TECHNOLOGY

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At the Intersection Daylight, electric light and circadian guidelines now converge

Our growing understanding about the impact of light on health has recently been transferred to building certification programs, with some including recommendations for indoor light exposure that supports physiology, sleep and wakefulness. Research findings indicate that lighting designed to work best with the human circadian system may result in light levels two or three times greater than the recommendation for visual tasks, with a corresponding increase in energy use. Logic suggests that an increased reliance on daylight in common applications like offices and classrooms should reduce the use of electric lighting and increase energy savings. Does this hold true for realistic applications? And if so, what extent of energy savings can be expected?

PNNL RECENTLY COMPLETED A three-year research project to investigate the energy implications of the integration of daylight and electric lighting to meet recommended light levels for human health and well-being. What follows looks at our findings from four key explorations.

- We looked at **lighting software tools**, which mostly reflect the historical focus on human visual responses, making it possible to predict illuminance but not necessarily account for the spectral characteristics of light sources and room surfaces. Today, these characteristics need to be accounted for as they influence the calculation of non-visual lighting metrics like equivalent melanopic lux (EML), melanopic equivalent daylight illuminance (mel-EDI), or circadian stimulus (CS), which have different weighting functions than the photopic weighting function, V(λ).

New software tools, like Lark and Adaptive Lighting for Alertness (ALFA), aim to fill this gap, making it possible to conduct spectral simulations of light in architectural spaces. Both tools improve upon the method used by Radiance, a lighting tool kit commonly used for simulations of daylight. Lark conducts annual simulations of daylight in either three or nine spectral bands and ALFA conducts point-in-time simulations of daylight and electric lighting using 81 spectral bands.

Increasing the number of spectral bands used in simulations allows for more accurate representation of light source spectral power distributions (SPDs), particularly valuable for simulating LED spectra that have narrow-band peaks and troughs. While 81 spectral bands offer a high degree of accuracy in modeling electric lighting, our analysis of over 1,000 LED SPDs found that

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nine bands were sufficient for representing most LED spectra and three bands often resulted in large errors. **Figure 1** highlights that three band analyses, like those possible in Lark, may underpredict melanopic quantities, likely due to the fact that Radiance, the underlying calculation method, was optimized for visual responses.

- We looked at **spectral sky models of daylight**, which are limited by the lack of measured data documenting daily and seasonal changes in sky spectra. At this time, annual spectral measurements of the sky are limited to a few locations throughout the world. Recent focus on improving spectral simulations has produced a framework for achieving consistency between models, which begins by collecting long-term, high-quality measurements of daylight spectra for multiple locations. As spectral sky models continue to improve, there will be an opportunity for more detailed research, design guidelines and recommendations related to spectral contributions of daylight in architectural environments. Until then, simulation efforts may benefit from using measured sky spectra from specific locations or using luminance-based spectral sky models.
- We looked at **application factors** like building location and orientation, window size and glazing material, and occupant positions and viewing directions, all of which influence the amount and spectrum of daylight extending into a space and reaching an occupant's eye. Of the factors we considered, one of the most influential was occupants' view direction. Current recommendations, like those included in the WELL Building Standard, indicate that circadian lighting metrics should be satisfied at the eye of occupants when seated (i.e., 4 ft above the floor and in a vertical plane). Unlike recommendations for horizontal illuminance, where a single value represents the metric at each point, multiple viewing directions exist at each point when a vertical plane at the occupant's eye position is considered. No clear guidance exists at present on how to account for the variability of occupant view direction, which is an important factor for estimating the quantity of light reaching the eye.

In our project, we adapted the continuous daylight autonomy metric to consider annual EML contributions from daylight (cDA_{EML}). Modeled after the original metric for illuminance, cDA_{EML} represents the fraction of occupied hours that daylight contributes to an EML goal. The cDA_{EML} metric can be helpful for understanding the impact

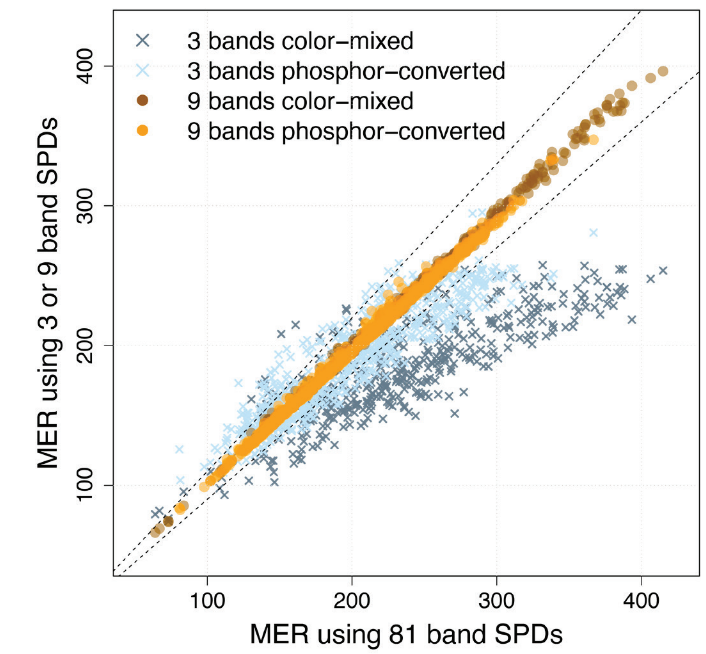

Figure 1. Comparison of using three or nine spectral bands versus 81 spectral bands to calculate Melanopic Efficiency of Radiation (MER) for over 1,000 color-mixed and phosphor-converted LED spectra. The dashed line is used to indicate 3 or 9 band values that are within ± 10% of 81 band values.

of occupant location and view direction on resulting levels of EML, as demonstrated in **Figure 2.** This analysis demonstrated that daylight contributions toward vertical illuminance and EML fall off significantly if an occupant's direct view does not include a window. This was true for workstations that were close to a window (within 10 ft) but positioned with the occupant's back to the windows. For these workstations, electric lighting will likely be needed to meet recommended circadian metric thresholds at the occupant's eye, despite the workstation receiving high levels of task plane illuminance from daylight. At the time of this analysis, EML was the primary metric used in the WELL Building Standard, but a similar approach could be used to understand daylight contributions for mel-EDI or CS.

- We looked at **glare and shading strategies**. While daylight can help meet circadian lighting recommendations and potentially reduce energy use by the electric lighting system, there can be unintended negative consequences. As illuminance at the eye is increased to achieve recommended levels of circadian lighting metrics, visual discomfort can result, particularly in offices where occupants spend most of their worktime in fixed workstations with a few view directions. Regular use of

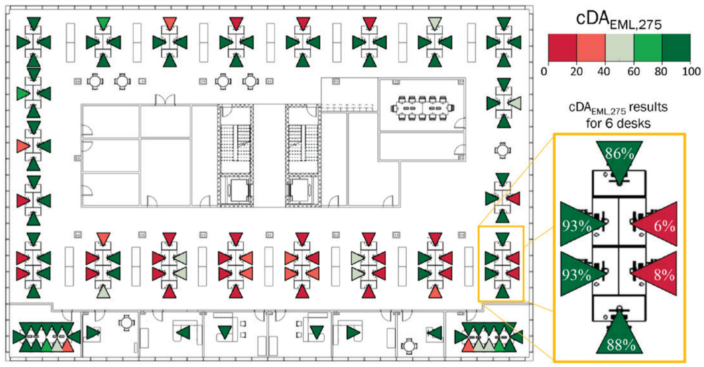

Figure 2. Office layout of continuous daylight autonomy ($cDA_{EML,275}$) results based on an EML threshold of 275 m-lx during occupied hours. Arrows indicate vertical view directions and a 5-point scale is used to report $cDA_{EML,275}$ values. Red arrows indicate positions that will need regular contributions from the electric lighting system. Green arrows indicate positions that get substantial EML contributions from daylight and require less supplemental light.

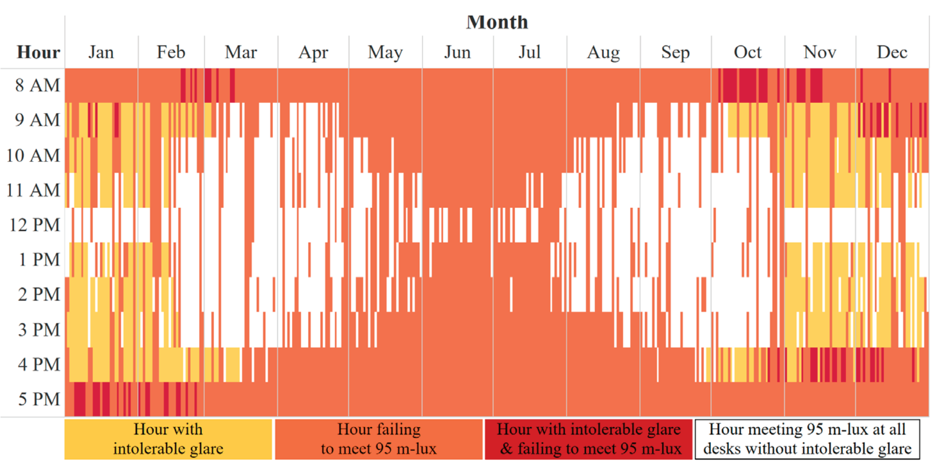

Figure 3. Hourly daylight simulations of an open-office space where at least one or more workstations are estimated to have intolerable glare, insufficient EML to meet recommendations, or both. The WELL Building Standard suggests that applications meeting existing daylight requirements will also provide at least 95 m-lx to all occupants.

interior blinds or other shading systems in response to visual discomfort will reduce the contributions of daylight, likely decreasing vertical illuminance at eye positions below the amount needed to meet circadian lighting metric recommendations. **Figure 3** shows that in our models, during the fall and winter months when the sun was lower in the sky, some of the time periods where daylight provided adequate vertical illuminance at eye positions had high levels of glare, leading the occupant to likely close the blinds and reduce or eliminate the daylight contributions.

As the metrics and recommendations continue to develop, PNNL's future research will focus on spectral simulation methods to improve the accuracy and reliability of these tools for users. For more information about this project, including details on the analyses, results and potential energy implications of circadian lighting metrics, please see the references included below, which can also be found on the SSL website: *https://www.energy.gov/eere/ssl/daylighting-and-electric-lighting-integration.*

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