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Lighting application efficacy: A framework for holistically measuring lighting use in buildings

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Lighting consumes significant energy in buildings, but current measurements of lighting efficiency are inadequate in capturing the spatial and temporal effectiveness of light. The most widely used lighting energy efficiency measure, luminous efficacy, quantifies the amount of light generated by individual light sources. While luminous efficacy provides manufacturers and designers with a useful metric for quantifying the energy efficiency of individual lighting devices, it does not fully address the use of lighting in architectural spaces. Instead, application efficacy, the relationship between the electrical power consumed by lighting hardware and the amount of light that contributes to the visual perception of building occupants, must be measured. Here, we propose a framework for calculating lighting application efficacy (LAE) based on the primary pathway of light in architectural settings: the generation and emission of light from a luminaire, the travel of the light throughout the space and into occupants' eyes, and the process of visual perception. The LAE framework will include the development of computational methods for estimating the proportion of emitted light that is directed to task areas and areas corresponding to occupants' visual fields using ray-tracing lighting design software. Future modeling and validation work will quantify energy efficiency of buildings.

KEYWORDS

building illumination, lighting application, energy modeling and analysis, energy effciency in buildings, lighting quality criteria, building lighting standards, building lighting standards, architectural engineering design

Introduction

Lighting consumes approximately 18% of electricity in buildings (National Research Council, 2017), and much investment and effort are dedicated to improving the energy efficiency of lighting hardware. This approach has demonstrated success–the widespread commercialization and adoption of light-emitting diodes (LEDs) has notably reduced the energy consumed by lighting in the United States (National Research Council, 2017). However, there are physical limits to the efficiency with which light can be generated by electricity, so the strategy of improving lighting hardware alone cannot produce energy conservation gains indefinitely.

The most widely used measure of lighting energy efficiency, luminous efficacy (unit: lm/W), quantifies the intensity of light generated by light sources, weighted by the spectral sensitivity of the human visual system, from one watt of electrical power. While luminous efficacy provides lighting manufacturers and designers with an accurate and useful metric for quantifying the energy efficiency of individual lighting devices, it does not fully address the use of lighting in architectural spaces. In buildings, the primary function of light is to facilitate the visibility of surfaces: walls, people, food, books, artwork, furniture, etc. Light strikes these surfaces, reflects off of them and enters the eyes of building occupants, resulting in visual perception. Light that does not enter an eye does not contribute to visual perception—for illumination purposes, it is wasted. Even when high luminous efficacy products are used, significant electrical power is wasted in real architectural lighting applications because only a fraction of the light generated is seen by building occupants at any moment.

Several modern lighting design practices perpetuate this problem. For instance, lighting application performance standards have been used for decades to guide lighting designers. These recommendations usually encourage rather uniform lighting (i.e., high illuminance uniformity) so that occupants can successfully engage in visual tasks throughout an architectural space [e.g., (IES, 2012; CEN, 2021)]. However, this often results in the unnecessary illumination of surfaces when occupants are not viewing the entirety of a space. Nonetheless, research has generated a range of potential approaches to maximizing the usefulness of light that is generated. For instance, "smart" dimming systems that automatically reduce the amount of illumination in a space by an amount that is visually negligible to occupants could be implemented relatively easily to reduce energy consumption by a small amount (Hu and Davis, 2016). More radical ideas, such as absorption-minimizing lighting systems that tailor the spectrum of light illuminating individual surfaces to reduce the amount of light lost to absorption (Durmus and Davis, 2015; Durmus and Davis, 2017) and gaze-dependent lighting systems that project light only to the portions of the visual environment being viewed by occupants at any given time (Hu et al., 2021), could save substantially more energy but would require more drastic changes to both lighting product design and architectural lighting design practices.

Researchers can quantify changes in energy consumption when they investigate different architectural lighting design strategies, but there is currently no practicable way for lighting practitioners to understand the effects of the wide range of design decisions (e.g., luminaire selection, surface reflectances, occupancy of the space, tasks undertaken in the space) undertaken when designing for specific environments. Similarly, lighting building standards, recommendations, and incentive programs encourage efficient use of lighting (e.g., incentivizing the use of energy-saving lighting controls), but they do not offer methods for quantifying the impacts of different design approaches. In this regard, the existing measure of lighting efficiency (i.e., luminous efficacy) is insufficient. Instead, application efficacy, the relationship between the electrical power consumed by lighting hardware and the amount of light that contributes to the visual perception of building occupants, should be measured (Rea and Bullough, 2001; National Research Council, 2017; Pattison et al., 2020). The ability to measure lighting application efficacy (LAE) can drive the adoption of more energy-efficient design practices, foster product innovation, and, ultimately, reduce the energy consumed by lighting.

Though relatively little research has been conducted on the measurement of lighting application efficacy, a few approaches to quantifying it have been previously proposed. For instance, Rea and Bullough developed an application efficacy calculation that characterizes luminous efficacy for a particular solid angle (a three-dimensional angular volume that is analogous to a plane angle in two dimensions) (Rea and Bullough, 2001). The U.S. Department of Energy (DOE) has proposed a lighting application efficiency framework that combines light source efficiency, optical delivery efficiency ("how efficiently light is delivered for all of the various 'jobs' of the lighting"), spectral efficiency ("the overlap of the ultimate spectrum that reaches the task or eye with an optimum spectrum for the activity or intent of the lighting"), and intensity effectiveness ("the difference between the intensity of the provided light and the optimum intensity for the specific intent of the light") (Pattison et al., 2020). While both approaches have merits, neither were designed to accommodate the full range of variables that influence the "illumination lifecycle," do not have the capacity to model changes in lighting conditions over time, and are not designed to explicitly invite additional ideas about the factors influencing the usefulness of light in real applications.

Here, we propose a framework to not only provide a functional measurement method and outline for future research in the area, but also facilitate advancement in lighting design practices. Many approaches to lighting design have evolved in response to the limitations of the older technologies, many of which do not apply to modern solid-state lighting (SSL) technologies. Furthermore, lighting design practices have been driven by what can be reasonably calculated, simulated, or measured. One aim for the proposed work is to serve as an impetus for the lighting design community to critically examine standard practices and re-think the customs and traditions that are no longer advancing the field.

A singular focus on application efficacy—in which the usefulness of every photon of light that is generated is prioritized above all else—is unlikely to yield optimal illuminated environments. That is not the aim of this work. Instead, application efficacy should be one consideration among many, such as color quality, glare control, and aesthetics. The lighting community needs to develop additional strategies for balancing the conflicting lighting goals and requirements for any particular architectural space, and information about application efficacy can stimulate that. It is envisioned that lighting professional associations may consider developing relevant guidelines for typical applications, such as methods for estimating occupancy, consensus about the most important task areas for specific types of spaces, etc.

The commercial availability of lighting hardware is another limitation that the LAE metric can influence. Lighting manufacturers optimize their offerings to the metrics that their customers care about. With regard to energy efficiency, that is currently limited to luminous efficacy. When LAE can be measured, manufacturers will likely be incentivized to develop and commercialize lighting systems that support innovative, application efficacy-focused design approaches.

Proposed framework

The LAE framework can enable the holistic evaluation of building lighting systems rather than individual luminaires. The primary objectives of the LAE framework are:

- To enable lighting industry stakeholders to evaluate the efficiency of lighting design solutions in a holistic manner.
- To characterize the energy performance of lighting systems, including adaptive lighting systems and technologies.
- To cultivate new areas of research and approaches to lighting design and product development.

The model that guides the LAE framework is based on the primary pathway of light in architectural settings: the generation and emission of light from a luminaire, the travel of the light throughout the space and into the eyes of occupants, and the process of visual perception. This definition of LAE can be mathematically expressed as

$$\mathrm{LAE} = \eta_{\mathrm{luminaire}} \times \eta_{\mathrm{spatial}} \times S_{\mathrm{visual}} \tag{1}$$

where $\eta_{luminaire}$ is the efficiency of the luminaire, accounting for the conversion of electricity into light, as well as losses from optics and other absorption of light within the luminaire, $\eta_{spatial}$ is spatial efficiency, characterizing the proportion of light emitted by the luminaire(s) that reflects off visually meaningful surfaces and ultimately reaches the eyes of occupants, and S_{visual} is the sensitivity of the visual system, accounting for spectral luminous efficiency, as well as other visual phenomena, such as adaptation and contrast effects.

It is also possible to add a temporal dimension to the LAE framework to account for the effects of changes in the numbers and behaviours of occupants over time, as well as occupancy-dependent dimming and switching with

$$\mathrm{LAE} = \sum_{t} \eta_{\mathrm{luminaire}} \times \eta_{\mathrm{spatial}} \times \mathrm{S}_{\mathrm{visual}} \tag{2}$$

where t is time.

Using the general LAE framework, various aspects of the illuminated environment that contribute to each of the three input variables can be characterized, and the sophistication of LAE measurements can be enhanced over time. Three broad stages of development are envisioned, as shown in Table 1. Many of the inputs to version 1 are already available since luminous efficacy is already measured—it is the product of radiant efficiency, light output ratio, and spectral luminous efficiency (Ohno, 2006). Our initial research will computationally develop methods for estimating the proportion of emitted light that is directed to task areas and areas corresponding to occupants' visual fields. This will yield a functional, albeit rudimentary, version of LAE for immediate use.

Subsequent research will refine each of the three primary input variables to create version 2 of the LAE. Experiments with human observers will characterize the perceptual effects of lighting contrast (to contribute to S_{visual}). The experimental set-ups will also be used to test and validate the spatial efficiency calculation methods ($\eta_{spatial}$). Calculation methods will be developed to account for changes in light source efficiency as a function of operating time (to contribute to $\eta_{luminaire}$), using the most widely accepted methods for modeling luminous flux maintenance (ANSI/IES TM-21-19 and/or IES TM-28-14) (IES, 2014; IES, 2019). The impact of occupant density (number of occupants per m^2) on spatial efficiency will be accounted for with the use of occupant density estimations published by standards organizations, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2013). This will enable lighting designers to calculate the average LAE over the life of an installation, as well as understand how LAE will change over that period.

Version 3 is intended to evolve as other researchers and practitioners contribute new ideas about the factors that influence the usefulness of light in illuminated spaces. The framework is designed to explicitly welcome contributions from all interested members of the lighting community.

LAE calculations will be performed using Radiance, which is a free and open-source software (Ward, 1994). Since Radiance is the most widely used lighting rendering engine (the simulation package underlying more conventional, user-friendly lighting software) and the proposed LAE calculation process will be made freely available, other lighting software developers will be able to update their existing software or build new tools to calculate LAE using the Radiance engine. The lighting industry's response to new metrics has largely depended on the useability and added value of the new metrics. Since the LAE framework will be more

TABLE 1 Characteristics of lighting applications that will be accounted for by the lighting application efficacy metric in each of the three broad stages of development.

	Luminaire efficiency ($\eta_{luminaire}$)	**Spatial efficiency** ($\eta_{spatial}$)	**Visual sensitivity** (S_{visual})
Version 1: Near-term low complexity	• Radiant efficiency • Light output ratio	• Proportion of emitted light directed to areas within occupants' visual fields • Proportion of emitted light directed to task area(s)	• Spectral luminous efficiency (V_λ)
Version 2: Medium-term moderate complexity	• Efficiency changes as a function of operating time	All of the above + • Impact of occupant density on spatial efficiency	• Effect of contrast on perceived brightness
Version 3: Long-term high complexity	• Control system efficiency • Efficiency changes from altered conditions (e.g., temperature)	All of the above + • Spatially dynamic lighting (e.g., gaze-dependent lighting) • Impact of occupant movement in buildings on spatial efficiency	• State of visual adaptation • Occupant age • Sensitivity as a function of location within visual field

comprehensive than current luminaire efficiency metrics and account for complex visual mechanisms (a limitation of previous metrics), it can offer substantial value to the lighting community.

After a lighting designer specifies the basic design parameters (e.g., characteristics of the room, luminaire specification and placement) in Radiance, the LAE calculation instructions will guide them through the steps involved in determining LAE: defining task areas, specifying occupancy conditions, and instructing the software to calculate the relevant irradiance values. Those values, as well as luminous flux maintenance information from luminaire specification data, will then be entered into the open-source calculation tools, which will then calculate LAE. This process can be used iteratively to understand how differences in the use of space, lighting hardware choices, etc., affect LAE. For instance, designers can determine how changes to the numbers and locations of occupants, locations of the primary task areas, and the layout of the luminaires impact application efficacy.

Discussion

The computational modeling and experimental validation of the lighting application efficacy framework can enable users to measure lighting efficacy in a holistic manner and guide the development of future lighting systems and technologies, as well as architectural design practices. The dissemination of the LAE framework to stakeholders in the lighting industry will be through a user-friendly calculation tool and a step-by-step calculation guide.

The LAE framework can provide the ability to better quantify lighting design solutions [e.g., (Dubois and Blomsterberg, 2011; Gentile, 2022)] and better evaluate both the energy efficiency and the visual quality of the illuminated environment. Illuminance levels at task surfaces and luminaire luminous efficacy values do not actually characterize the usefulness of light in architectural spaces. The LAE metric can allow lighting design recommendations and building energy standards [e.g., ANSI/ASHRAE/IES Standard 90.1 2019 (ANSI/ASHRAE/IES Standard 90.1, 2019), WELL Building Standards (IWBI, 2020), European Commission Energy performance of buildings directive (European Union, 2018)] to establish more specific and accurate guidelines associated with visual perception and the occupancy of a given space. The LAE tool will also enable users to make application efficacy predictions based on TM-21 and TM-28 luminous flux maintenance projections. The proposed framework may enable the development of real-time adaptive lighting systems that can account for changes in occupancy and other environmental factors. Therefore, the proposed LAE framework can enable substantial reductions in the energy wasted in the buildings in the near and long-term.

The intent of the LAE framework is to influence and support the lighting design process through the calculation of the lighting application efficacy. The LAE framework will not directly produce new lighting products or technology, but the modeling and validation work will provide clear insight into energy efficiency in the context of architectural lighting, from energy consumed by luminaires to visual perception.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DD and WD contributed to conception and design of the study. WD, WH, and DD wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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