U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

The Impact of Circadian Lighting Design Strategies on Lighting and Cooling Energy of an Office Space

February 2023

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Acknowledgments

The authors would like to acknowledge the valuable guidance and input provided during this report. The authors are grateful to the following list of contributors.

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This report was prepared by Pacific Northwest National Laboratory for the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office.

PNNL-33424

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Executive Summary

In a previous study by Pacific Northwest National Laboratory (PNNL), potential energy impacts of designing to meet circadian lighting recommendations with electric lighting were investigated (Safranek et al., 2020). That study found that meeting current horizontal illuminance recommendations from the Illuminating Engineering Society (IES) did not satisfy existing recommendations for equivalent melanopic lux (EML) at the eye, and in some cases meeting these EML recommendations required an average illuminance that was more than double the IES recommendations. It was estimated that electric lighting energy use may increase by at least 10% and in some cases by 100% because of increased luminaire outputs to meet circadian lighting design recommendations in WELL v2 Q2 2019 (IWBI, 2019). A key takeaway from the previous study is the need to consider daylight contributions in future evaluations, as daylight availability may allow for a reduction in electric lighting energy use.

The goal of this report was to provide estimates for the annual electrical and thermal energy loads of a medium office building designed to meet the circadian lighting metric recommendations by Brown et al. (2022) considering daylight and electric light. A workflow was established to conduct electric lighting, daylight, and energy simulations for a multi-space model. The workflow was used to simulate 12 total design scenarios, considering combinations of three electric lighting conditions and four control schedules for interior blinds. Each design scenario was evaluated for its ability to meet current EML recommendations of at least 275 m-lx at all workstations.

Several key results of this investigation include:

- Vertical illuminance and EML are heavily influenced by the view direction and location of the occupant/calculation point relative to daylight or electric light sources. EML estimates ranged from 64 to 316 m-lx between the 142 workstations under the same electric lighting conditions, highlighting the challenge of uniform light distribution in the vertical plane.
- Meeting the recommended 275 m-lx threshold with electric lighting was only possible for 30% of workstations under a 6200 K CCT lighting condition, despite some desks receiving more than double the IES recommended horizontal illuminance.
- Modeled after the continuous daylight autonomy metric, $cDA_{EML,275}$ quantifies the percentage of hours that daylight contributes to the EML threshold of 275 m-lx. The $cDA_{EML,275}$ results from this study suggest that for many workstations along the perimeter, daylight can provide the recommended 275 m-lx for most of the occupied hours throughout the year. This is not true for all perimeter workstations, however, as those that may be relatively close to a window (within 10 ft) but facing into the interior of the building received very limited daylight at the vertical view plane. Mapping $cDA_{EML,275}$ across the floorplan, like shown in Figure ES1, is helpful for understanding the impact of workstation view direction on resulting EML levels from daylight.

- For a typical daylight control scenario with blind control, supplementing an overhead lighting system with task luminaires reduced annual lighting energy use by 28%.
- Daylighting strategies aiming to increase daylight levels at the eye should consider the implications on electric lighting, cooling, and heating energy. The analysis showed a tradeoff between cooling and electric lighting energy. This is important to consider given that circadian lighting design is likely to become a factor that informs the control of shading systems as well as overhead lighting.

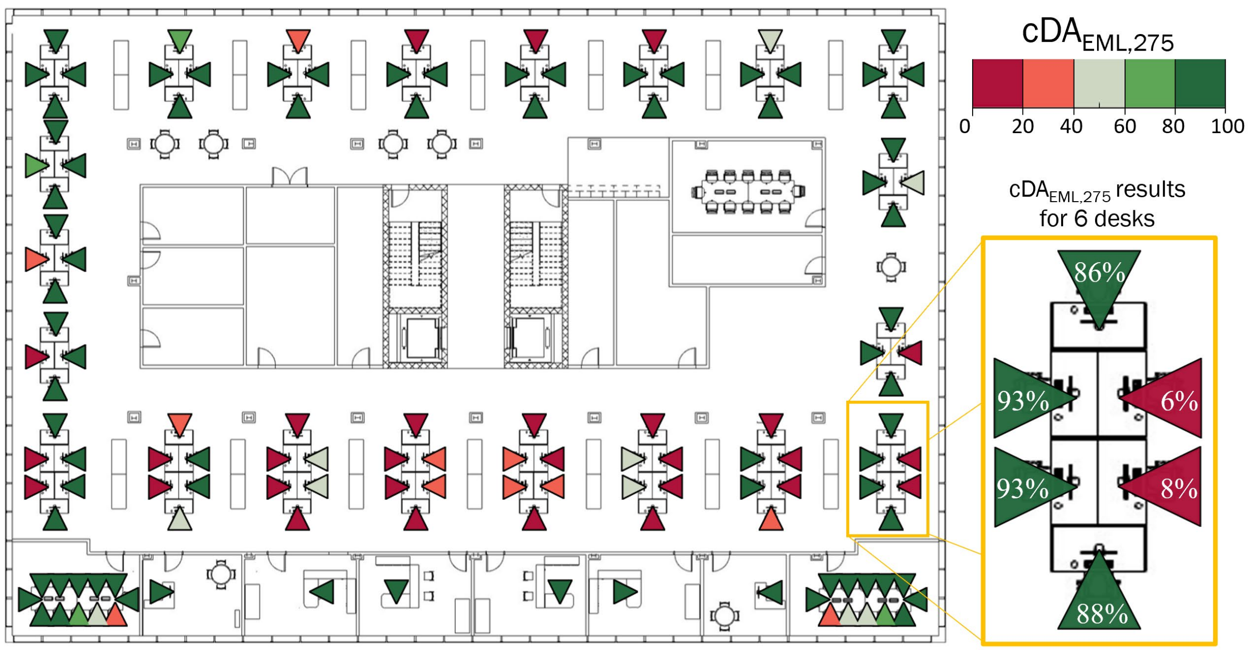

Figure ES1. Floorplan layout of continuous daylight autonomy ($cDA_{EML,\ 275}$) results based on an EML threshold of 275 m-lx during the occupied hours. These results are for a blinds schedule where blinds are always open, which has the most access to daylight. Each arrow corresponds to one of 130 vertical calculation points that had access to daylight, and the direction of the arrow indicates the direction of view. The five-point color scale is used to report cDA values in 20% intervals. Red arrows indicate calculation points that get minimal EML contributions from daylight while green arrows indicate calculation points that get enough contribution from daylight such that little supplemental light is needed to meet 275 m-lx for the occupied hours.

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1 Introduction

In a previous study by Pacific Northwest National Laboratory (PNNL), potential energy impacts of designing to meet circadian lighting recommendations with electric lighting were investigated (Safranek et al., 2020). That study found that meeting current horizontal illuminance recommendations from the Illuminating Engineering Society (IES) did not satisfy existing recommendations for equivalent melanopic lux (EML) at the eye, and in some cases meeting these EML recommendations required an average illuminance that was more than double the IES recommendations. It was estimated that electric lighting energy use may increase by at least 10% and in some cases by 100% because of increased luminaire outputs to meet circadian lighting design recommendations in WELL v2 Q2 2019 (IWBI, 2019).

A key takeaway from the previous study was the need to consider daylight contributions in future evaluations, as daylight availability may allow for a reduction in electric lighting energy use. Previous studies that evaluated daylight availability suggest that building occupants may not receive the recommended amount of circadian lighting from daylight alone depending on several factors such as their location, view direction in the space, shading devices, and other architectural factors (Brennan & Collins, 2018). Hence, the integration of daylight and electric lighting systems should be explored to provide effective design for circadian lighting metrics.

Current availability of modeling tools and data limit the spectral simulations of annual daylight. One approach to simulate the spectral characteristics of daylight is through models that convert sky luminance to correlated color temperature (CCT) as discussed by Inanici et al. (2022); a design tool using this approach has been recently developed (Maskarenj et al., 2022). Another approach is to use global horizontal sky spectra measurements, though these measurements are currently limited to a few geographical locations in the United States such as National Renewable Energy Laboratory (NREL) in Golden, CO (Andreas & Stoffel, 1981).

Previous investigations of using daylight to meet circadian lighting requirements (Table 1) focused on electric lighting savings, but not the effects of cooling and heating energy. The table shows a lack of studies that evaluated the impact of daylight and electric lighting on lighting, heating, and cooling energy. A comprehensive evaluation of energy is important because circadian lighting recommendations should, ideally, be achieved by a combination of daylight and electric lighting that uses the least energy.

The goal of this report is to evaluate the electric lighting energy and thermal loads of different combinations of daylighting and electric lighting systems designed to meet the circadian lighting metric recommendations made by Brown et al. (2022). The simulation space was the second floor of a medium office prototype building in Golden, CO; the 17,900 ft^2 area comprised of five zones and 142 workstations. To meet the recommendations made by Brown et al. (2022), all workstations should receive an EML of at least 275 m-lx at the eye of occupants during the daytime hours. Additionally, these light levels should be met with daylight when possible and supplemented with electric light as needed. This study used a combination of four daylighting control scenarios and three electric lighting control scenarios to compare the energy impacts of 12 total lighting conditions.

Table 1. Summary of previous studies that evaluated daylight contributions or electric lighting energy for meeting circadian lighting requirements. A dash (-) indicates an irrelevant field for studies that did not consider daylighting.

Study	Study Type	Daylight Considered?	Electric Lighting Energy Estimated?	Thermal Loads from Daylight Estimated?	Findings
Safranek et al. (2020)	Simulation	No	Yes	-	Electric lighting energy increases by 10-100%†
Zeng et al. (2021)	Simulation	Yes, D55 was assumed	Yes	No	When aiming to achieve 300 lx and 250 EML in an east-facing office without shading, electric lighting energy increased by 5% (using 5500 K lighting) to 19% (using 4000 K lighting), compared to a scenario meeting 300 lx requirement †
Shackelford and Meier (2021)	Field study	Yes, naturally occurring skies	Yes	No	Electric lighting energy increased by 31-42% when incorporating a 4-hour circadian lighting exposure (218 melanopic equivalent daylight illuminance) †
Jarobe et al. (2020)	Simulation	No	Yes	-	Providing a circadian stimulus of 0.3 or higher was more successful when targeting 500 lx of horizontal illuminance than when targeting 300 lx

† Compared to a scenario meeting 300 lx requirement.

Section 2 provides details on the simulation workflow, software tools, and assumptions used to predict annual estimates of EML from the lighting conditions and estimate the energy usage of the lighting and heating, ventilation, and air conditioning (HVAC) systems. Section 3 presents the simulation results with separate discussions on the contributions of daylight and electric lighting toward EML. The estimated electrical energy loads are compared to the potential heating and cooling loads for a more holistic discussion of the energy impacts of circadian lighting metric recommendations when scaled to a whole building. Section 4 summarizes the conclusions, limitations, and opportunities for future research.

2 Methods

2.1 Overview of Simulation Procedure

A workflow (Figure 1) was established to conduct electric lighting, daylight, and energy simulations for a multi-space model. The modeling software Rhino3D was used to create the model geometry and provided access to lighting software plug-ins (ALFA and ClimateStudio).

Electric lighting was simulated in ALFA, which predicts the intensity and spectrum of light at horizontal and vertical calculation points. ALFA uses 81 bins to represent the spectral characteristics of light sources and surface materials, allowing for increased accuracy when simulating LED spectra compared to lower resolution spectral simulation software tools (Abboushi et al., 2021). ALFA uses this additional information to predict illuminance as well as spectrally dependent metrics, like EML, at the eye position of each occupant.

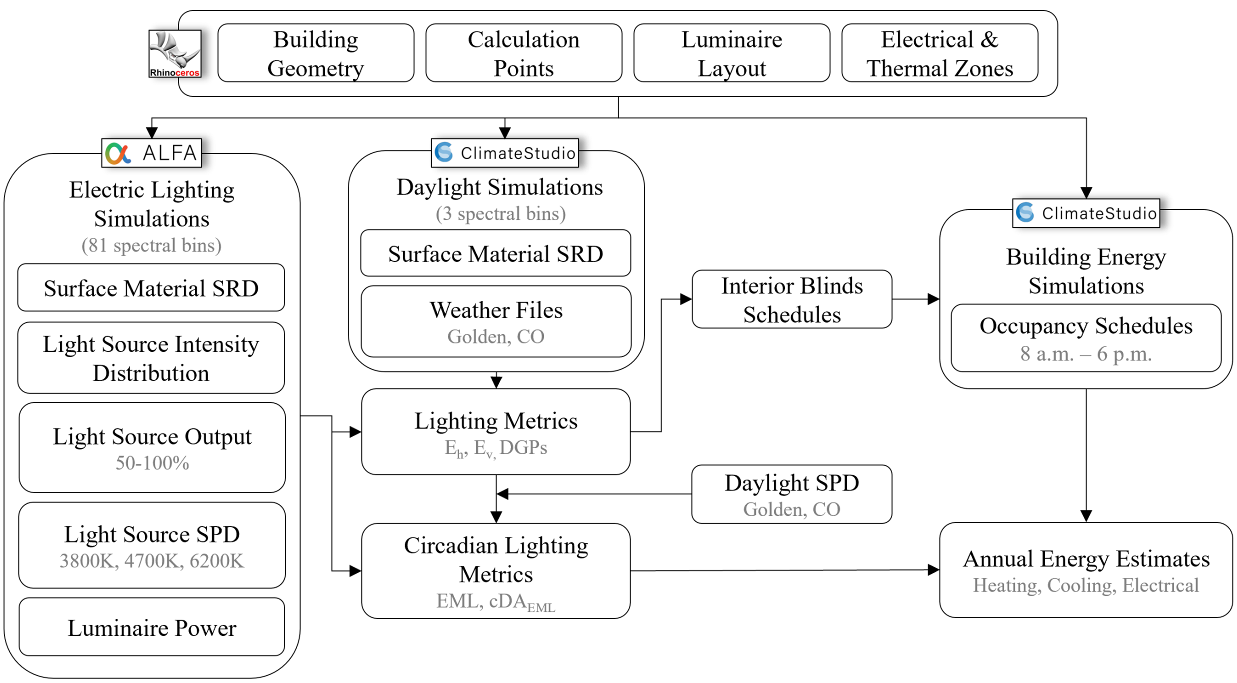


Figure 1. Workflow for conducting electric lighting, daylight, and energy simulations for a multi-space building model.

Daylight was simulated separately in ClimateStudio, which takes substantially less time to calculate annual daylight contributions compared to higher resolution spectral software tools like ALFA. ClimateStudio uses three bins to represent spectral quantities but does not currently account for sky spectra. Hence, supplemental spectral irradiance measurements from the NREL station in Golden, CO, were used to estimate EML. Two sets of schedules for interior blinds were established based on predicted illuminance thresholds and provided as input to ClimateStudio energy simulations.

The workflow was used to simulate 12 total design scenarios, considering combinations of three electric lighting conditions and four control schedules for interior blinds. The daylight and electric lighting conditions are described in further detail in Sections 2.3 and 2.4. Each design scenario was evaluated for its ability to meet current EML recommendations of at least 275 m-lx at all workstations (Brown et al., 2022). Estimated lighting and thermal energy usage of the 12 design scenarios was used to compare the energy impact of meeting circadian lighting metrics with daylight and electric light.

2.2 Simulated Model

The medium office prototype building model, developed by the Department of Energy (DOE), was replicated in Rhino3D. The model is one of 16 commercial building types, intended to represent 75% of the commercial building floor area in the United States for new construction. Each prototype model has a corresponding Excel scorecard that summarizes the building descriptions, thermal zone internal loads, schedules, and other information relevant for modeling whole-building energy consumption. Additional details like space types, occupant distribution, furniture and luminaires were added to create a high-fidelity model specifically for conducting lighting and energy simulations. A written description of this high-fidelity lighting model developed for the medium office prototype building is currently in progress (Collier et al., 2022).

To focus on the relationship between lighting and thermal loads, only the second floor of the medium office building was considered in the analyses presented in this report. As shown in Figure 2, the second floor was divided into five zones with 142 workstations (including individual seated positions in the conference rooms) distributed across roughly 17,900 ft^2. Six private offices and two conference room spaces were in zone 3, along the southern perimeter of the floorplan. The remaining zones were primarily open office space with 100 workstations and one additional conference room in the core zone. Roughly 4-ft-tall ribbon windows were uniformly distributed across the building façades, resulting in a window-to-wall ratio of 33%. The dimensions of the zones and windows, summarized in Table 2, are comparable to those specified in the Excel scorecard for the medium office prototype building.

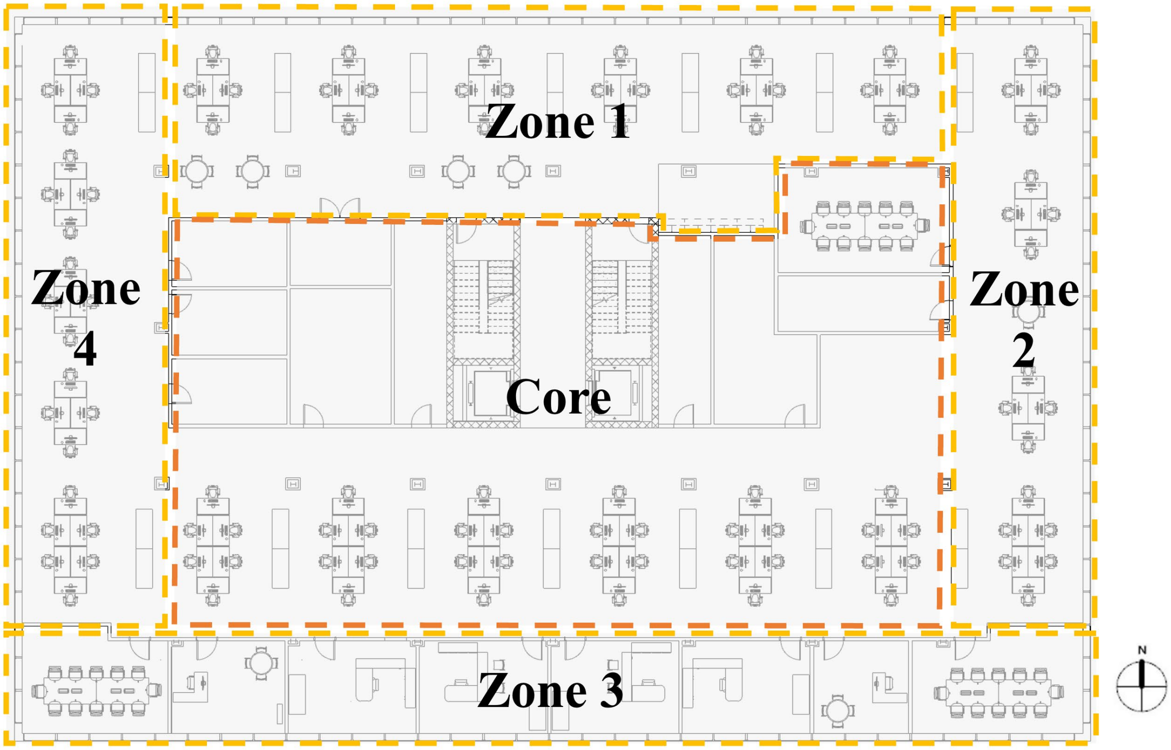
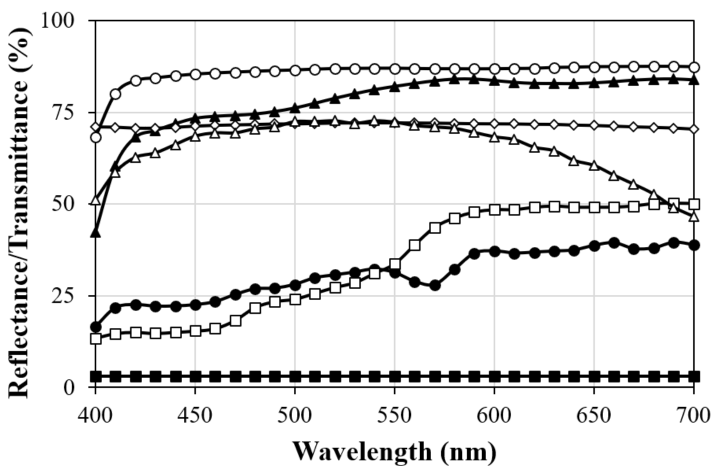


Figure 2. Floorplan of the DOE medium office prototype building (floor 2) which includes space types, occupant layout, and furniture for conducting high-fidelity lighting and energy simulations. Four perimeter zones (yellow) and one core zone (orange) were used for lighting and energy analyses.

Workstations and furniture were modeled throughout the office and conference spaces, informed by the occupant distribution specified in the Excel scorecard. Surface materials were assigned spectral reflectance distributions (SRDs) representing those typically used in office environments. Many of the SRDs were measured using a Konica Minolta CM-700D portable spectrometer, supplemented with spectral material definitions from the ALFA library. The average reflectance values and full SRDs can be seen in Figure 3.

Table 2. Description of the space distribution of zones used to represent the DOE medium office protoype building.

Zone	Number of occupants/ space type	Total Floor Area (ft^2)	Window Area (ft^2)
Zone 1	24 / open office	3,204	532
Zone 2	18 / open office	1,769	498
Zone 3	6 / private office, 24 / conference	2,239	845
Zone 4	22 / open office	1,968	498
Zone 5	36 / open office, 12 / conference	8,699	0
Total	100 / open office, 6 / private office, and 36 / conference	17,878	4,714



Surface Material	Average
White Ceiling Tile	86%
White Wall Paint	78%
Silver Window Frame	71%
Grey Flooring	31%
Workstations (Blonde Wood)	34%
Monitors	3%
Glazing	65%

Figure 3.Spectral reflectance and transmittance distributions for model surfaces. The reflection for room surfaces and transmittance for the glazing are plotted in 10 nm increments on the left and averaged per material on the right.. Average values calculated using all values between 400 and 700 nm.

Workstation height is 2.5 above finished floor (AFF) and workstations in the open office spaces included a 3 ft tall partition (Figure 4), with the same SRD as the workstations. Computer monitors were modeled atop the workstations but were not treated as luminous devices for this study. For lighting simulations, each workstation was assigned one horizontal and one vertical calculation point. Horizontal calculation points were placed atop the desks, 2.5 ft AFF. Vertical calculation points were placed 4 ft AFF, representing the eye height of a person sitting at each workstation facing a computer monitor.

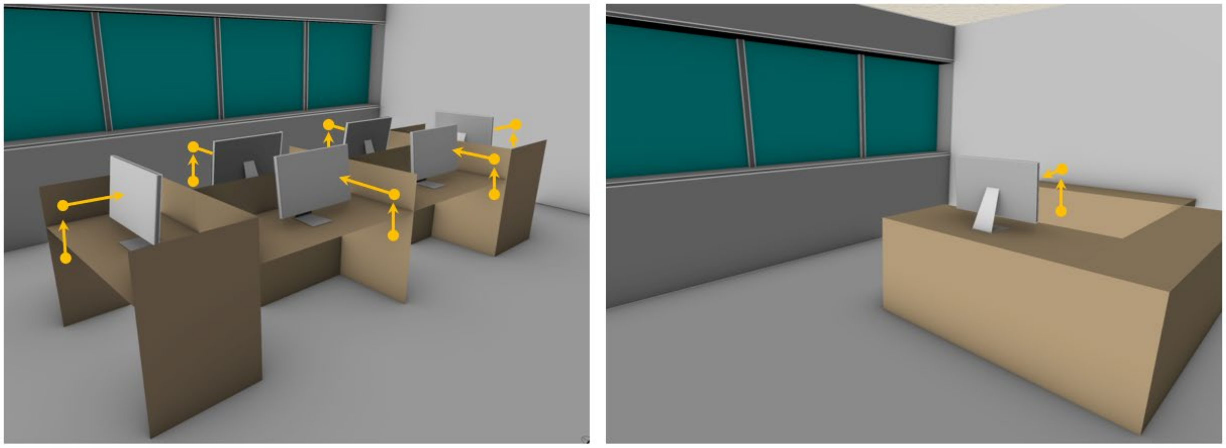


Figure 4. Examples of the workstations and placement of calculation points used in lighting simulation of open offices (left) and private offices (right). Yellow arrows represent the horizontal and vertical calculation points placed at each workstation. Vertical calculation points were oriented toward the computer monitor, representing the view of an occupant seated at the workstation.

2.3 Electric Lighting Simulation Parameters

A detailed electric lighting layout and luminaire schedule, developed by Collier et al. (2022), was used to create the high-fidelity lighting model used in this report. The lighting system was designed to meet or exceed IES space-specific illuminance recommendations for office applications while also complying with power allowances in ANSI/ASHRAE/IES Standard 90.1-2019 (referred to in this report as Standard 90.1-2019). Luminaires were selected from an ASHRAE database of sample products, and 13 luminaire types were used throughout the full model. Figure 5 depicts the lighting layout; open office spaces contained direct/indirect pendant luminaires while private offices and conference rooms used a combination of recessed troffers and wall washers.

ALFA was used to simulate the spectral characteristics of electric lighting and room surfaces in 81 bins (5-nm increments from 380-780 nm) . Luminaire intensity distributions were input using photometric data (.ies files) obtained from the manufacturers and SPD data was supplied from photometric testing of one luminaire sample in an integrating sphere at the PNNL Lighting Metrology Laboratory in Richland, WA (Royer et al., 2015). Three SPDs (Figure 6), with CCTs of roughly 3800 K, 4700 K, and 6200 K, from the test data to represent the range of settings available for the luminaires. For the CCT conditions, ALFA was used to predict horizontal illuminance, vertical illuminance, and vertical EML at the calculation points assigned to each workstation throughout office and conference spaces.

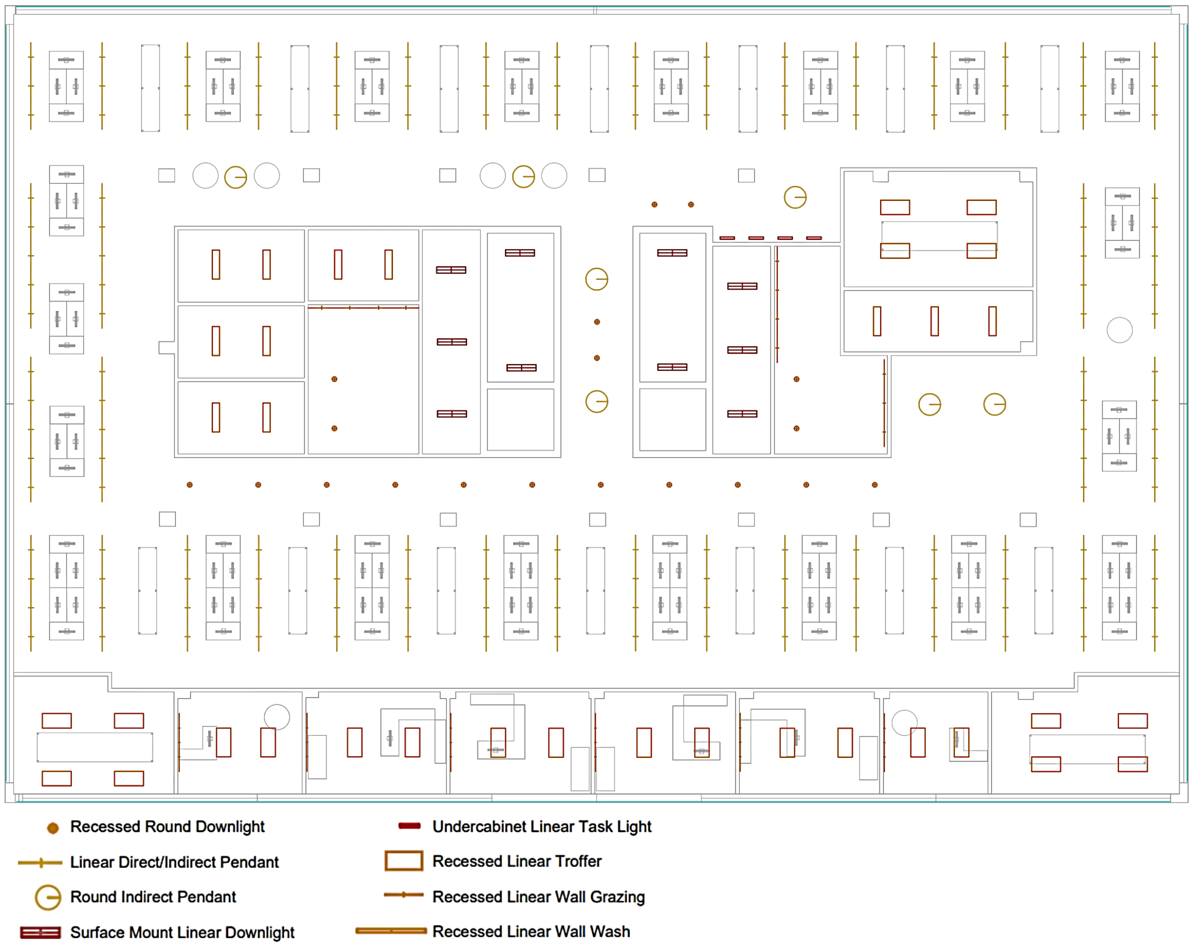


Figure 5. Luminaire layout for second floor of medium office building prototype model.

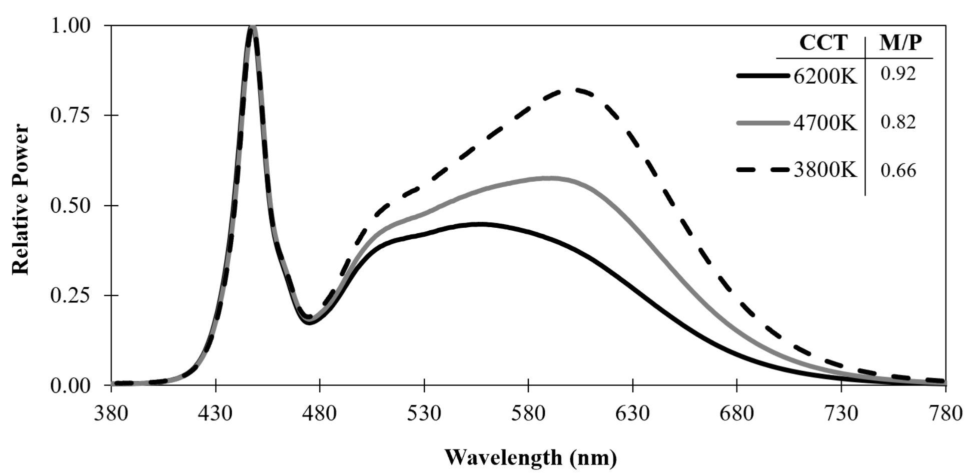


Figure 6. Relative SPDs for all luminaires. The corresponding CCT value and melanopic to photopic ratio for each SPD is listed on the right. To compare the SPDs without the contribution of room surfaces, at 100 lx the 3800 K, 4700 K, and 6200 K sources equate to 66 m-lx, 82 m-lx, and 92 m-lx respectively.

Following methods outlined in previous daylight/electric lighting analyses done by (Safranek et al., 2022), the light output of the electric lighting system was adjusted based on the availability of daylight throughout the office and conference spaces. As modeled for this report, IES recommendations for horizontal illuminance (average of 300 lx on the task plane) can be achieved in the office and conference spaces with the electric lighting system operating at roughly 50% light output. When supplemental light was needed for meeting circadian lighting metrics, the light output of the electric lighting system was increased in 1% increments from the visual task baseline (50%) to the minimum light output needed to meet 275 m-lx. Hourly electric lighting schedules, detailing the light output needed to meet the recommended EML threshold for the occupied hours, were used to estimate annual energy consumption for the electric lighting system. Luminaires were assumed to have linear dimming with a 1:1 relationship between light output and power. Luminaire power was not affected by CCT and depreciation factors such as dirt and lumen maintenance were not considered. For the open office spaces, luminaires were controlled as a group across the corresponding zone. Luminaires in the private offices and conference rooms were grouped and controlled per room. Rooms without workstations in the core zone were kept static at 50% light output to meet IES illuminance recommendations. It is assumed that there are no occupants working regularly in these spaces.

Table 3 provides estimates for lighting power, comparing the planned power with the interior power allowances listed in Standard 90.1-2019. The lighted floor area for the second floor of the lighting model is roughly 17,000 ft^2, resulting in an allowable power of 10,016 W using the space-by-space calculation method or 10,668 W using the building area method. The total connected load is 2,248 W, or 21% less than the power allowed by the building area method, thereby complying with energy code.

Table 3. Lighting power summary compared to Standard 90.1-2019 interior power allowances for the building area and space-by-space method.

	Space Type	Lighted Area (ft^2)	Allowable LPD (W/ft^2)	Allowable Wattage (W)	Actual Wattage (W)	Actual LPD (W/ft^2)
Building Area Method	Office	16,669	0.64	10,668	8,420	0.51
Space-by-Space Method	Open Office	9,466	0.61	5,774	5,745	0.61
	Enclosed office	1,518	0.66	1,002	336	0.22
	Corridor/Transition	1,101	0.41	451	231	0.21
	Active Storage/Auxiliary	1,188	0.38	451	374	0.31
	Conference Room	1,130	0.97	1,096	580	0.51
	Stairway	370	0.49	181	140	0.38
	Lobby	313	0.65	203	126	0.40
	Restroom	655	0.63	413	452	0.69
	Electrical/Mechanical	470	0.43	202	210	0.45
	Lounge	279	0.59	165	84	0.30
	Dining Area/Food Prep	179	0.43	77	142	0.79

2.4 Daylight Simulation Parameters

Estimating EML Contributions from Daylight

Annual simulations of photopic illuminances produced by daylight typically only consider the variation in intensity and direction of daylight, not the spectral characteristics. This is due in part to the limited amount of data describing the spectrum of daylight throughout the year as such datasets are limited to a few locations in the United States. For this report, a method was established for estimating the EML contributions from daylight using spectral measurements captured by the NREL. A spectrophotometer, managed and maintained by NREL (Andreas & Stoffel, 1981), collects SPDs and images of the sky dome in Golden, CO, in 1-nm increments every 5 minutes throughout the year. Data collection is ongoing, and a complete set of measurements from 2018 was used to create a full year of spectral sky conditions during daytime hours for the simulations detailed in this report.

The melanopic to photopic ratio (M/P) was calculated using the daylight SPD for each hour, based on the method outlined in WELL (Equation 1). Figure 7 displays the hourly distribution of M/P values throughout 1 year, during daytime hours. Average M/P for the year is 1.05, although there is deviation from this average value, especially in the evening hours. Interior daylight illuminance values calculated in ClimateStudio from an EnergyPlus weather file (.epw) for Golden, CO, are multiplied by the M/P value for each hour, providing an estimate of the EML contributions from daylight. Given that high-resolution spectral sky data, like those collected by NREL, are currently limited to only a few locations in the United States, it is not possible to conduct annual spectral simulations of daylight for different locations and climates.

Eq. 1

$$\frac{M}{P} = \frac{1.218 \int_{380}^{780} S(\lambda)M(\lambda)d\lambda}{\int_{380}^{780} S(\lambda)V(\lambda)d\lambda}$$

where $S(\lambda)$ is light source SPD,
$M(\lambda)$ is melanopic sensitivity curve,
$V(\lambda)$ is the photopic sensitivity curve,
and $k = 1.218$, equal energy constant

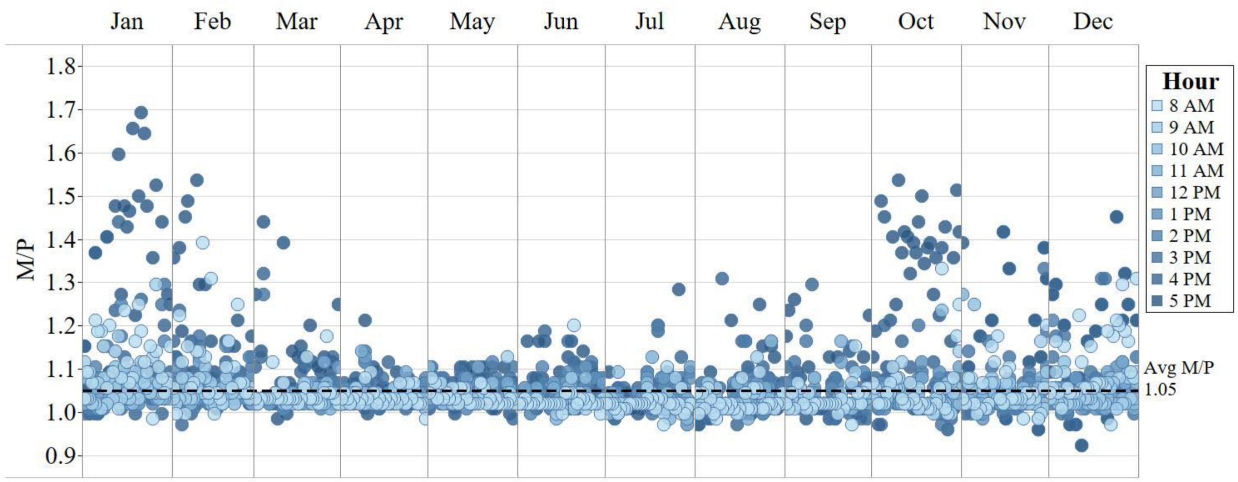


Figure 7. Annual M/P ratios of daylight conditions for Golden, CO. For hours between 8 a.m. and 5 p.m., M/P is calculated for every day of the year, based on a dataset of spectral sky measurements published by NREL.

Blind Schedules

No exterior obstructions like buildings or foliage were considered in the simulations of daylight; however, interior blinds were included. To investigate the impact of varying daylight contributions on interior EML levels and the resulting heating and cooling loads of the HVAC system, four blind schedules were considered: 1) blinds always closed, 2) blinds always open, 3) blinds closed according to IES LM-83, and 4) blinds closed if daylight resulted in perceptible levels of glare for any occupant in the respective zone. For simplicity, each façade orientation consisted only of one window group such that blinds were either open or closed for the entire facade (no partial blind positions).

A blind schedule was created based on the simulation protocol provided by IES LM-83 (IES, 2012), which accounts for direct contributions of daylight through an annual sunlight exposure metric. For this schedule, interior blinds are closed if 2% of the occupied floor area receives greater than 1,000 lx of direct sunlight, determined using a 2 ft x 2 ft grid of horizontal calculation points across the occupied area. Alternatively, a blind schedule was created using vertical illuminance to predict instances of intolerable or disturbing levels of glare with the simplified daylight glare probability metric ([DGPs], Weinold, 2009). If DGPs were greater than 0.35 for one or more occupants in a zone, it was assumed that the occupants would experience intolerable or disturbing levels of glare and the blinds for the corresponding window group would be closed for that hour. Figure 8 shows the hours affected by these control methods, per window group.

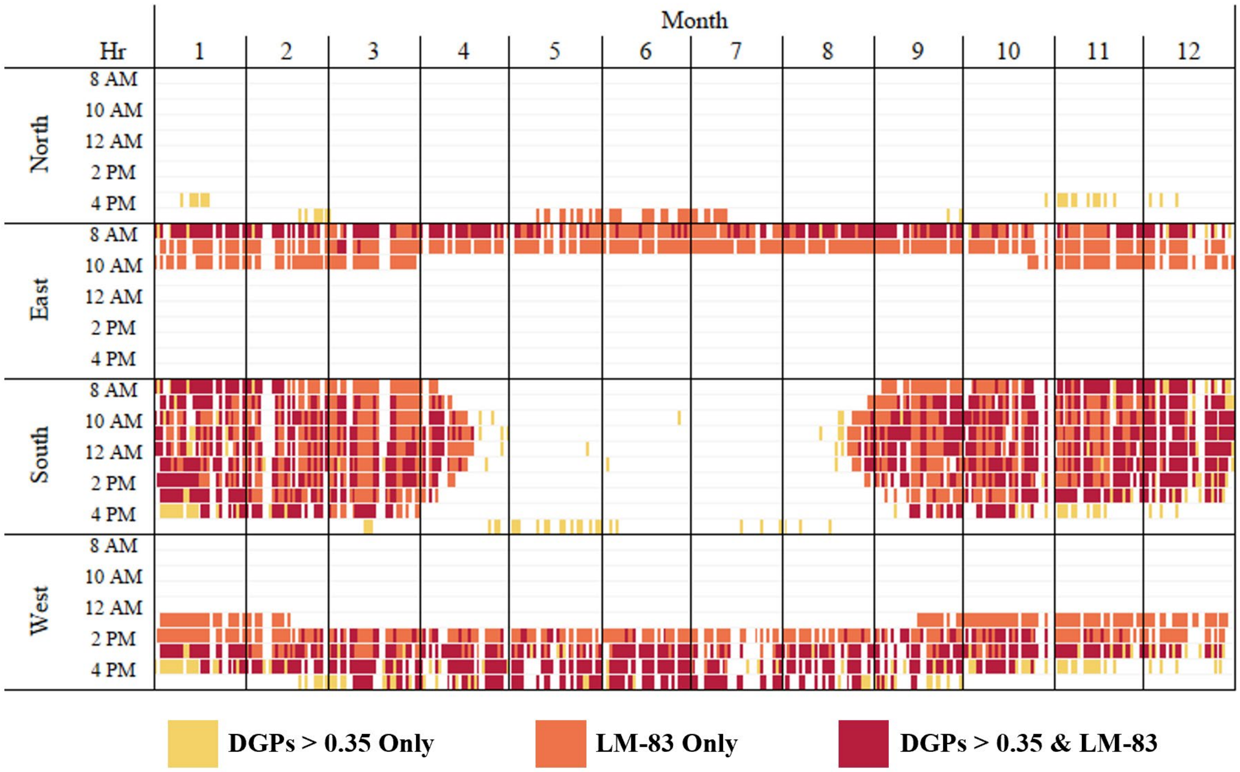


Figure 8. Annual interior blind schedules for each building façade. Hours where interior blinds would be closed due to disturbing or intolerable levels of glare, calculated with the simplified daylight glare probability metric, are shown in yellow. Hours where interior blinds would be closed in accordance with IES LM-83, are orange. Hours where interior blinds would be closed due to both DGPs and IES LM-83 are red.

Energy Simulation Parameters

The second floor was modeled as five thermal zones following the zone boundaries used for lighting analysis (Figure 2). For simplicity, all zones were modeled as open offices, except zone 3, which was modeled as closed offices per Standard 90.1-2019 climate zone 5. The ceiling and floor were modeled as adiabatic surfaces (no heat transfer occurs through these surfaces). The window glazing used was double pane, with a visible transmittance (T_{vis}) of 46% and solar heat gain coefficient of 0.3. Window frame was 2.5 in wide and had a conductance of 5 W/m^2-K and a U value of 1.62 W/m^2-K. The blinds were charcoal gray with T_{vis} of 7.2%.

The thermal simulations were done using Climate Studio software as an interface for EnergyPlus v9.4 and the ideal zones component. This component in EnergyPlus makes it easy to explore impacts on the thermal performance of a building without modeling a full HVAC system (DOE, 2022). Additional inputs for simulation are listed in Table 4.

Table 4: Key inputs used in the thermal simulations

Input	Value
People	0.05 P/m^2
Equipment	9.36 Q/m^2
Max heat supply air	30^o C
Min cool supply air	18^o C
Heating coefficient of performance	0.81
Cooling coefficient of performance	3.4
Minimum fresh air per person	2.34 L/s/p
Minimum fresh air per area	0.30 L/s/m^2
Economizer	No

3 Results

3.1 Estimated Contributions of Daylight Towards EML

Average EML, estimated for 1 year during the operating hours (9 a.m. to 5 p.m.) and summarized in Figure 9, varied notably across the 130 workstations that had access to daylight. The blinds open schedule, which had the greatest access to daylight, also had the greatest average EML levels. Nineteen of the workstations received 1000 m-lx or more on average; however, 55 workstations had an average EML less than the recommended 275 m-lx. Instances of an average EML greater than 1000 m-lx were less common with the IES LM-83 and DGPs schedules, resulting from the regular use of interior blinds. Between 58-60 workstations had an average EML less than 275 m-lx for these blind schedules. As expected, the blinds closed schedule reduced the contributions of daylight such that all the workstations received less than the recommended 275 m-lx.

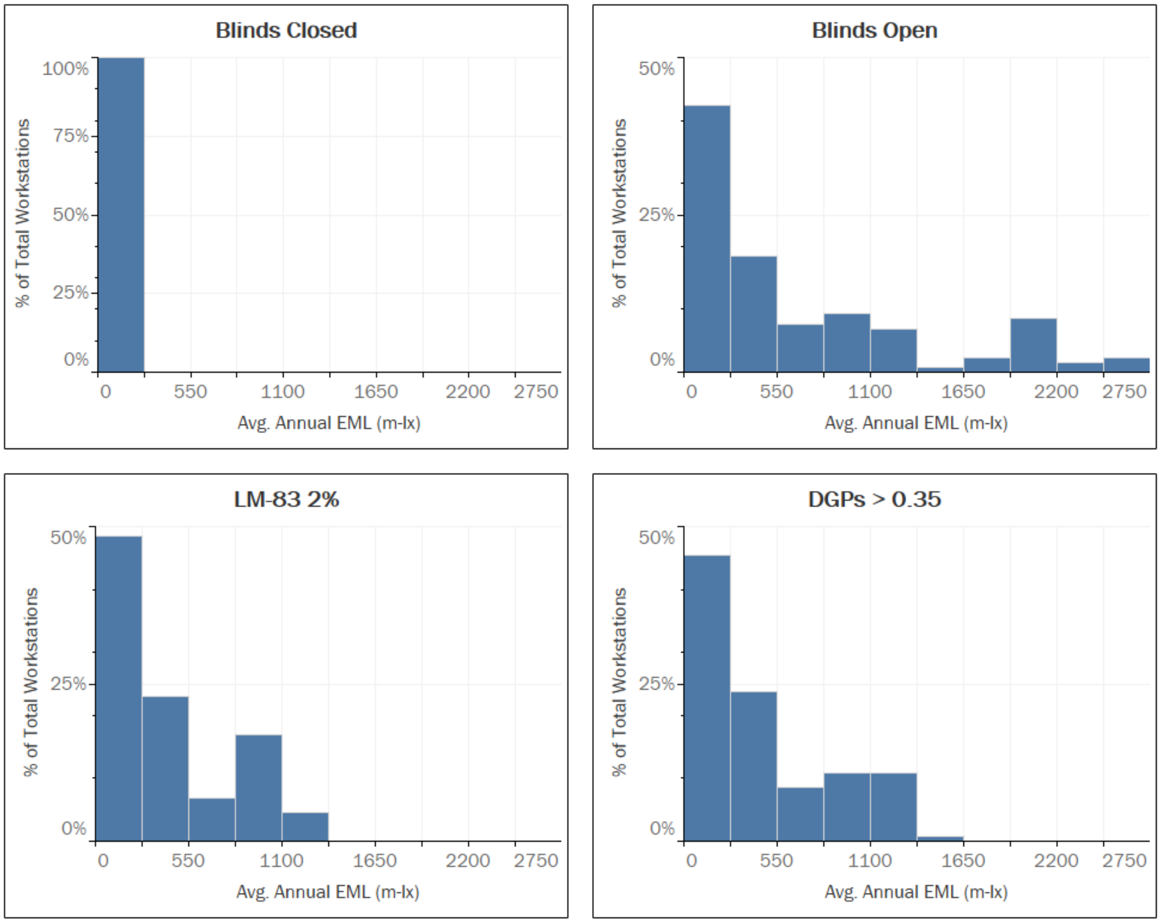


Figure 9. Histograms of average annual EML contributions from daylight for 130 workstations considering four schedules for controlling interior blinds. For each occupied hour of the year and each workstation, estimated EML is averaged and binned using 275 m-lx increments.

While average EML is helpful for understanding the magnitude of daylight contributions throughout the year, it is important to also estimate the frequency at which individual workstations may be falling below the 275 m-lx threshold. To determine the number of occupied hours that the EML contributions of daylight meet or exceed the recommended 275 m-lx threshold, hourly vertical illuminance values were used to calculate continuous daylight Autonomy ([cDA_{EML}], Abboushi & Safranek, 2022). Modeled after the continuous daylight autonomy metric, $cDA_{EML,275}$ quantifies the percentage of hours that daylight contributes to the EML threshold of 275 m-lx. For each vertical calculation point, full credit is given (value of 1) for hours that meet or exceed 275 m-lx and partial credit (continuously mapped from 0 to 1) is given for hours below this threshold.

Figure 10 summarizes the $cDA_{EML,275}$ results for all four blind conditions. For each blind condition, the results are separated by zone to further compare differences between building orientations (see Figure 2 for zone layout). As with average EML, the blinds closed and blinds open schedules provided an estimate of the range of $cDA_{EML,275}$ values possible without considering occupant adjustments to interior shading. For the IES LM-83 and DGPs blind schedules, most perimeter workstations have an estimated $cDA_{EML,275}$ greater than 50%. In each perimeter zone, however, there are several workstations that have a $cDA_{EML,275}$ of less than 20% and would need supplemental lighting for most of the year. The open office workstations located in the core of the building will require the most supplemental light, although there are several workstations that have a $cDA_{EML,275}$ greater than 50% despite being located farther away from a window.

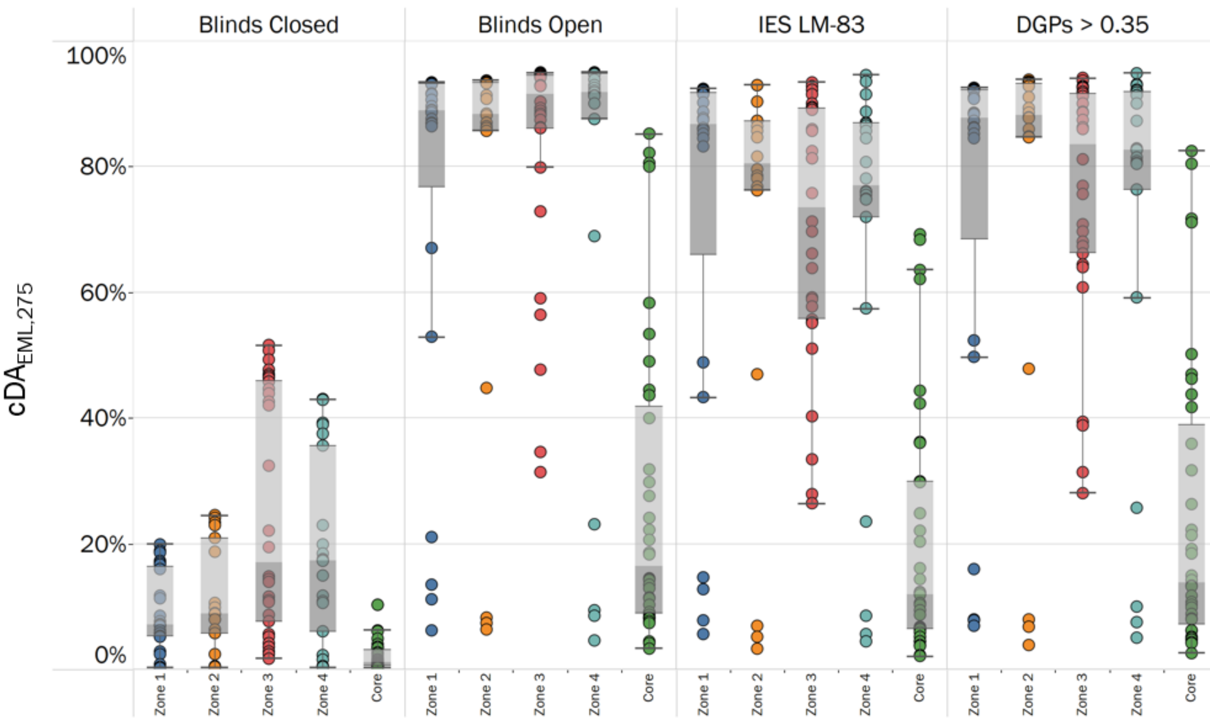


Figure 10. Continuous daylight autonomy ($cDA_{EML,\ 275}$) results, per zone, for the four blind conditions based on an EML threshold of 275 m-lx during the occupied hours. The dots represent the $cDA_{EML,\ 275}$ predicted for one of the 130 workstations with access to daylight, by zone. The center line of each box corresponds to the median value, with the extents of the box corresponding to the upper and lower quartiles. The whiskers indicate the data points that were within 1.5 times the interquartile range, with outliers displayed outside of these whiskers.

Mapping $cDA_{EML,275}$ across the floorplan of the office and conference spaces, as shown in Figure 11, highlights the impact of workstation view direction on resulting EML levels. For the 130 workstations with access to daylight, arrows indicate the view direction of each vertical calculation point and a 5-point color scale is used to report $cDA_{EML,275}$ values in 20% increments. Dark red arrows indicate vertical view positions that have a $cDA_{EML,275}$ of less than 20% and will need greater contributions from the electric lighting system to meet the EML threshold of 275 m-lx during occupied hours. Dark green arrows indicate vertical view positions with a $cDA_{EML,275}$

of 80% or greater, indicating that these positions get substantial EML contributions from daylight and require less supplemental light from the electric lighting system.

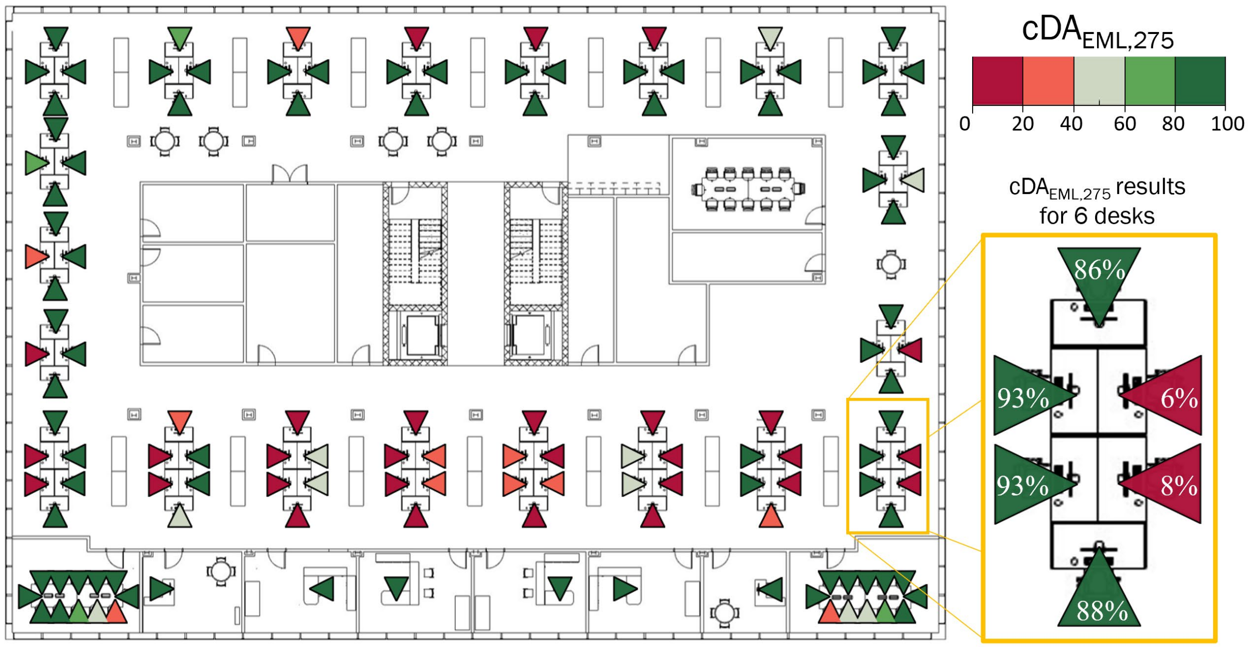
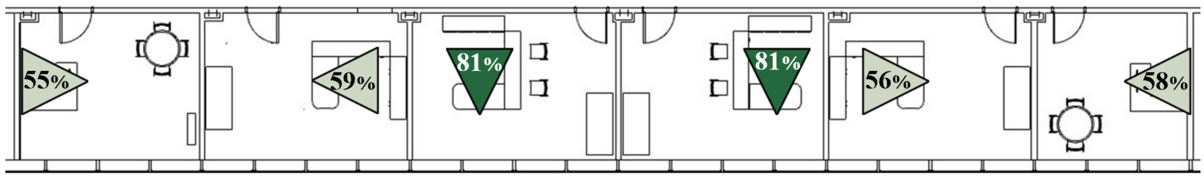


Figure 11. Floorplan layout of continuous daylight autonomy ($cDA_{EML,\ 275}$) results based on an EML threshold of 275 m-lx during the occupied hours. These results are for the blinds open schedule, which has the most access to daylight. Each arrow corresponds to one of 130 vertical calculation points that had access to daylight, and the direction of the arrow indicates the direction of view. The five-point color scale is used to report cDA values in 20% intervals. Red arrows indicate calculation points that get minimal EML contributions from daylight while green arrows indicate calculation points that get enough contribution from daylight such that little supplemental light is needed to meet 275 m-lx for the occupied hours.

The $cDA_{EML,275}$ results suggest that for many workstations along the perimeter, daylight can provide the recommended 275 m-lx for most of the occupied hours throughout the year. This is not true for all perimeter workstations however, as those that may be relatively close to a window (within 10 ft) but face the interior of the building received very limited daylight at the vertical view plane. These workstations generally have lower EML values than those with a partial view of a window and those that are toward the core of the space but face a window. For the open office spaces considered in this report, supplemental electric lighting will be needed to meet the recommended 275 m-lx at all workstations, despite many receiving substantial EML contributions from daylight alone.

As shown in Figure 12, $cDA_{EML,275}$ was also calculated per hour for the workstations in the private offices, along the south-facing perimeter of the building. Three office layouts were mirrored such that two workstations faced east, two faced west, and two faced south, with comparable views of the windows. While the annual $cDA_{EML,275}$ values were relatively similar for the east- and west-facing workstations, the hourly $cDA_{EML,275}$ values highlight diurnal differences; east-facing workstations reflect higher EML levels in the morning hours while the west-facing workstations reflect higher EML levels in the afternoon. Differences observed in the south-facing offices can be attributed to the distance of workstations from interior walls, which may cut off incoming daylight based on time of day.

Annual $cDA_{EML,275}$



Hourly $cDA_{EML,275}$

Hour						
9	76%	54%	90%	78%	76%	53%
10	65%	52%	88%	84%	68%	50%
11	56%	52%	87%	85%	56%	51%
12	54%	58%	88%	86%	54%	56%
13	52%	66%	87%	86%	52%	66%
14	54%	75%	86%	89%	54%	74%
15	53%	73%	74%	87%	54%	72%
16	51%	61%	74%	80%	51%	57%
17	36%	42%	58%	57%	36%	39%

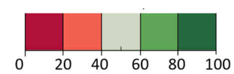


Figure 12. Continuous daylight autonomy using EML ($cDA_{EML,275}$) results for the private offices, based on an EML threshold of 275 m-lx during the occupied hours. For each office operating under the IES LM-83 schedule, $cDA_{EML,275}$ is averaged per hour (table values) and for the entire year (arrow values). Each arrow corresponds to a vertical calculation point, with the direction of the arrow indicating the direction of view. A five-point color scale is used to report cDA values in 20% intervals. Red arrows indicate calculation points that get minimal EML contributions from daylight while green arrows indicate calculation points that get enough contribution from daylight such that little supplemental light is needed to meet 275 m-lx for the occupied hours.

The $cDA_{EML,275}$ metric is helpful for comparing the impact of workstation location, view direction, and occupant schedule on resulting levels of EML. It is critical that $cDA_{EML,275}$ be calculated in the vertical plane as metrics commonly used for estimating daylight contributions in the horizontal plane, like illuminance or the original cDA metric, will not necessarily capture the lack of daylight reaching the eye of occupants with their back to windows.

3.2 Estimated Contributions of Electric Light Towards EML

With the electric lighting system operating at maximum light output, the estimated average horizontal illuminance for all workstations was roughly 570 lx with some workstations receiving almost 800 lx at the task plane. All workstations received at least 300 lx at the horizontal calculation points, which is the IES recommended light level for office applications. Changing the CCT of the luminaires resulted in relatively small differences in estimated horizontal illuminance; these differences can likely be attributed to the variation of SPD for each CCT condition within the bounds of the photopic sensitivity function as well as the raytracing method used by ALFA.

The CCT conditions for the electric lighting system had a greater influence over the EML values predicted for the vertical calculation points. Average EML ranged from 170 to 235 m-lx for the three CCT conditions with EML values increasing as CCT increased. The results of the ALFA simulations, (Figure 13), suggest that it is difficult to achieve the recommended EML thresholds with a typical overhead electric lighting system alone. Meeting the 275 m-lx threshold with electric lighting was only possible for 30% of workstations under the 6200 K CCT condition, despite some desks receiving more than double the horizontal and vertical illuminance recommended by IES.

There was notable variation in the individual EML values possible for the 142 workstations with estimates ranging from 64-316 m-lx. As with the daylight estimates, EML was influenced by the view direction of each calculation point because it is difficult to deliver uniform distribution of electric light in the vertical plane. The location of workstations relative to luminaires, reflective surfaces, or windows will also influence vertical EML, making it important to simulate contributions of electric lighting.

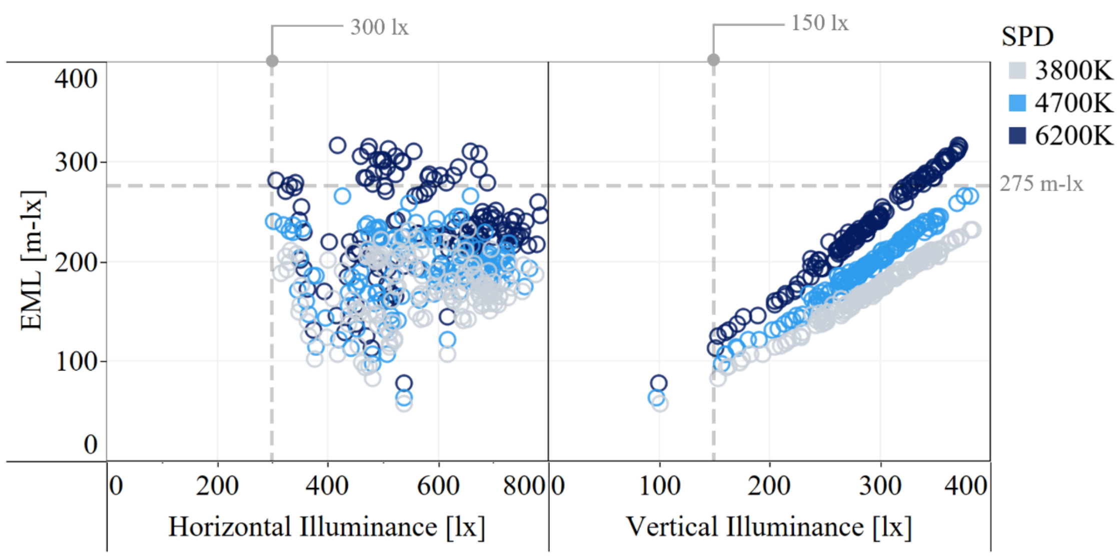


Figure 13. Illuminance and EML results for 142 workstations comparing three CCT conditions of the electric lighting system. Reference lines, in gray, indicate IES recommended horizontal and vertical illuminance levels as well as current daytime EML recommendations for indoor environments.

3.3 Combining Daylight and Electric Light to Meet EML Requirements

Combinations of the four daylight blind schedules and the three electric lighting conditions were simulated to understand the total EML possible throughout the open office and conference spaces as well as the potential energy impacts of designing to meet EML recommendations. Hourly dimming schedules (methods described in Section 2) were used to estimate the energy used by the electric lighting system to meet 275 m-lx at 100% of workstations in each space during the occupied hours. The results of this analysis are summarized in Table 5 (left) and indicate that the electric lighting system will use about 18,600 to 19,700 kWh annually, depending on the blind schedule and CCT condition. The difference between the blinds closed scenarios (least access to daylight) and the IES LM-83 scenarios (controlled access to daylight) is 490 to 683 kWh annually. Changing the CCT of the electric lighting system offered an energy savings of up to 300 kWh. Small differences in annual energy estimates indicate that the electric lighting system is operating at 90-100% light output for most of the occupied hours, despite any changes in the contributions of daylight or changes to the CCT of luminaires.

The $cDA_{EML,275}$ results presented in Section 3.1 indicated that a few workstations along the perimeter of the building receive very little EML contributions from daylight and will dictate what the electric lighting system will do for most of the occupied hours. To explore the energy savings possible with an alternate control scenario, a separate analysis was conducted where workstations with a $cDA_{EML,275}$ below 20% were excluded from the dimming calculations and supplied with a 6-W task luminaire to help meet EML goals (hereafter "alternate scenario considering overhead lighting and task lighting"). This alternate control scenario offers more opportunity to dim the electric lighting system while still meeting the recommended EML threshold at most workstations. Table 5 (right) shows the annual energy estimates for the same daylight blind schedules and electric lighting conditions, estimating a range of about 4,600 kWh between all conditions. The electric lighting system could be operated at an average 75% light output throughout the year, dimming to as low as 50% light output for some hours.

Table 5. Annual lighting energy estimates (kWh) for four blind schedules and three CCT lighting conditions, designed to meet 275 m-lx at all workstations with overhead lighting only (left) and an alternate scenario considering overhead lighting and task luminaires (right).

	Annual Energy Estimates (kWh)					
	3800 K	4700 K	6200 K	3800 K	4700 K	6200 K
Maximum Light Output	19,779	19,779	19,779	19,779	19,779	19,779
IES Visual Req. Only	9,889	9,889	9,889	9,889	9,889	9,889
Blinds Closed	19,687	19,679	19,663	18,133	18,126	17,952
Blinds Open	18,849	18,806	18,573	13,742	13,669	13,519
IES LM-83	19,197	19,161	18,981	14,868	14,701	14,293
DPGs > 0.35	19,082	19,039	18,773	14,373	14,245	13,949

The results of this analysis suggest that meeting 275 m-lx at all workstations in an open office environment can be difficult, even when including the contributions of daylight and high levels of electric lighting. It is important that occupant view direction be considered if daylight is to be used to meet recommended EML thresholds. More strategic implementation of electric lighting through zonal lighting control or task lighting can be useful for meeting 275 m-lx while also balancing electrical energy usage.

3.4 Comparison of Electrical and Thermal Loads

The simulated floor had small annual heating energy use, compared to annual cooling energy, in part due to the small area of the envelope that is exposed to the outdoors; both floor and ceiling were adiabatic. Heating energy ranged from 330 to 463 kWh, which is negligible compared to cooling energy, which ranged from 36,892 to 40,237 kWh. For this reason, we will focus our analysis on cooling and lighting energy. The energy analysis follows the two scenarios: 1) overhead lighting only, and 2) an alternate scenario considering overhead lighting and task luminaires as described in Section 3.3. Figure 15 shows energy use for the two lighting scenarios and cooling energy as a function of different shade controls. The percentages shown on top of each bar indicate the percent change compared to corresponding energy use under IES LM-83 strategy.

First, consider the lighting scenario of 4700 K using overhead lighting only. Compared to a baseline using IES LM-83 shade control strategy, the DGPs > 0.35 or blinds open strategies slightly reduced electric lighting energy (by 1-2%) but increased cooling load by 2-5%. Among the four strategies shown in Figure 15**,** these two strategies used the highest total cooling and lighting energy. On the other hand, the blinds closed strategy increased lighting energy by 3% but reduced cooling load by 4%. This reduction in cooling energy outweighs the increase in lighting energy, resulting in lowest total cooling and lighting energy use. Analysis using 3800 K or 6200 K showed similar results.

Second, for the lighting scenario of 4700 K supplemented with desktop luminaires, the IES LM-83 strategy yields the lowest total cooling and lighting energy use because the reductions in lighting energy – obtained due to the supplemental use of task lighting for occupants with cDA<

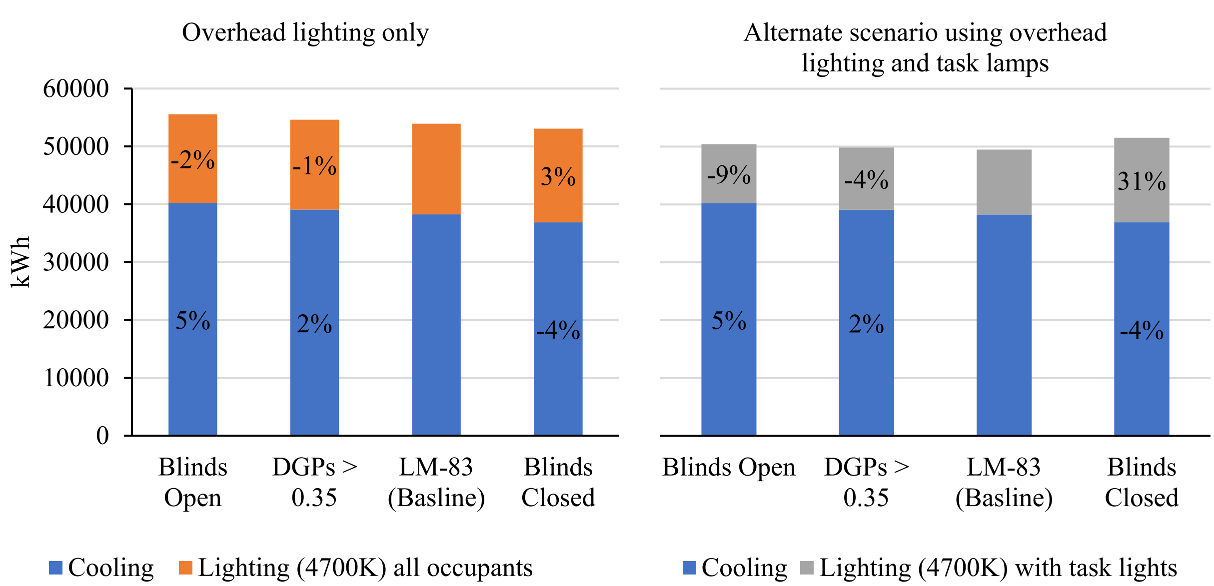


Figure 14: Annual cooling and lighting energy for a scenario with overhead lighting only (left), and for an alternate scenario considering overhead lighting and task luminaires (right). The percentages are compared to LM-83 baseline. Note that cooling energy is the same for both scenarios.

20% – outweigh the slight increase in cooling energy, compared to the blinds closed scenario. Analysis using 3800 K or 6200 K showed similar results.

These results suggest that 1) any adjustments made to shade control to increase circadian lighting contribution from daylight and reduce electric lighting energy should also consider the thermal implications; 2) for the scenario considering all occupants, cooling load is predominant and there were negligible savings from electric lighting regardless of the shade control strategy; 3) the use of supplemental task lighting for occupants that receive low daylight allows for larger reductions in electric lighting energy use and better incorporation of daylight, compared to varying shade controls. Under the LM-83 scenario, the use of overhead lighting supplemented with task lamps reduces lighting energy by 28%.

4 Conclusion

This report estimated the annual electrical and thermal energy loads of a medium office building designed to meet the circadian lighting metric recommendations by Brown et al. (2022) using a combination of four daylighting control scenarios and three electric lighting control scenarios. Several key results of this investigation are summarized below.

- Vertical illuminance and EML are heavily influenced by the view direction and location of the occupant/calculation point relative to daylight or electric light sources. EML estimates ranged from 64 to 316 m-lx between the 142 workstations under the same electric lighting conditions, highlighting the challenge of unform light distribution in the vertical plane.
- Meeting the recommended 275 m-lx threshold with electric lighting was only possible for 30% of workstations under the 6200 K CCT condition, despite some desks receiving more than double the IES recommended horizontal illuminance.
- The $cDA_{EML,275}$ results suggest that for many workstations along the perimeter, daylight can provide the recommended 275 m-lx for most of the occupied hours throughout the year. This is not true for all perimeter workstations, however, as those that may be relatively close to a window (within 10 ft) but facing into the interior of the building received very limited daylight at the vertical view plane. Mapping $cDA_{EML,275}$ across the floorplan is helpful for understanding the impact of workstation view direction on resulting EML levels.
- For a typical daylight control scenario with blind control (LM-83), supplementing an overhead lighting system with task luminaires reduced annual lighting energy use by 28%.
- Daylighting strategies aiming to increase daylight levels at the eye should consider the implications on electric lighting, cooling, and heating energy. The analysis showed a

tradeoff between cooling and electric lighting energy. This is important to consider given that circadian lighting design is likely to become a factor that informs the control of shading systems as well as overhead lighting.

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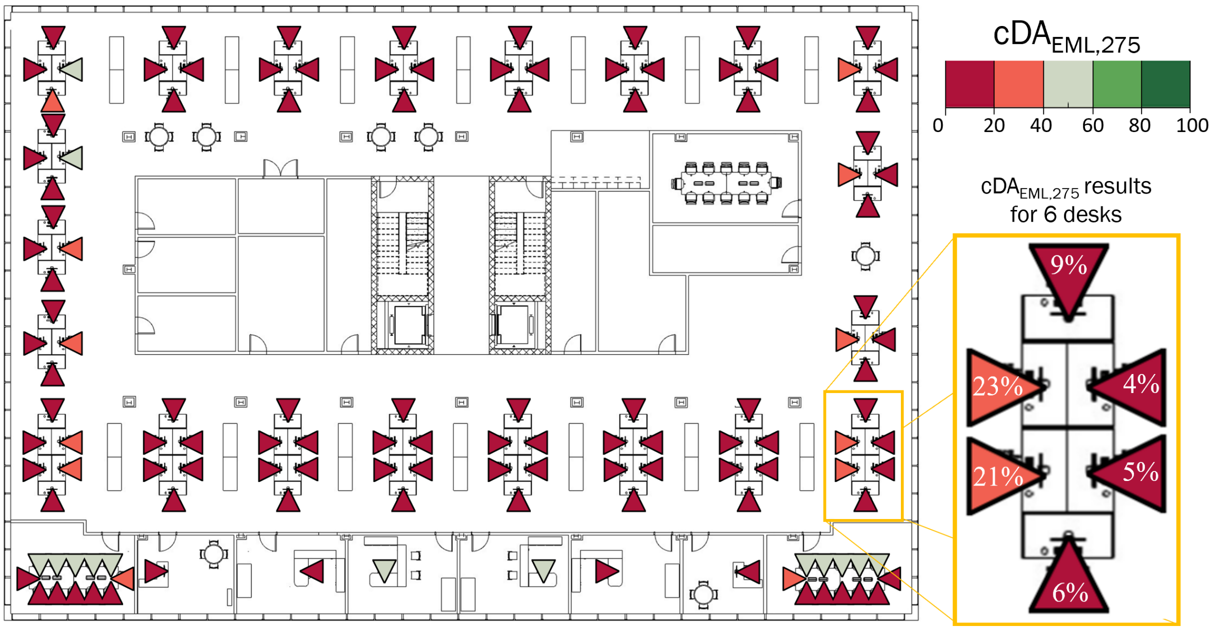
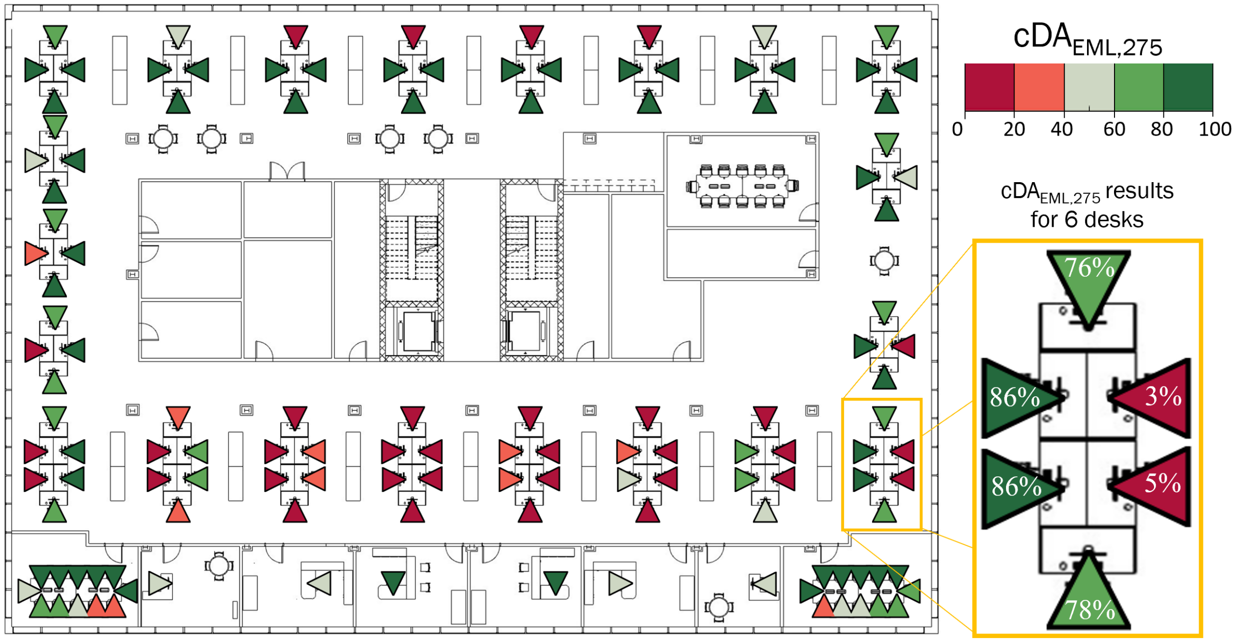
6 Appendix

Continuous daylight autonomy (cDA$_{EML, 275}$) results based on an equivalent melanopic lux (EML) threshold of 275 m-lx during the occupied hours. Results are presented per blind schedule. Each arrow corresponds to one of 130 vertical calculation points that had access to daylight and the direction of the arrow indicates the direction of view. The five-point color scale is used to report cDA values in 20% intervals. Red arrows indicate calculation points that get minimal EML contributions from daylight while green arrows indicate calculation points that get enough contribution from daylight such that little supplemental light is needed to meet 275 m-lx for the occupied hours.

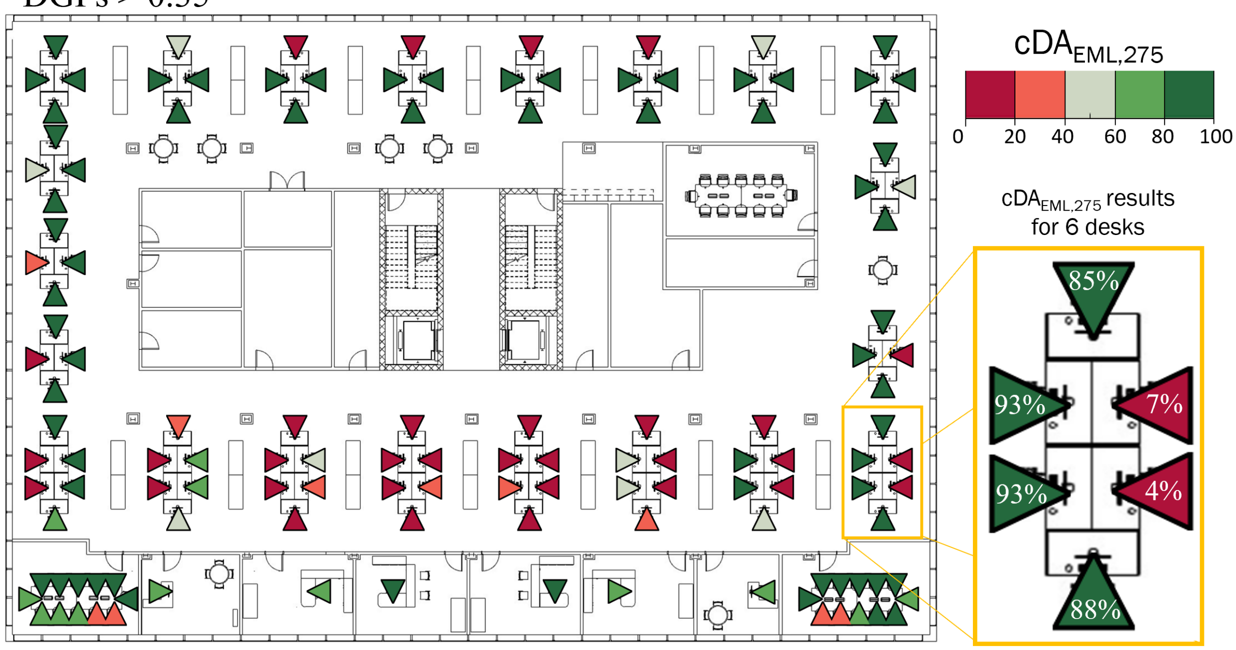
Blinds Closed



LM-83



DGPs > 0.35



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PNNL-33424 • February 2023