

Energy Impacts of Lighting for Wellness: Results from Simulation and Laboratory Studies and a Look Ahead.

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ABSTRACT

This paper describes emerging trends in lighting design related to promotion of circadian well-being for building occupants, and the potential effects of circadian lighting criteria on energy usage in office and educational facilities. Over the past decade, the performance of LED technology for general illumination has advanced significantly. Efficient LED products, increasingly paired with advanced controls, are widely available in the market, and with rapid penetration in many lighting sectors (outdoor and area lighting, commercial offices, schools, hospitals), lighting energy usage intensity has declined. This trend should continue as LEDs and advanced controls achieve greater market saturation. However, our research finds that evolving circadian lighting priorities in buildings have the potential to reverse some of these energy savings, with some common use cases requiring anywhere from 30% to over 100% higher light levels and lighting energy usage.

We discuss the limited and varying guidance to-date around lighting design for circadian performance, identifying policy gaps and underscoring the challenge this poses for lighting professionals and other stakeholders. We summarize recent simulation and laboratory experiments which quantify lighting energy impacts due to the shift from designing lighting systems solely for visual criteria (e.g. task illuminance, glare) to also include circadian criteria, and project these findings out in illustrative “what-if” lighting energy forecasts for offices and schools. Finally, we outline strategies that might reduce the energy impacts of circadian lighting design, balancing the imperative for healthy building environments with lighting efficiency and building decarbonization goals.

Introduction

Traditional lighting design practice in buildings focuses on occupant visual acuity and comfort, but increasingly the lighting environment’s role in occupant circadian wellness is also being recognized. This is owing to scientific findings of the past years including characterization of the relationship between light exposure and the neuroendocrine regulation of melatonin (Brainard 2001, Thapan 2001) and discovery of the intrinsically photosensitive retinal ganglion cells, or ipRGCs, and melanopsin, the photopigment most involved in optical radiation’s circadian effects (Bearson 2002, Hattar 2002, Provencio 2002). Importantly, melanopsin’s peak sensitivity is shifted to shorter wavelength radiation (480-490nm) than that of the visual system, peaking around 555 nm, as described by the photopic luminous efficiency function (CIE 1926).

The health implications of indoor lighting systems are receiving attention in inpatient and hospital facilities where health is paramount and occupants are active around the clock, and also in office and educational spaces, the focus of this study. In these building types, day-active people are indoors for the majority of daytime hours, elevating the importance of electric lighting

in meeting circadian needs. Studies have indicated potential performance benefits from lighting for occupants in offices (Viola 2008, Figueiro 2020) and classrooms (Mott 2012, Slegers 2013).

Light levels commonly targeted in day-active indoor environments, e.g. to meet task illuminance recommendations, have been found to be inadequate for supporting daytime circadian regulation (Brown et al. 2022). Under current practice, indoor light levels are often over an order of magnitude lower than the outdoor daytime light environment to which humans are evolutionarily adapted. As circadian lighting priorities evolve, a potentially serious challenge then arises; providing sufficient lighting from electric systems indoors may require notable increases in lighting energy usage. A single solution has not been settled on to-date that would provide what is currently understood to be the “right” light levels, spectrum, and exposure duration for circadian health without an impact on lighting energy, even with highly-efficient LEDs and advanced control systems. The question we raise is how can lighting practice adapt to meet circadian design goals while not forfeiting the significant lighting energy savings achieved to-date and projected forward from adoption of efficient LED lighting?

Current Circadian Lighting Guidance and Practice

Light, used here to refer to optical radiation from 380 to 780 nanometers, contributes to visual and non-visual responses in humans, mediated by the eye-brain processes that drive them. While research is still ongoing to understand non-visual response processes more fully, several quantitative metrics have been proposed to measure light in circadian terms. Equivalent melanopic lux (EML), melanopic equivalent daylight illuminance (mel-EDI, units of photopic lux), and circadian stimulus (CS, unitless) weight the spectrum of light with unique functions using intensity as a scaling factor. Accordingly, these quantities all require spectral information across visible wavelengths, which can be converted to the selected metric.

The EML metric is based on the response to light of the photopigment melanopsin (the melanopic response) in the ipRGCs (Lucas 2014). However, EML is not a recognized unit in the International System of Units (SI). The International Commission on Illumination (CIE) adopted a new melanopic metric, mel-EDI. As an SI-compliant EML replacement, mel-EDI quantifies optical radiation in terms of the amount of reference daylight, in SI units of photopic lumens and derivatives (e.g. lux), that would produce an equivalent melanopic response (CIE 2018) using a normalization constant. A scalar multiplier can be used to convert between EML and mel-EDI ($\text{mel-EDI} = \text{EML}/1.103$). CS is the calculated effectiveness of light at melatonin suppression using a more complex model of human phototransduction (Rea 2010). CS has not been formally accepted by the CIE or the Illuminating Engineering Society (IES), the North American body that, like the CIE, publishes consensus-based lighting standards, and there is no conversion factor between CS and mel-EDI. To date, the IES has also not adopted mel-EDI or EML.

Existing Recommendations

At this time, there are a few organizations in the U.S. that promulgate voluntary circadian lighting design recommendations for commercial spaces, including the International WELL Building Institute (IWBI), an organization devoted to health and wellness in the built environment and publisher of the WELL Building Standard, and the Underwriters Laboratory (UL), a global leader in product safety and standards. Recommendations from the WELL Building Standard are given in EML and mel-EDI terms, providing target thresholds that should be met with electric lighting for at least four hours daily at all workstations (WELL 2022). UL

Design Guideline 24480 offers strategies for promoting circadian entrainment with light for day-active people, prioritizing CS but also providing a compliance path matching the EML recommendations of WELL v2 2018 (UL 2019). The Collaborative for High Performance Schools (CHPS) publishes a guideline for circadian lighting in education spaces. The CHPS Core Criteria v3.0 includes EML and CS recommendations for classrooms, recommending 250 EML or “equivalent” CS at 75% or more of desk spaces for at least four hours per day (CHPS 2019). WELL also publishes classroom recommendations via the WELL Education Pilot, first issued in 2015 (WELL 2020), of 125 EML (which may include daylight) at 75% or more of desk spaces.

As one of the earliest and most cited providers of circadian lighting guidance, the recommendations in the WELL Building Standard are the focus in this paper. WELL offered recommendations for generic spaces as early as 2015, and continues to publish EML and mel-EDI thresholds in its L03 Circadian Lighting Design Feature. Circadian thresholds in WELL have mostly shifted upward since 2015 as shown in Figure 1. In 2018, a WELL v2 pilot was issued, to eventually replace v1 (in 2020), introducing a tiered points system where projects can earn one or more points toward certification depending on the extent to which recommendations are met. For v2, the three point tier is shown.

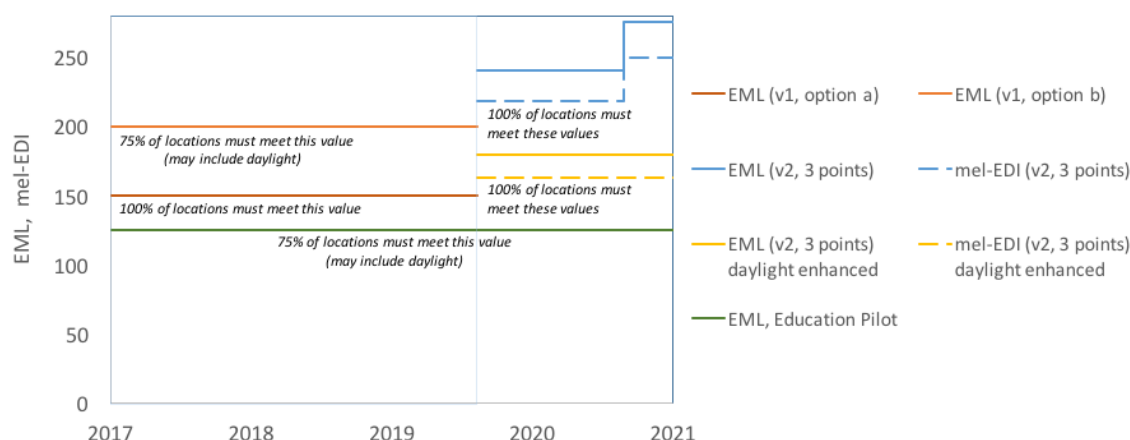


Figure 1. Evolution of WELL circadian recommendations for offices and schools. Thresholds must be met for at least four hours per day, starting no later than noon. Plotted levels must be met with the electric lighting system unless inclusion of daylight is specified. The WELL standard no longer includes CS equivalents. Sources: WELL 2022, WELL Education Pilot 2020

In generic spaces including offices, for projects that demonstrate “enhanced daylight” by meeting at least one of the WELL v2 daylighting features (L05 Daylight Design Strategies and/or L06 Daylight Simulation), lower electric-light EML and mel-EDI thresholds are listed, presuming that daylight will add to the lighting environment’s circadian effectiveness. Details on how the WELL circadian target thresholds were established or why they shifted from 2015 through 2021 are not published, though the latest issue of WELL references a recently published journal article by leading scientists in the fields of neurophysiology and sleep-, circadian-, and chrono-biology that proposes a minimum of 250 mel-EDI at the eye (Brown et al. 2022) all day.

Policy Limitations and Needs Assessment

A principal shortcoming of existing guidance for circadian lighting is that it is not put forward by the leading authorities on lighting practice (IES and CIE), where most lighting

professionals and building authorities go for lighting design guidance. Instead, they are voluntary standards with limited reach. Lighting designers, building managers and owners, policy professionals, and other stakeholders still await more clear “official” guidance on circadian lighting practice in order to understand and apply these concepts in buildings. In the meantime it has been pointed out by some that doing something now to provide adequate lighting for circadian health based on what is known is preferable to doing nothing while awaiting recommended practice from the authorities. As Houser et al. (2021, 111) state, “we believe it is better to try something consistent with known science rather than to do nothing. [While] we remain skeptical about ... precise numerical recommendations, we acknowledge that both the WELL and UL recommendations move lighting practice in a positive direction...”

It is likely that at some point in the future, official guidance on lighting practice for circadian health will be issued by recognized standards bodies. Schlangen and Price (2021, 12) remark that “new ... lighting standards are expected to incorporate ... minimum thresholds for daytime mel-EDI.” Regardless, the trend in the guidance that has been available, in WELL for example and in Brown et al. (2022), is toward increasingly higher light levels for circadian benefit. Generally, we expect that future circadian lighting guidance from the IES or CIE may recommend higher lighting levels than what has been standard practice in recent years.

Results from Simulation and Laboratory Experiments

Simulation Studies

WELL Option 1: Electric lighting only. To quantify the energy impacts of designing to circadian lighting recommendations in offices and classrooms solely with electric lighting, Safranek et al. (2020) conducted a simulation-based investigation using a spectral modeling software tool, Adaptive Lighting for Alertness (ALFA). Luminaire lumen output, spectral power distribution (SPD), surface reflectance, and desk orientations were varied, creating 45 unique simulation conditions for exploring the effect of each parameter on predicted levels of illuminance, mel-EDI (converted from EML in the original study), and CS. The office and classroom models were evaluated on their ability to meet circadian recommendations from WELL v2 Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0. For the simulated conditions, annual energy use was estimated for two scenarios: constant lumen output for the entire day or variable lumen output with four hour increases each day to attempt to meet circadian recommendations by WELL and otherwise lowered to a condition that satisfied IES recommendations for average horizontal illuminance only (300 lux at task plane, IES 2020).

Lighting conditions designed to meet IES recommendations for horizontal illuminance did not meet recommended mel-EDI or CS levels in any of the office and classroom simulations. In some cases, satisfying circadian metric recommendations resulted in a horizontal illuminance of over 800 lux. Additionally, achieving circadian recommendations required correlated color temperatures (CCT) that were higher than those typically used for office and classroom settings. For context, CCT provides a relative indication of the short-wave content of a source, with higher CCTs (cooler) having more short-wavelength content which is generally more efficacious at achieving mel-EDI thresholds given the melanopic peak sensitivity range.

The increase of light levels and consequent energy use did not however guarantee that circadian lighting metrics were satisfied for all view positions. All but one simulation condition failed to achieve the previous 3-point 218 mel-EDI threshold and all 45 conditions would fail the updated 3-point 250 mel-EDI threshold. When the light levels needed in order to meet mel-EDI

and CS thresholds were maintained for a full day, lighting energy increased from 50%-100% for the open office model and 21-42% in the classroom model; WELL mel-EDI recommendations for classrooms were lower than for offices. For the 4-hour circadian threshold scenario, lighting energy increased from 16-31% in the open office model and 10-21% in the classroom model, demonstrating the value of lighting controls capable of adjusting lumen output and/or CCT.

WELL Option 2: Electric lighting and “enhanced daylight.” While the WELL L03 Circadian Lighting Design Feature thresholds are for electric lighting only, daylight may influence levels of mel-EDI and is an important consideration in the estimation of these quantities in architectural settings with windows. Mirroring the analysis done by Safranek et al. (2020), the open office template was used in a new set of simulations to evaluate how daylight may contribute to meeting circadian lighting thresholds. The full open office model was roughly 2100 ft² with 40 workstations as shown in Figure 2. Thirty-two 2’ x 2’ LED troffers were modeled at spacing of 8’ x 8’. The southern wall had large windows with a window-to-wall ratio of 0.90. Workstations were at a height of 2.5’. Calculation points for horizontal and vertical illuminance were created at each workstation at 2.5’ and 4’ above the floor, respectively. Vertical calculation points, representing the seated occupant view, were pointed toward the computer monitors.

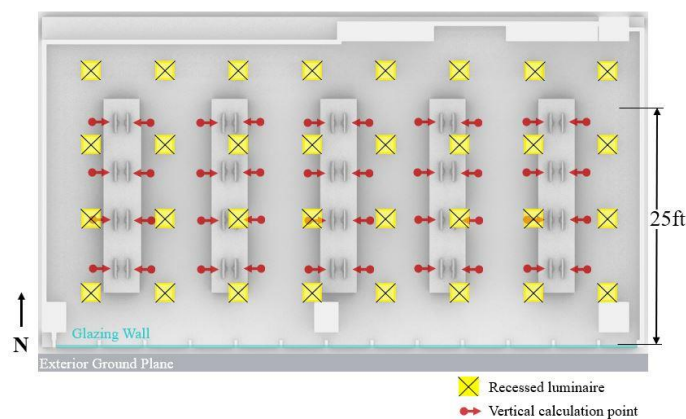


Figure 2. Open office model, vertical calculation points shown.

ALFA was used to simulate the spectral reflectance of room surfaces (Figure 3, right) and the simulations included three lighting system SPDs (Figure 3, left) from a tunable white (CCT adjustable) source. CCT values are used here to reference corresponding SPDs. The maximum power draw of the luminaires was 40.5 W for all CCTs with a linear relationship between lumen output and luminaire power. Estimates of annual lighting energy use assumed the space was occupied from 8 a.m. to 6 p.m. every day for 3650 annual operating hours.

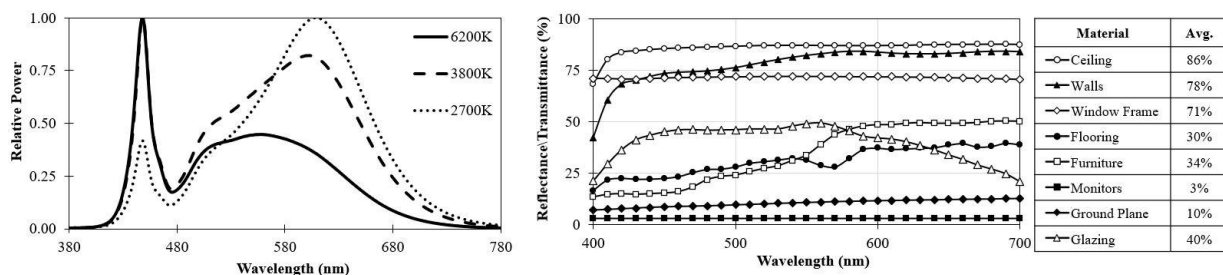


Figure 3. SPDs for three simulated CCTs (left) and simulated spectral reflectances in the open office model (right)

The simulation results for electric lighting only were compared to Option 1 and Option 2 recommendations from WELL v2 Q4 2021, detailed in Table 1. For Option 2, spaces that meet WELL “enhanced daylight” criteria require lower mel-EDI thresholds for electric lighting, as much of the light for circadian purposes is presumed to come from daylight in those spaces (daylight simulations are not necessary to demonstrate daylight compliance). The open office model complies with WELL criteria for enhanced daylight, including Feature L05 Part 1, requiring that 70% workstations are within 25’ of the transparent envelope glazing.

Table 1. WELL Standard Feature 03 Circadian Lighting Design thresholds (v2 Q4 2021)

Electric light levels, 100% of workstations, at least 4 hours, vertical plane 18” above desk.		
Option 1	Option 2 (Enhanced Daylight)	Points
≥ 150 EML [136 mel-EDI]	≥ 120 EML [109 mel-EDI], meets daylight strategies	1
≥ 275 EML [250 mel-EDI]	≥ 180 EML [163 mel-EDI], meets daylight strategies	3

Annual energy estimates for all scenarios meeting WELL thresholds were compared to a baseline condition satisfying IES visual illuminance criterion only (300 lux average horizontal illuminance). Energy results were calculated for three CCTs (2700 K, 3800 K, 6200 K) and two control methods (meeting circadian criteria four hours per day versus 10 hours per day). Results are illustrated in Figure 4 in the next section. Baseline illuminance corresponded to a luminaire lumen output of 47%, resulting in annual lighting energy consumption of 2223 kWh/yr. It was possible to meet the 136 mel-EDI threshold (one point, no daylight) with the 3800 K and 6200 K conditions, at an annual energy increase of 16%-89% depending on the control method (4-hour versus 10-hour). However, even at 100% lumen output and 45%-113% energy increase, none of the conditions met the 250 mel-EDI threshold (three points, no daylight) at all view locations.

It was however possible to meet the lower circadian criteria for electric light in enhanced daylight spaces. Meeting the 109 mel-EDI threshold for one point required a 5%-51% increase in annual energy usage, depending on the SPD condition and control method. Meeting the 163 mel-EDI threshold for three points was only possible using the 6200 K lighting condition, at a 27% energy increase for the 4-hour scenario and 68% energy increase for the 10-hour scenario. Even at WELL enhanced daylight circadian thresholds for electric lighting, energy usage is greater than what would be required to only meet illuminance recommendations.

Extension of WELL Option 2: Annual simulations of daylight for estimating mel-EDI.

Levels of mel-EDI from combined electric light and daylight are dependent on variables such as daylight availability, daylight penetration, occupant view direction, furniture layout, and potential glare. Although daylight simulation is not required by WELL, this section presents research involving annual daylight simulations to estimate daylight’s contribution to mel-EDI in the same open office model. The ability to conduct annual spectral simulations of daylight is currently limited by the available software tools and spectral daylight data. For this analysis, a simulation workflow was established, combining annual daylight illuminance values with a full year of spectral measurements for the sky condition, based on spectrophotometer sky images from Golden, CO collected by National Renewable Energy Laboratory (NREL) (Andreas and Stoffel 1981). Using Honeybee, a daylight modeling software tool, daylight illuminance was

calculated for every hour of the year at the 40 vertical calculation points. For each hour from 8 a.m. to 5 p.m., the melanopic to photopic (M/P) ratio was calculated using the corresponding measured daylight SPD, using the method outlined in WELL. Vertical illuminance for each of the 40 workstations was multiplied by the M/P ratio for the corresponding hour to get a simplified estimate of EML, converted to mel-EDI, from daylight. No window shades or exterior obstructions other than an exterior ground plane were included in the model.

Based on the daylight simulation results, electric light values per time step were calculated that in combination with daylight would achieve illuminance and mel-EDI thresholds, essentially emulating idealized daylight dimming operation. Note that while the simulated space meets the design thresholds for WELL enhanced daylight spaces (e.g. WELL L05 Daylight Design Strategies), the analysis centered on meeting the higher mel-EDI thresholds from WELL L03 (Option 1) with the combination of daylight and electric light (WELL thresholds are for electric light only). For most of the lighting conditions, meeting the one point 136 mel-EDI threshold with daylight dimming resulted in a notable decrease in annual energy use; the 6200 K lighting condition achieved a 47% decrease from the task illuminance baseline with no daylight dimming. Achieving the highest threshold of 250 mel-EDI was also possible using the 6200 K and 3800 K lighting conditions with a 14%-27% decrease in annual energy use compared to the baseline for the 4-hour control scenario, as shown in Figure 4.

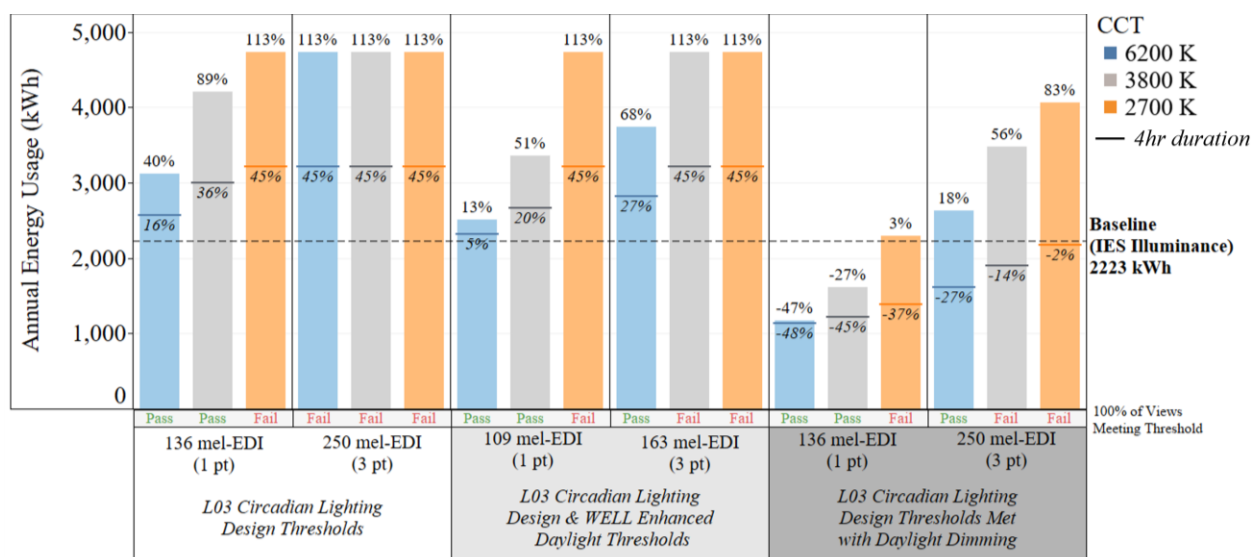


Figure 4. Annual energy usage for office lighting simulations. Dashed lines show baseline energy for task illuminance, without and with daylight dimming. Energy performance relative to the task illuminance baseline (no daylight dimming) is represented in percentage terms, with 4-hour control scenarios inside the bars and all-day scenarios at full bar height. Pass/fail results for meeting the specified WELL threshold is indicated along the top.

The introduction of daylight into the space also increases the potential for glare. Maximum hourly vertical illuminance values were used to calculate simplified daylight glare probability (DPG_s). There were 572 hours (16%) throughout the year when one or more workstations were subject to intolerable levels of glare from daylight. It is likely that in these instances, the occupants would deploy shades, reducing daylight availability. Though not quantified in this analysis, using electric lighting to compensate for lower daylight availability during periods of daylight glare and blinds usage would increase annual lighting energy usage.

Laboratory Testing

Little work has been done to measure the energy impacts of adding circadian lighting design criteria in physical environments like offices and classrooms (i.e. not simulation-based). To address this research gap, a project at Lawrence Berkeley National Laboratory (LBNL) in 2020/2021 measured circadian lighting energy impacts in a mock office environment (Shackelford 2021). The study included the use of tunable white LED systems that are often marketed for circadian benefit (e.g. programming periods of higher CCT light to boost circadian performance). For the lab tests, standard non-tunable troffer-style 2' x 4' LED fixtures (CCT of 3500 K) were first commissioned to meet visual criteria only as the base case (300 lux and 500 lux options). The same LEDs were then commissioned to meet visual and circadian criteria based on the WELL v2 Q3 2020 3-point threshold (218 mel-EDI) all day, and then through scheduled lumen output increases for only a 4-hour per day period (9 a.m. to 1 p.m.) for comparison. Then tunable white LED troffers (3000 K-5000 K) and pendants (2700 K-6000 K) were tested (same fixture quantity and location), with increased lumen output and CCT commissioned to meet the circadian threshold for the 4-hour period so that the impact of CCT tuning on circadian and energy performance could be measured. Each configuration (non-tunable fixtures and tunable fixtures, without and with circadian criteria) was tested over the course of one or more full days during three total weeks of lab testing.

Tests took place at LBNL's FLEXLAB in two 300 ft² mock office zones with cubicle-partitioned workstations. One office was an interior zone with no daylight, and the other was a daylit perimeter zone with south-facing windows and standard venetian blinds (glazing visible transmittance of 0.595, window-to-wall ratio of 0.48). Sky conditions during tests ranged from overcast to sunny. Luminaire-level daylight dimming was implemented in the daylit zone. Horizontal task illuminance was measured, as well as vertical spectral irradiance (W/m²/nm, one-nm resolution, 360-780 nm), and lighting energy usage for each test period via circuit-level current transformers and voltage probes for continuous power monitoring. A workstation with illuminance and spectral irradiance sensors is shown in Figure 5a. Spectral data was processed to calculate vertical illuminance at the eye, CCT, and mel-EDI. Alongside the spectral sensor was a glare sensing package (digital single-lens reflex camera with 120° wide angle lens and illuminance sensor connected to a central processor). A false-color luminance image from the glare sensor is shown in Figure 5b. Glare values were computed in terms of Daylight Glare Probability (DGP) for the perimeter zone and Unified Glare Rating (UGR) for the interior.

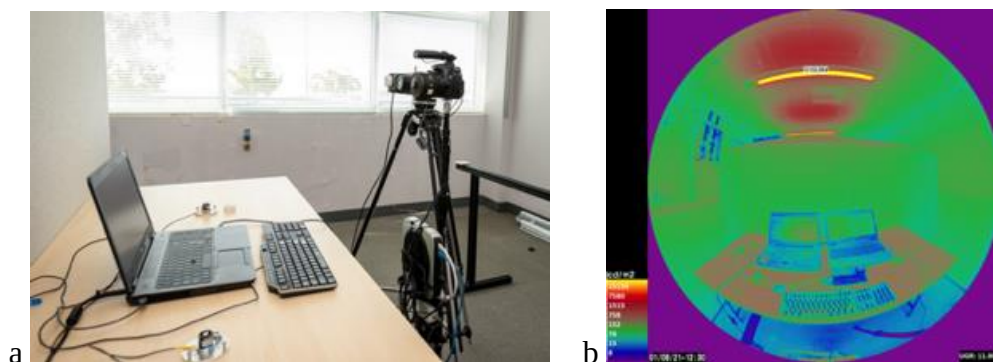


Figure 5. Daylit zone workstation with illuminance sensors on desk and spectrophotometer and glare camera on tripods (a), and false color luminance image from glare analysis (b)

Daily lighting energy was summed for each test case, normalized by floor area (kWh/ft²), and annualized (kWh/ft²/yr) based on a schedule of 12 hours per day for 261 days per year. For the perimeter zone with daylight, each of the lighting systems were commissioned to meet the task illuminance criteria, and the WELL circadian thresholds were met even with daylight dimming implemented. In other words, there was no energy penalty for the circadian criteria. DGP levels were also within acceptable limits. For the interior zone (no daylight), lighting energy results are shown in Figure 6. For the higher task illuminance criterion (500 lux), which required more light output and energy in the base case, the relative impacts of adding circadian criteria were lower; 11%-21% energy increase for the 4-hour circadian period, and 33% increase for the all-day circadian period. For the lower task illuminance criterion (300 lux) more common in modern lighting design, the impacts of the circadian criteria were higher, at 31%-42% lighting energy increase for the 4-hour circadian period, and over 100% increase for the all-day test. Importantly, these results are based on meeting the 218 mel-EDI threshold. This threshold has since risen to 250 mel-EDI, which would require higher lighting energy consumption.

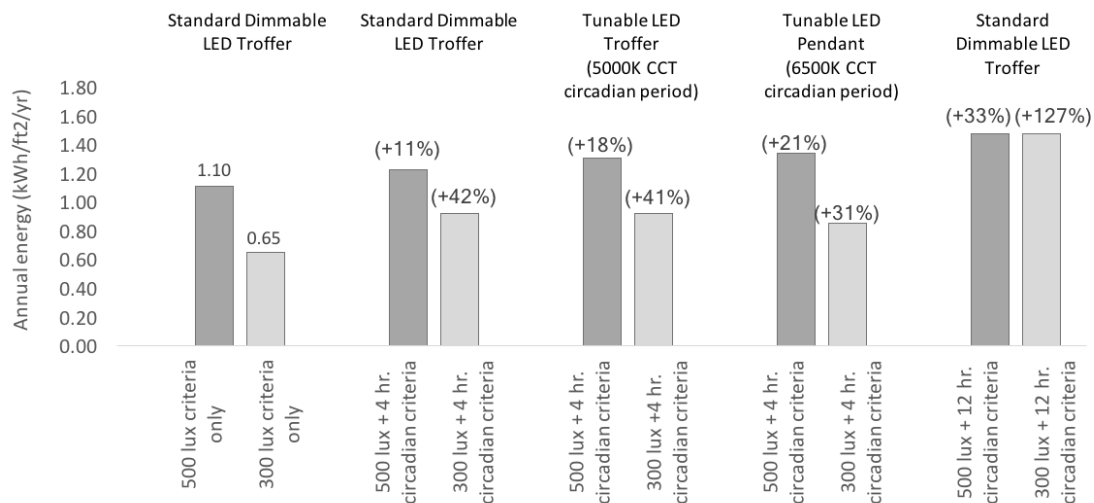


Figure 6. Interior office results from laboratory tests. Darker bars are 500 lux task illuminance criterion; lighter bars are 300 lux criterion. 'Lux criteria only' (left-most bars) is the baseline condition; relative energy in % terms is shown above bars for scenarios meeting task illuminance plus circadian thresholds

Summarizing Results from Simulation and Laboratory Studies

Summarizing results, the simulation and laboratory studies found a range of lighting energy impacts due to adding circadian thresholds to design criteria. Lighting energy increases from the studies are tabulated in Table 2. Depending on control scenario and light source SPD, meeting circadian thresholds without daylighting resulted in energy increases from 10% to over 100%. Daylighting considerably improved results, lowering or eliminating the incremental lighting energy and in cases with daylight dimming, providing energy savings relative to a baseline with no daylight dimming. Across studies, notable efficiency gains in meeting circadian thresholds were made with higher CCT light, as well as from implementing lighting controls to schedule lumen output and/or CCT increases only for 4-hour periods, as required by WELL.

Table 2. Summary of lighting energy increases due to circadian lighting thresholds

Study	Energy increase: without daylight	Energy increase: with daylight
Simulation, 2020	16%-100% (office) 10%-42% (classroom)	n/a
Simulation, 2021/22	16%- 89%	5%-68%, no daylight dimming.
Simulation, 2021/22, Daylight Dimming	n/a	-48%-+83%, no blinds, which may reduce daylight dimming.
Laboratory, 2020/21	31%-127%	No increase. Daylight dimming.

Lighting Energy Projections for Offices and Schools

To contextualize lighting energy projections going forward, it is useful to review the extraordinary changes that have happened in past decades. Looking at data from the US Energy Information Administration (EIA) Commercial Buildings Energy Consumption Survey (CBECS) and Annual Energy Outlooks there is a clear downward trend in commercial lighting energy intensity over time. In 2003, CBECS estimated that commercial buildings used 1.34 quadrillion BTUs, or quads, of lighting energy annually, at an energy intensity of 5.6 kWh/ft²/yr. (EIA 2022a). EIA's 2010's Energy Outlook estimated 1.0 quad of commercial building lighting energy, at an intensity of 3.7 kWh/ft²/yr. (EIA 2010). By 2020 the estimate was 0.5 quads, and 1.7 kWh/ft²/yr. (EIA 2022b). While LED lighting for general illumination was still in early stages in 2010, the commercial lighting stock had already been undergoing other important transitions; the shift from magnetic ballasts to higher-efficiency electronic ballasts, and from higher-wattage T12 fluorescent lamps to lower-wattage T8s, and generally lowering recommended practice for interior light levels; e.g. moving from 500 lux to 300 lux as the target for task illuminance. The decline in commercial lighting energy accelerated in the 2010s as high-quality high-efficacy LED lighting products proliferated in the market; with the share of LED fixtures installed in commercial buildings growing from 9% in 2012 to 44% by 2018 (EIA 2021).

The rapid uptake of efficient LED lighting has fundamentally changed the trajectory of lighting energy; compare 30-year EIA projections from 2010, 2016, and 2021 in Figure 7. Even with slight increases in commercial floor areas year over year, EIA now predicts total commercial lighting energy consumption will decrease continually, with improvements in average efficacy (lumens/Watt) being the primary driver. The EIA 2021 Annual Energy Outlook predicts commercial lighting energy will drop by 0.19 quads (36%) from 2020 to 2050 while average light source efficacy increases from 71 to 164 lumens/Watt (EIA 2022b).

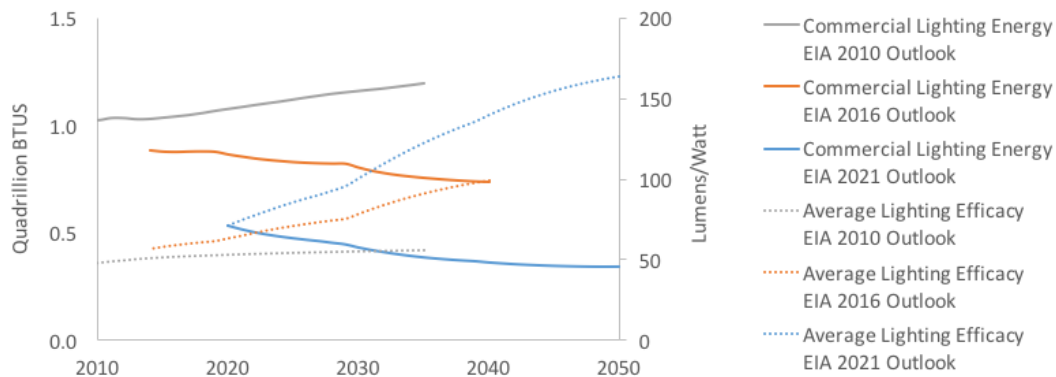


Figure 7. 30-year projections of annual commercial building lighting energy usage from the EIA on primary y-axis, and of average commercial lighting efficacy on secondary-y axis. *Source:* EIA, 2022.

These trends are heartening but the rising prioritization of circadian lighting criteria for day-active environments like offices and schools, and the higher lighting energy usage that may follow, runs in the opposite direction. In order to illustrate what the energy effects of circadian thresholds might mean for lighting energy trends going forward based on the results of the simulation and lab studies above, a simplified model was developed. A range of potential energy impacts was calculated based on hypothetical adoption rates for circadian lighting criteria year over year in offices and schools (1%/yr, low estimate and 2%/yr, high estimate), and hypothetical lighting energy increases in adopting buildings (50% increase, low estimate and 100% increase, high estimate). These rates were applied to EIA’s Annual Energy Outlook 2021 30-year projection for the office and school lighting energy fractions of commercial totals. The proportion of total lighting energy for offices (20.4%) and schools (10.8%) was derived from CBECS 2012 data (EIA 2022a), as the EIA Annual Outlook lighting projections are not subdivided by commercial building type and more recent CBECS data is not yet available. The resulting range of hypothetical office and school lighting energy increases are plotted in Figure 8. At the low estimate, 0.26 quads of additional lighting energy are used through 2050 (cumulative), with 0.96 quads at the high estimate.¹

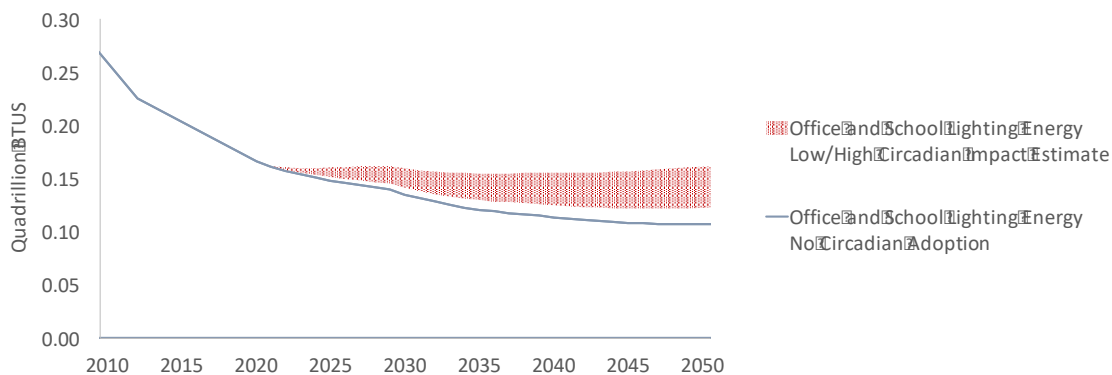


Figure 8. Illustration of a hypothetical range of lighting energy increases in offices and schools from circadian criteria, compared to EIA 30-year lighting energy projection, assuming no such increases.

¹ These are site energy totals, not source energy, which depending on primary energy fuel mix and conversion/transmission efficiency is a multiple of site energy. At source-to-site ratio of three, the hypothetical lighting energy impact (0.78-2.88 source quads) is equivalent to the energy in 4.5 to 16.7 billion barrels of oil.

Discussion

The scenarios plotted in Figure 8 are not meant to be definitive predictions about what will happen, but rather illustrative of the impacts that could result if the trends that we have discussed in circadian lighting manifest into changes in lighting system design and implementation in retrofits and new construction going forward. While the actual trajectory of circadian lighting adoption in offices and schools is unknown, it is time to start thinking about approaches to proactively address the associated lighting energy impacts. No single strategy is likely to “solve” this issue; rather, it may take advances and innovations in multiple directions to achieve the necessary lighting environments in offices and schools without exceeding lighting energy requirements. Solutions could include design, technology, and even behavioral changes, the sum of which could potentially reduce or eliminate energy increases from circadian lighting design. There is still substantial research and development, technology commercialization, and even changes of habit and behavior that may be needed for these strategies to have an impact and there is still uncertainty around where circadian lighting thresholds will settle and how widely they will be implemented.

Lighting controls One factor that could play a large role in mitigating energy impacts is lighting controls. Generally best practice for efficient lighting already includes more sophisticated controls than the light switches and timers of yesterday. Occupancy sensing, daylight dimming, and automated scheduling are crucial to keeping lights off, or dimmed, whenever possible to curb wasted energy. As seen in the simulation and lab tests, dimming and scheduling controls can also significantly reduce lighting energy used to meet circadian thresholds, given most prescriptions are for a sub-set of operating hours. The 4-hour schedules were much more efficient than raising light levels all day to meet circadian thresholds.

Daylighting Daylight is free and abundant, and provides spectral content with relative equal-energy across the visible spectrum that is highly effective at eliciting melanopic response. It is also locally synchronized with the diurnal circadian rhythm: “[N]atural light from the sun and sky delivers copious photons during daytime hours and few at night, perfectly synchronized with our body’s needs.” (Houser et al. 2021, 104). The challenge is that typical indoor environments provide illuminances orders of magnitude lower than levels outdoors (Schlangen 2021).

The simulation and laboratory studies found substantial benefit in meeting circadian thresholds with daylighting, reducing and in some cases eliminating incremental energy cost for electric lighting (though whole building energy implications accounting for daylight / HVAC impacts were not evaluated). Well-daylit spaces can enable daylight dimming of the electric lighting, satisfying visual criteria, saving energy, and potentially still meeting circadian criteria. A challenge is getting daylight deeply enough into buildings to benefit occupants not near windows. This was an issue in the daylighting simulations, where viewpoints in the interior often fell below the circadian threshold. Technologies are available and in development that bring daylight deeper into buildings. Tubular daylighting devices that use lenses and highly reflective ducting and diffusers can provide daylight in interior zones, where conditions permit their use. Window treatments and shading devices can also play a role in casting daylight deeper into spaces while managing glare issues that can arise. These include simple strategies like light shelves as well as daylight redirecting films that have become more commercially available. Further advances are still needed however. Promising results were found in a recent study on a

daylight redirecting blinds concept conceived of decades ago in which slat spacing and slat angle change with solar angle (closely spaced for low angles and widely spaced for high angles), bringing significant amounts of daylight up to 40' deep from the facade (Fernandes 2021), a large improvement over standard daylight penetration.

Effective daylighting is as much a matter of design as technology. If partitions or walls are situated close to the perimeter, cordoning off windows from the interior of a building, benefits are greatly diminished. Likewise daylighting opportunities are lost if manual blinds are lowered in instances of glare and left down for prolonged periods, which often happens in practice (Foster 2001), so devices that raise and lower window shading devices automatically may be useful. There is a potential for increased daylighting to impact thermal load (solar gains), countering the energy savings achieved by reducing the electrical lighting, so lighting and thermal performance need to be considered together. A holistic approach involving design and technology, including shading and electric lighting, sensors, and controls, could increase daylight effectiveness and availability, improving the indoor lighting environment with respect to circadian criteria and reducing lighting energy impacts.

Space programming and design Common spaces frequented by occupants, such as break rooms, conference rooms, cafeterias, etc. where occupants spend some time most days, could be strategically located (perimeter zones with good access to daylighting) and/or outfitted with enhanced electric lighting systems to boost performance with respect to circadian criteria. In this way a smaller fraction of the floor area could be leveraged for maximum effect, reducing overall lighting energy increases. Surface finishes and spectral reflectances also influence how much light is needed to meet circadian thresholds (Safranek 2020, Jarboe 2020). Furnishings, paints, carpeting, paneling and upholsteries can all be specified with a design intent to improve spectral reflectances that maximize delivery of short wavelength energy to the eye.

Behavioral: circadian routines, scheduled interventions A non-technical innovation in the realm of policy / behavior is the normalization, scheduling, and even incentivizing of periodic breaks for walks, meetings, and programs outdoors or in common spaces with high levels of daylight or enriched electric light (per the space programming concept above). Employers and administrators routinizing this sort of practice in their buildings would reduce the imperative to meet circadian lighting needs with general overhead lighting only. This strategy may not require any new technology but would require a cultural shift in offices, and to a lesser extent schools, which actually already have some precedent for this with the traditional practice of outdoor “recess”. The minimum duration and frequency of such breaks for effectiveness are beyond this study scope but would need to be considered.

Lighting technology It is clear from the studies that light source SPD, often represented simplistically via CCT, impacts a lighting system’s ability to meet circadian thresholds. Even at the highest output settings, it was often difficult to meet circadian thresholds with a CCT more typical in office and classroom settings. Higher CCTs, with short wavelength and visually cool light, were more efficient for meeting the thresholds but may result in an undesirable visual environment. Tunable white LED sources and controls are more expensive and complex to implement than non-tunable options. However, these types of systems may be the technology of choice for some facilities that intend to meet circadian criteria at lower energy cost, and that do not want to “over-light” to meet criteria, nor implement cooler CCT lighting at all times of day.

This will be a matter of balancing various priorities and preferences of occupants. Regardless, advanced controls, tunable white sources, and simply higher-CCT LEDs, are all viable commercial technologies that are available today to help minimize incremental energy impacts.

Solid-state lighting technology also allows for engineering of specialized spectral content. Some new LED technologies increase spectral content very narrowly within blue and cyan wavelengths (peak melanopic sensitivity range) to boost performance in circadian terms while maintaining lower CCTs to which occupants are more accustomed. This approach is being leveraged by myriad LED chip-makers and luminaire makers. This sort of innovation is meant to increase a light source's melanopic-to-photopic ratio (M/P), or melanopic daylight efficacy ratio (mDER), which is M/P in melanopic equivalent daylight terms. These metrics provide a comparative basis for lighting specifiers looking for better circadian performance and are increasingly being included in lighting product literature. Together with standard efficacy (lumens per watt) criteria, mDER and M/P can help with the specification of energy-efficient products for lighting projects seeking to meet circadian criteria. Light sources with high photopic efficacy and a high mDER or M/P value should deliver higher relative visual and circadian performance per unit of energy (Shackelford 2021).

A couple of other lighting technology ideas proposed for improved circadian performance per unit energy are luminaires with wider intensity distributions (i.e. lumen distribution weighted toward outward angles as well as downward) that deliver more lumens to the occupant's eye, and low-wattage desktop light sources with enriched short-wavelength output (Jarboe 2020, Soler 2021). However, glare could be an issue from either option, and user acceptance/preference is not yet known.

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