Light Pollution and Lighting Codes

An Analysis of the Light Pollution Control Effectiveness of the IDA-IES Model Lighting Ordinance and the IDA Pattern Outdoor Lighting Code

Christian B. Luginbuhl
U.S. Naval Observatory Flagstaff Station
cbl@nofs.navy.mil
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Executive Summary

Introduction

Efforts to control light pollution are becoming more common as citizens and communities concerned about environmental impact and energy savings join astronomers and dark sky advocates. A typical approach is to adopt municipal ordinances curbing the types of outdoor lighting that cause uplight and other wasteful or obtrusive lighting practices. The first comprehensive outdoor lighting code adopted in 1972 by Tucson, Arizona was often used as an example for other communities to follow. In 2000 the International Dark-Sky Association published the Pattern Outdoor Lighting Code (POLC) that served as an adaptable guideline for interested communities.

In 2011, another approach to municipal lighting guidelines called the Model Lighting Ordinance (MLO) was released jointly by the International Dark-sky Association (IDA) and the Illuminating Engineering Society (IES). The POLC and MLO represent two different regulatory approaches to protecting dark skies and limiting the off-site impacts of outdoor lighting such as glare and trespass. There are numerous lighting codes in use derived from the POLC. The newer MLO does not yet have any lighting codes built upon its foundation. Neither approach has been scrutinized in detail for effectiveness, nor have they been compared with one another.

The goal of this study was to evaluate the effectiveness of these two approaches using the maximum lighting amount and minimum shielding allowed, through application of the standards to15 actual commercial sites. The two codes were compared with each other and where possible with unregulated outdoor lighting practice.

Results

Total Lumen Amounts

The total lumen amount allowed by the POLC is reduced by more than 50% compared to average unregulated practice for commercial and business developments. The MLO total lumen allowances for these same projects often permit significantly more light than used in the average unregulated practice, in some cases more than 10X more, and 2X – 20X greater than under the

POLC.

Also, the MLO lumen allowances following the Performance Method are approximately twice the allowances determined under the Prescriptive Hardscape Area Method. These greater allowances are not significantly reduced by the “limits to off site impacts” under the Performance Method.

Direct Uplight and Sky Glow

The shielding standards of the POLC and MLO follow different approaches, and lead to substantial differences in the amount of light allowed to shine directly upward. POLC standards produce a 90% or greater reduction in direct uplight compared to average unregulated practice in all Lighting Zones (LZ). Under the MLO, direct uplight is dramatically increased in all LZ outside the darkest zone, allowing direct uplight lumen densities 2X or more greater than unregulated practice, and about 50X greater than POLC standards.

Relative sky glow impacts are assessed using a new metric called the Sky Glow Index (SGI), a measure that accounts for the effect on sky glow of light emitted directly upward from incompletely shielded fixtures and light reflected from the ground and other surfaces.

Sky glow impacts as measured using the SGI are reduced 80% or more compared to unregulated practice with lighting following POLC standards.

Sky glow impacts under MLO are about the same as those of unregulated practice for the darkest LZ but are dramatically increased in LZ where most commercial activities would occur, and up to 100X the impact allowed under the POLC.

Glare

An analysis of over 250 fixtures shows that the POLC “fully shielded” shielding standard provides glare control very similar to the MLO LCS G1 standard. However, the LCS standard is not mandatory under the MLO; another option has glare limited only by the limits to the maximum vertical illuminance at the property boundary: these limits are 17X – 500X brighter than those allowed under the POLC or the LCS G1 standard.

Lamp Spectrum

POLC limits most area lighting to yellow sources such as HPS, LPS and amber LED. As MLO does not address lamp types, the probable use of blue-rich white lighting under MLO means that *visible* sky glow for dark-adapted vision is likely to be increased an additional factor of 3X to 5X (i.e., up to 300X – 500X) compared both to POLC standards and to what is still common unregulated practice using HPS.

Conclusion

The POLC is found to provide substantial improvements over unregulated outdoor lighting practice in all evaluated light pollution impacts. In the "brightest" POLC LZ 3, the total lighting amount for commercial sites is reduced on average to about one-half or less of the amount used on unregulated sites; in POLC LZ2 they are reduced to one-quarter and less. The amount of sky glow expected is reduced nearly a factor of 100 compared to average unregulated outdoor lighting practice.

Under MLO standards, outside of MLO LZ 0 and 1, the total lumen allowances, direct uplight allowances, and amount of sky glow are notably greater than expected under POLC standards; in MLO LZ 3 and 4 they are dramatically greater. In LZ 2 and above sky glow impacts are greater than what can be expected even when lighting is unregulated.

The MLO approach to fixture shielding and "limits to off site impacts" is ineffective in limiting sky glow, light trespass and glare. The MLO allows any (including no) fixture shielding, permitting the installation of the most egregious types of lighting fixtures. Compared to POLC lighting codes with "fully shielded" standards, even the (optional) MLO Luminaire Classification System "BUG" shielding standards and "off-site impact" limits offer weaker control of glare and uplight than the POLC.

The POLC requires the use of yellow (LPS, HPS, amber LED) or warm-white LED (CCT<3500K) for general area lighting, which accounts for 80% to 90% of outdoor lighting, thus reducing many aspects of light pollution such as visible sky glow, glare, human circadian impacts, and impacts on many biological systems. MLO does not address lamp spectrum, and thus leaves this crucial aspect of light pollution unaddressed.

In general, the POLC is shown to be far more effective than the MLO in curbing the detrimental aspects of outdoor lighting. The analysis of the various MLO regulatory options shows that the Performance Method Option B provides notably poor control of both direct uplight (and therefore skyglow) glare, and light trespass.

We conclude that a substantial reduction in light pollution is attainable to communities that adopt lighting codes following POLC standards. Adoption of a code based on the IDA-IES MLO cannot realistically be expected to produce improvement. Certainly for the medium-sized and small communities and rural areas that most frequently seek to reduce light pollution and protect the natural night environment, the MLO represents a significant step backward in light pollution limitation and control compared to the older IDA POLC model.

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1. Introduction

1.1 Background

The first regulation to address the impact of outdoor lighting on night skies was a 1958 prohibition on sweeping advertising searchlights in Flagstaff, Arizona. This was followed by the first comprehensive lighting code in 1972, adopted in Pima County and Tucson, Arizona, in response to concerns of the astronomical observatories in the region. For the next 20 years this code served as a *de facto* model, used as the basis for lighting codes throughout Arizona and other states in the U.S. Many of these derived codes were modified with various purposes and with varying degrees of lighting and legal expertise, with the result of producing both advances in light pollution control and a variety of legal and lighting-technical errors.

With the aims of collecting the advances and correcting the common errors in these codes, the International Dark-Sky Association (IDA) undertook in 1998 its first effort to produce a model outdoor lighting code, resulting in the USA Pattern Code contained in the *IDA Outdoor Lighting Code Handbook* (IDA, 2000), published in 2000. Since then this model has served as the basis for scores of codes now in place throughout the U.S.

A developing alliance between IDA and the lighting industry in the early 2000s led to a renewed effort by IDA and the Illuminating Engineering Society of North America (IESNA or IES) to develop a new model lighting ordinance that would meet light pollution control objectives of the dark-sky community yet be more in line with the recommendations and practices of the lighting industry.

The *Joint IDA-IES Model Lighting Ordinance* (IDA-IES, 2011) was completed in June 2011. It is described as "as a valuable guide for environmentally responsible outdoor lighting in North America" and touted as an effective approach to "help municipalities develop outdoor lighting standards that reduce glare, light trespass, and skyglow" (IDA, 2011) and as an outdoor lighting standard that "curtails light pollution and improves the nighttime environment for night-sky viewing and astronomy, helps protect the natural environment from the adverse effects of night lighting… [and] conserves energy and resources to the greatest extent possible" (Clanton, 2010). The User's Guide contained within it claims "MLO will allow communities to drastically reduce light pollution and glare and lower excessive light levels" (IDA-IES, 2011). Thus, as for the 2000 Pattern Code, it is promoted principally as a method to protect the night sky and reduce other light pollution impacts.

The technical approach of the IDA-IES MLO is notably different than in the Pattern Code. Instead of standards based on the (limited) knowledge concerning the light pollution impacts of outdoor lighting as in the Pattern Code, MLO cleaves instead to an approach based on recommended practices developed by the lighting industry in the context of lighting design and energy conservation.

To address the critical aspect of lighting amount, the MLO contains lighting allowances based on the amounts recommended by the lighting industry for a variety of specific lighting uses and "activity" levels[1], thus rejecting the general (i.e., not use-specific or activity-level-specific) lumen cap approach developed in outdoor lighting codes over 20 years ago as exemplified by the 1989 Flagstaff and Coconino County lighting codes (FDSC, 2011), as well as the IDA Pattern Code. More specifically, guidance on lighting allowances was drawn (largely) from the energy densities in California Title 24 (and from ANSI/ASHRAE/IESNA Standard 90.1), which themselves are based upon the Recommended Practices of the lighting industry as represented by IES (PG&E, 2007).

When developing standards for total lighting amounts, lighting codes underlying the Pattern Code based their approach on an area's (or zone's) sensitivity to increased sky glow. That certain lighting uses (such as brightly illuminated car dealerships or service stations) may be implicitly restricted in areas with tight caps on total lighting amount is an understood and intended consequence of the general lumens approach[2]. In contrast, the MLO lighting amounts are explicitly devised to accommodate the recommended practices of the lighting industry. The lighting allowances and the idea of different "ambient" lighting conditions or levels are not based on dark sky protection in the zone or near it, and are further critically not based on the idea of "the minimum levels… for night-time safety, utility, security, productivity, enjoyment, and commerce" explicitly stated as a purpose of most lighting codes since the 1972 Tucson code as well as in the MLO itself (IDA-IES, 2011, Section I.a., pg.5). The industry recommendation and MLO allowance of more lighting in "brighter" districts is fundamentally at odds with the concept of "just the amount needed and no more" that lies behind the majority of lighting codes.

This way of devising lumen density and other standards in MLO represents an alternate approach in lighting codes: the zones and associated standards are defined by lighting levels, design recommendations, and even available products of the lighting industry, with the apparent assumption or hope that the desired environmental protection will follow as a consequence.

Yet the ability of lighting codes developed in this manner to curtail light pollution has not been shown. It is certainly clear that the lighting recommendations of the IES, and too many products of lighting manufacturers, have been developed with at best limited understanding of the light pollution impacts of outdoor lighting.

As these two lighting code models directly address total lighting and uplight amounts, a quantitative evaluation of many light pollution impacts from lighting following these differing guidelines is possible. This report describes such an analysis, including an evaluation of total lighting allowances (or "lumen densities"), total upward-directed light ("uplight"), expected sky glow impacts, trespass and glare. These impacts are also compared to what is known of those arising from unregulated outdoor lighting. The intention is to provide information on which of these two regulatory frameworks can be expected to best protect dark skies and limit light pollution.

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[1] Most commonly expressed as "low / medium / high activity" (e.g., Table 22.2 in IESNA, 2011b), but also "basic / enhanced security," "main business district / secondary business district," "dark surrounds / light surrounds," in this and other IES documents, and referring variously to the "ambient lighting level" of an area, visual adaptation level of persons using an area, or even "lighting expectation" or "desire" of users or owners.

[2] It is the nature of zoning laws in general to limit uses based (traditionally) on "compatibility" issues.

As lighting and light pollution impacts arise primarily from commercial uses (Luginbuhl *et al*. 2009 find commercial and industrial lighting accounts for over 60% of uplight), this analysis focuses on impacts of commercial lighting[3].

The remainder of Section 1 reviews light pollution types and definitions and describes the technical aspects of IDA-IES MLO and IDA Pattern Code critical to an evaluation of light pollution impacts. Section 2 presents results of detailed analyses of light pollution impacts; these results are discussed in Section 3. Section 4 presents the conclusions.

1.2 Light Pollution Impacts: Types and Definitions

What is light pollution? Many discussions assume that light pollution is simply the artificial increase in sky glow[4]. Such an interpretation arises naturally from the history of light pollution control efforts originating with astronomical constituencies (professional, amateur and "casual stargazers"), in the description of lighting codes or efforts to control light pollution as "dark sky," and even in the name of the International Dark-Sky Association.

Yet light pollution has many more facets than the artificial brightening of the night sky. Phenomena directly related to the use of artificial lighting at night include sky glow, trespass, glare, as well as more subtle issues of alteration of the natural night environment simply by the introduction of illumination (including both intentional and inadvertent illumination) and the introduction of light sources into the night environment/landscape/viewshed. Indirect effects include energy waste and effects on biological systems (including humans).

In this analysis we will address the following phenomena/effects:

- Total lumen amounts
- Total direct uplight amounts
- Artificial sky glow
- Light trespass
- Glare
- Lamp spectral power distribution

1.2.1 Total lighting amounts

For many measures of the environmental impacts of outdoor lighting use, the total amount of

[3] Municipally (or utility) owned lighting, in particular roadway lighting, is also a large contributor (Luginbuhl *et al.* (2009) find it to be16% of the total Flagstaff output). As a matter of legal jurisdiction (the land on which they are erected is not private), and involvement (to some degree) of engineers in the design process, streetlights are usually exempt from lighting codes. Streetlighting impacts should be considered in a larger discussion. Other important lighting is also outside of this analysis, such as signs, window spill, and automobile headlights.

[4] A frequently seen – yet erroneous – concept is that light pollution is wasted light, or even just direct uplight, with the interpretation extended conceptually to mean that a fully shielded lighting fixture causes no light pollution. This misunderstanding is common in the lighting industry, especially among fixture manufacturers.

light used is directly proportional to the total impacts. For example, a site using twice as much light as another will have twice the sky glow impact, assuming other aspects such as shielding are the same. The total lighting amount is also directly proportional to total energy used. Though energy use is not strictly a dark sky concern, it is commonly a principal concern of communities considering lighting ordinances.

To remove the effect of differing size projects on the dark sky impacts, and allow a more direct comparison of the effect of differing lighting standards, the analyses in this report will generally examine the amount of light used or allowed per acre, often termed "lumen densities."

1.2.2 Total direct uplight and sky glow

Light reaching the sky arises from light emitted *directly upward* from incompletely shielded fixtures, as well as from light emitted downward but then *reflected upward* from the ground or other surfaces. These two components, however, do not have equal impact on sky glow, because in general they are headed in different directions. Light emitted directly upward from incompletely shielded fixtures is usually concentrated at angles near the horizontal, while light reflected from horizontal surfaces is more strongly concentrated toward the zenith (see Figure 1). Research has shown (Cinzano & Diaz-Castro, 2000; Luginbuhl, Walker & Wainscoat, 2009; Falchi, 2011) that light propagating upward but at a small angle relative to the horizon is of much greater consequence for sky glow than light reflected from a horizontal ground surface, particularly when observed from some distance. A lumen emitted directly upward has a much greater impact on sky glow than a lumen reflected upward.

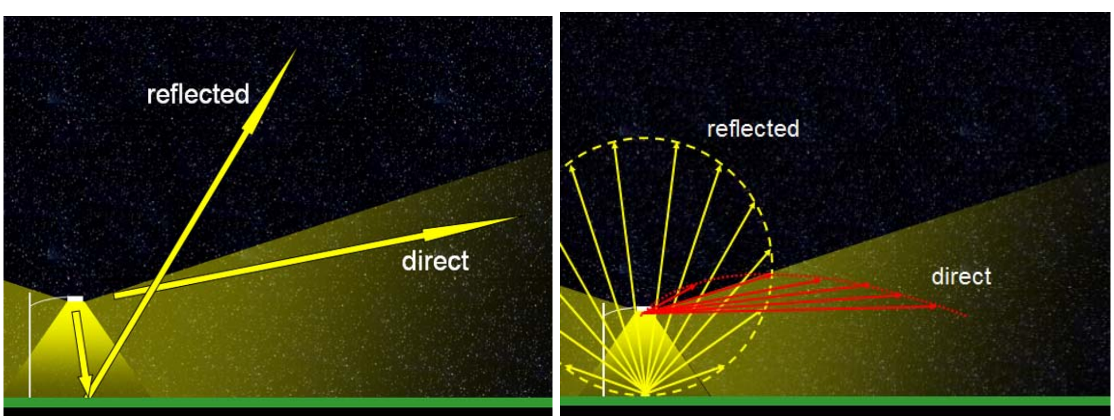

Figure 1. Sources (left) and angular intensity distributions (right) for light reflected upward from a horizontal surface and light emitted directly upward from an incompletely shielded fixture. The angular intensity distributions are representative; actual distributions will depend on many factors such as blocking, fixture photometric characteristics, and mounting details.

Though the relative sky glow impacts of direct- and reflected-upward emissions are highly dependent on details such as the amount and nature of blocking by buildings and vegetation near the ground and distance of the observation point from the light sources, for purposes of this study a lumen emitted directly upward will be conservatively considered to have an impact 5 times that of a lumen reflected upward[5]. We propose a metric called the sky glow index (SGI) that takes these effects into account. Specifically, the SGI is defined as (assuming a ground reflectivity of 0.15; LL = luminaire lumens; UL = direct uplight lumens; in this analysis all lumen outputs are measured in kilo-lumens):

$$\begin{aligned} \text{SGI} &= \text{reflected upward lumens} + \text{direct upward lumens} \times 5 \\ &= (\text{LL} - \text{UL}) \times 0.15 + \text{UL} \times 5 \end{aligned}$$

For two special cases SGI is evaluated as follows. For façade floodlighting, we will assume that all light strikes the building face[6] with 15% reflectivity, and that 50% of the reflected light propagates upward with sky glow impact factor of 5:

$$\text{SGI}_{\text{façade}} = (\text{LL} - \text{UL}) \times 0.15 + (\text{UL} \times 0.15 \times 0.5) \times 5$$

For canopy lighting, we will assume that all lighting is fully shielded (*i.e.* UL = 0), that the ground surface is concrete with reflectivity 0.25, and that the canopy blocks 75% of the reflected light from reaching the sky:

$$\text{SGI}_{\text{canopy}} = \text{LL} \times 0.25 \times 0.25$$

We emphasize the purposeful lack of sensitivity of the SGI to distance. The *absolute* impact of a given lighting installation on the overhead sky glow at an observation point will vary overall approximately as the inverse 2.5 power of the distance. The SGI as formulated here is intended only to evaluate the *relative* impacts of lighting installations with differing total amounts of light and shielding characteristics. From any particular observation point, a given lighting installation with an SGI of 30 will have twice the sky glow impact of the same installation in the same location with an SGI of 15.

MLO proposes a different standard apparently intended to address sky glow, based on the Outdoor Site-lighting Performance (OSP) "glow" measure proposed by Brons *et al.* (2008). Under the Performance Method Option B (see Section 1.4), the designer must calculate the amount of light (lumens) falling on the inside of a "virtual enclosure" over the site, with vertical walls at the property boundary and top located minimum 33 feet or 10 m above the highest fixture on the site. Under this option the design meets requirements of MLO if the ratio of the lumens falling on the inside of the box to the total site lumens is less than 15%. Yet, due to the complete insensitivity of this measure to both the total amount and direction of the light rays, it is not a suitable measure to predict the sky glow impacts despite the claims of Brons *et al.* (Rea *et*

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[5] Both theoretical and observational studies have shown that the direct uplight impact factor varies from 2 to over 100 (Cinzano & Diaz-Castro, 2000; Luginbuhl, Walker & Wainscoat, 2009; Falchi, 2011), in general increasing strongly with distance from the light source. The chosen factor of 5 is conservative and more representative of observation points near (within a few km of) the light sources. When sky glow in suburban or more distant locations is considered, such as in suburban areas of large cities, rural areas, and professional astronomical observatory sites, a factor of 20 or more would provide a more accurate assessment of the impact.

[6] Therefore there is *no* spill light directly into the sky: thus down-directed and up-directed façade lighting are equivalent for the SGI. In most up-directed façade lighting this will lead to an underestimate of sky glow impacts.

al. 2010). Though Brons *et al.* use the term “glow” to refer to this ratio, to minimize confusion with actual sky glow or measurements related to sky glow such as SGI, in this report we will refer to this as the “box ratio.”

For purposes of comparison of MLO dark sky impacts with unregulated lighting and other lighting standards, we will again generally consider the SGI per acre.

1.2.3 Light Trespass

Light trespass is light traveling beyond the property on which the light fixtures are installed and “trespassing” onto, into or over other properties where it is perceptible as illumination of the ground or other surfaces, or direct visibility of the source or of an illuminated surface[7].

Light trespass in lighting codes is often practically interpreted as illumination only – measured at the (horizontal) ground or at a “virtual” vertical surface. The usual regulatory strategy is to limit the illuminance at (or above) some location, most commonly (including in MLO) the property line. This strategy has been applied so frequently and for so long that many equate such a measure with trespass, though it is important to recognize that many aspects of light trespass are incompletely captured by such a measure, or even entirely missed by it.

In this analysis we will address vertical illuminance over the property line following the approach used in MLO, and refer to boundary vertical illuminance as “BVI” measures or limits. As a BVI has little sensitivity to the direction of the light rays, light headed downward across a property boundary is treated essentially the same as light directed horizontally, and even the same as light emitted toward the sky[8], even though the trespass (as well as sky glow) consequences are very different.

The analysis presented below shows that BVI limits are ineffective in curtailing critical light pollution effects such as glare and light trespass, and further impose inappropriate limits on reasonable lighting practices.

A form of light trespass not captured by illuminance is the direct visibility of light sources to observers located off the site. Consider the ubiquitous unshielded 60 W incandescent porch light. At just 100 feet the illumination from such a light is considerably less than 0.1 lux (less than half full moonlight). Yet this light source may be a prominent visual presence in a residential neighborhood or on a night landscape. At 100 feet this light, when directly observed with the eye, will appear about one third as bright as a full moon and much brighter than any other natural object (planets or stars) in the night environment. It will cast a visible shadow to a half mile, appear as bright as a first magnitude star to a distance of more than 5 miles, and will remain

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[7] A directly visible light source or illuminated surface causes trespass whether or not the light causes glare. This definition is broader than the more commonly encountered definition which refers only to off-site illumination, often considered as only arising from light directly emitted from the source.

[8] This crucial insensitivity to direction (apart from a cosine projection factor) is a property not only of the MLO BVI and box ratio measures (see sections 2.2 and 3.2), but also of the OSP “glow” and “trespass” measures of Brons *et al.* (2008).

visible to most observers out to a distance of more than 40 miles.

Apart from shielding standards intended to limit this "source visibility" trespass (which are nonetheless nearly always much looser for low output fixtures such as discussed here), we are aware of no standards intended to directly address this sort of trespass. We will not discuss it in detail here apart from the discussion and analysis of glare.

1.2.4 Glare

Glare is an uncomfortable and sometimes debilitating consequence of bright light sources (either fixtures or bright surfaces produced by floodlighting or internal illumination) within the "normal" field of view[9]. The high contrast produced by such bright sources, particularly in generally dark outdoor night environments, not only affects the visual behavior of the observer (perhaps causing him or her to avoid looking in directions near to the glare source), but it can also cause decreased visibility of areas or objects that would otherwise be easily visible.

Glare is also strongly affected by the spectral content of the light source, with bluer light sources (*e.g.*, metal halide or white LEDs) causing considerably greater glare than yellower sources of equivalent brightness.

The measurement, regulation and even conceptualization of glare are complex and sometimes controversial topics. Yet glare is a leading concern of communities seeking to address light pollution issues. Most lighting codes address glare indirectly through shielding standards, though this approach does not directly address quantities usually related to glare measurement (such as candlepower, luminance, illuminance at the eye, viewing angle, etc.).

The IDA-IES MLO seeks to limit glare using the Luminaire Classification System (LCS) BUG (Backlight Uplight Glare) ratings by limiting the maximum "G" ("glare") value of luminaires. Yet the "G" value in BUG is determined only by the luminous flux (lumens) contained within certain angular zones[10], and is the same whether all of the flux is concentrated into a high candlepower beam or distributed evenly through the zone at a much lower candlepower. Whatever the effectiveness of this approach, it can be entirely avoided through the Performance Method Option B (see Section1.4).

In this study we evaluate the maximum candlepower visible at ground level 500 feet from the fixture (equivalent to 4° below horizontal at the source) for fixtures meeting both "fully shielded" and MLO LCS "BUG" G0-4 standards.

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[9] The "normal field of view" concept is important: for example a well shielded street light would cause extreme glare to a person standing underneath and looking upward, but as such viewing angles are not "normal" such an installation would not generally be considered to be a source of glare.

[10] From 60° to 80° and 80° to 90° above nadir, in front of and behind the luminaire.

1.2.5 Lamp spectral power distribution

The spectral distribution of artificial light is not strictly speaking a kind of light pollution as described in the previous subsections, but rather a factor which may amplify or diminish other light pollution phenomena. In general, lamps with stronger blue emission, including all types of white lighting such as metal halide, fluorescent and white LEDs, produce more visible sky glow (primarily through the effect of the Purkinje shift[11]), greater glare, and greater biological and circadian disruption (through ipRGC response). When compared on a lumen-for-lumen basis, blue-rich sources such as white LEDs can be expected to produce 3 – 5X brighter sky glow than high-pressure sodium, and up to 15 times brighter than low-pressure sodium (IDA, 2010). The effects of SPD on glare and biological systems are less well quantified but nonetheless distinct.

Finally, there are many issues in dark sky protection, light pollution control, human visual needs and lighting usage which will not be addressed by this analysis. For example, the question of whether lighting zone concepts allowing increased property boundary illuminance or "trespass" levels (CIE) or lighting amounts (MLO) are valid approaches to dark sky protection will not be discussed.

1.3 Summary of the Pattern Outdoor Lighting Code

As a basis for evaluating dark sky impacts under existing "state-of-the-art" dark sky lighting codes, we will use the IDA Pattern Code (IDA, 2000), with several updates as reflected in the Coconino County, Arizona (Chapter 17 of the Coconino County Zoning Ordinance, amended 2001[12]). Besides strict standards for "fully shielded" fixtures (hereafter usually "FS"), these codes limit total site lighting to 17.5, 35 and 70 kilolumens (klm) per net acre in LZ1, 2 and 3. (These figures are the equivalent fixture lumens – these codes use "lamp lumens," with nominal values of 25, 50 and 100 klm/ac and 20, 40 and 40 lm/ft^2.) Canopy lighting (the only special-use category applicable in this analysis) is limited to 14, 28 and 28 lm/ft^2 in LZ1, 2 and 3, and counts toward the site lumen allowance at 100% when located 5' or less from the canopy edge, 25% when 5'-10', and 10% when over 10'. The Coconino code allows a maximum of 0/2.1/2.1 klm/ac in unshielded fixtures in LZ1/2/3; the maximum output of such a fixture is 1750 lm. These standards[13] will be referred to as the "POLC" in this report.

The Coconino lighting code (and the IDA Pattern Code as an alternative) also has restrictions on lamp types, requiring the use of low-pressure sodium for general illumination of areas such as parking lots and roadways. As general area illumination dominates outdoor lighting (Luginbuhl *et al.* (2009) find that this lighting accounts for over 90% of outdoor lighting), the implications of lamp type standards can be dramatic for light pollution impacts (IDA, 2010; Luginbuhl *et al.*, 2012). Nonetheless, the effects of lamp types are examined only qualitatively in the following

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[11] The Purkinje shift is the shift in visual spectral sensitivity caused by the differing photopigments in cone (daytime vision) and rod (day and night vision) cells.

[12] As of 15 November 2012 available at http://www.coconino.az.gov/uploadedFiles/Community_Development /Section17.pdf

[13] These standards are collected from two separate related codes, reflecting the dynamic nature of codes being used (and frequently amended) on-the-ground.

analysis; all other comparisons are based on simple luminous output (photopic lumens).

1.4 Summary of the IDA-IES Model Lighting Ordinance (MLO)

In contrast to the POLC, the IDA-IES MLO is more complex, with many more standards relevant to evaluating light pollution impacts. The principal methods used to regulate outdoor lighting in MLO are 1) lighting zones, 2) lumen allowances based on lighting zone, various area measures, and use, 3) luminaire shielding standards following the Luminaire Classification System (LCS) BUG standards (IESNA, 2011a), 4) limitation of measures termed “off-site” impacts based on illuminance at the site boundary, and 5) after-hours lighting reductions.

MLO allows two general methods for determining compliance: the ***Prescriptive Hardscape Area Method*** and the ***Performance Method***. (A prescriptive method based on the number of parking spaces is applicable only to sites with 10 parking spaces or less, and will not be further discussed here.)

In the Prescriptive Hardscape Area Method, total allowed fixture lumens[14] are determined based on the area of the “hardscape” with additional increments for each intersection of a site drive with a public roadway. The hardscape area includes the area within a potentially complex boundary defined to include “permanent hardscape improvements to the site including parking lots, drives, entrances, curbs, ramps, stairs, steps, medians, walkways and non-vegetated landscaping that is 10 feet or less in width.”

The Prescriptive Hardscape Area Method provides additional lumen allowances for outdoor sales areas (such as at car dealers or nurseries), drive-up windows and service stations. Finally, all luminaires must meet the LCS Backlight/Uplight/Glare (BUG) standards listed in MLO, with the additional significant restriction that all parking lot lighting must have no light emitted above 90°.

The Prescriptive Hardscape Area Method has the advantage of being simpler, requiring the user to measure (principally) only a quantity called the “hardscape area,” but the potential disadvantage (from the perspective of many developers) of allowing considerably less total light than the Performance Method in most cases.

Under the Performance Method, total lumen allowances are determined by a base (fixed) allowance per site, as well as an allowance based on the hardscape area. Except for outdoor sales areas and service stations, additional allowances are provided for up to three additional uses chosen from a list of six (entryways; façade lighting; canopies; guard stations; outdoor dining areas; drive-up windows). For outdoor sales areas only additional allowances are provided based on the sales lot area and frontage length; for service stations only additional allowances are available based on the hardscape area (again) and on the area of canopies.

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[14] “Fixture lumens” means the amount of light escaping the fixture. This allows a comparable treatment for fixtures using both “absolute” photometry (such as LED fixtures) and fixtures with only “relative” photometry.

To address "off-site impacts," the Performance Method requires the user to select from two options: either A) follow the LCS luminaire shielding standards[15] or B) use "industry standard" lighting design software to calculate 1) the fraction of lumens leaving the site (directly from unshielded luminaires and after reflection from the ground or other surfaces) and 2) the maximum vertical illuminance at any point on an imaginary vertical surface erected at the site boundary. The values determined from the analysis must be shown to fall below limits set for each lighting zone.

It is important to recognize that there are no luminaire shielding (or aiming) standards if Performance Method Option B is chosen.

MLO does not address lamp types or spectral characteristics.

Finally, as discussed in Section 1.1, though POLC designates LZ1 – LZ3 and MLO recognizes LZ0 – LZ4, it is important to remember that lighting zones in the MLO are potentially defined and applied differently than in POLC. In many areas regulated by POLC-like codes, the majority of a community's commercially developed areas have fallen in POLC LZ2 and LZ3[16]. In general it appears that commercial development would fall into MLO LZ2 – LZ4. To help maintain the awareness that the POLC and MLO LZs with equivalent numbers are *not* equivalently devised, and may not be appropriately applied to the same areas of a jurisdiction, we will generally refer to "POLC LZn" and "MLO LZn."

2. Light pollution impact analysis

To evaluate measures relating to the various aspects of light pollution or dark sky protection described in Section 1, site plans for 15 commercial development projects were assembled for this study (see Table 1). For evaluating impacts from lighting under POLC standards the only site plan information needed is the site acreage and the area of any sales canopies. The information needed to evaluate impacts of lighting under MLO standards includes detailed hardscape layouts (i.e. parking lots, drives, sidewalks, etc.), canopy area, building footprints, numbers of building entryways and drive up windows, building heights, sales lot area, sales frontage length, number of fuel pumps, and square footage of any outdoor dining areas. This detailed information was obtained from Monrad Engineering (personal communication), the author's records, and from several other sources, including IDA. The projects include seven shopping centers, three convenience-store/service stations (hereafter "c-stores"), a car dealer, motel, restaurant, office building, and a bank. Site plans for each of the projects analyzed are included in Appendix A. The sites range in size from under an acre to nearly 18 acres.

Some information affecting total lighting allowances under MLO was not available for many of the projects, typically specific details related to buildings such as number of doorways, number

[15] There is no additional restriction on uplight for parking lot or area lighting under this option, as there is under the Prescriptive Hardscape Area Method.

[16] Following the darksky goals of LZ's under POLC, described in Section 1.1, the designation of lighting zones is guided by the sensitivity of the region or nearby sites (*e.g.,* observatories) to obtrusive impacts of lighting (particularly sky glow). POLC lighting zones are not specifically tied to the degree of urbanization of an area.

and area of entryway canopies, building height and therefore façade areas, "drive-up" windows, and areas designated for outdoor dining. For this analysis estimates were entered for these items, including the assumption that exterior building walls were just 12 feet high. This detailed information is not needed to evaluate lighting allowances under the POLC.

Table 1. Projects analyzed in this study.

#	Name	Type	acres
1	Fry's/CM 9914	Shopping center	17.92
2	Safeway/CM 0151 w/o c-store	Shopping center	9.62
3	Safeway/CM 0151 c-store	C-store/fuel station	1.45
4	Thornydale Crossing	Shopping center	10.26
5	Fry's	Shopping center	5.60
6	Sellers Toyota	Car dealer	2.79
7	Motel 6	Motel	2.50
8	Red Lobster/Olive Garden	Restaurant	3.15
9	Love's Truckstop	C-store/fuel station	11.34
10	Conoco	C-store/fuel station	2.39
11	Homer Glen Center	Shopping center	4.84
12	Capital One Bank	Bank	1.55
13	Physicians and Surgeons Building	Office	4.69
14	Safeway 1983	Shopping center	11.82
15	IDA Site 9	Shopping center	0.80

To evaluate the light pollution impacts of lighting under POLC and MLO standards, we will assume that lighting designs use the maximum amount of light allowed, as well as the maximum amount of unshielded lighting allowed. This produces a consistent comparison of light pollution impacts between the different lighting standards.

Responsible lighting designers may challenge the assumption of the maximum allowance characterizing the amount of light that would be used, so the reasoning bears emphasis. The purpose of this analysis is to determine how much lighting the *codes allow*. As MLO specifies a variety of allowances for different uses on a site, ALL permitted allowances were included. Since both the POLC and MLO allowances are upper limits, using less is possible but not the purview of the codes. Should a developer use less than the maximum permitted, the designer or property owner may deserve some credit, but such an outcome cannot be ascribed to the standards contained within the code. What the codes allow is what the codes allow: this analysis is about the codes.

2.1 Total Lumen Allowance

2.1.1 Unregulated Practice

The average lighting amounts used on unregulated sites, as measured in the Luginbuhl *et al.* (2009) study, are presented in Table 2. The mean value is 155 klm/ac (using the higher Flagstaff plus Tucson value for auto dealers).

Table 2. Amounts of light used on unregulated sites (i.e., built before lumen amounts were limited beginning in 1989) in the Luginbuhl *et al.* (2009) study. N indicates the number of sites surveyed.

Land Use	N	Unregulated[1] (klm/ac)
Shopping Center	9	112
Fuel Station / C-Store	3	293
Auto Dealer	4	48 326[2]
Motel	9	105
Bank	2	167
Restaurant	5	316
average		*155*

[1]The unregulated values are adjusted from the mean effective lumen outputs presented in Luginbuhl *et al.* (2009) Table 1 by assuming a "depreciation factor" of 0.765 (lamp lumen depreciation=0.90, luminaire dirt depreciation=0.85).
[2] Includes two measures from Tucson. Note that the Tucson measures were selected partly because they were brightly illuminated: there is insufficient information to say whether these values are representative of the Tucson average. Nonetheless, this higher value is used to compute the average for all uses (last line).

2.1.2 POLC

In this and the following subsection we calculate the total lighting allowances under POLC and MLO standards.

Total lumen allowances under POLC standards are based for most developments on the acreage of the site, and do not depend in general on details of the site plan. Thus, three values characterize most development projects, regardless of project or site plan details: 17.5, 35 and 70 klm/ac in POLC LZ1, LZ2 and LZ3, respectively. For sites including service station fueling canopies the area of the canopy is allowed 14, 28 and 28 lumens per square foot in POLC LZ 1, LZ 2 and LZ 3 respectively. The POLC allowances are shown in Table 3.

Table 3. POLC total lumen allowances for the projects in Table 1. Three c-store sites with service station canopies have an additional allowance for the canopy; all others (12 sites) are based only on site acreage.

	POLC Lumen Allowance (klm/ac)		
Project #	**LZ 1**	**LZ 2**	**LZ 3**
3	62	124	159
9	25	50	85
10	42	83	118
c-store ave	**43**	**86**	**121**
others (12)	17.5	35	70
overall ave	**23**	**45**	**80**

2.1.3 MLO Prescriptive Hardscape Area Method

Total lumen allowances permitted by the IDA-IES MLO were determined following the ***Prescriptive Hardscape Area*** and the ***Performance Method*** for the projects listed in Table 1 (a third method, the ***Prescriptive Parking Space Method***, is intended for use on very small sites and is not applicable to the sites evaluated in this study).

As the MLO does not itself identify permitted or prohibited land uses in any of the lighting zones, the allowances by both the Prescriptive Hardscape Area and Performance Methods (Section 2.1.4) for all five lighting zones were evaluated, as described in greater detail below, producing a total of 10 allowances for each site.

The total lumen allowance following the Prescriptive Hardscape Area Method is set by determining the total square footage of hardscape on the site, with an addition of 600 square feet for each intersection of a site drive with a public road. Additional allowances are provided for outdoor sales areas, drive-up windows, and service stations. The calculated lumen allowances, per acre, are shown in Table 4.

2.1.4 MLO Performance Method

Besides an allowance based on the area of the hardscape, as in the Prescriptive Hardscape Area Method, the MLO Performance Method includes an additional fixed allowance per site (termed "base lumens"). In addition, all uses except service stations and outdoor sales facilities may choose up to three additional allowances from a list of six, including per-door allowances for entryways or exits, a per-square-foot allowance for building façades, a per-square-foot allowance for canopies, etc. Service stations are given an additional increment to the hardscape allowance as well as an allowance for any fueling canopies. Outdoor sales facilities (such as car dealers) are given additional allowances based on the area of the sales lots and sales frontage length.

As there are no descriptions within the IDA/IES MLO for what building faces may or may not be included toward the façade area, allowances were determined here assuming all building faces could be illuminated. The total Performance Method lumen allowances for all projects are shown in Table 4.

The MLO Performance Method includes, as one option (B), two additional constraints referred to as "limits to off-site impacts." The effect of these will be discussed below. These constraints can be avoided by adhering to the LCS BUG standards under Option A, allowing the full allowances listed in Table 4 to be used without reduction.

Table 4. MLO total lumen allowances for the projects in Table 1, following the Prescriptive Hardscape Area Method (upper) and Performance Method (lower).

	MLO Lumen Allowance (klm/ac)				
Project #	**LZ 0**	**LZ 1**	**LZ 2**	**LZ 3**	**LZ 4**
1	16	41	82	167	252
	18	44	113	227	340
2	16	41	82	168	256
	17	44	109	218	327
3	14	56	113	226	338
	14	81	362	723	1017
4	15	37	75	152	231
	16	42	103	206	308
5	15	39	79	164	253
	16	41	102	205	307
6	17	78	238	440	580
	17	78	238	400	580
7	15	37	76	157	245
	40	101	271	542	813
8	16	40	81	165	251
	17	44	111	222	334
9	17	52	104	208	314
	17	185	370	739	1098
10	17	66	136	284	444
	17	200	400	800	1163
11	9	23	46	96	149
	12	31	87	175	262
12	12	33	67	145	226
	13	36	89	177	266
13	13	33	67	138	212
	14	36	106	212	318
14	13	33	67	136	208
	14	37	100	200	299
15	13	32	66	142	227
	14	40	133	267	400
ave	**15**	**44**	**94**	**190**	**283**
	17	**76**	**180**	**354**	**522**

2.2 MLO "off-site" impacts

MLO addresses what it terms "off-site impacts" using either a) the LCS BUG standards or b) limits to the Brons *et al.* (2008) OSP "glow" and "trespass" measures, called box ratio and boundary vertical illuminance (BVI) measures in this discussion. This section concerns the box ratio and BVI measures; the LCS standards are addressed under Section 2.3.3.

To evaluate the effects of the MLO box ratio and BVI limits, five projects listed in Table 1 had "nominal" lighting designs developed. These lighting plans conform to POLC-like lighting codes (in Flagstaff and Pima County, Arizona) utilizing 35 and 70 klm/ac, with no unshielded lighting. These and several modified versions were analyzed to evaluate the impacts of the MLO "off-site" measures as well as the sky glow index (SGI) described in section 1.4.2. Table 5 summarizes these plans along with the measured box ratio, maximum BVI, and SGI.

Table 5. MLO box ratio, BVI maximum, direct uplight and sky glow index (SGI) for nominal POLC-compliant lighting designs (unitalicised entries). Projects labeled *A, B* etc. (and shown in *italics*) are modified from the nominal lighting designs to explore the influence of various aspects of lighting design on the off-site impacts and are briefly described in the notes to the table and discussed in Section 3.2. SGI is defined in Section 1.3.2. (Most of these latter designs are not POLC-compliant.)

Project #	Design klm/ac	Canopy klm/ac	Box Ratio	BVI max (lux)	Direct Uplight (klm)	SGI/ac
5	33	0	0.15	47	0	5.0
5A[1]	"	*0*	*0.08*	*4*	"	"
9	46	18	0.06	45	0	5.3
9A[2]	*55*	*18*	*0.07*	*45*	*11*	*12*
9B[3]	*55*	*18*	*0.09*	*4*	*19*	*15*
9C[4]	*46*	*18*	*0.06*	*14*	*0*	*5.3*
10	96	83	0.07	11	0	7.1
10A[5]	*110*	*83*	*0.11*	*12*	*7*	*24*
11	55	0	0.15	150	0	8.3
13	31	0	0.13	21	0	4.7
13A[6]	*310*	*0*	*0.13*	*210*	*0*	–

[1] same design as 5 but with all luminaires moved minimum two mounting heights from parcel boundary
[2] same design as 9 with the addition of 16 B5-U5-G5 "barnyard" luminaires
[3] same design as 9A but replacing 11 perimeter FS luminaires with floodlights aimed 60º above nadir (LCS for these fixtures as aimed is B0-U4-G5)
[4] same design as 9 but slightly changing measurement point spacing for BVI calculation (see Section 3.2.2)
[5] same design as 10 but with 10 fully shielded luminaires replaced with B5-U5-G5 "barnyard" luminaires
[6] same design as 13 but with all luminaire outputs increased 10X.

In the following discussions we enclose the MLO term "off-site" within quotation marks to indicate that, though the MLO refers to the BVI and box ratio values as "off-site" measures, in fact they are determined by measurements over or at the boundary of the site. Their effectiveness in addressing true off-site impacts (i.e., illumination and glare on other properties or on sky glow) is discussed in Section 3.

2.3 Direct uplight and sky glow index (SGI)

2.3.1 Unregulated Practice

The total direct uplight on unregulated sites is estimated from the Luginbuhl *et al.* (2009) study, using the average total lumen allowance of 155 klm/ac (cf. Section 2.1.1) and assuming 10%

emitted directly upward[17]. Thus, the direct uplight for unregulated lighting is approximately 15.5 klm/ac (hereafter 16 klm/ac), with an SGI per acre of (155 – 15.5) × 0.15 + 15.5 × 5 = 98.

2.3.2 POLC

To estimate the maximum amount of direct uplight permitted by the POLC described in Section 1.3, we assume that the "unshielded" allowances of 0/2.1/2.1 klm/ac in LZ 1/2/3 use fixtures with 50% direct uplight. C-store sites with the special canopy allowance are evaluated using the canopy and parcel sizes from projects 3, 9 and 10 (Table 1), and canopy lighting counts at 25% toward the total site allowance. The results, including the SGI, are summarized in Table 6 for both non c-store and c-store allowances shown in Table 3.

Table 6. POLC total lumen allowance, unshielded lumen allowance, maximum direct uplight and SGI/ac for non c-store and c-store sites. C-store allowances are average values for the three c-store plans (projects 3, 9 and 10) in Table 1.

		LZ 1	LZ 2	LZ 3
Non C-store				
Total allowance	klm/ac	17.5	35	70
Unshielded allowance	klm/ac	0	2.1	2.1
Direct uplight	klm/ac	0	1.1	1.1
	fraction	0.000	0.031	0.016
SGI/ac		2.6	11	16
C-stores (ave)				
Total allowance	klm/ac	43	86	121
Non-canopy allowance	klm/ac	9	18	53
Canopy allowance	klm/ac	34	67	67
Unshielded allowance	klm/ac	0	2.1	2.1
Direct uplight	klm/ac	0	1.1	1.1
	fraction	0.000	0.013	0.009
SGI/ac		3.5	6.9	12

2.3.3 MLO and LCS BUG standards

A similarly definitive determination of the amount of direct uplight permitted under MLO is not possible. The amount of direct uplight allowed under the Prescriptive Hardscape Area and Performance Method Option A, following the LCS BUG standards, depends on the number of fixtures used. Under a given total lumen allowance, more fixtures leads to more direct uplight.

Nonetheless, to estimate the maximum direct uplight reasonably achievable under the LCS standards, we assume that the total lumen allowances shown in Table 4 will be utilized with fixtures of 10,000, 5000 and 2500[18] lm per fixture. The total number of such fixtures allowed is

[17] Since Flagstaff has had strict shielding standards in place for much longer than the lumen caps adopted in 1989, the average unshielded fraction determined by the Luginbuhl *et al.* (2009) study of just over 8% is probably lower than would be expected in most communities.

[18] 2500 lm per fixture is typical of the lower-rated "decorative" or "acorn" fixtures. Under the MLO Hardscape Area Method these lights are permitted under special permit for parking area lighting; there are no restrictions on their

simply multiplied by the total uplight allowance in IES TM-15-11 for the appropriate "U" standard in MLO Table C-2 (i.e. 0/20/100/1000/2000 lm/fixture for LZ 0/1/2/3/4). The results are summarized in Table 7.

Table 7. MLO direct uplight, direct uplight fraction and SGI for lighting under MLO Prescriptive Hardscape Area and Performance Methods (Option A) using LCS standards and assuming 10000, 5000 and 2500 lm fixtures. Uplight lumen densities and SGI exceeding the POLC LZ3 non c-store values of 1.1 klm/ac and 16 (Table 6) are highlighted in yellow; those also exceeding unregulated practice of 16 klm/ac and 98 are highlighted in red.

	Prescriptive Hardscape					Performance (Option A)				
	LZ0	LZ1	LZ2	LZ3	LZ4	LZ0	LZ1	LZ2	LZ3	LZ4
10000 lm/fixture										
klm/ac	0	0.1	0.9	19	57	0	0.2	2	35	104
fraction	0.00	0.00	0.01	0.10	0.20	0.00	0.00	0.01	0.10	0.20
SGI	2.3	7.0	19	121	317	2.6	12	36	225	585
5000lm/fixture										
klm/ac	0	0.2	2	38	113	0	0.3	4	71	209
fraction	0.00	0.00	0.02	0.20	0.40	0.00	0.00	0.02	0.20	0.40
SGI	2.3	7.5	23	213	591	2.6	13	44	396	1091
2500lm/fixture										
klm/ac	0	0.4	4	76	226	0	0.6	7	142	418
fraction	0.00	0.01	0.04	0.40	0.80	0.00	0.01	0.04	0.40	0.80
SGI	2.3	8.3	32	397	1140	2.6	14	62	740	2104

2.3.4 MLO Performance Method Option B

If the direct uplight allowances and SGI for MLO lighting under the LCS BUG standards is uncertain due to the (unknown) numbers of fixtures used, the uncertainty under MLO Performance Method Option B is yet more uncertain. Here there are no explicit luminaire shielding standards; the expectation appears to be that the MLO "box ratio" and BVI maximum will effectively limit these impacts.

To explore at least some of the possible direct uplight lumen densities and SGI, lighting plans conforming to the MLO Performance Method Option B for LZ2 were developed for three additional sites from Table 1. These are summarized in Table 8. The box ratio and BVI calculations are performed assuming that asphalt surfaces reflect 7% of the incident light and all

use as "decorative" lighting under this method, and there are no special restrictions on their use under the Performance Method. Further, though 2500-5000 lm fixtures might seem unlikely to dominate lighting on a site, there is a WalMart in Flagstaff, AZ illuminated with LED fixtures of under 4000 lm each.

other ground and building surfaces reflect 15%[19]. Details of these designs are included in Appendix B.

We note that, in addition to the ability to accommodate notorious “barnyard” fixtures as noted in the modified lighting designs listed in Table 5 projects 9A and 10A, we find that the MLO Performance Method Option B standards also allow use of floodlights aimed at substantial angles above the nadir (50 – 60º) and other unshielded fixtures such as prismatic wallpacks (see Table 9). The majority of the installed lumens (75 – 85%) in the designs summarized in Table 8 were accommodated in these fixtures, as shown in Table 9.

Table 8. Light pollution impact summaries under MLO LZ2 Performance Method Option B, POLC LZ3, and unregulated practice (UR) for three projects from Table 1. The columns show the project number, MLO design lumen total and allowance (in parentheses), uplight lumen amount and fraction (in parentheses), Sky Glow Index (SGI) per acre for unregulated lighting (UR), lighting under POLC LZ3, and MLO, and ratio of MLO SGI to POLC SGI.

	MLO Performance Method Option B design		SGI / ac			
Project #	Total lumen density (allowance) klm/ac	Direct uplight density klm/ac (fraction)	UR	POLC LZ3	MLO LZ2 PM(B)	$\frac{SGI_{MLO}}{SGI_{POLC}}$
6	215 (238)	36 (0.17)	106	16	105	6.6
7	139 (271)	53 (0.38)	67	16	64	4.0
12	85 (89)	7.9 (0.09)	30	16	51	3.2

Table 9. Unshielded light fixtures and fraction of the total lighting budget used in the fixtures, for the indicated project designs following MLO LZ2 Performance Method Option B.

	Fixture				
Project #					All
6	0.49	0.04	0.23	--	0.75
7	0.44	--	0.37	0.04	0.85
12	0.69	--	--	0.06	0.75

2.4 Glare

Glare is a complex perceptual phenomenon, dependent on many more characteristics than can be determined from MLO or POLC standards. A quantity often related to glare is the illuminance caused by a glare source at the observer's eye. For our analysis of glare we evaluate the *maximum* vertical illuminance 500’ from a luminaire mounted at 35’ above ground. This is equivalent to

[19] Though these values are critical to the analysis, MLO does not specify what reflectances are to be used except (in a recent unofficial edition) to say that values lower than 7% are not permitted. It is unclear how the enforcing jurisdiction could evaluate what figures are used, and whether those used are accurate or reasonable.

the illuminance caused by the maximum candlepower in any horizontal direction 4.0° below horizontal[20]. This is abbreviated maximum VI500. The choice of 500' is arbitrary, though this distance generally reflects a true "off-site" impact, and a measurement based on the maximum is much more closely related to glare than the LCS "G" value which is based on the *average* candlepower. The maximum VI500 was evaluated for 252 fixtures, including 9, 73, 65, 68 and 37 with LCS "G" ratings of 0, 1, 2, 3, and 4, respectively, and 138 fully shielded. The results are shown in Table 10.

For example, Table 10 shows that at 500' viewing distance, 2% of the fixtures with LCS G2 rating produce less than 0.001 lux, 43% produce between 0.001 and 0.01 lux, 55% produce between 0.01 and 0.1 lux, while none produce more than 0.1 lux. As a point of reference, a full moon commonly produces about 0.3 lux. Thus all of the fixtures evaluated appear fainter than a full moon (either in the illuminance caused or in the brightness of the fixture viewed directly) at 500 feet distance; 1% and 3% of the G3 and G4 fixtures, respectively, appear about 1/3 as bright as the full moon. The brightest single luminaire evaluated with the LCS G2 rating appeared 13% (0.04/0.3) as bright as the full moon.

Table 10. The fraction of fixtures producing the indicated maximum vertical illuminance at 500 feet (VI500), for fully shielded (FS) fixtures and fixtures with LCS "G" ratings of 0 through 4. The last row shows the brightest single luminaire evaluated in each category.

VI500 (lx)	FS	LCS "G" Rating				
		0	1	2	3	4
0.0001 – 0.001	0.08	0.33	0.10	0.02	0.00	0.00
0.001 – 0.01	0.47	0.67	0.56	0.43	0.09	0.00
0.01 – 0.1	0.45	0.00	0.34	0.55	0.90	0.97
0.1 – 1	0.00	0.00	0.00	0.00	0.01	0.03
brightest	0.027	0.003	0.026	0.040	0.115	0.138

To evaluate glare arising from unshielded lighting allowed for fixtures under 1750 lm output in POLC LZ2 and LZ3, we assume conservatively that such fixtures can produce 2X the illuminance of an isotropic source of this luminous output, or $2 \times (1750\text{lm}/4\pi)$ / $(500\text{ft}*0.3048\text{m/ft})^2 = 0.006$ lux, or 1/50th full moon.

The maximum glare arising from unshielded fixtures allowed under MLO Performance Method Option B is assumed to be the maximum BVI specified for the Lighting Zone, or 0.5, 1, 3, 8 and 15 lux in MLO LZ 0 – 4, or 1.7X, 3X, 10X, 27X, and 50X full moon. This illuminance is equivalent to the maximum VI500 for a single fixture mounted at a parcel perimeter and viewed from the opposite boundary of a 500' parcel. A 500 × 500 foot parcel is 5.7 ac, a reasonable size for a commercial parcel.

[20] The maximum candlepower at 4° below horizontal is estimated by linear interpolation from the maximum candlepower at horizontal and 10° below horizontal.

3. Discussion

The IDA-IES MLO User's Guide describes how MLO lighting zones are to be applied and thus provides general guidance for determining the most likely zones where commercial developments such as examined in this study would be located.

MLO LZ0 is described as being intended for undeveloped or “wilderness” areas with no ambient lighting. MLO LZ1 is generally described as applying to rural and low-density residential areas, though the User's Guide indicates that some communities may apply LZ1 within business parks or even “rural town centers” (though we do not know what a “rural town” might be). It seems fairly clear that the writers of MLO did not envision that LZ0 and LZ1 would be applied within areas with significant commercial development, in small towns or large.

The guidance generally indicates that MLO lighting zones LZ2 – LZ4 are to be applied in developed areas. Following this understanding, we will usually consider the lighting standards for MLO LZ2 to represent the IDA-IES MLO minimum (tightest) standards for significant commercial development such as examined here.

POLC lighting zones are conceptually and in practice based on the sensitivity of the zone or regions near the zone to sky glow or other obtrusive aspects of lighting use and not in any direct way to the degree of development, lighting levels, activity, or urbanization of an area. Though there are significant urban areas[21] under POLC LZ2, in general we will use POLC LZ3 as representative of the standards applied to commercial development and the projects analyzed in this study.

3.1 Total Lighting Amounts

3.1.1 MLO

Figure 2 shows the maximum, minimum and average MLO allowances from Table 4. For MLO LZ2 allowances average 94 klm/ac (range 46 to 267) using the Prescriptive Hardscape Area Method and 180 klm/ac (range 87 to 400) using the Performance Method.

In MLO LZ3 these allowances rise to an average of 190 klm/ac (range 96 to 499) using the Prescriptive Hardscape Area Method and 354 klm/ac (range 175 to 800) using the Performance Method.

Finally, in MLO LZ4 the allowances rise to an average of 283 klm/ac (range 149 to 639) and 522 klm/ac (range 262 to 1163) using the Prescriptive Hardscape Area and Performance

[21] Approximately 2/3 of Flagstaff, Arizona (pop. 63,000) is LZ2 at 35 klm/ac. Though it has been contended that even 70 klm/ac is insufficient for meeting lighting-industry-recognized recommendations (Tucson/Pima OLCC, pers. comm.) we note that scores of commercial properties including nationally recognized retail franchises have been built in Flagstaff under a 35 klm per acre limit, including Walmart, Target, Kohl's, Home Depot, Staples, McDonald’s, Red Lobster, Olive Garden, and many others.

Methods respectively.

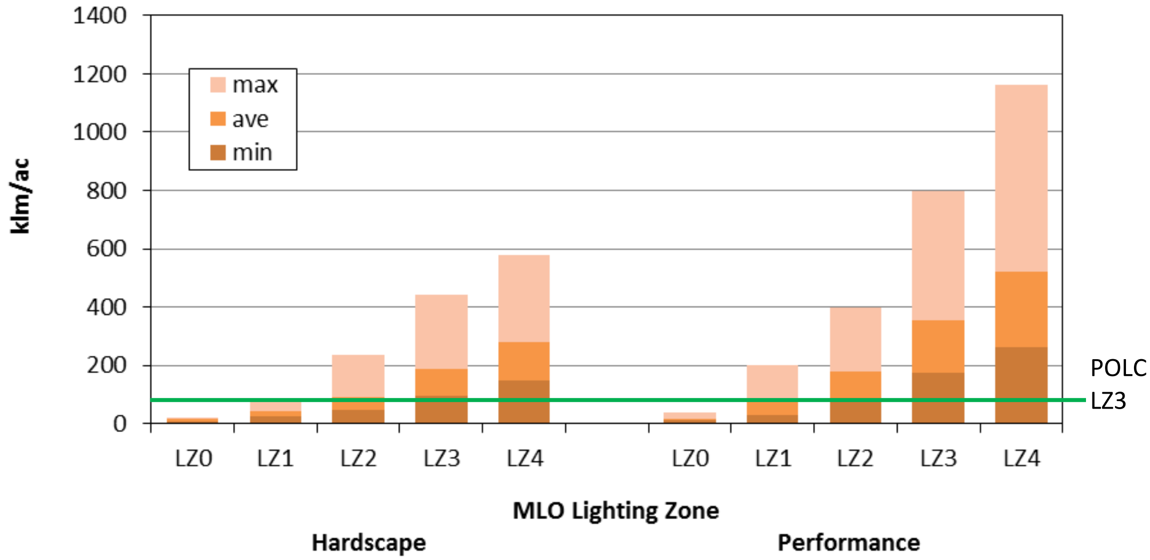

Figure 2. MLO maximum, minimum and average lumen allowances for the projects in Table 1, by Lighting Zone. The green line is at the POLC LZ3 average of 80 klm/ac (see Table 3 and Section 3.1.3).

The MLO total lighting allowances are strongly influenced by the method used to determine the allowance. The Performance Method allows consistently more light than the Prescriptive Hardscape Area Method: an average of 13% more in LZ0, 73% in LZ1, 92% in LZ2, 86% in LZ3, and 85% in LZ4.

Table 11 summarizes the MLO lumen allowances by land use. Comparing allowances for LZ2, the shopping centers, bank, office and restaurant projects show generally similar amounts (from 67 to 81 klm/ac using the Prescriptive Hardscape Area Method and 89 to 111 klm/ac under the Performance Method), while the fuel stations/convenience-store and auto dealer projects show mostly significantly greater allowances (117 and 238 klm/ac under the Prescriptive Hardscape Area Method and 377 and 238 klm/ac under the Performance Method, respectively). The motel and fuel station/convenience-stores show a factor of 2 – 3 difference between the Prescriptive Hardscape Area Method and the Performance Method in all lighting zones excepting only LZ0 for the fuel stations. This is due primarily to additional allowances for exterior entrances and service station hardscape under the Performance Method, substantially increasing the total allowances at the motel and fuel stations, respectively.

In summary, MLO lumen allowances following the Performance Method are for most uses approximately twice the allowances determined under the Prescriptive Hardscape Area Method, excepting only in LZ0 where they are generally similar. Allowances for service stations, auto dealers, and at least some motels are also approximately 1.5 – 3X the allowances for other uses analyzed in this study.

Table 11. Average MLO total lumen allowances by land use. N indicates the number of projects in the average from Table 1; MLO Lumen Allowance includes the Prescriptive Hardscape Area Method (upper) and the Performance Method (lower); values exceeding the POLC allowances of 70 klm/ac (non c-store) and 121 klm/ac (c-stores) are indicated in yellow; those exceeding even unregulated practice (column 8, from Table 2) are indicated by red. The Lighting Fraction in the last column is the fractional contribution of the land-use category to the total city-wide uplight from Luginbuhl *et al.* (2009) Table 2.

Land Use	N	MLO Lumen Allowance (klm/ac) LZ0	LZ1	LZ2	LZ3	LZ4	Unregulated (klm/ac)	Lighting Fraction
Shopping Center	7	14 15	35 40	71 107	146 214	225 320	112	0.095
Fuel Station / C-Store	3	16 16	58 189	117 377	239 754	365 1093	293	0.048
Auto Dealer	1	17 17	78 78	238 238	440 400	580 580	48 326[1]	0.007
Motel	1	15 40	37 101	76 271	157 542	245 813	105	0.050
Bank	1	12 13	33 36	67 89	145 177	226 266	167	--
Office	1	13 14	33 36	67 106	138 212	212 318	--	--
Restaurant	1	16 17	40 44	81 111	165 222	251 334	316	0.054

[1] includes two measures from Tucson reported in Luginbuhl *et al.* (2009)

3.1.2 Comparison of MLO to Unregulated Lighting Practice

To understand whether the application of MLO lighting standards will lead to reduced amounts of lighting in areas with no limits on lighting amounts, and thus expected decreases in sky glow (independent of shielding effects, discussed below), the amount of light allowed by MLO must be compared to unregulated lighting practice. Luginbuhl *et al.* (2009) published the results of a study in Flagstaff measuring the amount of light used for different land-use types in the absence of restrictions on lighting amounts.

Whether or not the measures of uncapped lighting amounts in Flagstaff, Arizona are typical for other areas is critical to understanding the expected impacts of MLO when applied to areas with no current lighting code. Flagstaff is a city of 65,000 inhabitants, and has a long history of regulations designed to protect dark skies. It is a legitimate question whether measures of unregulated lighting in Flagstaff can be considered representative of lighting in other communities, particularly larger ones. Yet before 1989 Flagstaff had no restrictions on the amount of light allowed; all of the measures underlying the Luginbuhl *et al.* (2009) estimate of unregulated lighting amounts were of sites built before 1989. There seems little reason to suspect that developers building in Flagstaff, with no legal restriction on lighting amount, would choose to use any less (or more) light than they might use anywhere.

Further, much research supports the idea that lighting practice does not vary systematically with size of the community. If there were a significant difference in the way outdoor lighting was done in the sense (as often claimed) that larger cities use more light per acre, per project, or per person, then the observed linear relation between city brightness and population would not hold (Walker, 1977; Garstang, 1986, 1989; Luginbuhl, 2001; Falchi & Cinzano, 2000). A plot of city brightness *vs.* population would show a steeper slope at larger populations than at smaller; this is not observed. The city-level studies (made in California, Arizona, and Italy), such as shown in Figure 3 for the southwestern U.S., indicate that a city of 2,000,000 inhabitants is ten times as bright as a city of 200,000 inhabitants, and forty times as bright as a city of 50,000 inhabitants. If the city of 2,000,000 inhabitants had on average more brightly illuminated parking lots, for example, then it would appear *more* than forty times the brightness of the city of 50,000 inhabitants (assuming the total area in parking lots is also proportional to population). This is not observed.

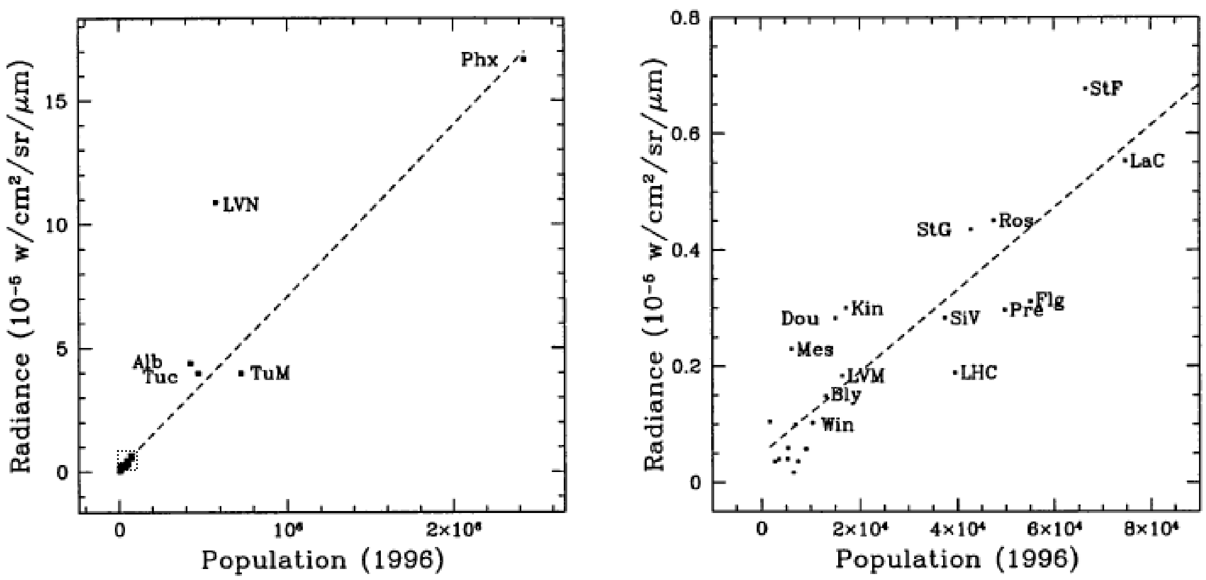

Figure 3. Integrated radiance *vs.* population for 27 cities in the American southwest from satellite measures made in 1996-97. The area in the small box in the left panel is expanded in the right panel. The dashed lines show the average radiance per capita for the cities under 80,000 population: extended to larger populations, it accurately predicts the brightness of the Phoenix (Phx) metropolitan area. Las Vegas, Nevada (LVN) is, not surprisingly, brighter than this relation would predict. Flagstaff (Flg) falls 23% below the average relation, which Luginbuhl *et al.* (2009) account for through the decreased impact of lighting installed following the 1989 lighting code (accounting for 18% reduction), and the unusually well shielded roadway lighting in Flagstaff (accounting for an additional 4%). Adapted from Luginbuhl (2001).

Measures of brightness vs. population at the state level (Elvidge *et al.*, 1999; see Figure 4) confirm the linear relation between population and brightness over a range from less than one million to 20 million residents. Here, the most densely populated states (California and New York), with population concentrated in the large urbanizations of Los Angeles and New York City, appear *fainter* than the average relation for the other states, an effect attributed to a decreased amount of light used per capita in dense urban areas, but possibly also influenced by the large amount of near-ground blocking of light in heavily built urban areas.

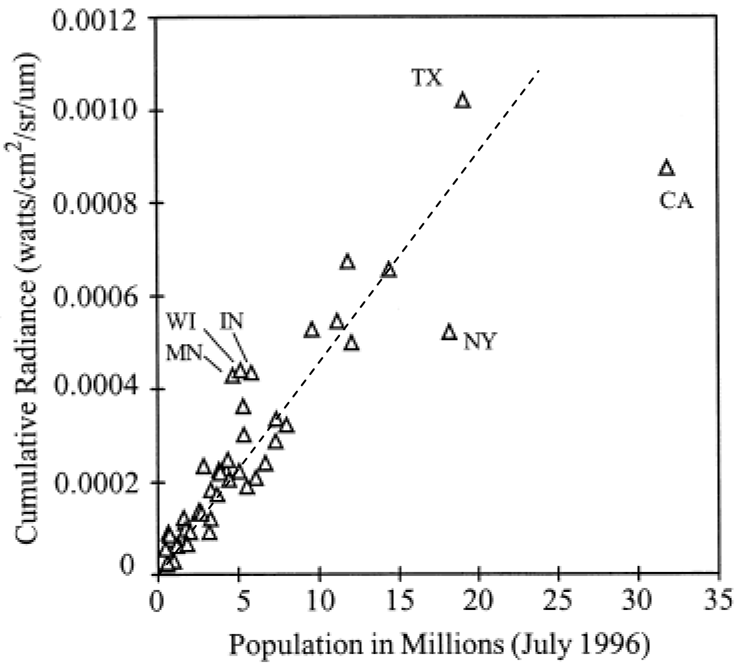

Figure 4. Cumulative radiance from DMSP satellite observations for the lower 48 states, *vs.* population. The higher Wisconsin, Minnesota and Indiana brightnesses are likely due to increased reflection from snow covered ground in these winter observations. From Elvidge *et al.* 1999.

Therefore comparison of MLO total lumen allowances to the amount of light used in Flagstaff, AZ, before adoption of the 1989 lumen limiting code should provide a reasonable estimate of whether application of the MLO standards would be likely to produce a decrease in the overall amount of light used and thus sky glow in a community not currently subjected to total lighting limits. The amounts of light used on unregulated sites in the Flagstaff area as determined by Luginbuhl *et al.* (2009) are listed in Table 11, and displayed along with the MLO allowances in Figure 5 through Figure 10.

These results show that both the MLO Prescriptive Hardscape Area and Performance Method allowances are less than the average amount of light used in unregulated practice for all land-use types (for which comparisons are possible in this study) in MLO LZ0 and LZ1.

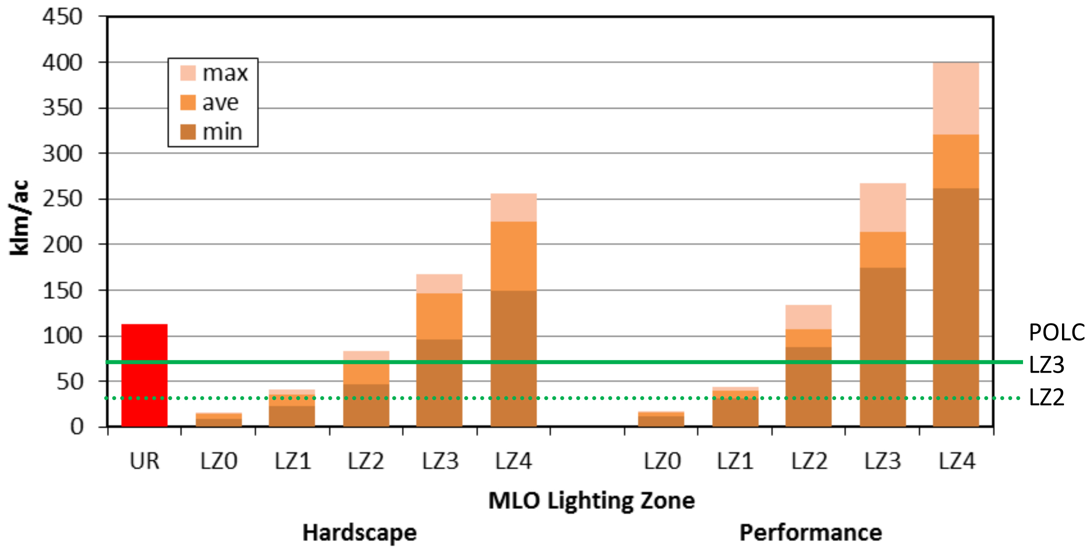

Figure 5. MLO average lumen allowances for the 7 shopping centers compared to unregulated practice (UR). The solid green line is at 70 klm/ac; the dotted line is at 35 klm/ac (see Table 3 and Section 3.1.3).

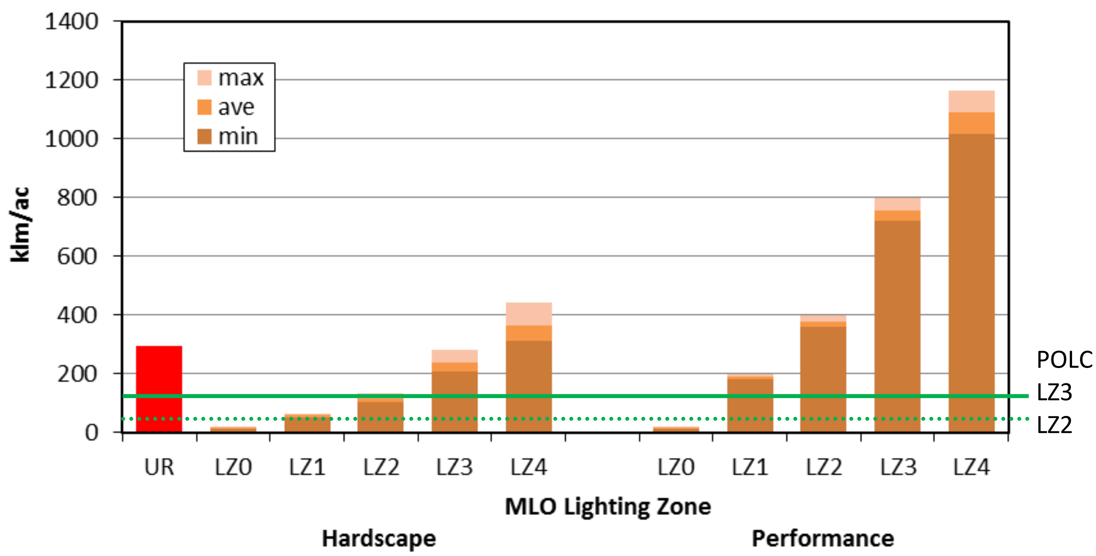

Figure 6. MLO average lumen allowances for the 3 fuel station/convenience stores compared to unregulated practice (UR). The solid green line is at 121 klm/ac; the dotted line is at 43 klm/ac (see Table 3 and Section 3.1.3).

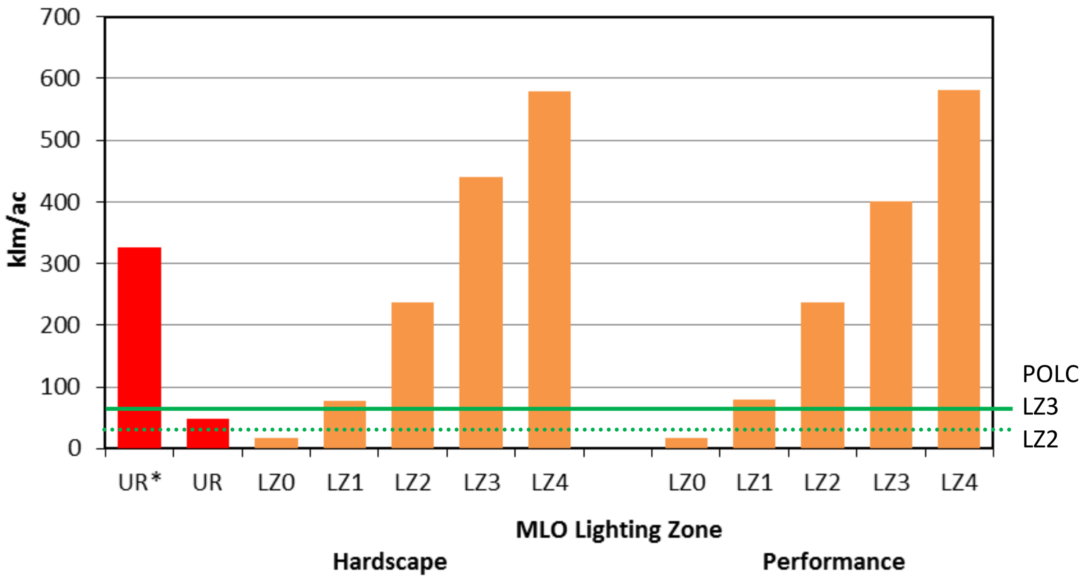

Figure 7. MLO lumen allowances for the single auto dealer compared to estimates of unregulated practice from Luginbuhl *et al.* (2009) (UR) and the Luginbuhl *et al.* value supplemented with two sites measured in Tucson, AZ (UR*). The green line is at 70 klm/ac; the dotted line is at 35 klm/ac (see Table 3 and Section 3.1.3).

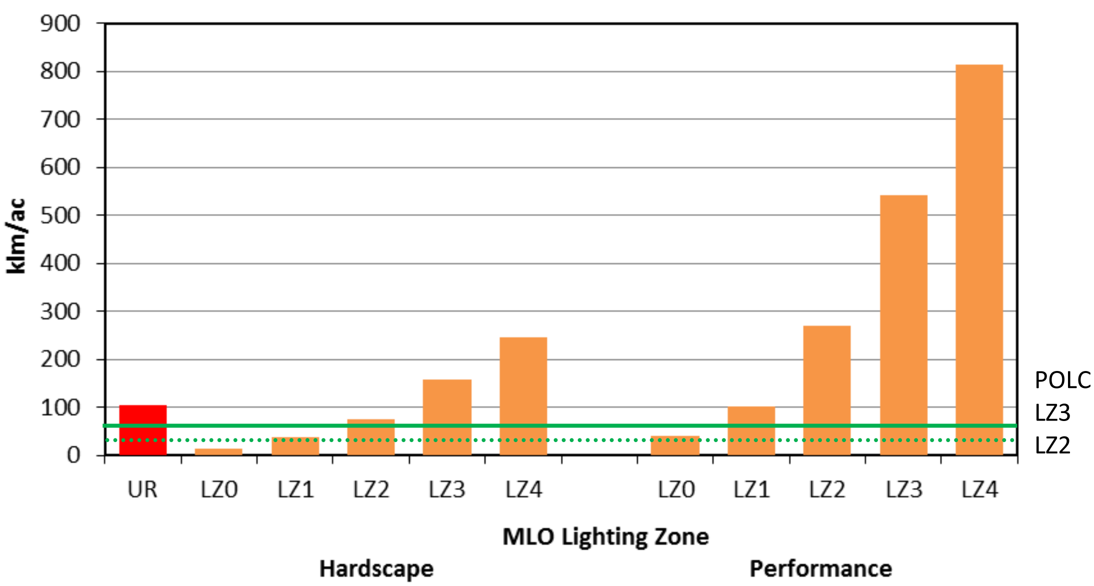

Figure 8. MLO lumen allowances for the single motel compared to unregulated practice (UR). The green line is at 70 klm/ac; the dotted line is at 35 klm/ac (see Table 3 and Section 3.1.3).

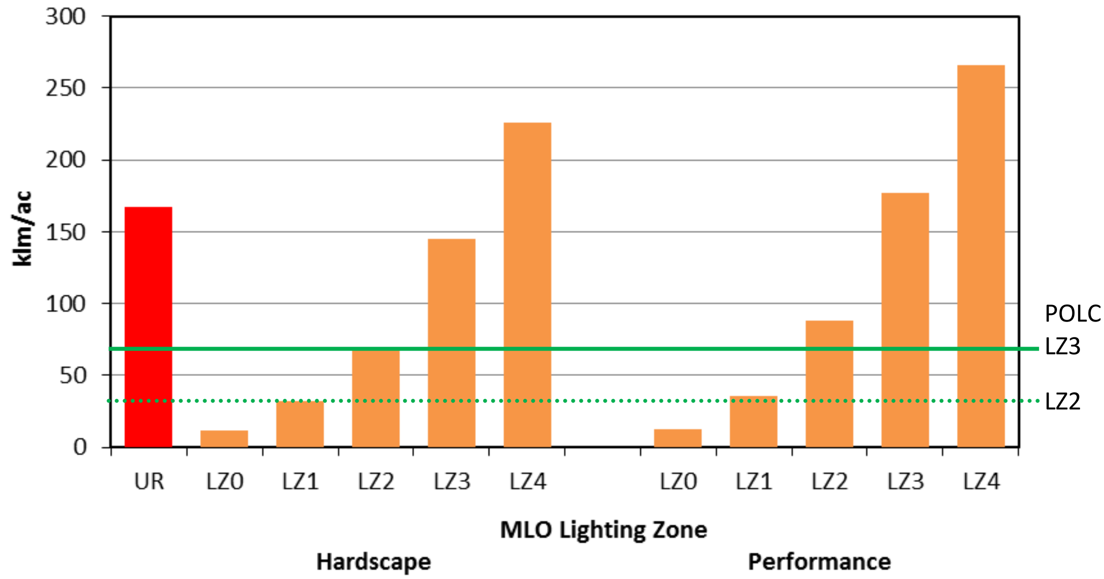

Figure 9. MLO lumen allowances for the single bank compared to unregulated practice (UR). The green line is at 70 klm/ac; the dotted line is at 35 klm/ac (see Table 3 and Section 3.1.3).

In MLO LZ2 the Prescriptive Hardscape Area Method yields lower amounts than the average unregulated practice in all six land-use categories for which sufficient data are available, though for the auto dealer (Figure 7) the allowance is five times the value determined in the Flagstaff sites only. However, the Performance Method – available as an option to any developer – shows significant reductions for only the bank and restaurant (allowing approximately 53% and 35% of unregulated practice, respectively – see Table 11, Figure 9 and Figure 10). For shopping centers the Performance Method allowance is similar to unregulated amounts (Figure 5), while for the motel and auto dealers the allowance is substantially more: 158% at the motel (Figure 8); and 75% – 496% at auto dealers (Figure 7).

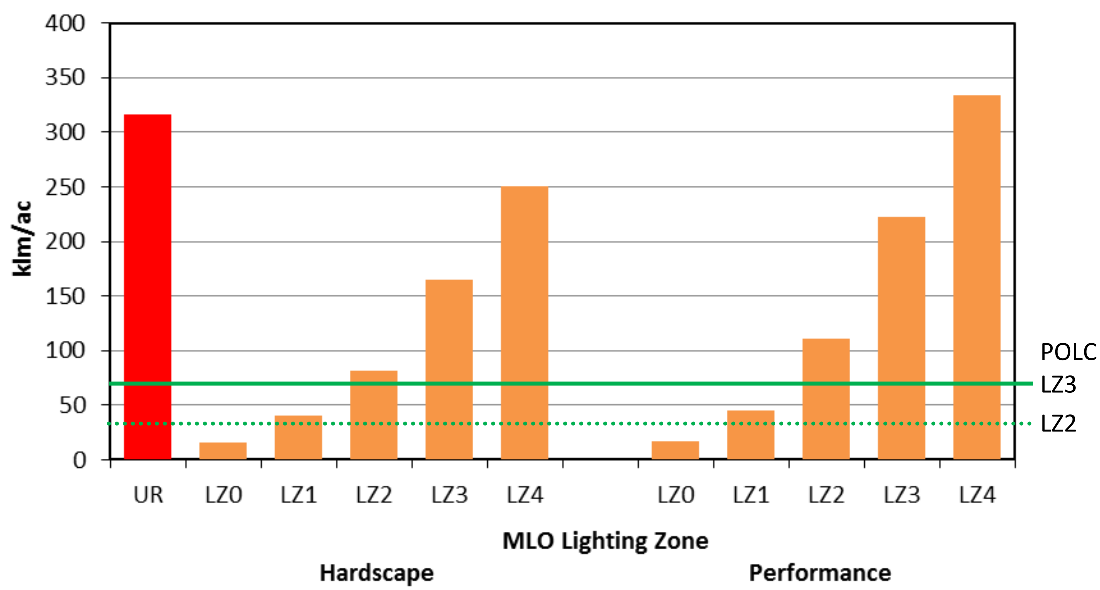

Figure 10. MLO lumen allowances for the single restaurant compared to unregulated practice (UR). The solid green line is at 70 klm/ac; the dotted line is at 35 klm/ac (see Table 3 and Section 3.1.3).

In MLO LZ3 and LZ4 most MLO allowances (19 of 28) exceed the average unregulated practice for all land-uses for which data are available. For the three high-intensity uses (fuel station/c-store, auto dealer, and motel) the Performance Method allows 400 – 754 klm/ac in LZ3, and from 580 klm/ac to over 1 million lm/ac in LZ4. These values exceed unregulated practice by factors of 1.22 to over 10. Fuel stations and motels are likely to be significant contributors to sky glow in all communities (together about 10% in Flagstaff); in many larger communities auto dealers are likely to be a large contributor as well.

In summary, the MLO total lumen allowances appear to represent a clear step forward (i.e. a reduction) in total lighting amounts compared to unregulated lighting practice in only MLO LZ0 and LZ1; in MLO LZ2 and particularly LZ3 and LZ4 many or most land uses would be allowed more light than used in the average unregulated practice, in some cases more than 10X more.

3.1.3 Comparison of MLO to POLC

Many lighting codes based on the POLC have established general caps of 70 klm/ac and less. With over 20 years' experience, these codes and this limit have been shown to be practical for lighting users and municipalities and effective at curbing total lighting amounts used. The actual lighting installed on the site and/or analyzed in Section 2.2 conforms to this limit or lower for many of the projects analyzed in this study (projects 5, 6, 8, 9, 11, 13). Essential lighting needs on all the sites are met; most have nonessential lighting such as façade lighting as well.

The demonstrated effectiveness of the Flagstaff lighting code in reducing the *growth rate* of sky glow (Luginbuhl *et al.*, 2009) hinges on both the reduction in total lumen amounts and improved shielding. As the majority of the projects developed since the adoption of this lumen limiting code are in the Flagstaff Lighting Zone 2, with a limit of 35 klm/ac, the benefits of achieving a lumen density of 70 klm/ac would be significantly less – besides using twice as much light, lighting at 70 klm/ac will in general have twice the light pollution impact of lighting at 35 klm/ac.

Thus, when assessing whether MLO lumen allowances represent a step forward compared to current effective lighting codes, a relevant yet conservative comparison is to a 70 klm/ac limit. The 70 and 35 klm/ac values determined for most sites (121 and 43 klm/ac for c-stores) from Table 3 are shown for reference in Figure 5 through Figure 10.

First comparing 70 and 121 klm/ac with the unregulated amounts listed in Table 11, the POLC allowances are substantially less than unregulated practice (20% – 67%) for all categories except the auto dealers surveyed in Flagstaff only and can thus be expected to produce substantial reductions in the various forms of light pollution.

On the other hand, in MLO LZ2 and above, nearly all (39 of 42) of the average MLO lumen allowances following both the Prescriptive Hardscape Area and Performance Methods exceed maximum POLC allowances (see Table 11). While the Prescriptive Hardscape Area Method allowances for some uses are quite close to 70 klm/ac in MLO LZ2, in MLO LZ3 they are about

2 – 6X greater, and in LZ4 3 – 8X greater. Allowances are yet larger following the Performance Method, exceeding maximum POLC allowances by factors of 1.3 to 12, depending on lighting zone and project type. Again, the MLO Performance Method is available to any lighting user.

As demonstrated below in Section 3.2, there are no standards within MLO, including the MLO limits to “off-site” impacts, that effectively limit the full utilization of these Performance Method allowances.

In summary, MLO lumen allowances in MLO LZ2 – LZ4 exceed the POLC LZ3 allowance in nearly every circumstance analyzed, by factors of up to 8X greater. In MLO LZ0 and MLO LZ1 lumen allowances are lower than POLC LZ3, but in general remain substantially above POLC LZ2 and especially POLC LZ1 allowances.

3.2 “Off-Site” Impacts

The MLO Performance Method includes, as an alternative to following the LCS shielding standards under Option A, an Option B with no explicit shielding standards but instead demonstrating that two measurements called “off-site” impacts are below certain limits. The stated goal is to limit light pollution impacts off site (such as sky glow, trespass and glare) potentially arising from the absence of shielding requirements and the large lumen allowances under Option B, using “performance” measures that are supposed directly sensitive to these impacts. The two “off-site” criteria are a limit to the “box ratio” (see section 1.2.2) of 0.15 in all lighting zones and a maximum illuminance on the interior sides of this same “box” – BVI (see Section 1.2.3) – with limiting values dependent upon lighting zone. These “off-site” values must be calculated using sophisticated lighting design software that includes light reflecting from and between the ground and “physical objects” on the project site.

MLO does not state what reflectance values are to be used for any surfaces, nor is there any practical way to verify whatever reflectance values a designer may use though they are critical to the analysis. Further, MLO does not state what if any depreciation factors are to be used in this calculation. Though these omissions are certainly critical issues for a legal document, for purposes of this analysis we assume reflectance of 0.06 for all hardscape, 0.15 for all other surfaces including buildings[22], and initial lumen outputs. Though these reflectance values are low, they are not proscribed by MLO, are defensible, and it seems likely designers would use them or similar as they reduce the “box ratio” and BVI.

3.2.1 Maximum Box Ratio

Table 5 shows that for sites without canopies (projects 5, 11 and 13), the box ratio for the nominal designs is about 15% (15%, 15% and 13%). For the two fuel station/c-stores with

[22] Vegetation is not included in these calculations, though trees, etc., are “physical objects” which MLO specifies must be included in the calculations (MLO Section IV.2 Option B 1). Though it is clear vegetation can have dramatic effects we do not see how it can realistically be included due to software and other practical limitations.

canopies (projects 9 and 10) the ratio is between 6% and 7%. It is important to note here that all of these nominal lighting plans include only fully shielded fixtures. Yet without canopies the 15% limit is approached though these sites are using much less than the MLO lumen allowance.

To explore whether the box ratio of 0.15 effectively places a limit on the total lighting amount, project 13 was altered by increasing the output of all luminaires by a factor of 10 (see Table 5 project 13A). Though of course this is an artificial change (i.e., this change is not meant to represent a realistic lighting design), this analysis gives a sense for the effect of changing lumen amounts on this ratio. As expected, both the box lumens and the site lumens increase in the same proportion, so the ratio is not changed, remaining at 13%. Thus, the box ratio maximum does not affect the total lumen allowance permitted under the MLO Performance Method.

For sites such as fuel stations with large amounts of light located under canopies (or sites where light fixtures are located at some distance from property lines – see design 5A discussed under section 3.2.2 below), and thus a lower box ratio, the ratio not only does not limit the total amount of light used on the site, but apparently leaves room for substantial amounts of unshielded light (remembering that under this Option B there are no luminaire shielding standards).

To explore this possibility, sixteen B5-U5-G5 luminaires of 9500 lm each (these are classic “barnyard” fixtures) were added to the parking area of project 9. The results (see Table 5 project 9A) show that the box ratio was only slightly increased (from 6% to 7%), whereas direct uplight was increased from zero to 11,000 lm. Further, since these luminaires were not located close to any site boundaries, the maximum BVI was not changed. The sky glow index (SGI) was increased 70%, from 10 to 17 per acre.

Since the box ratio still remains substantially below the 15% limit, there is room to add still more unshielded fixtures to project 9 without exceeding this criterion. The 11 fully shielded luminaires located near the perimeter of the site, incidentally leading to the high maximum BVI of this design (45 lux), were next replaced with floodlights aimed toward the interior of the site and 60° above nadir (the equivalent LCS ratings for these fixtures as aimed is B0-U4-G5). The box ratio increases to 9%, still well within the MLO limit. Further, the maximum BVI decreases from 45 to 4 lux, bringing this design now within the MLO Performance Method Option B criteria for LZ3 and LZ4, though glare, light trespass and sky glow have all been substantially increased. Wasted direct uplight has been increased from 0 lm to 19,000 lm, while the SGI is now twice that of the nominal POLC compliant design.

In summary, the limit on the box ratio – the ratio of total lumens leaving a site to total lumens produced on the site – does not limit the total amount of light allowed on the site following the Performance Method Option B. For sites without canopies and with typical luminaire-property line setbacks, this ratio is about 15% – the MLO limit – when exclusively fully shielded fixtures are used. On the other hand, for some of the brightest sites (i.e., those using the greatest amount of lumens), canopies can bring this ratio considerably below 15%, thus opening the possibility for substantial amounts of lighting using very poorly shielded fixtures such as “barnyard” and floodlights.

Finally, it should be emphasized again that the box ratio is demonstrably not useful for estimating the sky glow impacts of an outdoor lighting installation, as it contains no information on the direction of the light striking the insides of the box, critical to sky glow impacts (Luginbuhl, Walker & Wainscoat, 2009). It does not even distinguish light headed toward the ground from light headed for the sky (Rae *et al.*, 2010).

3.2.2 Maximum Boundary Vertical Illuminance

The limits to maximum vertical illuminance on the imaginary vertical surface over the site boundary – BVI – in the MLO are 0.5, 1, 3, 8 and 15 lux in MLO LZ0 through LZ4, respectively[23]. These values are from the work by Lewin (2000), though we note that this study most directly evaluated glare, not illumination levels or "light trespass." Nonetheless, Lewin determined illumination levels at the eye resulting from light sources judged to produce an "objectionable rating" of 3 on the following scale:

1. Not objectionable (acceptable)
2. Slightly objectionable
3. Quite objectionable
4. Very objectionable
5. Extremely objectionable

Though the rating scale used in the study indicates that only "1" is "acceptable," the maximum illuminance values listed above[24] were set such that ratings from 1-3 were effectively "accepted," including the rating described as "quite objectionable." This seems a surprising interpretation, especially in a "model" lighting ordinance purported to "drastically reduce light pollution and glare" (IDA-IES, 2011, pg. 2). Nonetheless, we will leave such issues for discussion elsewhere.

The BVI was calculated for the five projects summarized in Table 4 using a nominal measurement point spacing of 20 feet, with no attempt to manipulate, minimize (or maximize) the BVI by adjusting point locations[25]. These calculations show that all of the nominal designs exceed the MLO BVI criterion in LZ0 and LZ1, and one of the projects (11) exceeds the criterion in all zones (though simple manipulation of point locations allows a BVI calculation that would pass the LZ4 limit). As none of these projects were designed with the BVI criterion as a design constraint, the specific values of the BVI maximum for these designs are less important than an examination of the factors that lead to the MLO criterion being exceeded, the criterion's likely effects on lighting designs, and its effectiveness in achieving its goal of limiting light trespass.

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[23] The ambient vertical illuminance under natural (i.e., no lighting) moonless conditions (Duriscoe, 2012, pers. comm.) is about 0.4 millilux, so the lowest BVI recommended by MLO for LZ0 is over 1000x brighter.

[24] The Lewin (2000) study actually measured "objectionable ratings" for only CIE Environmental Zones E2, E3 and E4 (equated to LZ2 – LZ4 in MLO). Lewin added a value for E1 (LZ1), and MLO added a value for LZ0; neither of these has any basis in measurement – nothing is known about the "objectionable rating" these limits might represent.

[25] An unofficial version of MLO, briefly posted at the IDA and IES websites in early 2012, indicates that the BVI is to be calculated with an "adaptive" calculation grid. This functionality is not available in AGI32 ver. 2.36, (nor in any other lighting design software the author is aware of), and is not part of the official MLO, so is not attempted here.

In every case, the BVI maximum occurs, unsurprisingly, near a light fixture. To highlight this sensitivity, the nominal design for project 5 was rearranged to move all luminaires a minimum of two mounting heights from property boundaries. (This is not a practical lighting solution for this site, of course). Yet we see the dramatic effect on the BVI maximum (see Table 5 project 5A), which decreases from 47 to 4 lux. This shows that a tight BVI limit will cause lighting designers to seek to locate light fixtures away from property boundaries. Though at first glance this may be thought a desirable outcome, in many circumstances it may not be possible nor even desirable. (Note also that the box ratio was decreased from 0.15 to 0.08, which shows another avenue to allowing substantial amounts of unshielded light as explored in section 3.2.1.)

In project 10 the BVI maximum (11 lux) occurs at the site boundary nearest to an auto fueling canopy. This canopy is located 25 feet from the adjacent highway frontage. The design illuminates the ground under the canopy to 150 lux initial. This arrangement is unremarkable for a service station: such a setback from an adjacent roadway is not unusually large or small, although the illumination level is lower than commonly seen at service stations. Yet despite the typical geometry and modest illumination levels, the BVI maximum indicates that this design is allowed in MLO LZ4 only. It is hard to imagine what a designer could do to bring this under MLO constraints for LZ3 and lower.

Yet despite the oversensitivity of the BVI measure to this reasonable low impact lighting design, the BVI approach is ineffective at limiting flagrantly unshielded lighting. Project 10 was redesigned replacing most of the interior site lighting (10 fixtures) with unshielded 9500 lm B5-U5-G5 fixtures (see Table 5 project 10A). Total direct uplight was thus increased from 0 lm to 7,000 lm. It would be hard to describe this as other than a poor, glaring and trespassing lighting design. Yet the BVI maximum is barely affected, increasing from 11 to 12 lux, while the SGI nearly doubles from 21 to 38 per acre. It would still be permitted in LZ4, with room for many more B5-U5-G5 fixtures.

In some cases locating light fixtures far from property boundaries to meet MLO BVI criteria might be possible while still meeting lighting needs. In others it is impractical, inadvisable or impossible. In the actual case of project 5, the principal offending fixtures are three fully shielded 3500 lm fixtures illuminating high-traffic and high-conflict (pedestrian and automobile) pedestrian crossings of the site entrance drives, entering the site from the adjacent arterial and collector roadways. The high BVI maximum on project 11 arises from a similar situation. It is hard to imagine how to illuminate these critical areas, inescapably located very close to property boundaries, without running into trouble with the MLO Performance Method Option B BVI limit. Another high BVI value, of second severity on the project 5 site, arises at two fully shielded emergency egress lights located on a non-frontage face of the building and approximately 10 feet from the adjacent collector roadway. Without significantly changing the location of the building, the BVI limit would be very difficult to meet due to these lights as well. This design is not a high-intensity lighting use – it is a supermarket using 35 klm/ac, by any objective measure a low impact lighting use. Such situations may leave designers with no option but to use the Prescriptive Hardscape Area Method, and present MLO with another circumstance where the Prescriptive Hardscape Area and Performance Methods yield substantially different results.

On the other hand, as shown here and above in section 3.2.1, the BVI limit is insensitive to poorly shielded fixtures if they are located at some distance from the property boundary, or aimed away from the adjacent property boundary, even though such fixtures would still cause substantial amounts of sky glow, light trespass and glare.

The framework under which the MLO BVI limits are implemented is insensitive to many aspects of light pollution and light trespass. For example, the consequences of, or appropriate limits for, light trespass at all property boundaries within a lighting zone cannot be considered equal, not even approximately so; a commercial-commercial, or commercial-roadway boundary has considerably different sensitivity to trespass than a commercial-residential boundary. Variation in sensitivity to adjacency impacts is commonly recognized in land-use zoning, and addressed for example through variation in setback distances and/or landscaping buffer requirements. Yet the MLO sets the BVI maximum based on the single criterion of the subject parcel's lighting zone; the limit is not sensitive to an adjacent parcel's lighting zone, lighting design or land-use. In fact, the way this limit is specified leads to a nonsensical situation at the boundary between two adjacent parcels with different lighting zones: the parcel allowed more light is allowed to trespass onto the fainter parcel more than the faint parcel is allowed to trespass onto the brighter parcel. Finally, as different communities have different setback requirements and many different rules regarding what are and are not suitable adjacent land uses, it seems problematic to establish light trespass standards based solely on lighting zone.

Finally, we note the extreme sensitivity of the BVI measure to the placement of the points at which the measurement is calculated. As a practical matter the illuminance cannot be calculated at every point, only at discrete points. Where these points fall relative to luminaires near the site boundary can drastically change the maximum BVI detected by the software[26]. This provides an obvious avenue for gaming the MLO standards, “adjusting” the calculated values of the BVI through intentional adjustment of measurement locations without actually addressing the issue of trespass at all.

In summary, the MLO BVI standards do not provide effective limits on the lumen allowances, sky glow impacts, or unshielded lighting. Luminaires located near property boundaries, such as on building faces when building setbacks from property boundaries are small, luminaires used to illuminate critical areas such as pedestrian walkways at site driveway entrances, and even canopy lighting at typical property-line setbacks, will cause the MLO BVI limits to be exceeded in nearly every circumstance, even with fully shielded luminaires. This criterion is on the other hand insensitive to unshielded luminaires located at some distance from property boundaries. On sites with large lumen allowances but unusual structural shielding (such as fuel stations) or large luminaire-property boundary setbacks, large amounts of unshielded lighting may be installed without exceeding the BVI limit. Finally, the linking of this criterion to a site's lighting zone only (with no cognizance of the lighting zone or land-use on the other side of the boundary) leads to nonsensical trespass results.

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[26] Maximum BVI for the nominal Project 9 design was computed using AGI32 with automatic grid point spacing from 18.0 to 20.0 feet with 0.2 foot increments. The calculated maximum BVI ranged from under 15 to over 45 lx, or more than a factor of three.

3.3 Direct uplight and sky glow index (SGI)

Comparing uplight lumen densities and sky glow impacts is complex – we must consider four lighting scenarios (1 – unregulated lighting, 2 – lighting regulated under POLC standards, 3 – lighting regulated under MLO LCS standards, and 4 – lighting regulated under MLO Performance Method Option B standards), in three (POLC) or five (MLO) lighting zones. To simplify the comparison, we first discuss the uplight lumen densities. These relate directly to wasted energy, commonly a principal concern of communities adopting lighting codes. We will follow this with a discussion of the sky glow index (SGI), recognizing that this is a more direct dark sky concern, a "light pollution" consequence of uplight.

When discussing MLO impacts we will also generally focus on the larger allowances produced by the Performance Method. This is intended to realistically evaluate the maximum impacts that are allowed under MLO standards. The same treatment is given to the POLC results, where we generally compare to impacts under the most generous total lumen and unshielded allowances, using the POLC LZ3 (70 klm/ac) limits rather than the POLC LZ2 (35 klm/ac) or LZ1 (17.5 klm/ac) limits. In the case of MLO, though the Prescriptive Hardscape Area Method gives generally lower total allowances and stricter shielding standards[27], no developer is compelled to use this method: the larger allowances and greater impacts allowed under the Performance Method (either Option A or Option B) are available to any designer and project.

3.3.1 Direct uplight

The direct uplight observed in unregulated practice (cf. Section 2.3.1) of 16 klm/ac is reduced by a factor of 15X (1.1/16 or 93%) under POLC standards for LZ2 and LZ3 (see Table 6). As a fraction of total lighting energy wasted this represents a reduction from 10% to 1.6% – 3.1%. Direct uplight is completely eliminated under POLC standards for LZ1.

Direct uplight lumen densities for unregulated lighting (Section 2.3.1), under POLC LZ2 and LZ3 (Section 2.3.2), and under the MLO Prescriptive Hardscape Area Method and Performance Method Option A using LCS standards (Section 2.3.3, Table 7) are shown in Figure 11.

Under MLO LCS standards direct uplight is also eliminated in MLO LZ0 and is below the POLC maximum of 1.1 klm/ac in MLO LZ1, ranging from 0.1 to 0.6 klm/ac under the scenarios analyzed in Section 2.3.3. In MLO LZ2 the LCS standards allow considerably more direct uplight than the POLC maximum (2 – 6X more) if fixtures of less than 10,000 lm each are employed.

[27] Particularly there is a requirement of zero uplight for parking lot lighting that is removed under the Performance Methods.

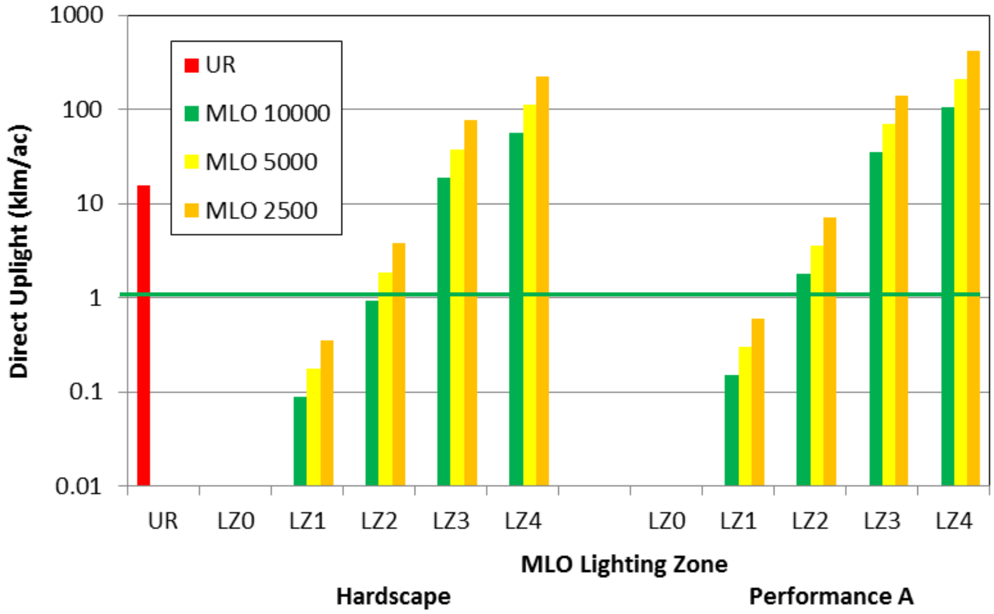

Figure 11. Direct uplight lumen densities for unregulated lighting (UR) and under MLO Prescriptive Hardscape Area Method and Performance Method Option A LCS standards (Table 7). The green line is at 1.1 klm/ac, the maximum direct uplight density under the POLC (Table 6). Note the logarithmic scale necessary to display the wide range of direct uplight lumen densities under MLO.

Under MLO LCS standards in MLO LZ3 and LZ4 the direct uplight lumen densities at 5000 lm per fixture[28] exceed by large factors both the POLC maximum and unregulated practice for all scenarios analyzed. The Performance Method increase compared to unregulated practice ranges from 4.4X (71/16) to over 13X (209/16). Compared to the POLC maximum of 1.1 klm/ac, MLO LCS standards in MLO LZ3 and LZ4 allow uplight lumen densities beginning at almost 65X (71/1.1) greater and reaching as high as 190X (209/1.1) greater.

Under MLO Performance Method Option B the uplight lumen densities can be much larger still, dramatically exceeding POLC densities in even MLO LZ2 (Section 2.3.4 and Figure 12). For the three MLO LZ2 designs summarized in Table 8 and Table 9, the uplight densities are 7.9 – 53 klm/ac, or up to 7X that of the MLO LCS amount with 2500 lm/fixture. Again, MLO Performance Method Option B is available to any developer for any site.

Finally, we note the wide variation in direct uplight lumen densities following these three MLO methods. Using the most dramatic example, Project 7 produces either 4, 7, or 53 klm/ac direct uplight following the Prescriptive Hardscape Area Method, Performance Method Option A and Performance Method Option B, respectively. In general, the standards of the MLO Performance Method Option A produce direct uplight densities approximately twice those under the MLO Prescriptive Hardscape Area Method (see Figure 11 and Table 7). This wide variation is an unexpected and undesirable characteristic for alternative regulatory options in the same code

[28] To further reduce the complexity of comparison, when discussing below the impacts of the MLO LCS standards on allowed uplight lumen densities and SGI, we will focus on the analysis at 5000 lm per fixture. We note that contrary to the general analysis emphasizing the maximum impact this is an intermediate impact.

intended to achieve the same purpose.

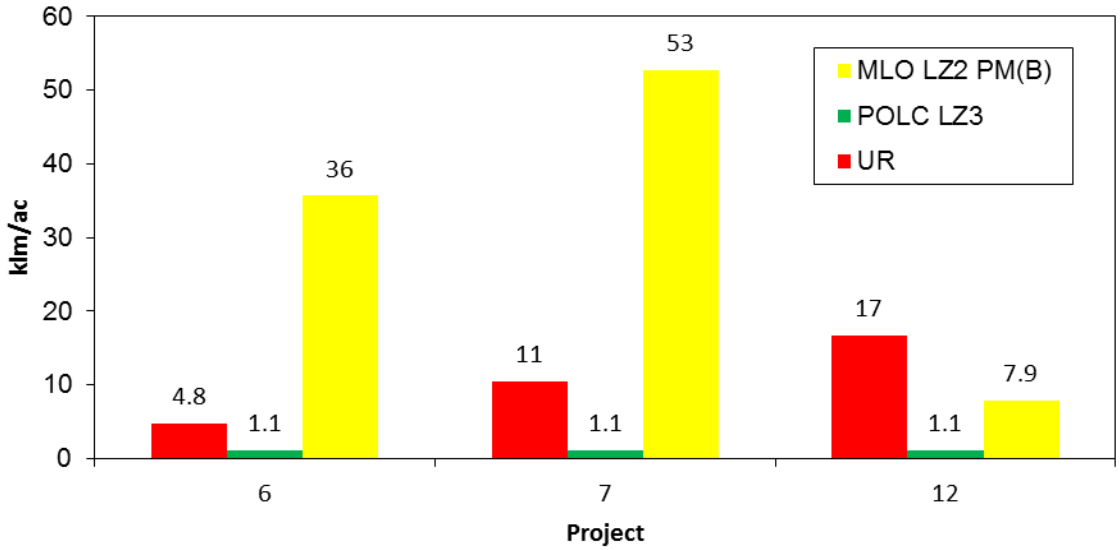

Figure 12. Direct uplight lumen densities of the projects in Table 8 with lighting designed following the POLC LZ3 standards and MLO LZ2 Performance Method Option B. UR indicates the direct uplight density for unregulated lighting for the specific site uses (car dealer, motel and bank, respectively), following the results of Luginbuhl *et al.* (2009) with 10% direct uplight.

In summary, direct uplight is dramatically reduced compared to unregulated practice following POLC standards, yet dramatically increased in all zones above LZ1 following MLO Performance Method Option B. POLC standards represent a 90% or greater reduction, while MLO LZ2 standards allow uplight lumen densities up to 3X greater than unregulated practice, and about 50X greater than POLC standards. In MLO LZ3 and LZ4 the increase is even more dramatic. In the lower numbered zones, the MLO Prescriptive Hardscape Area and Performance Methods using LCS standards allow less direct uplight (less than unregulated practice in MLO LZ0 – LZ2 and less than POLC LZ2/3 in MLO LZ0 – LZ1), but as any developer is permitted to use the MLO Performance Method Option B, the larger uplight lumen densities represent the largest MLO impacts.

3.3.2 Sky glow

Examining the potential sky glow – the most direct light pollution impact – from these various standards through the SGI, Table 7 and Figure 13 show a very similar story to the uplight lumen density analysis above. The expected SGI/ac of unregulated lighting (red bar, Figure 13), estimated at 98 (see Section 2.3.1), is reduced 84% – 98% by POLC standards for POLC LZ1 – LZ3 (horizontal green lines, Figure 13).

Comparing to unregulated lighting practice, MLO LCS standards reduce SGI in MLO LZ0, LZ1 and LZ2 (98% in LZ0 – 37% in LZ2), with moderate to dramatic increases in MLO LZ3 and LZ4 (117% in LZ3 – 1000% in LZ4). Compared to POLC standards, MLO LCS standards can be expected to produce at most a very slight improvement in MLO LZ0 only. In MLO LZ1 the

SGI/ac is similar to that in POLC LZ2; in MLO LZ2, LZ3 and LZ4 the MLO LCS standards at 5000 lm/fixture allow, respectively, an SGI 3X, 25X and 68X greater than the largest SGI under POLC.

The MLO Performance Method Option B allows for a yet larger SGI. For the MLO LZ2 analyses summarized in Table 8 and Table 9, the SGI can increase by a factor of two or more over that found for the MLO LCS standards shown in Figure 13, leading to an overall increase by a factor of up to 6X (105/16) compared to POLC LZ3 standards. Though we have not executed any designs conforming to MLO Performance Method Option B standards for LZ0 or LZ1, we expect that the complete release from luminaire shielding standards under this option means that the low SGI indicated for MLO LCS standards (2.6, see Table 7) can be substantially exceeded following MLO Performance Method Option B.

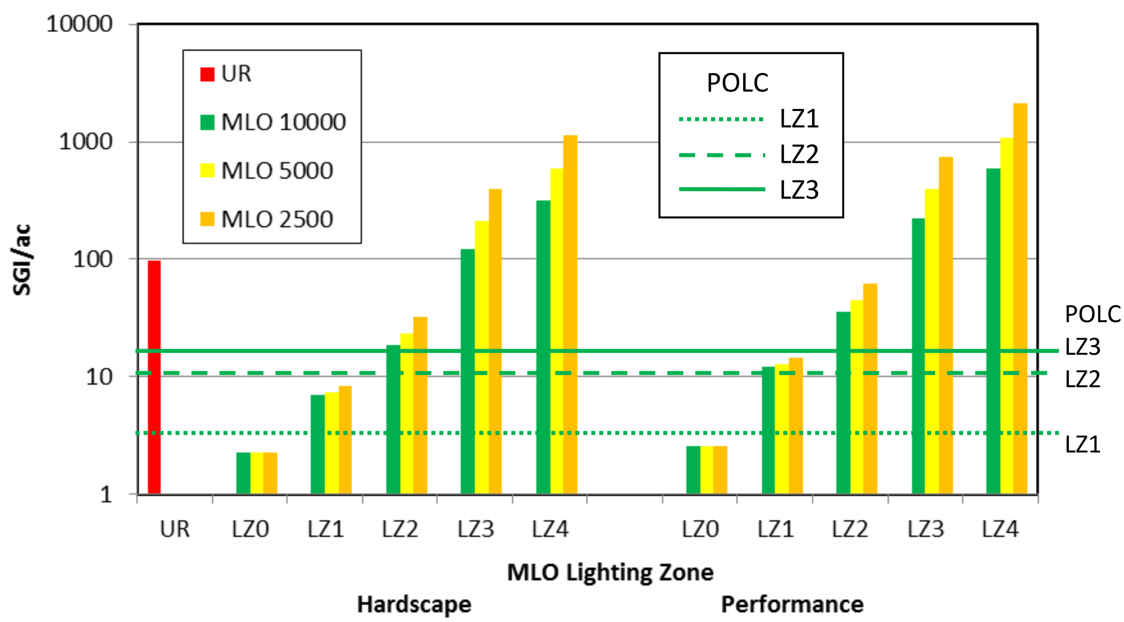

Figure 13. Sky glow index (SGI) per acre for unregulated (UR) and MLO lighting under the LCS standards (Table 7). The solid/dashed/dotted green lines are at 16, 11 and 3.5, the maximum SGI under the POLC for LZ3/2/1 (Table 6). Note the logarithmic scale necessary to display the wide range of SGI under MLO.

As MLO does not address or regulate lamp types, blue-rich sources can be (and increasingly in the nascent solid-state age are being) used for outdoor lighting. The result for visible sky glow is that in most circumstances located in moderate-sized to small communities and in all rural or remote areas, the visible sky glow can be as much as 3 – 5X greater than for HPS (and up to 15X greater compared to LPS) (IDA, 2010).

Finally, here also the MLO Performance Method Option B standards allow SGI values approximately twice those under the MLO Prescriptive Hardscape Area Method (see Figure 13 and Table 7), indicating again that the different MLO approaches to controlling light pollution impacts do not produce similar results.

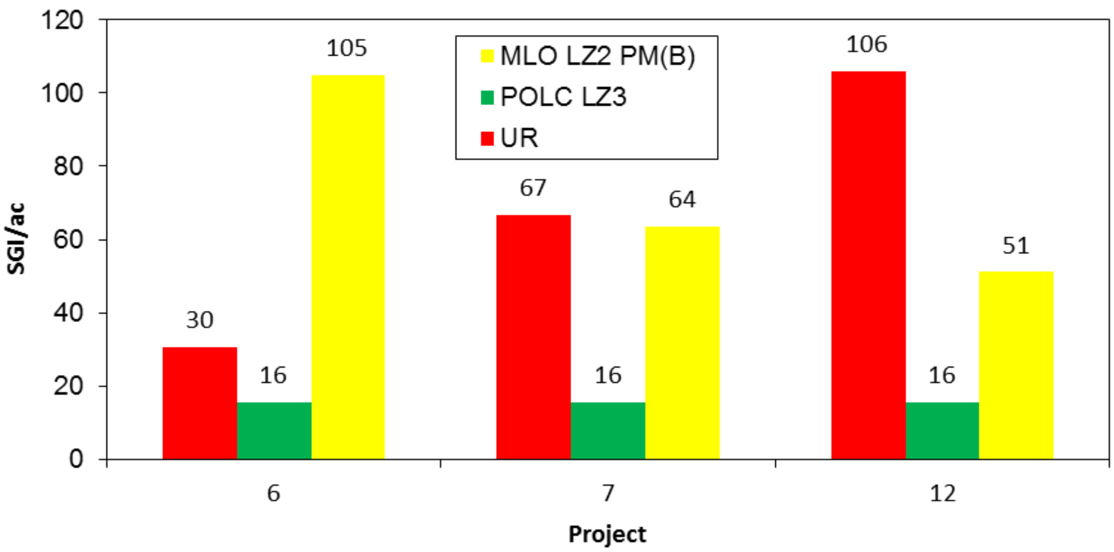

Figure 14. SGI/ac of the projects in Table 5 following the POLC LZ3 standards and MLO LZ2 Performance Method Option B. UR indicates the SGI for unregulated lighting for the specific site uses (car dealer, motel and bank, respectively), following the results of Luginbuhl *et al.* (2009) with 10% direct uplight.

In summary, sky glow impacts measured using the Sky Glow Index are dramatically reduced compared to unregulated practice with lighting following POLC standards, yet approximately equal (MLO LZ0, LZ1) to dramatically increased (MLO LZ2, LZ3 and LZ4) following MLO standards, especially following MLO Performance Method Option B. POLC standards represent an 80% or greater reduction in SGI compared to unregulated practice, while MLO LZ2 standards allow an SGI approximately equal to unregulated practice and at least 100X greater than POLC standards. In the higher MLO lighting zones the increases would be yet more dramatic.

Despite the (apparent) expectation that "limits to off-site impacts" in the MLO Performance Method Option B will control the important light pollution impacts of uplight, sky glow, trespass and glare, this method, with no fixture restrictions on uplight fraction or glare, allows lighting designs dominated by unshielded floodlight and prismatic fixtures.

3.3.3 Does MLO limit sky glow?

The writers of the MLO contend that the MLO use-specific lumen allowances and "off-site" standards effectively control important light pollution impacts, that they "… will allow communities to drastically reduce light pollution and glare and lower excessive light levels" (MLO User's Guide, pg. 2). They have even suggested that these MLO standards are more effective than the shielding and general lm/ac standards of the POLC discussed and analyzed here. However, the amount of light propagating into the sky and the resultant sky glow is not directly addressed with any of the MLO "off-site" metrics. The analysis of this report demonstrates that the MLO approach is in fact dramatically less effective than the POLC approach and does not appear certain to produce sky glow reductions even compared to unregulated lighting practice.

Lighting industry representatives have often expressed the opinion that strict shielding (commonly appearing in lighting codes as "fully shielded" or "full cutoff" standards) unnecessarily constrains good lighting design and limits "creative solutions" to lighting problems and light pollution by talented designers. MLO appears to subscribe to this philosophy, allowing in nearly all lighting zones substantial amounts of direct uplight through LCS BUG standards, and removing *all* luminaire shielding restrictions under the Performance Method Option B. Yet the impacts on uplight and sky glow of this approach appear clear and represent a huge step backward compared to current state-of-the-art lighting codes like the POLC.

3.4 Glare

Glare is a complex visual phenomenon, and measuring it often involves metrics that capture only certain aspects while missing others. The types of glare (IESNA, 2011b, pg. 4.28) related to visual performance include measures of the illuminance at the eye caused by the source, which is directly proportional to the intensity of the source (measured in candela) and inversely proportional to the square of the distance[29].

In this study we first compare the effectiveness of POLC fully-shielded and MLO LCS standards at controlling glare. The measure used in this study, the maximum vertical illuminance produced by luminaires at 500' distance (VI500), is a measure much more closely related to most aspects of glare than the LCS "G" rating even though the "G" stands for "glare" in the LCS (IESNA, 2011a).

The figures shown in Table 10 are displayed graphically in Figure 15. This presentation clearly shows, for this sample of 252 fixtures, that the POLC "fully shielded" criterion produces glare control slightly worse than the LCS G1 but slightly better than LCS G2; the brightest FS fixture (VI500 = 0.027 lux) is nearly identical to the brightest G1 fixture (VI500 = 0.026 lux) and fainter than the brightest G2 fixture (VI500 = 0.040 lux).

The maximum VI500 values arising from G3 and G4 fixtures are considerably worse than those determined for the fully shielded fixtures, with 90% or more having maximum VI500 of 0.01 lux or greater and with maximum VI500 values 4X and 5X brighter than for fully shielded fixtures.

The maximum VI500 of 0.006 lux or 1/50th full moon estimated for unshielded or "partially shielded" fixtures allowed by POLC is considerably lower than commonly arising from fully shielded or even LCS G0 fixtures containing higher output lamps. POLC allows only 2100 fixture lumens/ac in such fixtures, or essentially one fixture per acre.

[29] Most measures also include the inverse angular separation between the source and the viewing direction, and the inverse of the background or average scene luminance.

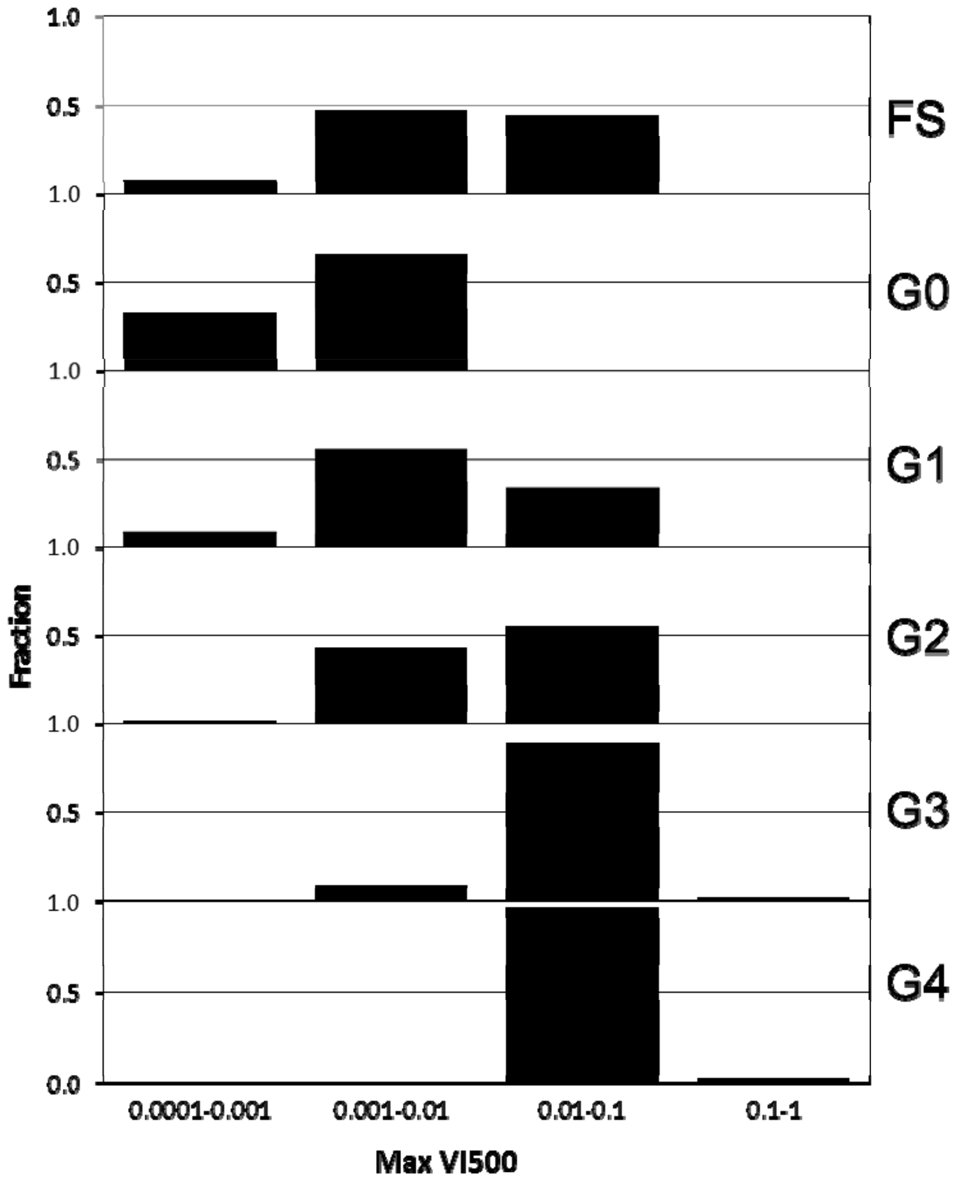

Figure 15. Histograms of the figures in Table 10, showing the fraction of fixtures causing the indicated maximum vertical illuminance at 500 feet (VI500). The fully shielded (FS) fixtures show maximum VI500 measures quite similar to those meeting the LCS G1 specification.

To more fully understand the impacts of these glare measures, we return to the original work by Lewin (2000) used to set boundary vertical illuminance limits by the CIE, IES and MLO. Lewin's work more fundamentally investigated acceptability – or "objectionability" – of glare; we find that by Lewin's original interpretation, in "Environmental Zone E2" (equivalent to MLO LZ2), glare sources producing illumination at the eye of 3 lux (or appearing 10X as bright as a full moon) were judged "quite objectionable." Sources producing an illumination at the eye of 1 lux (3X as bright as full moon) were judged to be "slightly objectionable." Thus, when considered as single sources in isolation, all of the fixtures evaluated, including the brightest LCS G4 fixture at VI500 = 0.138 lux, would have been considered by Lewin no worse than "slightly objectionable" when viewed from 500 feet[30].

The evaluation of VI500 using LCS ratings is an incomplete and inaccurate overall assessment of the glare control provided by MLO standards, as in MLO Performance Method Option B, there are no LCS or other shielding standards at all. The designs described in Sections 2.2 and 2.3.4 show that unshielded barnyard lights, prismatic wallpacks and even sideways-directed floodlights are permitted using this option. Here the BVI maximum "off-site impact" limit effectively provides a cap on maximum VI500, but at the relatively very high BVI limits of 0.5 – 15 lux, or 1.7X – 50X full moon brightness. And again, the MLO Performance Method Option B is available to any designer for any site.

As the POLC "fully shielded" standard is practically implementable using no more than a layman's visual examination of the fixtures, or even images or drawings of the fixtures, it has a distinct practical advantage over the photometric LCS approach and can be effectively applied even in the absence of photometric data. As the consistency, reliability and availability of fixture photometric measures have always been an obstacle to lighting code implementation (even with the earlier "cut off" classifications), this advantage would appear substantial. The degree of glare control it offers is essentially the same as the LCS G1 rating.

In summary, an analysis of over 250 fixtures shows that the POLC "fully shielded" shielding standard provides glare control very similar to the MLO LCS G1 standard in MLO LZ1. Fully shielded fixtures viewed from a distance of 500 feet can show a maximum illumination of about 0.03 lx or 1/10th full moon, essentially identical to the brightest LCS G1 fixtures evaluated. Nonetheless, as there are no LCS or other shielding standards under MLO Performance Method Option B, the maximum glare possible under MLO is limited only by the limits to the maximum vertical illuminance at the property boundary: these limits of 0.5 – 15 lux in MLO LZ0 – LZ4 are 1.7X – 50X full moon brightness. As noted in the uplight analysis, completely unshielded fixtures, including sideways directed floodlights, can be used under this option.

3.5 Lamp spectral distribution

The spectral distribution of light sources used for outdoor lighting has a large impact on many aspects of light pollution, such as glare and sky glow. Sources rich in shorter wavelengths generally have larger impacts, often much larger, due principally to the sensitivity of the human eye for both low-light and off-axis visual, and non-visual processes[31]. The IDA paper on blue-rich white lighting (IDA, 2010) indicates that the sky-glow impacts of blue-rich lighting are in general 3X to 5X greater than the equivalent amount of HPS lighting and as much as 15X greater than LPS. Given this distinct dark sky impact, lighting codes expecting to effectively address sky glow must grapple with this issue and not avoid it.

Nonetheless, the IDA-IES MLO has no reference to lamp types. The POLC version 2.0

[30] The single study by Lewin underlying light trespass metrics in the lighting industry literature and MLO relied on a very small sample of subjects (30 people).
[31] Non-visual processes include circadian rhythms and coupled hormonal cycles that affect many aspects of biological processes in humans (and other organisms).

(Luginbuhl, 2010) requires the use of HPS, LPS, or warm-white LED sources for "Class 2" lighting, that is most area lighting (80% or more according to Luginbuhl *et al.*, 2009). The POLC as implemented in some Arizona communities (*e.g.*, Flagstaff, Coconino County) limits "Class 2" lighting to low-pressure sodium[32].

For example, even if the use of white LEDs leads to a 50% decrease (0.5 ×) in the total amount of lumens released into the night environment (through improved application efficiencies or reductions in light levels), this blue-rich source will result in an overall sky glow increase of 0.5 × 3X to 5X = 1.5X to 2.5X compared to HPS; without overall lumen reductions (in practice the more likely scenario), sky glow would increase 3X to 5X. In such a circumstance, even assuming such dramatic overall lighting amount reductions were realized, it would be hard to claim that progress was being made in reducing light pollution when visible sky glow increases 50% to 150%.

4. Conclusions

This report presents an evaluation of the light pollution impacts of the IDA-IES Model Lighting Ordinance (MLO) and the Pattern Outdoor Lighting Code (POLC) described in Section 1. The analysis includes the total amount of outdoor lighting allowed, the so-called MLO "off-site" impacts, direct uplight allowances, the amount of sky glow expected, and glare. The analysis compares the MLO to POLC as well as where possible to unregulated lighting practice.

The POLC is found to provide substantial improvements over unregulated outdoor lighting practice in all evaluated light pollution impacts. In the "brightest" POLC Lighting Zone 3, the total lighting amount for commercial sites is reduced on average to about one-half or less of the amount used on unregulated sites; in POLC LZ2 they are reduced to one-quarter and less. The amount of sky glow expected, evaluated using the Sky Glow Index (SGI) and accounting for both light emitted directly upwards and reflected upwards, is reduced nearly a factor of 100 compared to average unregulated outdoor lighting practice.

Under MLO standards, outside of MLO Lighting Zones 0 and 1, the total lumen allowances, direct uplight allowances, and amount of sky glow are notably greater than expected under POLC standards; in MLO Lighting Zones 3 and 4 they are dramatically greater. These lighting amounts and sky glow impacts are greater than what can be expected even when lighting is unregulated. The MLO Performance Method Option B provides notably poor control of direct uplight and therefore sky glow.

Glare under the POLC "fully shielded" standard is controlled in all zones as well as in MLO LZ1 following the LCS ("BUG") standards. Under the MLO Performance Method Option B there are no effective limitations on glare.

[32] Though it has been often contended that LPS lighting is only an "astronomers" solution to light pollution, often suggested as applicable or feasible only in areas dominated by professional astronomical observatories, the dramatically lower sky glow impact of LPS (and even HPS) is beneficial from much more than a professional astronomical perspective. The common existence of low-pressure sodium codes in areas of sea turtle nesting attests to this, though the benefits are perceptible to many other organisms including humans.

POLC requires the use of yellow (LPS, HPS, amber LED) or warm-white LED (CCT<3500K) for general area lighting, which accounts for 80% to 90% of outdoor lighting, thus reducing many aspects of light pollution such as visible sky glow, glare, human circadian impacts, and impacts on many biological systems. MLO does not address lamp spectrum, and thus leaves this crucial aspect of light pollution unaddressed.

Finally, the analysis shows that the MLO Prescriptive Hardscape Area and Performance Methods do not provide similar results in terms of total lumen amounts, uplight amounts, glare, or "off-site" impacts, an undesirable characteristic of a model regulation purporting to control light pollution. The Performance Method particularly allows for the most egregious forms of polluting lighting fixtures and designs.

Given these results, we conclude that a substantial reduction in light pollution is available to communities adopting a lighting code following POLC standards; adoption of a code based on the IDA-IES MLO cannot realistically be expected to produce improvement. Certainly for the medium-sized and small communities and rural areas in which codes based on the POLC approach are in place, the standards of the MLO represent a significant step backward in light pollution limitation and control.

We conclude that a substantial reduction in light pollution is attainable to communities that adopt lighting codes following POLC standards. We find no evidence that communities adopting MLO can expect reduction in light pollution over that produced by typical unregulated lighting, despite the claims of MLO to be a method to "drastically reduce" light pollution. Certainly for the medium-sized and small communities and rural areas that most frequently seek to reduce light pollution and protect the natural night environment, the MLO represents a significant step backward in light pollution limitation and control compared to the older IDA POLC model.

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