or suburban areas or in their outskirts. Little concern has been expressed in the past about the adverse effects of artificial light on the captive species. It is increasingly common for zoos to take part in national and international efforts to save endangered species by captive breeding and rearing programs. The material in preceding sections should give cause for concern over the suitability of the night time environment in zoos. As a first guide, total illumination within a zoo from all artificial light sources including artificial skyglow with a cloud overcast should be dim enough to cause no more than mild interference with the lunar photocycle. This would require the maximum illuminance in any location and direction to be less than say 0.1 lx.

Information on the actual levels of illuminance in zoos has not been found in the literature. The writer has made numerous measures in and around Melbourne Zoo, however. This Zoo is situated about three kilometres north of the commercial centre of Melbourne. It is surrounded by dozens of pole-top metal halide lights at about 9 m intervals, supposedly for security. In 2008, the illuminance in the plane of the boundary wall ranged from 1.0 to 2.5 lx at the top of the 2-m high wall and increased with height over the next 3 to 5 m. Adjacent to the Zoo is the State Netball Hockey Centre [sic], which was completed in 2000. It was furnished with about 206 sports lights and 158 other outdoor lights, all with metal halide lamps. The main hockey pitch has colour TV broadcast standard lighting. In use, it can flood up to two thirds of the Zoo area with spill light of between 1 and 30 lx.[17] Lighting associated with nearby roads and train and tram services adds to the overall amount of stray light in the Zoo.

Excessive artificial illumination at night is a known threat to animal health and wellbeing. Exposure of zoo animals to this threat may constitute ill-treatment or cruelty.

Formby and Wiley (2000, p 87) stated that there is no cancer in nature other than in humans and domestic pets. While the actual situation is not as black and white as this, humans and pets do have relatively high rates of cancer. Whether pets spend their nights indoors or outdoors, like their owners they tend to be exposed to unnatural quantities of light at night.

4.5 SOCIAL ISSUES OF OUTDOOR LIGHTING

4.5.1 Outdoor lighting and crime

The effect of outdoor lighting changes on crime has typically been studied with field trials. This method involves comparison of crime counts in test and control areas before and after an increase is made in the lighting of the test area. By the early 1990s, scientific reviews in the USA and UK had established that outdoor lighting was ineffectual for crime prevention. However, common belief in the efficacy of lighting against crime seems to have persisted, perhaps because of confusion with the commonly experienced beneficial effect of lighting in reducing the fear of crime.

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[17] Julianne Bell and other members of the Royal Park Protection Group assisted in making these measures in 2000.

Since the mid 1990s, the resurgence of interest in the UK in the use of lighting for crime prevention can be traced primarily to one researcher's PhD results from field trials in two UK towns, eg Painter and Farrington (1997; 1999a). The published papers exhibit strong bias (Clark 2002) towards the belief that lighting prevents crime.[18] Additional papers by Painter and Farrington (1999b; 2001) made no attempt to correct or explain the apparent bias (supposing that this was even possible),[19] and they build on results that appear to be seriously erroneous. The lead researcher was supported by lighting industry grants but this is not acknowledged in all of the papers. None of the papers mention the lead researcher's personal relationship with a lighting industrialist, admitted later according to the reporter in a news magazine article (Private Eye 2005). These apparent omissions are not an indication of bias but if the circumstances are true, the papers should have followed scientific method by advising readers of the situation because it would appear to imply a substantial potential for conflict of interest and consequent unwitting bias.

Farrington and Welsh (2002) did a meta-analysis of published lighting and crime trials including the two mentioned. The results indicated that lighting increases (not the ab initio installation of lighting) decreased crime by about 20%, an improbably large value (Clark 2002, 2003). Marchant (2004; 2005a, b; 2006a-d, 2007) has shown convincingly that the statistical analyses of all field trials of lighting and crime to date are invalid because they all ignored the fact that individual criminals often commit multiple crimes. The number of crimes in a test or control area is larger than the usually unknown number of independent crime events that should have been used instead to determine the before-after changes and their statistical significance. Furthermore, most if not all field trials had a test area that was chosen for a lighting upgrade at least partly because it had a relatively high level of crime to begin with, and the phenomenon of regression towards the mean biases the results towards a systematic false positive effect of lighting. Meta-analysis does not correct for systematic bias in the input data. Instead, its effect on the result of the analysis is one stage further from the proper scrutiny that is an essential element of scientific method.

Farrington and Welsh (2004, 2006) have tried to defend their work against Marchant's criticisms but the latest version of their meta-analysis (Welsh and Farrington 2008) still appears to be invalid for both reasons, viz erroneously high statistical significance of the input data from individual trials and preservation of the pro-lighting systematic bias in the input data.[20]

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[18] To check the extent of this bias in the conduct and original analysis of the trials in Painter's thesis, the writer applied to see the thesis. A librarian at the University of Cambridge advised that access would be refused at least until 2008.

[19] For instance, one of the treatment areas appears to have been given extra police patrols and crime prevention pep talks attended by the researcher. Crime in the treatment areas in both trials was significantly higher initially than in the respective control areas to the extent that both trials should have been abandoned at the outset.

[20] The UK Home Office compounded the problem by refusing to withdraw Farrington and Welsh (2002) and by refusing an offer of Clark (2002, 2003) at no cost for publication in the same Home Office Research Study series. It seems contrary to scientific method for a scientific work to be published in a forum that does not accept major scientific criticism of that work for publication. The Home Office also has a duty of care to ensure that government funds are not used counter-productively. At the

Morrow and Hutton (2000) reported that installation of more and brighter street lights in Chicago alleys produced a 21% increase in crime relative to a well matched control area. The increase in light flux in the test area was 3.8 times but a smaller increase also took place in the control area so that the differential increase was about 3.4 times. The observed increase rather than a decrease in crime was much to the consternation of the researchers, who should have been disinterested in the sense associated with scientific method. They ignored the most likely interpretation, ie that lighting increased crime, and instead tried to find reasons to explain the result as wrong. They also cut short the statistical analysis. If such an approach were more widely adopted, it would seriously retard the progress of science.

The Morrow and Hutton paper was not mentioned in the Farrington and Welsh meta-analysis. Surprisingly, given that it is readily found by an Internet search engine such as Google, it was still not mentioned let alone included in the 2008 revision of the meta-analysis. Including it and correcting or allowing for some major faults in the other included studies would change the result to inconclusive. But this would be a waste of time because the Morrow and Hutton paper is about yet another field trial with no account of the effect of multiple offences, so it is therefore also invalid according to Marchant's work.

Despite the strength of the case that the Farrington and Welsh meta-analysis results are unreliable, the Australian/New Zealand Standard AS/NZS 1158 set for lighting of roads and public spaces continues to rely on that superseded reference and its discredited results as a justification for increasing outdoor lighting 'according to the known or perceived risk of crime'.

In 2004, the UK government had been convinced by sections of the lighting industry to spend £300 million on streetlighting upgrades primarily to reduce crime (eg Cozens, Neale, Whitaker et al. 2003), and the cost has since grown to over £1 billion. Crime in England and Wales fell steadily from a peak in 1995 to a minimum at the end of 2004 and has since risen slightly, but not by an amount of statistical significance (Nicholas, Kershaw and Walker 2007). There is no sign of the decreases that should have taken place according to Farrington and Welsh (2002) but the small rise is in the order of what could be expected according to Clark (2003).

Taking the work of Painter, Farrington and Welsh at face value, Cozens, Neale, Whitaker et al. (2003) enthusiastically supported the use of lighting as a crime reduction measure. They discounted previously published work that had found no evidence in favour of this measure, while experiments that appear to have been done badly were lauded as helping to establish the importance of lighting for crime prevention. Several experiments claimed to show this supposed effect actually do not. Speculative explanations for the apparently successful results were accepted uncritically. This includes the credulity-stretching claim that the presence of brighter lighting at night reduces crime by day.

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time of writing, the Home Office was still actively promoting the Farrington and Welsh report as support for the ongoing process of upgrading street lighting throughout England, despite the lack of evidence that the relighting to date has reduced crime at all

More examples of advocacy of lighting as a crime prevention measure occur in published material of the schools known as *Crime Prevention Through Environmental Design* (CPTED) and *Situational Crime Prevention* (SCP). 'Mixed' (expected and counter productive) results from practical application of increased lighting are explained away by claims that lighting seems to work best when combined with other measures such as better locks and increased police presence. In stark contrast, the Farrington and Welsh meta-analysis includes several trials affected by such substantial confounding factors but Farrington and Welsh ascribed the whole of the observed crime changes to the effect of lighting alone, thereby inflating the supposed benefit!

CPTED and SCP material also claims that lighting assists in crime deterrence by aiding natural surveillance. This is fine as far as it goes, but the rest of the story is generally not mentioned, viz that lighting simultaneously provides assistance for the commission of crime. Given the attractiveness of the idea that more and brighter lighting could reduce crime and thereby avoid much greater expenditure on extra police, it is no wonder that politicians in the UK approved the streetlighting upgrade proposed by the lighting industry.

Clark (2003) provided statistically reliable epidemiological evidence that the overall net effect of lighting is in the order of a few percent increase in crime for each factor of ten increase in artificial light flux. Therefore the net effect of lighting must be to assist or encourage more than hinder or deter the commission of criminal acts.

Installation of more and brighter lighting is also counterproductive as an anti-graffiti measure. Even casual observation will readily reveal that graffiti tends to be less common in places that are dark at night, and rare in unlit parts of tunnels.

Clark (2003) makes it quite clear that the effect of imposed darkness at night is to reduce the crime rate, over and above any temporal and spatial displacements of crime. This sets the causal direction in the observed positively correlated association between lighting and crime. Three months after Clark (2003) was posted on the Internet, confirmation came on a grand scale in the power failure of August 2003 that affected the northeast part of North America. Despite some early sensationalised news accounts to the contrary, there were actually no newsworthy increases in crime anywhere, just large decreases. When this became clear in New York City, politicians and police were quick to claim that the reduction there was because of the extra police deployed there and their competence. The claim can now be seen as ludicrous, given the relatively modest statistically reliable effect observed by Klick and Tabarrok (2005): a 50% increase in police presence observed in a smaller scale event reduced crime by just 15%.

The reduced crime effects of a lighting reduction or lighting blackout persist even when the loss of lighting lasts for months. For example, in Des Moines, Iowa, 39% of the roadlights rated above 70 watts on main traffic routes were turned off in September 2003 as an economy measure. Reported vandalism, burglary and robbery in the city dropped 3.5% in the first four months of 2004 (Alex and Paluch 2004) after rising 10% in 2002 and dropping 6% in 2003. In the northern Swedish town of Övertorneå and parts of the neighbouring town of Haparanda, a dispute between the local council and its electricity distributor resulted in the streetlighting being switched off for over five months during autumn 2006 and the 2006-7 winter. Since the switchoff, the number of thefts and burglaries halved and there were no traffic accidents that could be attributed to the darkness (SVT 2006; SVD 2007; Cumming 2007). There are many comparable examples,[21] even back in the gaslight era (Baldwin 2004). Of course, time series analysis without a control is vulnerable to confounding, so such results are only indicative, not conclusive.

There is no doubt at all that people generally feel safer with more and brighter lighting (Boyce, Eklund, Hamilton and Bruno 2000). It is therefore ironical that more and brighter lighting is actually conducive to increased actual crime. At present, there seems to be no way around the dilemma this poses, although reduced-glare lighting might help a little by optimising the fear-reducing effect. Fortunately, full cutoff lighting advocated to minimise light pollution is also reduced-glare lighting. One of the reasons why sections of the lighting industry do not like full cutoff lighting is that semi cutoff lighting puts more light near the horizontal specifically to light up the faces of potential assailants, unmindful that the evidence favours the interpretation that assailants get even more assistance from being better able to choose their victims by seeing their faces.

Whenever lighting reductions are proposed for environmental reasons, opposing vested interests tend to trumpet the need of lighting for security. The use of the word 'security' in this context has overtones of 'spin', in that it implies both actual safety and feelings of safety, a false combination of opposites insofar as the effects of lighting are concerned.[22] In most cases 'security lighting' is an oxymoron, and use of the term in advertisements should now be subject to penalties under fair trading laws.

Given the invalidity of evidence for a beneficial effect and the clear evidence to the contrary, advocating lighting for crime prevention is like advocating use of a flammable liquid to try to put out a fire. Fundamental changes in lighting practice are now required by the facts- use only the minimum practicable amount of outdoor artificial lighting and thereby keep the crime rate lower than with present lighting practice.

4.5.2 Commercial lighting excesses

As mentioned above, some species are repelled by light (negative phototaxis) and others are attracted (positive phototaxis, eg moths to streetlights at night). Humans appear to be attracted by light and would be in the positive class if it is legitimate to use the term to describe human behaviour. The term 'moth effect' has been used to describe a tendency for drivers and pilots to steer towards bright lights at night, but ascribing this to phototaxis or similar phenomena appears to be simplistic (Green 2004).

Shopping precinct managers and retailers also use the term 'moth effect' to describe the effect of bright lighting in attracting potential customers. Regardless of whether this is phototaxis or not, the effect is strong enough to encourage stepwise increases in commercial lighting over time as a way of trying to cope with competition. This 'ramping' of illumination at fast food outlets, convenience stores, petrol filling stations,

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[21] .News received from the Campaign for Dark Skies Newsletters Nos 33 (2008) and 34 (2009) is that the Essex, UK trials of a midnight streetlight curfew have resulted in an overall reduction of crime, with substantial reductions in some locations. The scheme has now been taken up by twenty local authorities across the UK.

[22] This condemnation does not extend to the use of lights switched on temporarily by intrusion detectors to provide a visible alert.

car dealer yards and retail precincts has been responsible for much overlighting in the absence of adequate regulation in the US (IDA IS145 1998) and elsewhere. Illumination of billboards is another example. Self regulation by industry groups has failed dismally in these cases, which is one of several reasons why legislative control of outdoor light flux is essential.

4.5.3 Other reasons for overlighting

Self-aggrandisement of property owners, managers and occupants including governments, corporations and sporting clubs, along with architects, structural designers, artists etc appears to manifest itself in some cases by an urge to floodlight property and places such as buildings, bridges, towers and other structures, sports facilities, monuments, gardens, trees and even natural features such as cliff faces. Sometimes an element of competition becomes evident when the lighting is ramped up. These practices need to be recognised for the counterproductive use of resources they are and made illegal.

In Melbourne some years ago, proposals to illuminate the city's main river and banks were promoted by urban designers as a 'river of light' concept with 'play of light on water' effects. Certainly the increased illumination could be expected to increase usage of the areas at night, in line with the desire to create a 'vibrant' night life. The lighting increases have taken place regardless of environmental objections raised at the time, and so many pole-top lights have been installed in some areas that they have been described in news media as 'light farms'. Comparable schemes for lighting up popular near-city beaches have also taken place. These are also examples of overlighting. Publicity for installations like these often includes claims that they are 'environmentally friendly' when this is patently untrue: every existing, additional or brighter light carries an environmental cost, and they are all more or less environmentally malign. 'Low environmental impact' lighting is about the best description that might be justified.

4.5.4 Losses of indigenous cultural heritage

Archaeological and anthropological studies have established that many regional civilisations around the world developed their own creation myths as a basis for religious guidance and control of social behaviour and laws. Generally these myths have a close and extensive connection with the features of the day and night sky (Aveni 2008). The sun is always of great importance, of course, but it is well outnumbered by the stars and constellations represented in the pantheons and stories. Some names and attributes of ancient origin are still a prominent part of modern culture in developed nations, eg the zodiac. In countries where native and traditional culture of celestial origin still exists, its everyday practical continuation and full meaning is likely to be dependent on the extent to which the celestially derived entities can be readily related to the present appearance of the night sky.

Missionaries, racists, invaders and empire builders have a long and extensive history of acting by commission or omission to modify, suppress or destroy aspects of their target population's culture including language, religion, customs, art and records. Relatively recently, the wisdom of doing so has been questioned but the losses have not yet stopped.

Indigenous cultural heritage has increasingly been recognised as worth preservation, not just as textbook descriptions, museum pieces, images, language and music recordings and the like, but as living practices.

The case of Australian aborigines (including Torres Strait islanders) is pertinent. Their 'Dreaming', the creation myths that govern their tribal and nomadic lives and survival in harsh environments, are often delightful and extraordinary. The stories are intimately connected with features of the night sky, including the dark nebulae. However, artificial lighting at aboriginal settlements generally appears to have been supplied with little or no consideration for minimisation of upward waste, glare and loss of dark adaptation, and the appearance of celestial features from the vicinity is accordingly diminished. This hampers the story telling and inevitably results in the loss of details and episodes. These are losses of key items of cultural heritage. The losses mount when individuals move to towns and cities although these individuals generally seem unaware that such losses have taken place. Already the names of the stars and constellations of almost all of the Australian native language groups have been lost forever. What remains of the names and stories is precious, not only to the natives themselves but to humanity in general. Therefore to allow unnecessary light pollution to continue anywhere in Australia, let alone grow, increases the threat of virtually total loss of the living cultural heritage in question. Doubtless much the same applies to indigenous populations in other countries.

Others have already drawn attention to the fact that the pristine night sky "is the one part of our environment that we have shared with all cultures in all periods of human history, and is a key part of mankind's cultural inheritance" (eg Bailey 2006). Certainly within countries such as Australia, the view of the night sky has long been one of the few cultural aspects common to all indigenous regions, language groups and tribes.

Recognition of this issue has added in some measure to global calls for reductions in light pollution, such as the strongly worded declaration by UNESCO (2007). But it would be hard to find politicians anywhere who had even heard of that declaration and others like it, let alone take action for compliance. Fixing light pollution is something positive that governments can do for their native peoples as well as for everyone else and save money as a result.

4.6 Illuminated Advertising Signs

The amount of light pollution produced by conventional illuminated advertising signs is a much greater part of the total available light output of the lamps used than is the case for present road and path lighting. Despite this, planning authorities generally appear to be largely unaware or unconcerned about the amount of light pollution generated by advertising signs and the adverse consequences of that light. It is helpful to be aware of the kinds of controls that already apply in many jurisdictions to other aspects of illuminated advertising signs and the reasons for these controls, so that trends to more, bigger and brighter signs might best be dealt with in the context of minimising the overall adverse environmental, health and social costs of total outdoor light flux. It is a common mistake to try to deal with such issues in isolation.

4.6.1 The rise of advertising signs

Outdoor advertising signs are undeniably an important part of current commercial and retail practice. After they were first introduced some long ago it must have become evident that the attention-getting power of such signs depended on their perceived angular subtense and contrast with the visual surround as well as on the subject matter and its presentation. Diminishing returns on signage expenditure helped to set limits on the physical size and number of signs on premises. Off-premises signs allowed increased exposure to potential customers, but similar constraints applied.

The situation changed late in the 19th century when artificial illumination of signs at night became more practicable. If the mean luminance of a sign is L_S and that of the background is L_B, the contrast is $(L_S - L_B) / L_B$. For a painted white sign of reflectance say 85% against a painted black background with reflectance about 5%, both similarly illuminated by daylight, the contrast can be as high as about (85 - 5) / 5, ie 16. For an illuminated sign at night seen against an unlit background or the night sky, contrasts in the thousands or more are readily achievable. This might be fine for the advertiser but a nuisance or worse for viewers trying to see something else in the visual scene. The advertising industry has become adept at trying to control what consumers look at and see, and light is one of their most important tools.

In an era when streets were dimly lit, if lit at all, presumably there were few objections to the light spill from illuminated signs. In due course, the sizes and brightness of advertising signs tended to increase. Their numbers also grew, which must have increased the numbers of objectors concerned about aesthetics by day and sleep disturbance by night. The potential of advertising signs as a road safety hazard has also become an increasingly important issue. For understanding the problems of advertising signs in the environmental, health and social contexts of excessive artificial light at night, it is convenient here to draw largely on extensive records of US experience. Where documents cited use the term ‘billboard’, it is treated here as synonymous with ‘advertising sign’.

4.6.2 US experience with billboards

In the USA, the federal Highway Beautification Act (HBA) of 1965 effectively banned billboards along federally funded roads. The Act stipulated that states that do not adhere to the Act are subject to penalties equal to ten percent of their federal highway funds. Unfortunately, sections of the outdoor advertising industry have vigorously exploited legal loopholes that actually force the retention of offending billboards (Scenic America 2007a).

Organisations such as Scenic America have been formed by objectors to seek legislation that re-establishes the original intent of the HBA, which was primarily concerned with the protection of aesthetic values in scenery. Opposing them is the Outdoor Advertising Association of America, an industry peak body that lobbies against billboard restrictions in general. At present, the following US states have legislation banning the construction of new billboards (Scenic America 2007b):

- Vermont - Removed all billboards in 1970s
- Hawaii - Removed all billboards in 1920s
- Maine - Removed all billboards in 1970s and early 1980s
- Alaska - State referendum passed in 1998 prohibits billboards

The total of US cities and communities prohibiting the construction of new billboards is estimated to be at least 1500 (Scenic America 2007b).

Industry lobbying was successful in 1978 in having the US Congress make concessions to allow on-premises business signs in view of federally funded highways. Since then, electronic displays have been introduced in which individual picture elements (pixels) can be varied in colour and intensity to change the displayed sign or image. Digital electronic techniques allow this to be done so quickly that video sequences can be displayed. (These 'giant video screens' are now increasingly in use for action replays and advertising at major sporting events.) Although the HBA clearly prohibits moving and flashing displays on billboards, the 1978 concession has been exploited by the industry in setting up networks of on-premises digital (or electronic) billboards (DBBs or EBBs) within sight of federally funded highways. This appears to be part of a strategy to have off-premises digital signs also exempted from the provisions of the HBA (Scenic America 2007c).

An Internet search for existing restrictions on outdoor advertising signs indicated that a large number of states, regions, towns etc in the USA and elsewhere have their own ordinances including illumination bans and limits. There seems to be little commonality in the wording, usually no reasons are given to support the restrictions imposed, and there appears to be little if any concern about upward waste light or energy consumption. One of many controls on signs in New Zealand, for example, is summarised here for interest (Transit New Zealand 2007): it is a national measure to limit adverse effects of advertising signs on road safety and the environment in the vicinity of state highways. A broad definition of advertising sign or device is provided. Illumination and reflectorisation of signs is not permitted: this would appear to rule out electronic displays that emit light, but would allow electronic displays such as liquid crystal displays illuminated by ambient light. Sign surfaces must be parallel to the road boundary, which limits the ability of drivers to see them other than with substantial foreshortening. A reason given for this restriction is that it is intended to prevent back reflections from headlights, however.

4.6.3 Driver distraction by conventional and electronic billboards

This matter has been under investigation and discussion in the road safety literature over many years. Only a few recent studies are presented here to indicate current knowledge and opinions.

The hazard of distraction of drivers is a key issue arising from a review of studies of dynamic advertising signs (SRF 2007), ie signs with flashing or moving displays. The review mentions a 1999 survey by the (US) National Alliance of Highway Beautification Agencies: as many as 36 US states had banned some kinds of signs or imposed restrictions on them. Dynamic signs were often mentioned. The VicRoads *Ten Point Road Safety Checklist* that arose from the Parliament of Victoria 2006 Report of the Road Safety Committee on the Inquiry into Driver Distraction is reproduced in full in SRF (2007), along with additional operational requirements for electronic advertising message signs, eg such signs must not display animated or moving images, or flashing or intermittent lights, and must not be visible from a freeway.

SRF (2007) also includes the views of four subject matter experts: Harder considered EBBs a driver distraction threat; Davis stated that a causal relationship between EBBs and accidents had not yet been established but should be possible with careful attention to the scientific issues; Robinson said that multi-image signs should not change more often than every 6.2 s on fast roads [VicRoads specified 30 s] and the requirements for EBBs might need to be different; while Wachtel believed that it is neither feasible nor necessary to demonstrate a causal relationship between EBBs and road safety (or its reduction). Instead, he thought that scientific understanding was already adequate for development of operational guidelines and ordinances.

The US Federal Highway Administration remains concerned about the driver distraction hazard posed by billboards. To try to counter this, the Outdoor Advertising Association of America recently released two reports in which it was claimed that conventional and electronic outdoor advertising signs did not have an adverse effect on road safety. An independent peer review (Wachtel 2007) of these reports indicated that they were seriously biased and otherwise flawed scientifically. Wachtel concluded that rigorous scientific studies have yet to be done on this matter, so that any liberalisation of existing restrictions on billboards visible to drivers would be ill-advised at present.

The first purpose of an advertising sign would appear to be to attract attention. In so doing, it distracts the viewer from attending to other visual tasks. For drivers, such distractions become more dangerous as their durations increase. In a 9-month observational study of 100 drivers (Klauer, Dingus, Neale et al. 2006), looking at an external object was found to increase the rate of accidents and near-accidents by a factor of 3.70, with confidence limits of 1.13 to 12.18. With the method of analysis used in this study, it was not possible to identify occasions or the proportion of occasions on which the object was an advertising sign.

Although the two papers criticised by Wachtel (2007) were too poor scientifically to allow much to be drawn in the way of reliable conclusions, some of the observational data collected indicated trends for glances at electronic signs to be substantially longer than for glances at conventional signs. Electronic signs are therefore likely to be more hazardous.

The attributes of an advertising sign that increase the total time it is observed by drivers are probably also the attributes that relate to its commercial value. Leaving aside aspects of content (eg sexual, emotional), physical, psychophysical and dynamic attributes are pertinent. These include size, shape, orientation and distance, spatial and temporal variations of luminance and colour within the display and the contrasts between the display and its background. It may be that a small sign with minimal content, eg distance to the next food and fuel centre, or the moderately sized name or logo of a company on a company building, is an acceptably small and brief distraction. But until research is done to quantify effects of other attributes and the derivation of acceptably safe values, it would appear prudent for all other commercial signs visible to drivers subtending more than about 0.5º within say 60º of the road heading to have the sign visibility limited to comparably low values. High priority should therefore be given to removal of all or most of the artificial illumination of signs, and removal of any dynamic attributes such as flashing or moving elements of the display. This would preclude the use of video screens in any position where drivers could see them, even if the intended audiences are mostly pedestrians. Exceptions should be permitted only to the extent justified by rigorous peer-reviewed scientific work. Safety has to take precedence where there is any reasonable doubt.

4.6.4 Other road safety issues of illuminated signs

Glare from a bright light source at night can cause discomfort and reduce visibility of other objects in the field of view. It is generally recognised that glare, particularly from oncoming headlights, has contributed to road accidents at night. It is technically complex to define glare quantitatively for limiting the allowable adverse effect on road users, but examples do exist. At the other end of the scale is the sort of qualitative limitation used in the Victorian road regulations, which prohibits lights so bright that a driver is ‘prevented from having a clear view ahead’. This regulation has apparently not been enforced to any extent in Victoria for decades, and there are many other places in other states and countries with similar problems. Car dealership floodlighting and ‘security’ lighting, often misaimed and overbright, are common sources of avoidable glare. In the context of this section, so are the floodlights used to illuminate advertising signs, as well as the illuminated, transilluminated or self-luminous surfaces of the signs.

Of course, a level of glare that might be acceptable for a driver with excellent vision may be severely disabling temporarily for a driver with marginally acceptable vision. The presence on the windshield surfaces of one or more of aftermarket tinting film, volatiles from the car upholstery, condensation, raindrops and dirt, in combination with marginal vision forms a set of worst cases that should be used to argue for no high-glare fixed lighting of any kind to be visible within say 75º of a driver’s direct ahead line of sight. Compliance with this condition would require all road and public lighting luminaires to be full cutoff types and advertising sign luminances to be orders of magnitude dimmer than is generally the case at present, as in the following table from Clark (2003), based then on a draft of the Czech Clean Air Act.

TABLE 1. Maximum Luminance and Intensity for Illuminated Billboards and Signs

Maximum Area, m^2	Mean Luminance, cd/ m^2	Total Intensity, cd
1	100	100
3	48	145
10	21	215
30	10	310
100	4	460
300	2	660
1000	1	1000

Governments with a determination to reduce the contribution of glare to road accident causation should consider adopting an approach like that in the table, which allows a slow increase of the total intensity o signs as they are made larger.

From the discussion in the preceding section about signs as a driver distraction hazard, it would need to be appreciated that the values in the table would apply only to signs where the sign content is minimal in attention-getting. Lower luminances would need to be applied where the sign content is inherently distracting, as for an image with sexual content, but administration and compliance could be costly. Also, spill from signs into bedroom windows may well exceed the limit of 0.1 lux from all sources that is derived in Section 5.3 below, even for signs compliant with Table 1. For example, a sign with a total intensity of 1000 cd illuminating a window at about normal incidence would have to be at least 100 m distant in dark surroundings, and even further away in the presence of other stray light at night.

At least in the shorter term, the need to deal decisively with the anthropogenic component of climate change could well see the end of most illuminated signs anyway.

4.6.5 Obtrusive effects of advertising sign illumination

A Google search produced 26 900 hits for 'billboards light pollution'. Many of the web pages listed were concerned with the unpleasantness and even misery caused to residents when large brightly lit billboards are set up nearby, and with possible ways of trying to deal with the problem. Affected residents often find that they are at a financial and hence legal disadvantage in trying to stop a proposed sign and virtually powerless in practice to obtain amelioration of the nuisance once the sign is in operation. Properties receiving rent for signs typically find their property value increased but residential property values in the vicinity tend to fall because of loss of amenity.

Unresolved complaints about obtrusive lighting was one of the reasons why Standards Australia decided in the 1990s to issue a standard to limit the obtrusive effects of outdoor lighting other than road and public lighting. The outdoor advertising industry in Australia was represented on the drafting committee and sought provisions that it would not find onerous. Eventually the industry opted for self-regulation while insisting successfully that the standard would specifically exempt illuminated advertising signs from any need for compliance. Sports lighting interests likewise managed to have TV broadcast standard lighting exempted. The resultant Australian Standard AS 4282-1997, *Control of the obtrusive effects of outdoor lighting*, thus does not apply to many of the most obtrusive lighting sources in modern cities. Self-regulation in the case of advertising signs effectively means that the sole or primary constraint on the brightness of sign lighting is economic.

Planning authorities in Australia seldom seem to put the wellbeing of residents uppermost when they consider applications for illuminated signs. Generally this appears to be an outcome of state governments failing to see the issue of light pollution as warranting the degree of direction and coordination that is actually necessary to deal with obtrusive lighting in general. It is left to local government to deal with. Difficulties arise with light pollution that crosses municipal boundaries, and with variations in interpretation of AS 4282 from one council to the next. Consequently, councils avoid enforcing this non-mandatory standard regardless of federal and state government policy for compliance with all applicable Australian Standards. As a result, illuminated signs, along with other commercial lighting, floodlit buildings and structures and outdoor sports lighting, continue to set the pace in Australia for lack of concern about degradation of the night environment and indifference to the rights of local residents. Judging from the content of Internet forums on astronomy, outdoor lighting and ecology, obtrusive lighting also appears to be an ongoing and widespread problem in many other countries.

In the many years since its introduction, initially as an interim standard from 1995 to 1997, AS 4282 has apparently not helped much in attempts to curb the upward 'ratcheting' of sign brightness and size that passes for competition in the outdoor advertising industry. It is now clearer than ever that lighting, size and placement of advertising signs need to be under stringent mandatory control to prevent the excesses that have blossomed in Australia under the promise of industry self-regulation.

Given that company logos and the tops and sides of company buildings are often floodlit or transilluminated or self-luminous as a form of advertising, such lighting should also come under controls similar to those for advertising signs, supposing that any such lighting will continue to be permitted at all in future. To cope with this prospect, Table 1 would need to be extended by at least four rows, with continuity in the three geometrical series.

Illuminated advertising signs and other lit displays in more-or-less vertical planes have a propensity to put half of their available light output more or less uselessly above the horizontal. This effect is not easy to eliminate in any of the three most common types: floodlit opaque billboards, 'neon' or 'electric' signs and internally lit translucent signs. Typically about half of the light reflected or transmitted/emitted by conventional signs travels in directions above the horizontal, lighting up the sky. The peak output of light is generally normal to the plane of the sign and therefore in or close to the horizontal direction, almost the worst possible in terms of the resulting light pollution and artificial skyglow.

Much more effort needs to go into making the light output directional, aimed at where the sign is allowed to be seen from, while still complying with luminance restrictions such as those suggested above.

Another major problem with advertising floodlighting relates to whether the floodlighting is located above and shining down or below and shining up, or both. The lighting and advertising industries prefer low placement because of easier access for lamp replacement, lack of shadows on the sign surface in sunlight, and easier confinement of downwards light spill. But that arrangement puts the maximum amount of light above the horizontal, and has therefore been vigorously opposed by the dark sky movement.

4.6.6 Limiting or banning illumination of advertising signs

Lighting roads and paths with full cutoff fittings has the virtue that associated GGEs and the amount of light pollution are close to the lowest values possible for a given lamp type and the amount of light utilised. Conventional illuminated signs are highly inefficient by comparison in terms of the amounts of wasted light and the GGEs associated with that waste.

The effect of banning illumination of advertising signs can be quantified by extending the analysis of Section 3.3 above. The quantity A becomes zero, so the total ambient outdoor light flux T′ is given by

$$T' = L + W + V, \text{ with } W = 0.3\ L \text{ and } V = 0.1\ L \text{ as before.}$$

For the city centre,

$$T' = (1 + 0.3 + 0.1)\ L, \text{ ie } 1.4\ L \text{ or } 1.4\ T / 1.7.$$

The total direct upward flux T'_{DU} from these sources is

$$T'_{DU} = 0.15\ L + 0.5\ W + 0.15\ V, \text{ ie } 0.315\ L.$$

The total downwards flux reflected by the terrain is

$$T'_{RU} = (0.85\ L + 0.5\ W + 0.85\ V)\ R_{T,}\ \text{ie } 0.109\ L.$$

The total upward flux is

$$T'_{U} = T'_{DU} + T'_{RU},\ \text{ie } 0.424\ L,\ \text{or } 0.72\ T_{U}.$$

So, removing all illumination from advertising signs would reduce city light pollution by 28%, and reduce the outdoor ambient light flux by 1- 1.4 / 1.7, ie 18%.

The results here and in Section 3.3 above depend on the numerous assumptions made, but they are relatively insensitive to variations in the initial conditions. They should be regarded as indicative of the results that could be expected if the various processes described were modeled numerically using input data from actual measurements. What this analysis does indicate reliably, as has long been known intuitively, that advertising sign illumination causes a disproportionate amount of light pollution. Putting it another way, cessation or reduction of advertising sign illumination would lead to a considerably larger aggregate reduction in light pollution than the resulting aggregate reduction in ambient outdoor light flux.

The results of the analyses would be no less valid if they described the changes that would be introduced by the operation of a lighting curfew. Progressively earlier curfews could be a way of phasing out illumination of existing signs during adjustment to the reducing income gained from the signs. Exemptions or concessions might be claimed for some signs, eg on-premises signs while the company was genuinely open for business on that specific site at night, but fully offsetting additional reductions in other sign illumination or commercial outdoor lighting would need to be in place and subject to audit.

The importance of these results in relation to GGEs is that GGEs from the generation of electricity used to produce outdoor light flux typically represent about a tenth of all GGEs resulting from all electricity usage. The actual fraction is often poorly documented if known at all for individual countries, but there are reliable comparisons between many countries in terms of waste upward light flux measured from space. On a per capita basis, these values are generally much higher in developed countries than in developing or undeveloped countries (Clark 2003). Changing the amount of light being used in a particular country results in a more-or-less proportionate change in the GGEs associated with that lighting.

Reduction of the amount of light pollution from outdoor advertising and other sources will take on a new and urgent status in view of recent discoveries into the role of unnecessary light exposure at night in certain serious illnesses. These matters are raised in Chapter 4 below.

4.7 BUILDING HEIGHT LIMITS

Planning schemes often impose limits on the height of buildings that can be constructed in particular areas. In part this arises from a desire to limit overshadowing and overlooking of nearby properties. There may also be reasons associated with height limitations of firefighting equipment, earthquake resistance, stability of foundations and intrusion into aircraft flight paths near airports. Regardless, developers may be able to increase their profits substantially if they can gain exemptions or higher limits.

Accordingly, challenges to height limits in planning laws and regulations appear not only to be common but are often placed in the hands of accomplished lawyers who may also benefit from any concessions that can be won.

In the present context, the question arises as to the effects of increased building heights on light pollution. The following analysis was prompted by a case in Melbourne where a change in a planning scheme led to an inadvertent omission of height limits in an area close to Victoria's major war memorial and the heritage-listed Melbourne Observatory. Before the omission could be rectified, developers lodged a proposal for a new building with a height way above all other buildings in the vicinity. Public objections to the proposal were primarily based on issues of overshadowing, overlooking and visual obtrusiveness. However, the proposed building is of such a large size that it would have the potential to exacerbate the existing light pollution problem significantly in Melbourne generally and to increment the problem substantially in the local area.

In cities in general, variations in heights of building arise over time with changes in land value, building costs, advances in building technology, returns on investment and so on. In general, buildings tend be packed together in a way that obstructs views of much or all of the horizon from most of the windows. To put it simply, if imprecisely, half of all the windows will be below the average height of buildings in the area, and unobstructed vistas will tend to be available only from the upper levels of high buildings, buildings on rising ground and buildings near the urban perimeter. This bears on the matter of light pollution emitted by building windows. Windows are generally vertical planes, which maximizes the amount of light they emit toward the horizon in the azimuth direction they face. If the view is obstructed to some extent, so too is the long-distance near-horizontal passage of escaped internal light that can make a major contribution to artificial skyglow in the far field.

The entrapment of stray light in the large scale terrain texture of cities has been used by lighting proponents recently to try to justify the use of luminaires that are not fully shielded. In the following section the existence of such light-trapping structures is used instead as a reason to enforce uniform maximum building heights.

4.7.1 Modeling light pollution from buildings

Consider a simple model city with a square boundary having sides of length L in a flat region. Individual buildings are all of height H, and equal breadth and width W. Each building has four vertical plane sides of area HW. Each building is supposed to radiate the same amount of internal light through each window. The area of windows is supposed to be in fixed ratio to the area of a building side. So the total light flux radiated in a given solid angle along the horizon from windows in a building wall will be proportional to HW.

To extend the range of validity of the model in the direction of smaller total numbers of buildings without the need to include specific values for inter-building spacing, the buildings are supposed to be distributed in a stepped grid that maximises the opacity of the city to light travelling horizontally through it. If N buildings with constant spacing can fit along one of the city sides, the total number of buildings in the city is N^2. Two forms of model city are considered: (i) Dense City, where N is at least 3, the area is L_D^2 and NW/L_D is just under unity so that there are no unobstructed lines of sight from one side of the city to the other, and (ii), Sparse City, which occupies a much larger area L_S^2 and has $NW<<L_S$.

In Dense City, the emitted light able to reach the horizon facing each side of the city is proportional to L_DH, so the total for the whole city will be proportional with the same constant to $4L_DH$, ie 4NWH. In Sparse City, the buildings are so far apart that very little of the horizontal light from each building is obstructed by any other building. The total horizontal light emitted by buildings in the limiting case will be proportional to $4N^2WH$.

For the same total number of buildings (N^2), Dense City buildings emit less maximally polluting light into the far field than that emitted by the buildings of Sparse City.[23] The factor is $4NWH/4N^2WH$, ie 1/N. The lesson from this is that an isolated tall building is disproportionally more light-polluting in the far field than a similar building surrounded by others close by. As an example, if $N^2 = 100$, the isolated tall building is 10 times worse. Legislators and urban planners need to understand this and block applications to build isolated buildings that are taller than their surrounds unless, as a necessary but not sufficient condition, stringent permanent measures will be in place to block light emissions from the building at night.

Now the issue arises as to the effect of putting a taller building in a city that has lots of lower buildings. For simplicity, imagine that Dense City has one of its buildings doubled in height. The total light emitted horizontally from the existing buildings plus the upwards extension will be proportional to 4NWH + 4WH, ie an increase of 4WH. If the extra built volume had been achieved instead by putting in one more building like the others already on the ground, the total emission would increase because of the increased length needed in the Dense City side. That total emission would become $4WH(N^2 + 1)^{0.5}$, so the increase would be $4WH[(N^2 + 1)^{0.5} - N]$. Doubling the height of one building instead of adding another at ground level would therefore result in an increment in the total emission of $4WH[1 - (N^2 + 1)^{0.5} + N]$. For $N^2 = 100$, say, this factor amounts to $4WH (11 - \sqrt{101})$, nearly as much as the total emission from an isolated building. To put it another way, the increment from doubling the height of one building can be as much as twenty times as large as that from adding another standard height building.

While the above analysis is simplistic and approximate and the results are for worst cases, there is apparently nothing in the literature or in practical experience to suggest that the real-life situation is markedly better. It is clearly apparent in Figure 2 that in the absence of cloud, the light sources that are most effective at providing unwanted illumination in the far field are the sides of tall buildings and illuminated tops of tall buildings and other tall structures. If there is any doubt in important cases, accurate numerical modeling could be applied to proposed developments. Of course, there is a risk for developers that the more accurate results could be even more damning.

To summarise, given the various adverse effects described above as consequences of too much artificial light at night, allowing developers to extend existing buildings upwards,

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[23] The spaces in which light trapping by city buildings occurs have been described as 'cavities' in attempts by lighting engineers to discount the need for light spill control, but the accompanying argument against light spill control is seriously flawed (Cinzano 2009).

to replace existing buildings by significantly taller ones or to add taller buildings in areas where the buildings are of more or less uniform height is therefore likely to impose loss of wellbeing or increase the risk of serious illness or both on some hapless individuals, even if they live some distance away. Increased downwards pressure on biodiversity over extensive areas (Section 4.4 above) is also a most undesirable outcome. The risks may be reduced by limiting the taller buildings to emit no more than a few percent of the light that would currently be associated with a typical extended or new building of comparable dimensions. This situation also applies to relatively tall buildings near city boundaries or in surrounding suburbs, and to buildings that may be no higher above ground than others in the area, but are nevertheless situated well up on sloping terrain or on top of a hill.

Nothing in this section should be interpreted as suggesting that waste light trapping in town and city centres makes these places safe. The ambient outdoor light levels in these places are generally much brighter than they are elsewhere. Not only is this a health hazard but a crime hazard also: town and city centres are typically areas with the highest crime rates (Clark 2003).

4.7.2 Extension of the analysis to advertising signs and screen displays

Some aspects of the preceding analysis are applicable also to advertising signs and large screen displays. Like windows and building sides, such signs and screens are generally in or close to a vertical plane and they also emit light in most if not all directions in a hemisphere that has its flat surface coplanar with the light-emitting surface. Some of the light is emitted in or near the horizontal plane where it contributes maximally to artificial skyglow. Signs and screens that are small, and mounted below the average height of buildings in towns and cities, contribute mainly to the local ambient light at night. When the signs and screens are placed higher, they are generally made larger. Their total light emission is proportional to the product of their luminance and area, and a larger fraction of the emitted light is typically able to reach the far field before being absorbed by terrain or scattered into space. In terms of minimising the potential for environmental damage and light-induced illness, signs and screens that are large, high and brightly lit are the most troublesome and should be the first to be subject to severe limitations if not outright bans. This clearly includes building logos, names and decorative lighting (which can also be considered as advertising).

4.8 JUSTIFYING OUTDOOR LIGHTING

4.8.1 Taking account of adverse effects

Outdoor lighting has proliferated greatly since the widespread introduction of electric light in the late 19th century. It has led to many improvements in the quality of life. For example, major sporting events with television coverage take place routinely under sports lighting that is about four log units brighter than strong moonlight and seven log units brighter than natural dark conditions in the open. The lighting industry has done very well on the basis of the many social benefits that its product has brought, particularly the more productive, more enjoyable and less fearful use of the natural dark hours. It promotes its product on the basis of these benefits, and on the myth of lighting for crime reduction. It grows or at least maintains its prosperity by the installation of ever more and brighter lights.

The world has changed, however. Sustainable limits to consumption of finite resources and production of waste are being approached or exceeded as the world population continues to grow. While it is not the major global consumer of energy or materials, outdoor ambient artificial light, which includes road lighting, ‘security lighting’, sports lighting, decorative lighting, illuminated signs, escaping internal light from buildings and vehicle lighting, is a substantial minor component and needs to be subject to more rigorous scrutiny of its overall value, taking full account of its many disbenefits as well as its benefits (see Chapter 2 above).

The disbenefits can usefully be related to three categories: outdoor lighting as a whole, light pollution, and avoidable light pollution:

A. Disbenefits of outdoor lighting as a whole:

- Large amounts of coal, gas, oil and nuclear fuels are consumed in generating the electrical energy used to power most outdoor lighting. The processes variously result in air and water pollution, GGEs, radioactive waste and seismic activity.
- Public lighting is a substantial cost ultimately borne by taxpayers.
- Exposure to artificial light at night can lead to serious illness as an outcome of endocrine disruption, sleep disturbance and sleep loss.
- Sleep problems caused by outdoor lighting can also lead to increases in the rate of traffic accidents and industrial accidents.
- Dark adaptation is reduced by artificial lighting, increasing the risk of road accidents, pedestrian accidents and criminal ambush when moving into adjacent areas that are unlit or less brightly lit. (The solution is not to light up the whole world!)
- There is statistically reliable evidence that the crime rate increases with the mean flux density of artificial light in cities.

B. Disbenefits from light pollution

- Light pollution causes artificial skyglow, which hinders professional and amateur astronomy, handicaps education about Earth’s place in the universe and deprives the public of the beauty of night sky.
- Glare is a form of light pollution. It can be unpleasant and it can degrade visibility, thereby increasing the risk of traffic accidents and surprise assaults.
- Spill light extends the areas in which criminal acts are facilitated more than deterred by the presence of artificial light at night. On cloudy nights, an increased amount of light pollution is reflected back to the terrain, further facilitating crime.
- Light pollution includes ecological light pollution, which is artificial light that has any adverse effect on biodiversity. Effects include geographic disorientation of bird migration, restriction of the daily vertical migration of plankton, interference with breeding cycles, incineration of moths etc.

C. Disbenefits from avoidable light pollution

The presence of avoidable components of light pollution unnecessarily leads to

- Avoidable waste of natural resources
- Avoidable additional tax burden

- Environmental degradation, including avoidable emission of greenhouse gases
- Avoidable traffic, pedestrian and industrial accidents
- Avoidable facilitation of crime
- Avoidable threats to biodiversity
- Avoidable hindrances to astronomical research, education, recreation and aesthetic pleasure (eg UNESCO 2007).

Large reductions in outdoor lighting and especially in light pollution now appear to be necessary for health, safety, environmental, ecological and social reasons. Particularly because of the compelling need to reduce GGEs, no new lighting should be installed anywhere without independently audited overcompensating lighting energy reductions at the site or elsewhere. Furthermore, it is the continuation of existing lighting that has to be justified, not its reduction in coverage and intensity for the reasons given in this document.

Proposals for reduction or removal of existing lighting may generate vehement opposition. One reason is that some people appear to be afraid of the dark, but it is dimness that is needed, not darkness. Another possible reason could be that some individuals ascribe sacred status to light because of the religious text 'God is light', the common association of light with goodness and darkness with evil, and the use of candles, lamps and light in religious and quasi-religious ceremonies. Some theological texts go further and state 'light is God'. Some churches have a black backdrop to the altar with 'LIGHT' on it in white. It may be difficult to convince people with such beliefs that too much light can be bad.

Clark (2003, Table 3 and Section 5.5.4) used satellite measures of upward waste light from 153 cities in 52 different countries to show that there are wide ranges over cities in the amount of outdoor light flux per person or per unit area. For example, Minneapolis (USA) was the 8th brightest in mean illuminance and had over twenty times as much light per person and per unit area than did slightly smaller Christchurch (NZ), which was 150th on the list. A citizen survey in Christchurch indicated that street lighting did not appear to be of major concern to respondents: 87% of respondents said that they had not been prevented from going anywhere in the city at night through lack of street lighting, although 69% did not feel safe by themselves in the central city at night (Macintyre and Price 1998).

4.8.2 A larger niche for solid state lighting?

As with GGEs in general, equitable sharing of resources on a global scale would put pressure on cities in developed countries to reduce their outdoor lighting on a per capita basis to a globally sustainable level. One of the ways of bringing about such a change would be to reduce the individual wattage rather than the number of streetlights. This might encourage the greater use of solid-state light sources such as light emitting diodes (LEDs), which are already ubiquitous as indicator lamps and are increasingly employed for other limited lighting tasks such as vehicle interiors and bicycle headlights. In the sizes that would be required to replace existing streetlights, their heat output becomes problematic.

Practical trials of LEDs for street and path lighting have been undertaken for many years. In general, the light output from existing LED assemblies is at the low end of the performance required by national lighting standards, which is not to say that such assemblies are of little use. Good electrical efficacy has been attained in one case by using LEDs that produce green light. The output is claimed to be effective for visibility in mesopic conditions (eg, illumination like moonlight). The luminaires are claimed to result in reduced light pollution (Innolumis 2009). The makers also claim that colour recognition "remains accurate" (a half truth at best, of course) while aiding security (which would be more accurately put as aiding the feeling of security).

The advent of white LEDs had to await the invention of blue LEDs and their combination with red and green LEDS to give a white output. A second way of getting a white output was also invented, in which blue LEDs irradiated a phosphor that emitted yellow light. Before any decision to go ahead with trials of LED lighting, it is necessary to ensure that their effect on melatonin levels will be acceptably small. LEDs could readily be assessed by the methods given in the Appendix. In the meantime, it has to be said that existing white LEDs of both types appear to emit unacceptably high proportions of toxic short-wavelength light. Green LEDs, as mentioned in the preceding paragraph, and yellow-green combinations would appear to be more acceptable in this regard.

5. MANDATORY LIGHTING CONTROLS

5.1 EXISTING NATIONAL LIGHT POLLUTION LAWS

Many regions, provinces and states in various countries have mandatory controls on obtrusive light emission and energy consumption of outdoor light sources. Spain has a national law on light pollution but it only applies in the Canary Islands. The honour of being the first country with a *national* law dealing with light pollution across the whole nation goes to Czechia, which included provision for municipal lighting controls in its Protection of the Atmosphere Act of 25 March 2002. When introduction of the Czech law was being debated, opponents with vested interests predicted increases in lawlessness and accidents. Consequently the need for compliance with the light pollution controls was removed from the law despite the absence of valid evidence to justify these concerns. The current version of the Act merely defines light pollution of the air and empowers municipalities to ban skybeams. Many municipalities have done so.

The original form of the Czech law was based on law number 17/2000 of the Lombardy region in Italy. In Lombardy itself, introduction of the regional law had substantial popular support and produced a somewhat surprising result: it revitalised the Italian lighting market by introducing an emphasis on improved technical performance (Bonata 2002). By 2007, 17 of the 21 regions in Italy had laws against light pollution. Of all the regional light pollution laws, regulations and ordinances dealing with light pollution in Italy and elsewhere, the Lombardy one appears to provide one of the best foundations for other governments to start with (Bonata 2002). However, it was formulated before the exponential growth of outdoor lighting was identified as the key problem, so exponential increases are still possible. Self-regulation does not work as a solution, so in future, laws should also include mandatory reducing caps on total light flux both in regions and nationally.

The world's second national law that included light pollution came into force in the UK in April 2006. Following a House of Commons inquiry into light pollution, the UK Environment Protection Act 1990 was amended by Section 102 of the Clean Neighbourhoods and Environment Act 2005. Artificial light is included in the statutory nuisance provisions (Morgan-Taylor 2007). Allowing 'exterior light' to be 'emitted from premises so as to be prejudicial to health or a nuisance' is now a criminal offence. The restriction of the law to light from 'premises' was quite deliberate in order to exclude other important sources of light and light pollution such as streetlights and public transport terminal lighting. The stated intention was to deal with these other sources separately, and action along these lines does appear to be progressing.

In August 2007, the UK Highways Agency issued revised standards for highway lighting. The Personal Injury Accident (PIA) reductions that can be attributed to road lighting for financial justification of new or changed lighting have been reduced substantially, with the effects that fewer road links will now qualify for lighting and the illuminance minima have been reduced (Highways Agency 2007a).[24] Furthermore, in Highways Agency (2007b), the design of the lighting has to comply with the following:

> "2.1 The road lighting shall be designed in accordance with the recommendations of BS 5489-1 Code of Practice for the Design of Road Lighting – Part 1: Lighting of Roads and Public Amenity Areas, together with the additional requirements set out in this Standard.
> 2.2 All road lighting shall be designed and installed such that the installation will emit no direct light above the horizontal."

Note that there is no provision for changing the existing spacing of light poles because there is generally no essential reason to do so. Sections of the lighting industry have been claiming for many years that the introduction/retrofitting of fully shielded or full cutoff luminaires would require higher or closer poles or both, but the argument is contrived and specious, relying as it does on maintenance of arbitrary limits in uniformity of illumination. There appears to be no evidence that small reductions in uniformity accompanying the introduction of full cutoff luminaires on existing poles would have any important adverse effects, but there would certainly be beneficial reductions in glare and unwanted light spill.

Thus the UK now has national regulations against upwards waste from road lighting luminaires as well as laws against obtrusive lighting from premises, which would include most advertising signs. This piecemeal approach is better than nothing, but overall control on all forms of outdoor lighting or all sources of outdoor light flux would appear to be a better way to go.

In Germany, an official directive was issued in 2000 on the measurement and evaluation of light pollution (eg for North Rhine and Westphalia, LNRW (2000)). Illuminance

[24] Scenta (2009) reported that UK Department for Transport research about to be published no longer supported the long-standing claim that street lighting reduced accidents by 30%.

maxima were set for bedroom windows, ranging from 1 lx in country areas to 15 lx in city centres. Lower maxima were set for the second half of the night.[25]

The legislature in Slovenia passed the world's first national stand-alone light pollution law on 30 August 2007. It is largely based on the lighting law in Lombardy, Italy, but includes some usefully stricter limits. In most cases, outdoor lighting must be fully shielded and installed to ensure that no direct emission of light takes place above the horizontal. Residences are protected against light spill. Municipalities are responsible for limiting energy used for lighting, by limiting intensities, numbers of luminaires and hours of use.

In November 2007, the President of Croatia accepted a new law on the protection of nature. Article 31 deals with the definition of light pollution and reasons why limits need to be enforced. It is like the law in Czechia insofar as it could be relatively easy for the lighting lobby to have it rendered ineffective, but this has apparently not yet happened in Croatia. In the meantime, every day that passes without materialisation of the claimed ill effects is likely to weaken any attempts to reduce the effect of the law.

5.2 FORM OF LIGHTING CONTROLS REQUIRED

Most national and regional governments have been slow off the mark in dealing with light pollution, if indeed they have done anything at all. Whether this is because of ignorance, political disinclination or lobbying by the lighting and power industries is not clear in most cases. What is clear is that the reasons for, and necessary extent of, mandatory changes in lighting practice have increased greatly since Glickman, Levin and Brainard (2002) wrote:

> "Visual performance, rather than circadian function, has been the primary focus of architectural lighting systems. It is now necessary to reevaluate lighting strategies, with consideration of circadian influences, in an effort to maximize physiological homeostasis and health."

The introduction of mandatory lighting controls is probably most needed in the developed countries, especially those with high per capita GGEs, but the form of controls could be the same for all countries. Such lighting controls should:

a. allow just enough outdoor ambient artificial light at night in populated areas when required for wayfinding and safe movement of pedestrians and vehicles,
b. limit unnecessary exposure to artificial light at night and avoid or ban the use of lamps that emit substantial proportions of blue light to minimise circadian disruption and weakening of a key natural defence against breast cancer and other cancers,
c. limit the total amount of outdoor artificial light in the plane of windows of habitable rooms to safe values, regardless of location, given that even faint light inside bedrooms anywhere at night can lead to sleep loss and sleep disturbance, with subsequent increased risk of traffic and industrial accidents,
d. minimise the GGEs associated with all forms of outdoor artificial lighting, including street and public lighting, traffic signal lights, illuminated road traffic

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[25] Comparable limits and lighting zones were incorporated in CIE (2003). Although this is an international standard, it is not mandatory unless individual countries make it so by legislation or regulation.

signs, illuminated billboards and outdoor display screens, sports lighting and loss of internal artificial light from buildings,

e. ensure that the lighting energy sector meets or surpasses national and state obligations under the UN Framework Convention on Climate Change, the Kyoto Protocol and related or follow-on protocols,
f. achieve sustainability in the total national and regional energy usage for the production of ambient outdoor artificial light,
g. eliminate visual amenity loss and traffic hazards arising from glare and distraction caused by inadequately shielded lights and illuminated, transilluminated or self-luminous surfaces such as advertising signs and video display screens,
h. by applying reducing caps to the total outdoor ambient light flux and by avoiding the use of lamps with a substantial blue-light output, reduce artificial skyglow interference with astronomical research, education and recreation, maintenance of indigenous culture, aesthetic pleasure and tourism,
i. reduce crime to the minimum possible with minimal outdoor light flux while limiting the fear of crime to tolerable levels, and
j. minimise the adverse effects of ecological light pollution (Longcore and Rich 2004) on
    - health and wellbeing of outdoor pets (Wiley and Formby 2000), farm animal herds, and wildlife,
    - agriculture and
    - all other forms of biodiversity (Flannery 2005; Rich and Longcore 2005).

One ramification of these findings is the need to act against over-illumination, which has become increasingly prevalent since 1950 (Wikipedia Over-illumination 2008). Another is the need to work towards the reduction and eventual elimination of all outdoor sports lighting at night. This is particularly important in the case of daylight equivalent levels of lighting used in elite and professional competitions, as spectators as well as the competitors are placed at risk of initiation and proliferation of various forms of cancer. A further ramification is the need to eliminate most, if not all, architectural and decorative floodlighting, billboard lighting and outdoor video displays. Whatever might be retained, of course, must generally bear some of the burden of reduction, such as the provision of less light for streets and public places.

Of the possible measures required for enforcement, taxes or other penalties on the amount of light emitted wastefully above the horizontal or its energy equivalent could well have a salutary effect. Where an electricity agency or company provides outdoor lighting services, the customer municipality or individual should not have to pay the energy costs corresponding to any direct light emission above the horizontal or any other avoidable waste.

5.3 Spill Limits for Health, Wellbeing, Safety and Biodiversity Conservation

Navara and Nelson (2007) cited several studies in which adverse effects on biota were observed when the total ambient illuminance was as low as 0.1 lx, ie in the brighter part of the range of natural moonlight with no cloud and no light pollution. On this basis 0.1

lx might reasonably be chosen as the maximum allowable light spill from all sources[26] in ecologically sensitive areas. This would assist biodiversity conservation.

Would such a limit provide adequate safeguards against effects of artificial light at night in inducing circadian dysrhythmia and suppressing melatonin? For a given amount of visible light flux, lamps with a blue output or blue-rich white output have the most marked effects. Low pressure sodium lamps are remarkably safe in this regard. Incandescent lamps and high pressure sodium lamps emit appreciable proportions of blue light. Mercury vapour lamps, with or without fluorescent layers, are worse again (eg Navara and Nelson 2007), along with fluorescent lamps and compact fluorescent lamps (especially the cool white types), metal halide lamps and TV and video display screens. Lighting manufacturers have put a lot of resources over decades into the development of 'white' light sources and are consequently promoting widespread use of such sources (eg Knight and Deveci 2007), seemingly unaware that relatively blue-rich light may cause biological harm when blue-poor light with the same apparent brightness might be safe.

Of course, blue-rich light sources could be made biologically safer at night by the fitment of blue-absorbing filters or lenses, giving the light a yellow or orange tint, but this would tend to make most if not all such lamps uncompetitive with low- and high-pressure sodium lamps for general outdoor lighting purposes. Blue-rich light sources, including display screens and billboards, would appear to be best avoided unless high quality colour rendition is essential for a particular purpose and the purpose is also essential, not just highly desirable for commercial or aesthetic reasons. As mentioned above, the lowest human threshold found so far for an adverse effect of blue light is 0.4 lx. Some other mammals appear to have lower thresholds for blue light effects. For humans, all cases would appear to be adequately covered by a 0.1 lx limit. Consistent with the precautionary principle, it would provide a small allowance for the gap in knowledge about lower thresholds for melatonin change possibly being applicable in the case of chronic exposure to light at night for many years. Alternatively, it would allow for a case where light from a sole source of spill is incident obliquely on a window but falls directly on eyes. If there is 0.4 lx at the eyes and the angle is about 75º, the value in the plane of the window would be 0.1 lx.

As it happens, keeping the illuminance in the plane of windows of habitable rooms to less than 0.1 lx is also consistent with the requirement to minimise avoidable adverse effects of outdoor lighting in reducing sleep quality and thereby increasing drowsy driving accidents next day, and facilitating crime. In the case of environmentally sensitive and rural areas or any other locations where there may be few or no residences, or in any cases where external access to residential windows is difficult or impracticable to arrange, the 0.1 lx limit can be applied to the property boundary.

Many of the mandatory limitations for outdoor lighting suggested in the preceding section are effectively met by a universal 0.1 lx spill limit. No compelling reason was found in the literature or emerged in the analysis to justify varying the window spill limit

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[26] The intention, here and elsewhere, is to block the practice of allowing exemptions or separate treatment for light sources provided for specific purposes, such as highway and street lighting. Other light sources such as security, sports, decorative and advertising lighting may otherwise be exempt from any limits at all. Animal and human eyes do not make such discriminations and react only to the total amount of light.

according to the existing practice of rural to central urban lighting zones. In fact, the whole concept of lighting zones has been completely discredited by the finding that the safe level of spill light is less than all spill levels currently set by the CIE for lighting zones.

The underlying principles for this new approach are that it is based on sound scientific evidence of the established and likely adverse effects of light exposure at night and that as an aspect of basic human rights, individuals have to be spared from avoidable hazardous exposure to environmental factors that can have adverse effects on their health, wellbeing and safety. ‘Human rights’ here include ‘children’s rights’, and young children at least commonly spend hours in bed before existing lighting curfews begin. Therefore the spill limit set is for all of the dark hours, not just during lighting curfew hours.[27]

Doubtless this approach will generate opposition, particularly because of the need to reduce the high levels of ambient artificial light that have become a feature of most urban centres. But custom is no guarantee of soundness of practices, especially when those practices have developed in response to mistaken beliefs and vested interests.

It is ironical that recent years have seen the residential re-population of urban centres in response to planning policies. Now the urban centres that were brightly lit to produce ‘vibrant’ nightlife need to be dimmed greatly to help avoid the nightmares of cancer, crime, crashes and climate change.

5.4 LIGHT POLLUTION CAN AFFECT BIODIVERSITY OVER LARGE AREAS

The preceding section’s very tidy result of a universal safe level for light spill at bedroom windows is unfortunately not enough to ensure adequate levels of biodiversity conservation. It is still necessary to consider that many life forms are sensitive to light at levels as dim as or even fainter than the absolute visual threshold for humans, and that this capability has survival value. Altering the natural environment, even by seemingly tiny amounts, can be inimical to various species. Light pollution from towns and cities cannot be reduced to zero without turning all the lights off or living entirely underground. These are hardly feasible solutions. Useful limits are possible for conventional towns and cities, however.

The vertical plane illuminance E_d of spill light at an unobstructed distance d from an illuminated city is proportional to apparent total intensity I of the radiating sources. Because of atmospheric light absorption and terrain curvature in the real world, E_d tends to diminish with distance at a greater rate than if the inverse square law applied, so that the far-field relation between the quantities does not have the usual form of $E_d = I / d^2$, but

$$E_d = I / d^n,$$

[27] This is not intended to be a criticism of the concept of lighting curfews, which has much to commend it.

where n might have a value of 2.7, say.[28] So for a city where E_d is 0.1 lx for example at 10 km from the city centre, the value of E_d would drop by a factor of 100 to 1 mlx at a distance of about 55 km instead of 100 km if the inverse square law applied. Nevertheless the area over which the spill exceeds 1 mlx is nearly ten thousand square kilometres, and the size of the area affected is important in terms of biodiversity threats. Reducing the light pollution source intensity I by a factor of ten would reduce the area affected by a factor of about six, for example. With present lighting practices, this sort of improvement and beyond is readily achievable by reducing the amount of waste light emitted in the near horizontal direction from all sources of outdoor light flux. It can be done with relatively minor effects on the amount of useful light reaching the ground in the populated areas where light is needed.

Even this is not the whole story. Sensitivity to light levels as faint as overcast starlight has survival value for predators and prey alike. Although humans and their animal pets and herds are now not generally at risk of predation at night, predation remains a key activity in the food chain in general. Light levels above the lower of the absolute light thresholds for a predator-prey pair may influence the outcome of attempted predation. Predator-prey balances are important in the maintenance of biodiversity. Although outdoor stray artificial illumination brighter than about 1 μlx can have a potentially adverse effect on biodiversity, it is only a millionth of the supposedly safe level for stray light set by the CIE for boundaries of environmentally sensitive areas. Although it is probably impracticable to set limits much lower than 0.1 lx, the potentially large area over which damaging faint spill occurs can be minimised by systematically reducing or eliminating all unnecessary and wasteful lighting. This still provides adequate scope for all necessary lighting, provided due attention is paid to minimising spill.

6. AUSTRALIA AS A CASE STUDY

6.1 COMPLIANCE WITH THE KYOTO PROTOCOL

This section is about the ramifications of Australia's late reversal, in December 2007, of its policy of the last ten years not to ratify the Kyoto Protocol. This came about with a democratic change of the federal government. Australia is a special case in the context of this report because several key circumstances are quite different from those of most or all other countries. For instance, Australia:

- is heavily dependent on GGE-intensive black and brown coal for electricity generation;

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[28] This is conventional wisdom. It appears to be at odds with the results shown in Figure 3, where the skyglow falls off even more slowly than with the simple inverse of distance. This is what could be expected in the near field, ie when the contributing sources of light pollution are spread out too much to be treated as a collective point source. It applies likewise if the sources of light pollution are widely distributed as a consequence of urban sprawl, which certainly applies to Melbourne. The limiting case would be for an endless city without a brighter central area- there would be a constant level of artificial skyglow. In Figure 3, the most distant reading is boosted by the relative proximity of the large provincial city Bendigo and the nearby town of Heathcote, contributing to the apparent anomaly in the calculated exponent.

- was allowed to increase its GGEs by 8% over 1990 levels in an over-generous but short-sighted concession its previous federal government demanded in 1997 under the Kyoto Protocol;
- was allowed further generous concessions in the form of discounted GGEs for stopping land clearing;
- is variously described as the world's worst, or one of the worst, per capita emitters of greenhouse gases;
- does not use nuclear power stations and this seems unlikely to be changed soon, if ever;
- has only a small capacity in renewable energy supplies at present, representing a few percent of total electricity generating capacity;
- has had in place for some years programs to increase energy efficiency and energy efficacy, so that the gains available by further increases might be limited and slow to achieve;
- claims to be on track to meet its 8% GGEs target growth under the Kyoto Protocol, although this is disputed by The Climate Group (2008), which claims that the present achieved value is 9%, so further cuts in GGEs need to be achieved by 2010, and
- still ignores the sham of trumpeting compliance or near compliance with a growth target in the Kyoto Protocol when most other countries had a reduction target.

Regardless of these circumstances, many of the issues that apply to Australia apply elsewhere as well, and Australia can learn from other countries as well as providing useful precedents, as this Chapter indicates by examples.

Having agreed to ratify the Kyoto Protocol, Australia now has a binding obligation to meet its agreed target. Growth in GGEs from fossil-fuel usage has actually increased by much more than the target growth of 8%; for example energy usage in the state of Victoria has actually increased by about 30% since the Protocol base year of 1990. Because any land clearing concession will be smaller in future, compliance with future reductions to values set below 1990 levels will require substantial cuts to existing fossil-fuel usage until renewable energy supply capacity can be increased sufficiently, which is likely to have a lead time counted in decades rather than years. For most of that lead time, Australia and nearly all other developed countries will be participating in a successor climate change response in which the mandatory GGE reductions are expected at present to be in the range of 25% to 40% of 1990 levels by 2020, but could well need to be more severe because some of the natural responses to climate change appear likely to introduce positive feedback.

An example of such responses is the melting of polar ice and the greater absorption of solar radiation by the exposed less-reflective underlying peat, soil and rock. Australia's supposedly 'smart' action to be allowed an increase in GGEs under the Kyoto Protocol will result in a more onerous compliance burden after 2010 because the base year for all countries appears set to remain as 1990.

Although there are many difficulties in implementing a fair global system for GGE reductions, such a system needs to incorporate what may be called the principle of equitability, viz that a burden is minimal for all concerned if it is shared fairly. Compliance with the Kyoto Protocol is known to be a burden and there is no reason why compliance with any follow-on agreement will be different. If any country, state or region does not carry its fair share of the burden, others have to make up the shortfall- climate change mitigation does not allow for 'free lunches'. The same applies to energy use sectors. If the lighting sector is allowed to get away with its massive and irresponsible world-wide expansion in energy usage since 1990, some other energy use sector(s) must face additional reduction burdens.

Debate about what might be considered 'fair' has already begun in international forums. A few developed countries have tended to see this as giving each country a right to emit greenhouse gases in proportion to its gross domestic product, which would tend to maintain the status quo in terms of rich and poor nations. In a nutshell, this approach is unconscionable and appears unlikely to receive majority support. More countries have argued for allowable emissions to be tied to a universal per capita rate, which will be a small fraction of the present per capita rate of countries such as Australia and the USA. The process required for all countries to reduce their GGEs to a common globally sustainable GGEs rate per capita has already been named 'convergence'. Some of the developing countries would like to see 2050 set as the target year for completion of convergence.

Discussion of the rights and wrongs of the present situation is beyond the scope of this document. But what is clear is that compliance with GGE limits is likely to become more onerous over time and increasingly subject to international enforcement. Garnaut (2008) mentions the possibility that the required reduction for Australia by 2050 could be as much as 90%, ie to just 10% of 1990 levels. If this is applied to outdoor lighting in Melbourne, in the absence of additional supplies of renewable energy and increases in luminous efficacy the reduction required would be to about 2.8% of the present (2008) level. The state and federal governments have not yet come to grips with the scale of action required to comply.

6.2 Dealing With the Immediate Problem

There are numerous possibilities in fossil fuel usage reduction for the required GGE reduction in Australia by 2010, but most of them would create significant hardship, for example petrol rationing. Switching unnecessary lights off outright and selectively reducing the wattage or disabling a proportion of other lights are among the easiest to do, although the savings achievable relative to the whole GGE reduction required are rather modest. Reduced street lighting after a curfew, say 10-30 pm or 11 pm as in AS 4282 (1997) or later, is applied already in many places or under active consideration as a possible variant or additional measure. Sufficient experience already exists to be sure that reducing lighting and light waste in a sensible fashion not only reduces GGEs but can actually save money. This is in contrast to most other GGE reduction methods, which actually cost money.

Another possibility is to use lamps with increased luminous efficacy, following a recommendation by the UN International Energy Agency (IEA) (http://www.iea.org). Accordingly, the governments of Australia, Brazil, Canada, Eire, USA and Venezuela have already decided to phase out incandescent (tungsten filament) light bulbs that can be replaced by compact fluorescent lamps (CFLs). CFLs can produce as much light while using only about a fifth as much energy. Generally there are to be no bans on usage of incandescents, just bans on sales (Wikipedia Light Bulb 2008).

Unfortunately, several problems will limit the effectiveness of replacement of incandescent lamps by CFLs and other high intensity discharge (HID) lamps:

- Anecdotal accounts on the Internet suggest that the actual GGEs reduction could fall short of that expected because of a tendency for people to use nearly as much energy after converting to CFLs by increasing the number of lamps in use or using higher wattage CFLs than the recommended equivalent to the removed incandescents in order to get more light.
- HID lamps generally contain mercury (some more than others, eg Culver (2005); AGO (2007)) but few governments have done the right thing and ensured that all used HID and fluorescent lamps are collected for mercury recovery or proper containment of the mercury. (Demolition workers at the World Trade Centre site suffered mercury poisoning as a result of mercury release by the many fluorescent tubes that were broken (Harder 2007).) Mercury can stay toxic even longer than radioactive waste.
- Most CFLs at present are not usable with dimmers, so existing dimmer switches have to be removed or the dimmers have to be bypassed electrically. Dimmer-compatible CFLs have recently reached the market but tend to be expensive.
- Compared with a given amount of visible light emitted by LPS and HPS lamps, fluorescent lamps, CFLs and non-sodium HID lamps produce much more of the short-wavelength visible light (see Appendix) that is now known to be a risk factor for prostate cancer, breast cancer, other cancers and circadian disruption.
- The projected long lifetime of CFLs is much reduced if the lamps are switched on and off frequently, as tends to be the case with domestic indoor and outdoor lighting.
- Tungsten lamps that only come on when activated occasionally by movement sensors do not use as much energy as CFLs that have to be left on all night because they don't work with the sensors or other electronic switches.

6.3 A Specific Example in Victoria

6.3.1 The extent of the problem

Victoria uses brown coal (lignite) for most of its electricity generation. Partly because of its relatively high water content, brown coal produces substantially greater GGEs than does black coal for a given amount of energy released by burning. Lighting typically uses about 10% of the electricity supply, so reducing lighting by one tenth, for example, would reduce electricity usage and associated greenhouse gas emissions only by about 1%. It would appear much easier and quicker to reduce overall electrical energy usage by such an amount than to introduce an equivalent increase in the renewable component of the electricity supply (eg by wind farming or solar panels). As Earth Hour and similar events have demonstrated, unnecessary use of lighting contributes substantially to outdoor ambient light levels at night. It appears possible to reduce existing lighting by half or more, permanently, without greatly impacting on overall amenity.

Outdoor lighting in Victoria is a prime candidate for corrective action because its growth has been grossly in breach of the Kyoto Protocol so far, and it would be unfair to expect other energy use sectors to suffer extra cuts to make up for irresponsible excessive growth in lighting over the past 19 years and earlier. Although electrical energy use in Melbourne (the state capital city) is a large part of the total for all Victoria and fixing lighting in Melbourne would have a useful impact in reducing the state's overall electrical energy use, it is neither necessary nor desirable to restrict the proposed lighting reform to Melbourne. As mentioned above, Figure 1 is more-or-less indicative of the situation throughout Australia. Regardless, the abundance and consequent large-scale use of brown coal in Victoria makes the problem relatively worse, because growth has to be reversed to shrinkage and the land clearing concession that allowed large increases in fossil fuel usage in Australia under the Kyoto Protocol will be much less applicable as an offset in future. Victoria's use of brown coal may increase the compliance burden on the other Australian states unless that usage is cut by a factor substantially larger than the national target reduction under the Kyoto Protocol and follow-on agreements.

With this background, proposed lighting reductions are calculated below. They are assumed to be applied over all sources of waste outdoor lighting flux, which can be expected in cities to be roughly equal contributions from road/path lighting, illuminated signs and internal light loss from buildings. This does not necessarily mean equal contributions from the energy inputs to these categories. If reductions in one of these sources must be limited or avoided altogether for any reason, cuts required in one or both of the other two would need to be correspondingly larger.

From the data used to generate Figure 1, in the absence of intervention to reduce lighting growth the increase in artificial skyglow over Melbourne by 2010 will be 38 times the allowed 8% increase applying to 1990 GGEs in Australia under the Kyoto Protocol. Skyglow is several processes away from GGEs but its changes are a reasonably good proxy for changes in total outdoor light flux which in turn is a reasonably good proxy for changes in energy use by the outdoor lighting sector. That energy use is closely coupled to changes in the associated GGEs. Ignoring whatever likely small disproportions occur over time between increases in skyglow and GGE increases from energy use for outdoor lighting, the outdoor lighting sector would need its 2010 GGEs to be reduced by 72.5% of its expected 2010 value in order for it to comply with the Protocol. Thus all but about 27.5% of all present outdoor lighting in Melbourne, nearly three quarters of it, would need to be decommissioned, or equivalent energy use reductions made in some other way, eg by use of lighting curfews and increased efficacy of conversion of electricity into light.

Another way of looking at the problem is to consider that the total of new and increased lighting since 1990 or its equivalent capacity needs to be reduced to just 2.7% of that total for sector compliance with the Protocol. Even if the proxies and observations are in error by an unlikely total factor of 30%, say, and in the right direction, the required cut in new and increased lighting since 1990 would still be to less than 4%, still massive. It would appear that the Australian state and federal governments have been 'asleep at the wheel', so to speak, while new lighting and upgrades have been installed in a fashion that has clearly been way out of control at state and federal levels.

In a nutshell, growth in outdoor lighting in Melbourne has been excessive and is far from compliant with the Kyoto Protocol at present. The situation is probably similar over the whole of the populated areas of Australia. This is a priority matter for the federal and state governments to deal with. By itself, an early fix might not achieve overall compliance for Australia but would be a useful step in the direction required.

Clark (2003) drew attention to reliable positive correlations of crime and outdoor lighting in the Melbourne CBD and on national scales. Melbourne city officials and the police were provided with the complete document, advised accordingly then and reminded since. Despite this, street and pedestrian lighting has been increased several times as a supposed deterrent in the trouble spots. Crime has actually continued to increase, eg in 2008, assaults had increased by 24% to 2064 since 2003-2004, along with comparable increases in sexual assaults, robberies and homicides (The Age 2008). A similar blunder has been made by continuing a series of increases in illumination of metropolitan railway stations. They are now lit to daylight levels using metal halide lamps that emit a copious proportion of blue light. The transport officials involved have failed to provide crime figures that would justify any of the increases. All they have managed to provide instead is a claim that customer satisfaction has improved. Presumably this reflects a decrease in the fear of crime, but it comes at the risks of increases in crime and various types of cancer. The officials have been informed of the cancer risks but they have ignored their duty of care to inform patrons of these risks.

It is important to understand the processes in circumstances like these examples. Firstly, a public facility such as an 'entertainment' precinct (bars, discos, singles clubs) or public transport station receives adverse media publicity about street crime. There are public calls for counter action such as more police and, through almost universal confusion between feeling safe and being safe, more outdoor lighting. Politicians tend to choose more lighting as it is a much more visible sign of their action for a given expenditure. Increased lighting increases patronage because people feel safer. The number of crimes would increase in step with patronage if the crime rate remained constant, but the net rate typically increases by a few percent for each tenfold increase in total light flux (Clark 2003). So the total crime figures tend to rise disproportionally, and the news media naturally find this newsworthy. More light is added as a supposed fix and the effect compounds. Calls by the writer and others to reverse the process are resisted by the owners and operators of the facilities as a threat to patronage and hence profitability. In response to the writer's enquiries, the police have justified their support for ever more lighting by claiming in correspondence that even if lighting does increase the crime rate by a relatively small amount, their task to reduce the fear of crime can take priority over their task to reduce crime! Perhaps the police regard any proposed reduction of lighting as a threat both to their own feelings of security and to their job security. They need to think again, with emphasis on their actual safety, their personal health, and the safety and health of those close to them.

Ultimately, the way to reduce fear of crime is to reduce the actual crime rate. Minimising outdoor lighting can do this while saving money and reducing the many adverse effects of non-essential and otherwise excessive lighting.

6.3.2 Sustainable low energy lighting trials

Across Australia, paying for main road lighting is usually the responsibility of a government roads department. Public lighting and lighting of streets other than main roads is typically the largest single item of expenditure for local governments. Concerned by the cost of electricity for public lighting, and by the GGEs associated with generating that electricity, action groups set up by various local councils have conducted trials to determine if the use of lamps such as T5 linear fluorescents[29] could provide the required amount of light reliably while using less electricity.

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[29] 'T5' signifies that the tube diameter is 5/8 inch (15.9 mm).

At present most suburban streets in Melbourne are lit by 80-watt mercury vapour (80-W MV) lamps. The luminaires in use are the ‘flower pot’ type, which are obsolete because of their excessive upward waste light,[30] and the newer ‘cobra head’ type, which typically emit about 10% upward waste in their installed orientation.[31]

Trialled luminaires have generally included a type with twin 14-W linear T5 fluorescent lamps. It gives about the same amount of light on the ground as that from the usual 80-W MV types. The amount of upward waste with this luminaire horizontal is claimed to be only about 4%, a minimum inherent in the design. Trial installations seen by the writer typically have the luminaire canted (upcast) at about 20 degrees to the horizontal, and the upward waste and maximum spill are thereby substantially greater.

When a trial in northern Melbourne suburbs started in 2004, the applicable Australian Standard (AS/NZS 1158.3.1:1999, *Lighting for roads and public spaces*) specified the allowable upward waste light ratio for the installed luminaires as 12%. This was reduced to 10% in the 2005 edition of the standard and a further reduction to 8% was agreed in the current edition. It appears that the trials installations might not meet the stricter limits.

Other lamps tested include 50-W HPS, which has about the same photopic light output as the 80-W MV and the pair of T5 lamps. However, AS/NZS 1158.3.1 Section 2.6 states that the output of HPS should be derated to 75% in calculations because at low luminances the eye has reduced sensitivity to the orange-tinted blue-poor light from HPS (eg Lewin 1999; Akashi and Rea 2001), and that lamps should generally have the highest colour rendering index possible.[32] The standard thus favours blue-rich light sources in street lighting at a time when an increasing number of local and regional lighting ordinances in other countries give explicit preference to HPS because of its high photopic luminous efficacy. In Melbourne, nearly all main roads and some suburban street intersections are already lit with HPS, regardless of its mediocre colour rendering.[33]

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[30] Regardless, new and replacement luminaires of this type are still being installed in some council areas in Victoria.

[31] This is still a lot for taxpayers to pay for when it is beamed off into outer space. It also represents a 10% avoidable component in the associated GGEs. There appears to be no direct incentive for municipal lighting and power contractors to minimise this waste in Victoria as they are paid for the number of lights rather than for the service required, which is the amount of useful light on the road.

[32] No reason is given to justify this requirement. Even with white light, colour discrimination tends to fail at illuminances less than that provided by the full moon, however. Note also that the direct light of the sun near the horizon can be more orange-red than the light of HPS.

[33] On a recent flights from Melbourne to Moscow and return, the writer was struck by the overwhelming predominance of HPS in the outdoor lighting of city after city across South East Asia, India, the Middle East and Russia. In comparison, a greater proportion of the outdoor artificial light flux in Australian cities appears to be from MH or fluorescent sources.

It appears that there was little enthusiasm for using HPS in the trial report (AGL 2007), reflecting the interests of lamp manufacturers and the preference of the applicable standard. In visibility, colour rendition, perceived level of safety and suitability for use in residential areas, lamps with a white-light (blue-rich) output were claimed to be superior to HPS lamps. Of course this is a reflection of the direction in which leading lighting professionals have been guiding the profession for well over a decade.

The luminaires with HPS lamps in the trial were well outnumbered by the luminaires with twin T5 lamps. The electrical engineering evaluation concentrated on the latter but appeared to be thorough. Environmental aspects other than GGEs were not addressed, a really serious mistake in the circumstances. HPS was not recommended as a replacement for existing MV installations.

A subsequent evaluation of twin-T5 luminaires and other low energy lights for minor road lighting was made by the Technical Reference Group of the Victorian Sustainable Public Lighting Action Group (VSPLAG-TRG 2008), which "found that the T5 (twin 14W & twin 24W) & the compact fluorescent (CF) (32W & 42W) low-energy lights were comparable or better in performance than the current standard, the 80W MV… The 50W HPS light was found to be unacceptable due to its yellow light and relatively higher energy consumption" [sic]. Again there was no mention of adverse environmental or ecological factors relating to the light output, not even the issue of light spill.

Two decades ago, lighting engineers urged acceptance of HPS lamps as replacements for LPS lamps (which use only about two-thirds as much electricity) by explaining that the output beam distribution and spill control could be managed far more easily with the compact source of a HPS lamp instead of the long tube of an LPS lamp. Now, some of the relevant commercial literature is trying to make a virtue of the tubular format of the T5 lamps. In fact, the T5 lamp format and the design of the trial luminaire militate against the ready application of ad hoc shielding in the case where a resident complains of excessive light spill. The applicable Australian Standard does require consideration of mitigation in such cases, but effective shielding would be impracticably large for the twin T5 luminaire. It is extraordinary that the evaluation overlooked this and other important matters, especially as earlier versions of the present report were circulated to individuals and organisations involved in the project, even before the project started in some cases.

Other ignored matters include the desirability and (im)practicability of modifying the twin-T5 luminaire to achieve zero horizontal and upward spill, the increased skyglow and glare nuisances of blue-rich light, the severe consequences of blue-rich light spill into windows of habitable rooms, the suitability or otherwise of the lamp-luminaire combination for dimming or switch off in the second half of the night, and the great importance of using sodium lamps instead of the other lamps trialled because sodium lamps contain substantially less mercury (AGO Guide 2007, Item 5. Environmental Issues). Regardless, the Victorian Government accepted the report's findings and has provided substantial funding for initial bulk installations of the twin-T5 luminaires.

The total replacement of Melbourne suburban streetlights by twin-T5 luminaires has therefore started. It is a major project with a cost understood to be in the order of a hundred million dollars. Several of its potential environmental and ecological outcomes will be profoundly damaging, judging by the material in this present report. But no Environmental Effects Statement has been sought, authorised or prepared, let alone approved. Nor have any of the authorities involved met their apparent duty of care by warning residents that the cancer risks of light and light pollution from the twin-T5 luminaires will be substantially greater than is necessary.

On top of all this, the basic reason for doing the project in the first place has not been thought through properly. Certainly there is a need to reduce the costs of outdoor lighting, including the capital costs (which are actually higher for the twin-T5 luminaires). Likewise there is a need to reduce greenhouse gas emissions, and this is addressed in isolation by the project. But as the present report indicates, the main problem with GGEs from streetlighting is unconstrained growth. Even if the expected reduction of about 60% in streetlighting-associated emissions is achieved with twin-T5 luminaires, this gain will be wiped out in less than ten years if the present rate of streetlighting increase across greater Melbourne is comparable with the rate of increase for all outdoor light flux. Since 1990, as already mentioned the total amount of outdoor lighting growth and accompanying greenhouse emissions across greater Melbourne are approaching 38 times the allowed maximum growth for Australian GGEs under the Kyoto Protocol. By proposed international agreement it is likely that total GGEs in 2020 will need to be substantially less than the 1990 level. By ignoring this in a one-for-one streetlight changeover and the installation of even more streetlights in many outer suburban areas that currently do not have them, state and local governments could be placing themselves at risk of having to make rapid and massive reductions of street lighting in future years, along with the risk of litigation by residents who have drowsy driving accidents or develop serious illnesses attributable to the adverse effects of streetlight spill entering bedrooms.

In place of the twin-T5 luminaires, a proposed combination of a 50-W HPS lamp in a commercial-off-the-shelf full cutoff luminaire[34] would have many advantages, especially if the lamp type is the twin-arc type with an extended operating life. Although it would not provide as large a reduction in energy usage, it is well tried standard technology, and should have smaller capital and maintenance costs than the twin-T5 arrangement. Suggestions by the writer to have even one example of the proposal tried have been ignored or rejected on specious grounds by local councils involved in the twin-T5 trials. One of the reasons given is that the pole spacing required to achieve the specified uniformity of illuminance may be slightly less for full cutoff luminaires. However, the slight loss of uniformity that would occur with existing pole positions is utterly trivial in comparison with the effects of alternative or additional actions that are already in place or under active consideration elsewhere, viz decommissioning of every second streetlight or even two of every three, and dimming or total switchoff after a lighting curfew.

7. CONCLUDING REMARKS

In Melbourne, the observed/extrapolated growth in artificial skyglow from 1990 to 2010 is likely to be about *38 times* the maximum growth that could have been expected if lighting energy usage had complied with the Kyoto Protocol maximum growth of 8% in greenhouse gas emissions generously allowed for Australia. Compliance of the lighting energy use sector with the Protocol by 2010 would require as much as 97% of the

[34] For example, GE M-250R2RC or equivalent. So-called ‘sky friendly’ lighting suppliers can advise further. They can be found by Internet search.

increase in installed lighting since 1990, or its equivalent in power consumption, to be removed. Indications are that lighting growth elsewhere in Australia has likewise had an exponential trend and been similarly excessive.

Exponential growth of artificial skyglow is also occurring in other developed countries. It is unsustainable and hazardous. There is no reason to believe that the situation will improve unless and until governments introduce and enforce mandatory limits for lighting with the aim of capping and reducing the total outdoor ambient light flux at night.

While anthropogenic greenhouse gas emissions continue at unacceptably high levels in Australia and elsewhere, no foreseeable improvements in luminous efficacy of lamps or renewable energy supplies will allow more than minor mitigation of the reduction burden in the short to medium term. All outdoor lighting must share fully in meeting this burden or some other energy use sector will have to bear additional cuts.

Quite small amounts of stray artificial light entering bedrooms at night can interfere with sleep. This tends to result in increases industrial and traffic accidents next day, and it may be a factor in the obesity epidemic. Light exposure at night can and does interfere with the human melatonin cycle. The adverse consequences of this are still emerging. The World Health Organisation has accepted that shift work increases the risk of cancer in humans, probably through interference with the melatonin cycle. Laboratory and epidemiological studies indicate strong links between artificial light exposure at night and the initiation and proliferation of breast cancer and prostate cancer. There is separate evidence that risks of some other cancers also appear to be increased by artificial light exposure at night. Present lighting standards to date have taken no account of these adverse effects.

The suppression of melatonin and interference with sleep by light exposure at night is maximal for light with a wavelength of 460 nm, which is in the blue part of the visible spectrum. Sodium vapour lamps with blue-poor orange-tinted light output are commonly used for road lighting. Sections of the lighting industry have been pressing with some success for their replacement by more expensive types of lamp that use more electricity and emit greater amounts of blue light in the course of achieving a whiter output. It is beyond reasonable doubt that avoidance of exposure to the short-wavelength component of artificial light at night is particularly important for maintenance of health and wellbeing. No account of this has been taken by governments in legislating for the energy saving replacement of incandescent lamps by compact fluorescent lamps. As a necessary but not sufficient response, CFLs that have more than the minimal possible output of blue light need to be taken off the market quickly.

The motor vehicle industry is increasingly using high intensity discharge lamps instead of incandescent lamps in vehicle headlighting, thereby increasing the short-wavelength component of the light. Likewise, some other vehicle white lighting is now supplied by LEDs instead of incandescent lamps, again with a substantial increase in the short-wavelength component. No account appears to have been taken of the adverse health effects that will result. The use of such lighting in new vehicles needs to stop quickly, and existing vehicles need to be recalled by manufacturers for such lighting to be replaced by less hazardous sources or retrofitted with yellow filters that absorb most of the troublesome blue content of the light.

The facts have changed. Governments have a duty of care to reconsider their energy-saving lamp legislation as a matter of urgency. If vehicle manufacturers do not act swiftly enough to recall vehicles in order to reduce the hazard of excessive blue light output at night, governments should introduce legislation requiring such recall and corrective action.

Environmental, ecological and health reasons justify large reductions in outdoor ambient artificial light flux at night. Lighting reductions will tend to increase fear of crime but reliable scientific evidence indicates that such reductions will also reduce actual crime, an outcome that must take precedence. Road and street lighting reductions may increase traffic accidents in some circumstances, but this effect is now known to be much smaller than was believed for many years. It is also likely to be offset by lighting reductions in general, given that such reductions are also likely to produce a reduction in traffic accidents by reducing sleep disturbances, given that sleep disturbances increase the likelihood of drowsy driving next day. Present levels of spill light and artificial skyglow can contribute to habitat degradation over land and sea areas much larger than the populated areas emitting the waste light, so reductions in this waste are necessary to reduce biodiversity losses. Experience indicates that voluntary reductions in outdoor lighting will be insufficient: legislated reductions and ongoing strict enforcement will be required.

Excessive outdoor light levels appear to be a consequence of individual and corporate ignorance, carelessness, selfishness and greed. Self-regulation of lighting use by industry has failed dismally in aspects such as illumination of outdoor advertising signs. Excessive lighting contributes to artificial skyglow, which is becoming an ever more serious hindrance to astronomical research and education and is a threat to conservation of indigenous culture. Much of the problem arises from stray light emitted from light sources in directions just above the horizontal. Redirecting this light towards the ground may allow useful reductions in lamp wattage, but vested interests tend to oppose this by claiming there may be a small reduction in uniformity of illumination. Increasing skyglow is primarily a consequence of continuing increases in the number and power consumption of outdoor light sources, with increases in the amount of internal light escaping from buildings as an important additional factor.

The introduction of a universal maximum of 0.1 lx for the total artificial light spill at windows of habitable rooms, or at property boundaries, would go a long way towards reducing most of the adverse effects of light pollution to more tolerable and less hazardous levels.

Mandatory caps on regional total light flux would also appear to be justified by the evidence presented about the adverse effects of excessive light at night. There is also a strong and independent case for the introduction of mandatory regional caps on energy used for lighting. Annual reductions in such energy caps must be an integral part of any such scheme in order to reduce the energy used for outdoor lighting towards a fair share of the constraint required for global compliance with the need to reduce greenhouse gas emissions.

Follow-on control of greenhouse gas emissions after the Kyoto Protocol period ends in 2012 is likely to be onerous for many countries. For Australia, the 2050 target could reasonably be set at as small as 10% of the 1990 value. It appears unlikely that either the Protocol target of 2010 or its 2020 and 2050 successors could be achieved solely by any foreseeable availability of renewable energy and offsets from re-afforestation, so that substantial ongoing reductions in fossil-fueled energy use would appear to be necessary. Outdoor lighting should be targeted particularly because of its profligate expansion since 1990. The level of outdoor lighting in Melbourne might need to be reduced to only 2.8% of the present (2009) level, and comparably severe cuts are expected to be applicable to other Australian cities and towns.

Commercial decorative lighting and illumination of advertising signs are considered to have the highest priorities for reductions in the outdoor lighting energy use sector. Outdoor sports lighting likewise needs to be reduced or eliminated, sooner rather than later. Few if any concessions will be possible. Proposals to power additional or new lighting in any of these categories by renewable ('green') energy supplies should be regarded as unacceptable ploys because environmental and health aspects of excessive artificial light at night are ignored. If additional sources of renewable energy are proposed to be made available for such purposes, there is a higher priority for the energy to be used instead to reduce the fossil-fueled component of the grid supply.

There are unresolved scientific issues about the extent of the road accident hazards of advertising signs that are visible to drivers, especially for signs that are artificially illuminated, or self luminous as in variable or video-capable display screens. If the government is serious about road safety it needs to eliminate such signs in the meantime because of the strength of the prima facie case that the signs are devised and intended to attract attention and are therefore a potential distraction for drivers. No illuminated advertising signs other than company names on premises open for business should be permitted in positions where they can be seen by drivers, and even for permitted signs there is a need to limit their size and brightness and to shield their light emissions from travelling at or above the horizontal.

Light pollution is unusual if not unique among forms of pollution in general, insofar as it is generally not difficult to fix, its adverse effects can be halted quickly and the fix will usually end up saving money. The latter should increase motivation of governments to introduce mandatory sweeping reforms to lighting practice along the lines presented in this report.

The professions of architecture and urban design in particular will need to alter course as a consequence of lighting reforms in addition to the changes that have already begun in connection with greenhouse gas reduction and climate change mitigation.

8. RECOMMENDATIONS

Based on the information presented in this paper, it is suggested that all levels of government in Australia and in other countries in general should implement the following:

A. Apply mandatory outdoor lighting strategies and controls, including provisions to:

- limit *total* external incident artificial illuminance in the plane of windows of habitable rooms to 0.1 lx regardless of location of the dwelling, disregarding the present lighting zones concept of the International Commission on Illumination (CIE) and standards incorporating them as they perpetuate lighting practices that are inimical to health, safety, energy conservation, biodiversity conservation, astronomical observations and conservation of any remnant indigenous cultural heritage,

- apply a similar 0.1 lx limit at property boundaries in environmentally sensitive locations and locations where windows are not readily accessible or not present,
- conserve energy and assist seeing by reducing glare, limiting spill light and preventing overbright lighting,
- require full cutoff shielding of outdoor luminaires in all cases, including commercial lighting, road lighting and sports lighting, with exemptions, if any, only by specific exception for a limited time and subject to public scrutiny and appeal,
- limit the size, luminance, intensity and hours of operation of all existing outdoor illuminated advertising signs, outdoor displays screens and outdoor projected displays, and cap their total energy use (which may well need to be subject to stepwise reduction until the energy use has reached small or zero values),
- ban all new illuminated advertising signs other than on-premises company names with minimal size and luminance, and ban illumination of those signs at all times when the company is not genuinely open for business at that site,
- ban all outdoor use of projected image displays regardless of whether the light source is a lamp, luminescent panel, solid state array or a laser, or any combination of these,
- ban all searchlight skybeams and laser skybeams used for commercial purposes at any time,
- ban all floodlighting luminaires with non-zero upward waste light ratios as installed, and impose strict limits on the usage duration and total light flux of any other floodlighting that may be permitted in the public interest,
- specify curfew times for specific types and locations of outdoor lighting including street lighting,
- limit the emission of internal light at night from glazed doors, windows and skylights by measures including enforced use of drapes and blinds,
- disallow all applications for increased heights for buildings or increased height limits in planning overlays unless any expected increase in outdoor light flux can be more than offset by audited permanent reductions in outdoor light flux in the vicinity;
- avoid waste of resources by inappropriate use of lighting to try to control crime and graffiti, and
- apply reducing caps to outdoor lighting energy usage in line with international obligations to reduce GGEs, and insist that only a 1990 base year should be used in lighting energy constraints under the Cities for Climate Protection (CCP) scheme or any other GGE reduction scheme.

B. Educate the public about adverse effects of artificial light exposure at night on:

- human health and wellbeing,
- health and wellbeing of pet animals, captive animals and wildlife**,** and
- ecology and biodiversity generally.

C. Educate the public about the contribution of lighting to greenhouse gas emissions.

D. Educate the public and particularly the police, security industry, architects, lighting industry and local government about actual effects of lighting on crime and the fear of crime.
E. Educate the public about the adverse effects of light pollution and artificial skyglow on:

- astronomical research, education and recreation,
- aesthetic appreciation of the night sky, and
- conservation of residual indigenous cultural heritage connected with features of the night sky.

F. Discourage the use of lamps containing more than the lowest practicable amounts of mercury, and institute mercury collection services for all discarded lamps containing mercury.
G. Where appropriate, encourage the use of *low pressure* sodium lamps in full cutoff fittings because of their minimal mercury content, their high luminous efficacy, their reduced skyglow effect, and their freedom from blue light emission and investigate their value for essential lighting in areas where graffiti deterrence is also required.
H. Introduce national and regional lighting strategies with laws and regulations, including mandatory technical constraints in cases where the relevant national standards do not adequately represent the national interest in general or the specific aims and interests of environmentalists, ecologists, naturalists and astronomers, regardless of whether they are professional, educational or amateur.

In applying these recommendations in countries other than Australia, appropriate allowance may need to be made for differences in political, legal, economic and cultural systems. Where bans are mentioned in the above list, they should apply forthwith to all new lighting for the specified purposes, and sunset provisions should apply to all existing lighting for these purposes so that phasing out is achieved within say five years.

If any person, group or government does not agree with the research, conclusions and recommendations in this report and wishes to oppose implementation, it is up to them to demonstrate precisely where and why the literature cited, the analyses made or the findings are erroneous, and to publish their claims. Unsupported or inadequately supported assertions or beliefs, or mere desire to perpetuate existing lighting practices are of no value at best, and potentially dangerous.

9. ACKNOWLEDGEMENTS

Several suggestions by Dr Jan Hollan have been incorporated into successive versions of this report to improve relevance and accuracy of parts of the text. Dr Tom Richards kindly supplied the photograph reproduced as Figure 2, along with a set of zenith visual limiting stellar magnitudes incorporated into Figure 1. Geoff Dudley contributed measurements of sky luminance and bedroom stray light at night. He and many other interested persons have also assisted by drawing attention to news items and references on light pollution, and by suggesting clarification of technical issues where an unrealistic expectation of prior knowledge had been assumed for readers. Discussion on the Web forums '*Lights*' and '*Outdoor Lighting Forum*' has helped shape the scope and form of this report. Responsibility for content of the report nevertheless remains with the writer, of course.

Finally I wish to acknowledge that the successive versions of this report are testimony to the support provided by my dear wife Ruth over the many years in which the time consumed by this work stretched her patience.

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APPENDIX: COMPARISONS OF COMMON LAMP TYPES IN SUPPRESSING MELATONIN AND CAUSING SKYGLOW

A1. INTRODUCTION

The first widely used artificial sources of light were flames of burning carbon compounds such as wood, fats, waxes and oils. These sources tend to have spectral power distributions like those of theoretical 'black bodies' at absolute temperatures in the range of about 1000 to 2000 degrees Kelvin, viz a smooth curve rising from low values at the short wavelength (violet) end of the visible spectrum to a peak at or beyond the long wavelength (red) end of the spectrum. As the temperature of a black body source increases, the spectral peak increases in magnitude and shifts towards shorter wavelengths. The colour of the light changes from red through orange, yellow, white and finally bluish white. The importance of theoretical black bodies is that their radiation at given wavelengths and total light output can be calculated precisely and there are practical approximations to them in the form of laboratory furnaces and the ubiquitous incandescent filament lamp. The stars typically provide a useful range of natural approximations to black bodies. Their subtle colours give an indication of their surface temperature. Sunlight that has passed through the atmosphere has a pastel yellow colour corresponding to a black body of about 5500 K. Daylight and skylight are typically perceived as white (about 6500 K) and bluish white (to about 9000 K) respectively, but the viewing conditions can affect colour perception markedly because of the phenomenon of colour constancy.

Gas flames gradually supplanted oil lamps and wax candles in the 19th century. The yellow flame could be made a little hotter so there was more light. It was also a little whiter and better for distinguishing colours. Then the gas mantle was invented, a fragile gauze enclosure for the flame. It contained materials such as lime that produced brighter and whiter light than the bare flame. The incandescent lamp followed and eventually supplanted the gas mantle because of its greater light output, lower cost, convenience and relative safety.

Other kinds of light source were devised and new kinds are still being invented. The neon lamp has an electrical discharge in neon gas in a glass bulb or tube, and produces orange-coloured light. Different gases provide different colours, so gas mixtures provided a way of changing the often strongly coloured light obtained with a single kind of gas. Increased gas pressure and other improvements allowed more light to be produced for a given amount of electricity (eg high intensity discharge lamps), or the lamp could be made smaller for the same light output (eg the compact fluorescent lamp).

Often these improvements have involved lamps whose output was concentrated in narrow parts of the spectrum, viz spectral lines. Such lamps tend to give coloured objects an anomalous appearance, eg low pressure sodium lamps make everything look orange-yellow and mercury vapour lamps give lightly pigmented skin a ghastly pallor. The addition of phosphors to the inside of the glass bulb or tube helps to reduce this effect in the case of mercury vapour lamps. Thus the phosphor coating of a fluorescent lamp is akin to the mantle of a gas lamp insofar as it surrounds the primary source of light, adds to the light output and makes it whiter.

In ordinary circumstances, differences in the spectral power distribution of the light from different kinds of lamp are primarily evident in the colour of the light and the extent to which colour discrimination and the appearance of coloured objects differ from observations made in natural daylight.

Generally the spectral power distribution of a particular lamp is only fully apparent when the light is examined with a spectroscope or its photographic equivalent. For many types of lamp, the apparent colour of their light is sufficiently different from that of any black body for difficulties to arise in trying to assign an equivalent colour temperature. This has led to a standard way of calculating the nearest colour temperature: the value so assigned is called the correlated colour temperature (CCT).

Lamps that emit more of the so-called 'warm' colours, viz red, orange and yellow tints, have CCTs in the range from about 1700 K to 4000 K. They are loosely described as 'warm white' to 'white'. The overlapping range from about 3500 K to 6500 K encompasses 'white' light, 'cool white' light and 'daylight', and more of the total light tends to come from the violet, blue and blue-green parts of the spectrum. In general, the whiter the light and the nearer and more smoothly the spectral power distribution matches that of typical daylight, then the better the colour rendition. This can be described quantitatively by the lamp's colour rendition index (CRI). A CRI of zero applies to a monochromatic source, as is nearly the case with low pressure sodium light, a high pressure sodium lamp has a CRI of 25, fluorescent lamps have CRIs from 51 to 93 and 100 can be attained with tungsten filament lamps (Hunt 1991, Table 4.2).

A2. SPECTRA OF COMMON LIGHT SOURCES

Figure A1 is a composite display of the spectra of various common light sources, natural as well as artificial. The spectroscope used was constructed by the writer primarily for astronomical observations but it also proved suitable for field observations of artificial light sources. The dispersing element is a 1200 lines per millimetre blazed reflection grating used in the first order. Achromatic lenses were used for collimation and imaging. The slit was adjusted to and left at a width broader than the best resolution value to keep exposure times reasonably short. A ground glass diffuser well in front of the slit was used to ensure full and even illumination of the slit and grating. The camera used was a Nikon D70S with a lensless adapter fitted to the imager drawtube. The assembly was attached to the tripod-supported altazimuth mount of an astronomical telescope.

The illuminance from the subject light source was measured with a Hagnar precision light meter in the diffuser plane of the spectroscope. The camera exposure time was chosen to make the product of its duration in seconds and the illuminance in lux as close as practicable to 50. This ensured that each spectrum was made with a fixed amount of visible light to facilitate comparisons.

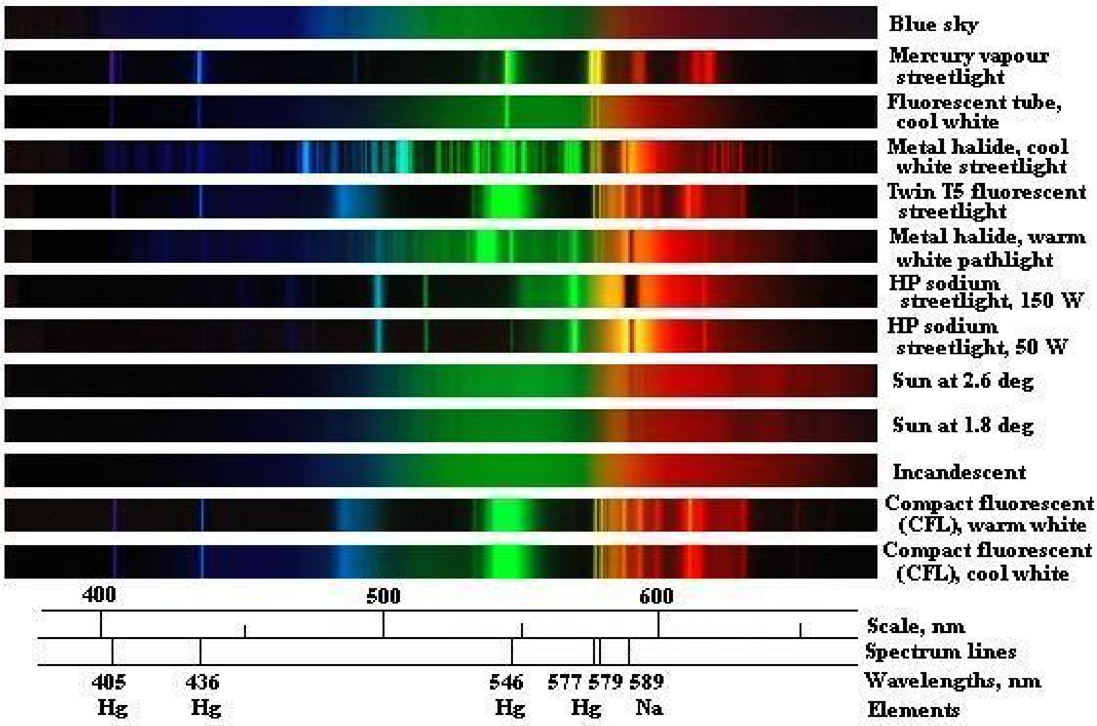

Figure A1. Grating spectra of common light sources with fixed arbitrary slit width and constant photopic light exposure.

In the order shown in the figure, the light sources are:

- afternoon clear blue sky at 45º altitude and 90º in azimuth from the sun,
- 80-W mercury vapour streetlight, barely showing fluorescence from the bulb coating (Melbourne suburb)
- 40-W fluorescent tube lamp, cool white (domestic indoor fitting)
- metal halide streetlight, 100-W?, slightly bluish white appearance (City of Melbourne),
- streetlight with twin 14-W T5 fluorescent tubes (Sustainable Public Lighting trial, Melbourne suburb),
- metal halide path light, warm white appearance (City of Melbourne park light),
- 150-W? high pressure sodium streetlight (City of Melbourne),
- 50-W high pressure sodium streetlight (Sustainable Public Lighting trial, Melbourne suburb),
- setting Sun at 2.6º altitude,
- setting Sun at 1.8º altitude,
- 75-W incandescent reflector lamp (domestic),
- 11-W compact fluorescent lamp, warm white (domestic), and
- 11-W compact fluorescent lamp, cool white appearance (domestic).

The original intention was to obtain the spectral output graphs with standard astronomical image processing software, and to use the data in calculations. Although published data were used instead, the spectra have been reproduced here as they show features mentioned in section A1. Note the amount of blue light in the daytime sky and the paucity of blue light from the sun at low altitude and from an incandescent lamp.

The high pressure sodium lamps emit much of their light in the vicinity of the yellow spectral line of sodium vapour, but the centre of that region is dark (from self-absorption by the vapour). The same feature is present in the spectrum of the metal halide path light, indicating that sodium has been added to the lamp to improve colour rendition. The other metal halide lamp does not have this addition. The compact fluorescent lamps (CFLs) and the T5 fluorescent have a typical ‘tri-phosphor’ (or ‘three-band’) spectrum. Differences between the ‘warm’ and ‘cool’ CFLs in the figure are subtle, but the whiter output of the ‘cool’ lamp is a result of more bluish light and less red.

A3. RELATIVE OUTPUT OF MELATONIN SUPPRESSING LIGHT

If of suitable intensity, light in the visible range of the spectrum (wavelengths of about 380 nm to 780 nm) can be detected by the human visual system. At wavelength λ within this range, the sensitivity of the visual system in daylight or bright twilight conditions (known as photopic conditions) can be denoted by V_λ. The peak photopic response is in the green part of the spectrum, at about 555 nm. A complete set of V_λ values, based on observations by several observers, was defined by the International Commission on Illumination (CIE) in 1931 as the standard luminosity curve for use in calculations of visual quantities (eg Hunt 1991, Appendix 2).

In its dark adapted state at night, the human visual system has greater sensitivity to light than is the case in photopic conditions and the peak response is at about 510 nm (blue-green in photopic conditions). Dim light conditions down to the absolute threshold of vision are called ‘scotopic’, and the scotopic luminosity curve is designated by the set of V'_λ values also defined by the CIE. (There is a transition range called ‘mesopic’ roughly corresponding to late twilight conditions. Visual response in mesopic conditions is intermediate between photopic and scotopic responses.)

At a wavelength λ, the power output of a light source can be called P_λ. A set of P_λ values over a range of wavelengths is called a spectral power distribution (SPD) for the light source.

If the luminosity curve is scaled so that its integral from 380 nm to 780 nm is unity, the total sensation of light from a particular light source is proportional to the integral of P_λ V_λ over that range. In practice, such convolutions are approximated by summations, typically at wavelength steps of 5 nm or 10 nm, depending on the accuracy desired. If only the relative visual sensations from different light sources are of interest, the scale of the V_λ curve and the scale of the SPD are immaterial provided they are constant from one light source to the next.

Melatonin is a hormone-like chemical found in most living things. Melatonin in humans and many other species is secreted only in dark conditions, so its level varies cyclically over 24 hours. In humans with a natural pattern of sleep at night, light exposure of the eyes at night can reduce or stop the production of melatonin, especially when the exposure is after midnight. The wavelength dependence of such biological effects of light is called the action spectrum. For melatonin, it is usually given for the ‘eyes open’ condition, although action spectra for the ‘eyes shut’ condition are sometimes used when appropriate, eg when light is shone on eyes closed voluntarily or during sleep.[35] Laboratory and theoretical studies indicate that the action spectrum of melatonin suppression in humans has a peak at about 460 nm (Brainard, Hanifin, Greeson et al. 2001) The effect in mammals generally appears to be largely confined to the shorter wavelength parts of the spectrum (violet, blue and blue-green parts in photopic conditions), although intense exposures even as far along the spectrum as 700 nm can produce small responses in rodents (Hanifin, Stewart, Smith, Tanner, Rollag and Brainard 2006).

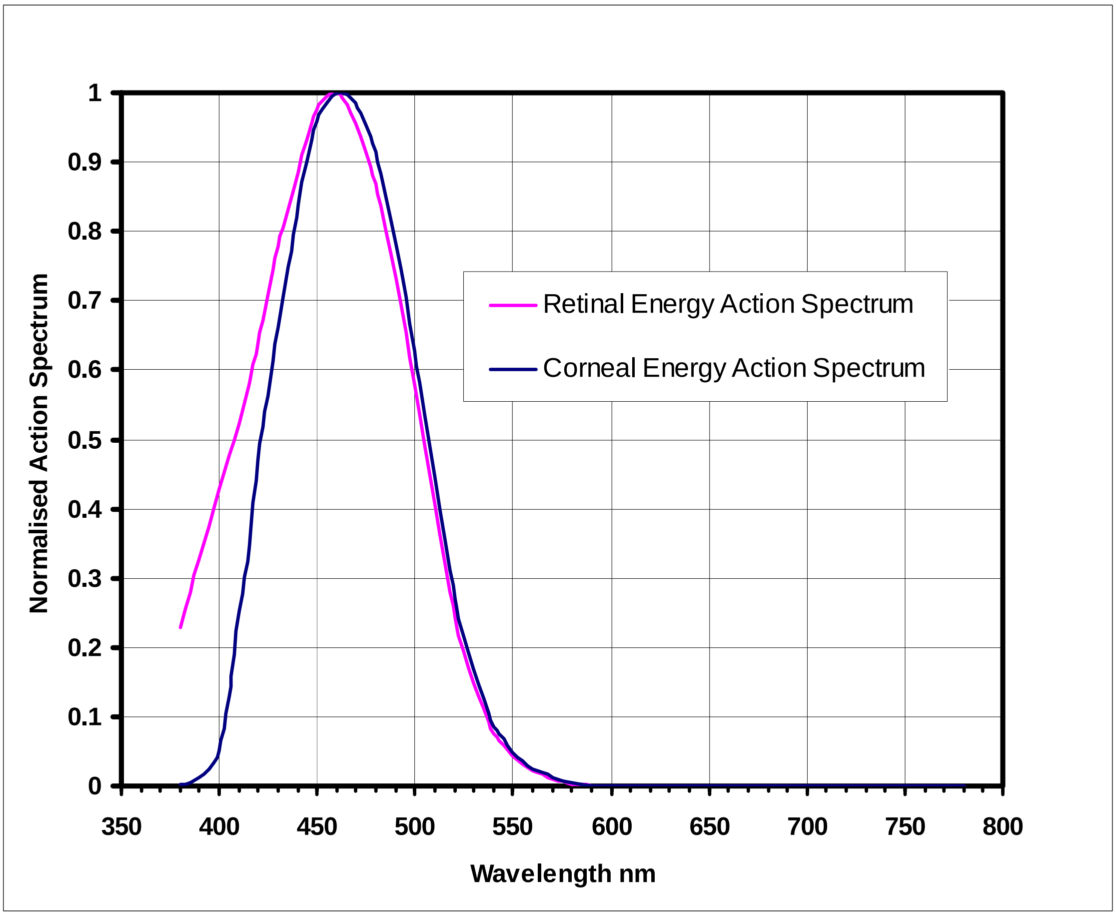

Figure A2. Normalised energy action spectra for melatonin suppression in humans, based on data of Brainard, Hanifin, Greeson et al. (2001) and Boettner and Wolter (1962).

The Brainard, Hanifin, Greeson et al. (2001) data were based on a best fit to the absorbance of an opsin, retinaldehyde. The actual opsin involved in humans is now known to be melanopsin, but this makes little difference to the present results as the peak wavelength is unchanged. Their data were in the form of fluence (photon density) at the retina. These were converted here to an energy-proportional basis by dividing by

[35] Robinson, Bayliss and Fielder (1991) measured the transmittance of adult and neonatal human eyelids. Essentially the lids are long pass red filters, with transmittances of 14.5% and 21.4% respectively at 700 nm, and less than 3% at 580 nm and below.

the wavelength, and converted to values at the cornea, again wavelength by wavelength, by multiplying by the spectral total transmittance values of the human eye (Boettner and Wolter 1962, their Fig. 7). The resulting normalised action spectra are shown in Figure A2. They are reasonably consistent with recent observations at 420 nm by Brainard, Sliney, Hanifin et al. (2008).

Because the melatonin action spectrum is separated in wavelength from the photopic and scotopic luminosity curves, light sources with different amounts of short wavelength light for a given amount of visible light will differ in the suppression of melatonin that will result from a given exposure. These differences can be calculated accurately with little difficulty.

Convoluting the action spectrum values at the cornea with the SPD of a particular light source gives a quantity that is proportional to the melatonin-suppressing effect of that source. The ratios of this quantity to the photopic or scotopic visibility of the light source are independent of the ordinate scale of the SPD of the source. These ratios are here called respectively the Photopic Melatonin Suppression Factor (PMSF) or Scotopic Melatonin Suppression Factor (SMSF) for the particular light source.

Provided that the particular kind of Melatonin Suppression Factor is calculated in the same way for several light sources, the individual MSF values show the relative melatonin-suppressing effect between the various light sources.

To put this MSF information for different lamp types into a more readily comprehensible form for the present purpose, the MSFs of a high pressure sodium lamp are used as a benchmark for comparison. Other lamps are then assigned a Melatonin Suppression Ratio (MSR), photopic or scotopic as the case may be, using the formula

$$MSR_{lamp} = MSF_{lamp} / MSF_{HPS}.$$

The MSR for a lamp represents the ratio of its melatonin-suppressing effect relative to that of a high pressure sodium lamp in circumstances where both lamps are producing equal illuminances, photopic or scotopic as may be the case.

It has not been thought necessary at this stage to take account of the increase of light absorption (especially short-wavelength visible light) by the ocular media (especially the crystalline lens) with increasing age. Although much of that compound effect is cancelled out by working with relative quantities, it still might appear to be at odds with the statement by Turner and Mainster (2008) that a 10-year-old child has circadian photoreception that is 10-fold greater than that of a 95-year-old adult with intact crystalline lenses. Again, however, much of that factor arises from the reduction in pupil size with age, and of course that reduction also applies to the amount of visible light reaching the retina. The present results are considered applicable to the bulk of the human population. If the needs of the people making up that bulk are met, the needs of older people in this respect are also likely to be met. There does not appear to be enough evidence at this stage to say whether additional requirements might be required for the systemic health of children.

A4. Spectral Characteristics of Typical Lamps

TABLE A1. RELATIVE MELATONIN SUPPRESSING EFFECT OF LAMPS

Reference, Lamp Description	Lamp or Source	Correlated Colour Temperature kelvin	Photopic MSR Relative to HPS	Scotopic MSR Relative to HPS
Hunt (1991), LPS	Low pressure sodium	1740	0.0127	0.0356
Hunt (1991), HPS	High pressure sodium	2000	1.0	1.0
Hunt (1991)	Illuminant A	2854	2.624	1.179
Ohno and Jergens (1999), #4	Metal halide	2900	3.197	1.438
Hunt (1991), F12	Tri phosphor fluorescent	3000	2.345	1.186
Ohno and Jergens (1999), #1	Tungsten halogen	3200	3.139	1.273
Hunt (1991), MBF	Mercury vapour, coated bulb	3800	2.585	1.548
Ohno and Jergens (1999), #3	Tri phosphor fluorescent	4000	3.861	1.507
Hunt (1991), F2	Normal fluorescent	4230	3.835	1.546
VLI (2009), 950 Series	*Metal halide 'natural white'	5000	4.2400	1.527
Hunt (1991), F10	Tri phospor fluorescent	5000	4.624	1.587
Hunt (1991), F7	Broad band fluorescent	6500	6.356	1.740
Hunt (1991) Xenon	High pressure xenon	6500	6.916	1.771
Ohno and Jergens (1999) #7	Cathode ray tube, set bluish	9300	7.6020	1.715

*Note that this lamp is typical of many commercially available examples in which the spectral continuum has been increased relative to the spectral lines: this tends to increase the colour rendering index to high values. This particular lamp was selected because its SPD was available in an online graph that could readily be enlarged and printed for direct measurement of the ordinates.

To show how these melatonin ratios work in practice, calculations were made for various common types of light sources listed in Table A1. One SPD was extracted from a graph in commercial literature. The remaining SPDs were obtained from the scientific and technical literature, and are presumed to be highly reliable. In some cases the CCTs are approximations rather than exact values, but this has no appreciable effect in the present application. No induction lamps were included as their characteristics are similar to fluorescent lamps with similar phosphors.

The two rightmost columns in Table A1 show photopic and scotopic MSRs relative to a HPS lamp. The photopic results are plotted against CCT in Figure A3, and the scotopic results likewise in Figure A4. As the CCT of a lamp increases with its proportion of short wavelength light, lamps with high CCTs thus tend to have high MSRs but the relationship in the two cases is not a single function across lamp types. This raises the possibility that SPDs could be manipulated by physical changes in lamp design to minimise the MSRs for a given CCT, but the scope for doing so would appear to be limited, and it might also result in an unwanted reduction of the CRI.

Both graphs indicate that only LPS produces less of the active short-wavelength visible light when it is matched to the same photopic light output as that of the comparison HPS. All of the remaining lamps produce relatively more melatonin-suppressing light than HPS. In photopic conditions, in no case of the remaining lamps is the amount of active light less than double that of HPS and it is often more (Figure A3).

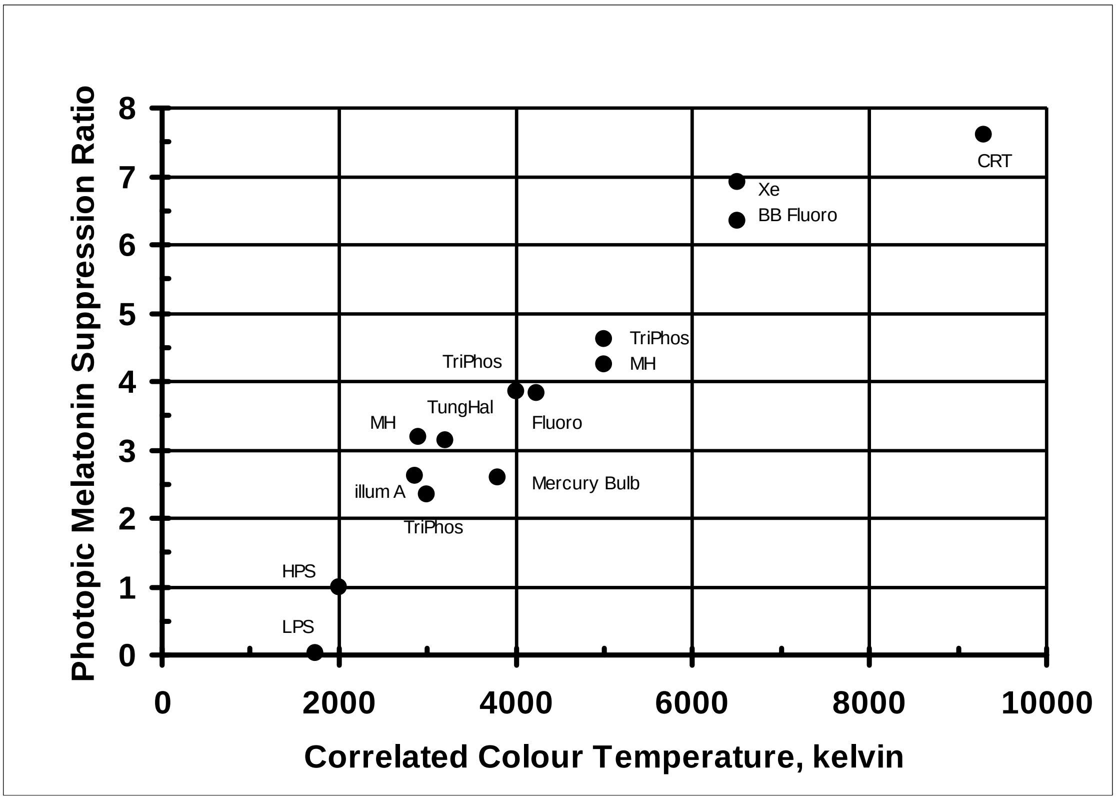

Figure A3. Photopic Melatonin Suppression Ratio for various lamps relative to HPS.

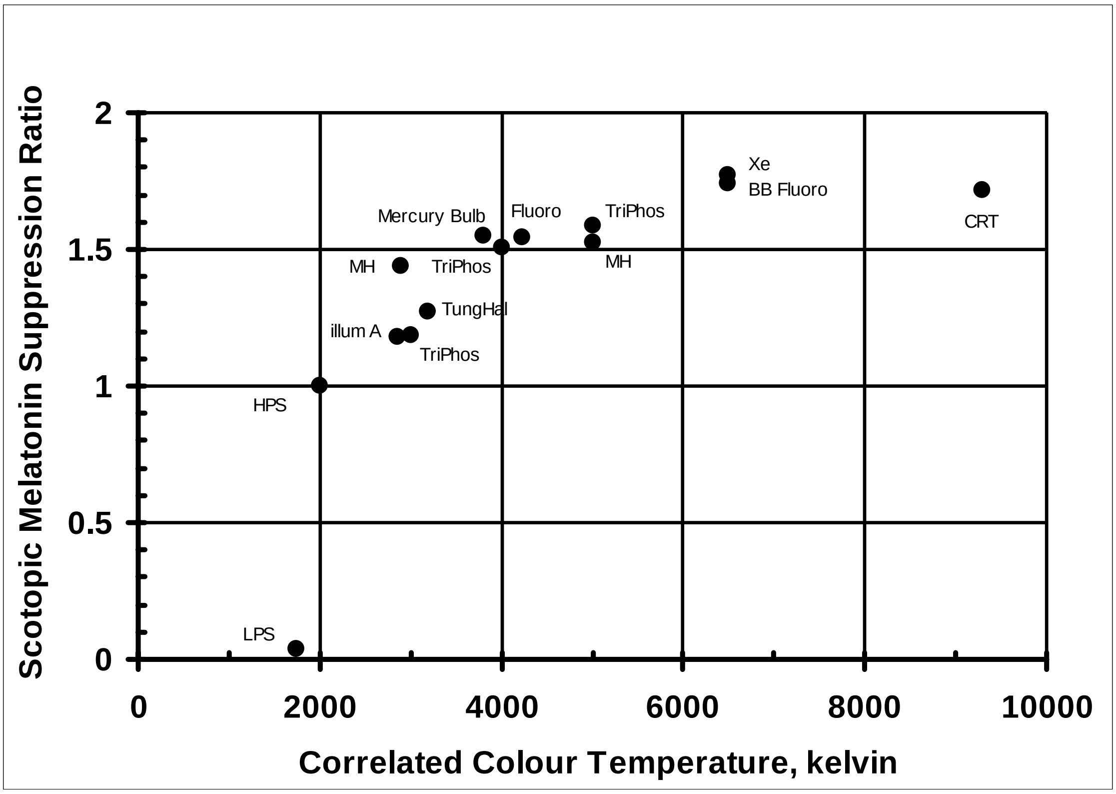

Figure A4. Scotopic Melatonin Suppression Ratio for various lamps relative to HPS.

The MSRs are not as great when equal scotopic visibility is the criterion (Figure A4), but HPS still produces relatively less of the active shortwave light than the other lamps types apart from LPS. If minimising melatonin suppression at night is important, the revival of LPS for outdoor lighting would appear to be well worth serious consideration, provided that the bulky LPS lamps must only be used in specially designed luminaires that do not allow direct emission of light above the horizontal.

A5. RELATIVE SCOTOPIC OUTPUT OF VARIOUS LAMPS

Towards the perimeter of the illuminated field of a streetlight on a moonless night and in the absence of other lighting, the viewing conditions will tend to change from photopic through mesopic to scotopic. It might be thought ideal or at least useful for visibility to be more or less constant across the changeover range in distance or angle. Under this criterion, lamps with a large ratio of scotopic to photopic output would tend to be better than lamps with a relatively small ratio. HPS lamps are acknowledged to be in the latter category. Indeed, in the Australian Standard for street and path lighting, the choice of lamp type is biased against HPS lamps by the application of a 25% derating to their photopic output.

The scotopic and photopic responses for a particular lamp at a wavelength λ can be found as the product of the lamp's SPD value at that wavelength and the respective luminosity values, V'_{λ} or V_{λ}. Summing each set of products, wavelength by wavelength, gives the two responses. Dividing the scotopic/photopic ratio for a particular lamp by that for a HPS lamp gives the relative amount of scotopic response

TABLE A2. RELATIVE VISIBILITY AND RELATIVE SKYGLOW VISIBILITY FOR VARIOUS LAMPS					
Reference, Lamp Description	**Lamp or Source**	**Correlated Colour Temperature kelvin**	**Scotopic Output Relative to HPS**	**Photopic Skyglow Relative to HPS**	**Scotopic Skyglow Relative to HPS**
Hunt (1991), LPS	**Low pressure sodium**	**1740**	**0.357**	**0.94**	**0.219**
Hunt (1991), HPS	**High pressure sodium**	**2000**	**1**	**1**	**1**
Hunt (1991)	**Illuminant A**	**2854**	**2.226**	**1.1290**	**2.4630**
Ohno and Jergens (1999), #4	**Metal halide**	**2900**	**2.222**	**1.2220**	**2.5790**
Hunt (1991), F12	**Tri phosphor fluorescent**	**3000**	**1.977**	**1.127**	**2.146**
Ohno and Jergens (1999), #1	**Tungsten halogen**	**3200**	**2.466**	**1.1530**	**2.7920**
Hunt (1991), MBF	**Mercury vapour, coated bulb**	**3800**	**1.669**	**1.1140**	**1.8900**
Ohno and Jergens (1999), #3	**Tri phosphor fluorescent**	**4000**	**2.562**	**1.1790**	**3.0110**
Hunt (1991), F2	**Normal fluorescent**	**4230**	**2.48**	**1.1720**	**2.9370**
VLI (2009), 950 Series	***Metal halide 'natural white'**	**5000**	**2.776**	**1.1820**	**3.3020**
Hunt (1991), F10	**Tri phospor fluorescent**	**5000**	**2.913**	**1.2140**	**3.4950**
Hunt (1991), F7	**Broad band fluorescent**	**6500**	**3.654**	**1.2610**	**4.5730**
Hunt (1991) Xenon	**High pressure xenon**	**6500**	**3.905**	**1.2680**	**4.9300**
Ohno and Jergens (1999) #7	**Cathode ray tube, set bluish**	**9300**	**4.433**	**1.34**	**5.5600**

when the lamp has the same photopic output as the HPS lamp. Such results for the Table A1 set of lamps are shown in Figure A5. The actual data points are given in column 4 of Table A2.

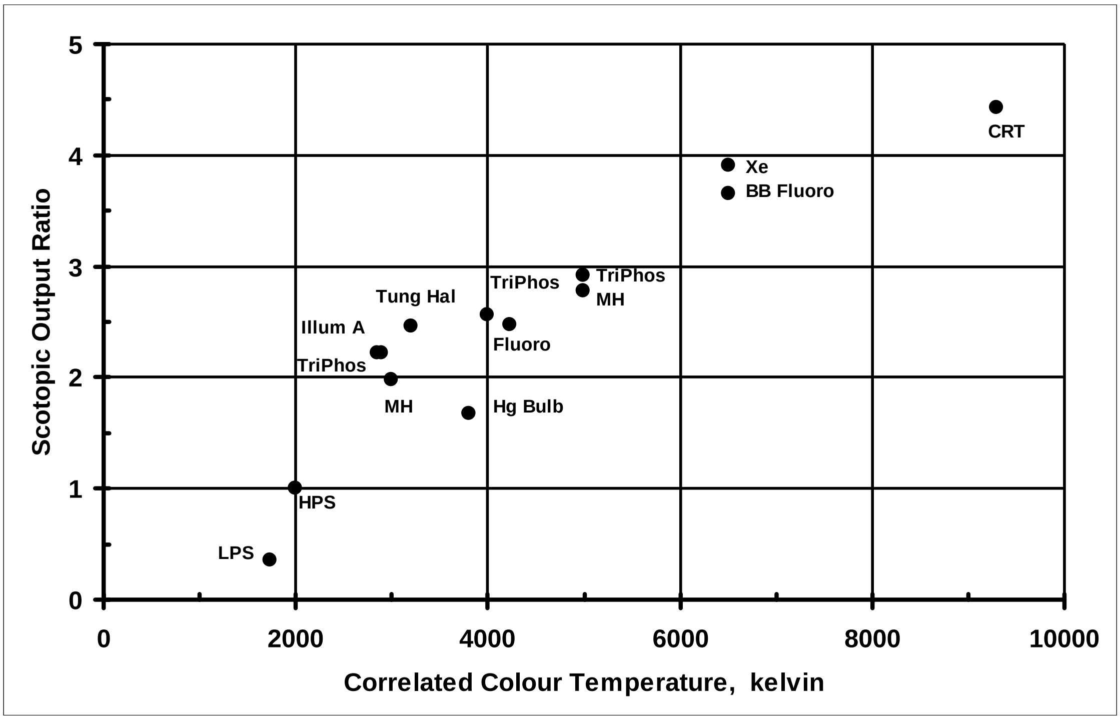

Figure A5. Scotopic output of various lamps relative to the scotopic output of a high pressure sodium lamp, with all lamps having equal photopic output.

The fact that sodium lamps do not perform as well as most other lamps in scotopic conditions is well known. In isolation, this reason has justified some displacement of HPS and much more displacement of LPS by other types of lamp. But even this argument can be refuted if the comparison is made not with lamps of equal photopic output but with lamps having equal electrical power consumption: the scotopic performance of the sodium types is then acceptably good and the photopic performance tends to be outstandingly better than the performance of other types.

A6. Rayleigh Scattering of Light from Various Sources

Another important issue in connection with the spectral characteristics of various lamp types is that the amount of light scattered by the atmospheric molecules is markedly dependent on the wavelength of the light, λ. This effect needs to be explored in order to ascertain whether lamp types recommended to reduce adverse effects on the melatonin cycle will increase, have no effect on, or reduce artificial skyglow. The topic of atmospheric scatter of light from different light sources has already been considered by many others (eg Knox and Keith 2003) but not for the present purpose.

As Rayleigh (1871) brilliantly showed, the polarisation and blue colour of the sky result from scattering of sunlight by molecules of air, which are much smaller than the wavelengths of visible light. The amplitude of the scattering depends on the inverse square of the wavelength, so the intensity of the scattering is proportional to the inverse fourth power of the wavelength. There is also an $(n-1)^2$ term, where n is the refractive index of air. As n is also wavelength-dependent, Rayleigh showed that the total scattering effect is inversely proportional to approximately the 4.2 power of wavelength.

Water droplets and particles of dust, salt, smoke etc. suspended in the atmosphere are the disperse phase of the atmospheric aerosol. They add to atmospheric scattering of light but generally this is a relatively small and variable component. As many of the particles approach or exceed the wavelengths of visible light, there is usually no strong wavelength-dependence of scattering. For these reasons, non-Rayleigh scattering is not included in the following calculations.[36] Because the results of interest are again comparisons between lamps, relative rather than absolute quantities are used, with further substantial savings in effort.

Firstly, a scattering coefficient $\lambda^{-4.2}$ was calculated at 5-nm intervals for wavelengths in the range 380 nm to 780 nm. These values are proportional to the Rayleigh scattering for a light source with a constant spectral power across the wavelength range, ie an 'equal energy' source. This set of values can thus be considered as the SPD of artificial skyglow from an equal energy light source. The photopic visibility of this skyglow is proportional to the sum of the products of this distribution and the luminosity curve ordinates, V_λ, wavelength by wavelength. Likewise, the scotopic luminosity coefficients, V'_λ, can be used instead to get a quantity proportional to the visibility of the artificial skyglow under scotopic conditions.

The respective equal energy skyglow values were then multiplied by the various SPD values in turn to give the relative photopic and scotopic responses for Rayleigh skyglow created by each lamp. Comparisons between lamp characteristics were made with the quantities scaled so that the photopic output of each lamp matched that of HPS (columns 5 and 6 of Table A2, Figures A6 and A7).

Apart from LPS, which has outstanding performance in terms of producing less skyglow than HPS for equal photopic visibility of direct illumination, all other lamps produce relatively more skyglow than HPS.

[36] Knox and Keith (2003) likewise concluded that it was appropriate to confine their calculations to Rayleigh scattering. In assessing the relative effects of MH and HPS lamps in producing skyglow, they compared results for equal power inputs to the lamps as well as for the equal photopic outputs used here, an in addition they included spectrally dependent reflections from asphalt and concrete. They concluded that in those circumstances MH produced two or three times as much skyglow as HPS. The present results are consistent with their findings.

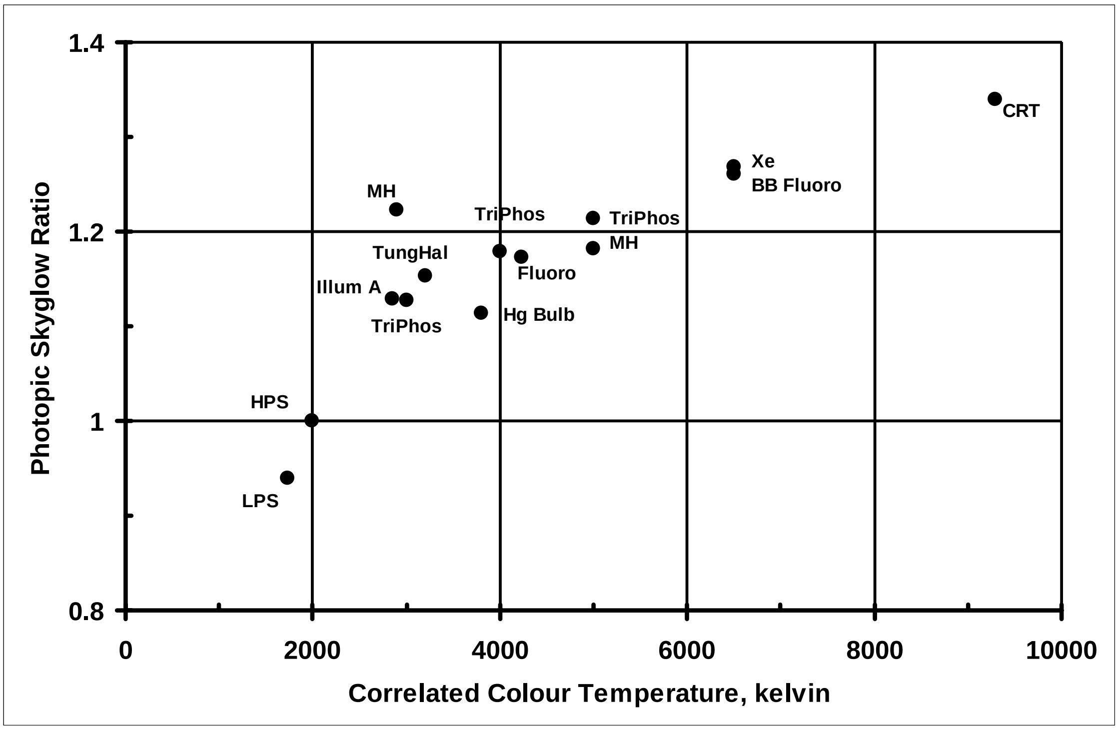

Figure A6. Photopic skyglow from Rayleigh scattering of light from various lamps relative to the photopic skyglow from a high pressure sodium lamp, with all lamps having equal photopic output.

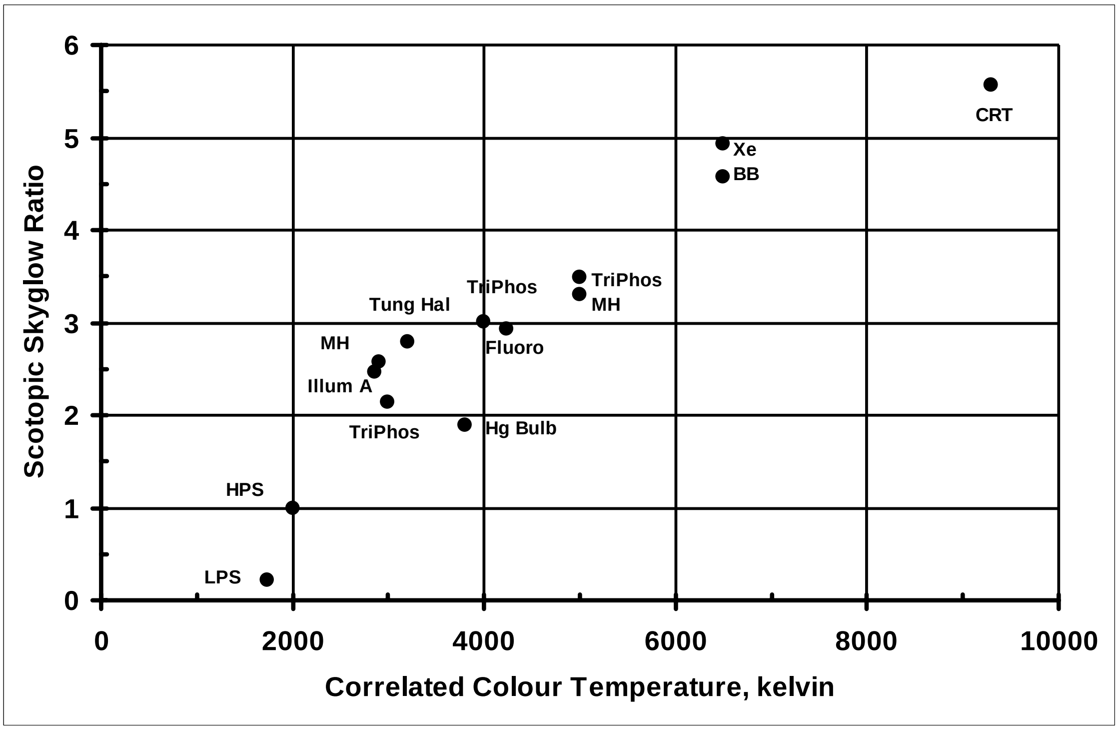

Figure A7. Scotopic skyglow from Rayleigh scattering of light from various lamps relative to the scotopic skyglow from a high pressure sodium lamp, with all lamps having equal photopic output.

If an isolated site existed where all of the artificial skyglow was produced by direct light spill or reflection from spectrally neutral surfaces using one type of lamp for outdoor lighting, say, then Figure A6 indicates how much photopic skyglow would be reduced at the site if the lighting were changed to HPS giving equal photopic illuminance. For instance, if the lighting had been provided with broad band fluorescent lamps, the changeover would cut photopic skyglow by a factor of 1.26, and for scotopic skyglow, by a factor of 4.57.

A7. CONCLUDING REMARKS

This work confirms claims made by light pollution campaigners and others that for a given amount of photopic illumination, there can be large differences in spectrally-dependent characteristics between common lamp types currently used for lighting at night, all else being constant. This is particularly so for the relative scotopic output of various lamps, and for the relative photopic and scotopic luminances of the ‘light domes’ above outdoor installations of particular types of lamps at night. LPS and HPS lamps are markedly less environmentally degrading than other common lamp types in these respects.

It is well known that LPS lamps in isolation are useless for hue recognition. Typical HPS lamps are much better, but still not good for visual tasks that require high quality colour rendering. Other high intensity discharge lamps with higher CCTs tend to give better colour rendering because of their increased output in the blue part of the visible spectrum. But the best way of improving colour rendering of discharge lamps is to ‘fill in’ the spectral regions between the spectrum lines. Ways of doing this include the use of phosphor coatings, adding more elements to the gas in the discharge path, and increasing the gas pressure. The resultant changes seem to be more evident in graphs of the SPDs than in colour reproductions of the spectra, mainly because of truncation and compression of the intensity scale inherent in ordinary colour printing.

Lamps emitting a greater proportion of short wavelength light relative to HPS are also perceived to give brighter illumination than the sodium lamps at distances from the luminaire where conditions are mesopic or scotopic. However, the relative amounts of light pollution caused by the non-sodium lamps in photopic units and especially in scotopic units also increase with the short wavelength content of the output. This was once of concern primarily to astronomers. Now this content is known to be a serious ecological issue and a serious human health issue.

It is well established for mammals that exposure to short-wavelength visible light (ie blue and violet) at night can interfere with endocrine cycles such as the melatonin cycle, and thereby degrade mammalian defences against some cancers. Large scale epidemiological studies have indicated that the incidence of human breast and prostate cancers is reliably and substantially greater in the more brightly lit cities (Kloog, Haim, Stevens, Barchana and Portnov 2008; Kloog, Haim, Stevens and Portnov 2009).

For outdoor use, HPS lighting provides a useful degree of colour rendering, high electrical efficacy, relatively inexpensive lamps, long operating lifetimes and minimal blue-violet output. It would appear difficult to justify the use of any other type for outdoor public lighting, with the exception of LPS, which is superior again in terms of electrical efficacy and produces virtually no toxic blue-violet light output at all. LPS also has excellent characteristics in terms of minimising light pollution provided that it is used only in specially designed luminaires installed to radiate no direct light above the horizontal.

The primary drawback of LPS is that in the absence of light from other sources, it does not allow hue discrimination, and colour discrimination is limited to judgements of lightness and darkness. Despite claims that this increases crime, there is no reliable evidence whatsoever for this. But the lack of hue discrimination may have the benefit of deterring types of graffiti that depend on colour for their visual impact, however.

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