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DAYLIGHTING AND ELECTRIC LIGHTING:

SYSTEMS INTEGRATION

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Abstract

This scoping study sets the stage for transforming the design and implementation of integrated lighting systems (daylight and electric), and thereby helping to achieve long-term objectives in energy savings goals established by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). While integrated lighting systems may reduce building energy use, a broader network of non-energy benefits affecting overall health, comfort, and satisfaction of building occupants may also influence technology investment objectives when considering the entire lifecycle of the built environment. Lighting systems in today's typical buildings are disconnected from other systems and their control mechanisms. Being disassociated from the inputs and outputs of those systems, and unable to capture and capitalize on the information those systems gather, prevents realizing the dynamic nature of holistic human responses to light inside buildings. In the future, lighting in new and existing buildings must be adaptable throughout the course of a day to changes in the quantity and quality of daylight, information flows throughout a building's connected systems, changes in the requirements for optimal lighting for occupant comfort, health, and well-being.

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EXECUTIVE SUMMARY

This scoping study sets the stage for transforming the design and implementation of integrated lighting systems (daylight and electric), and thereby helping to achieve BTO's long-term objectives in energy savings. In this context, daylighting systems are the active and static building envelope components (transparent and translucent glazing, coatings and light redirecting films, active and static attachments[1] installed internally and externally), including skylights or other elements that bring light to the building interior; electric lighting systems are the active and static sources (lamps, fixtures, luminaires, and sensors and controls), that supply light to the building interior. The study explores the breadth and depth of professional and industry practices, dissemination pathways, and research thrusts that are needed to address how next-generation technologies for these systems should be connected, integrated, and optimized for future buildings and their resilience to short- and long-term change, and how the information and practices necessary for successful implementation are communicated up and down the chain of responsible professions and industries. While integrated lighting systems may reduce lighting energy use in office buildings by greater than 200 TBTU relative to a 2030 baseline condition of 260 TBTU, a broader network of non-energy benefits affecting overall health, comfort, and satisfaction of building occupants may also influence technology investment objectives when considering the entire lifecycle of the built environment.

Lighting systems in today's typical buildings are often disconnected from other systems (e.g. demand response, HVAC, and energy management control systems) and their control mechanisms. Daylighting systems are disconnected from electric lighting systems, and both are typically disconnected from other mechanical, electrical, plumbing, safety and security, and information systems to name the most common. As a result, electric lighting systems are often unresponsive to available daylighting (and are static[2] in intensity, spectrum, and distribution), and transparent facade elements would be hard pressed to be described as daylight systems, as they are unresponsive to bioclimatic design influences. These systems are rarely integrated with each other, let alone the suite of other systems in contemporary buildings. Being disassociated from the inputs and outputs of those systems, and unable to capture and capitalize on the information about occupants, environmental conditions, and systems status, prevents realizing the dynamic nature of holistic human responses to light inside buildings.

Why is this important? The average American spends nearly 90% of their time indoors, and, as a result, their health and well being are being impacted by no greater influence than where they spend their time.[3] It has also become evident that we are in a time of significant change and uncertainty, not the

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[1] [Façade] attachments are products installed either internally or externally on a [building façade] that can serve a variety of purposes including: adding to the room aesthetic, protection, enhanced view and natural light, reducing draftiness, lessen glare and heat from the sun, or privacy. (https://aercnet.org/resources/window-attachments/)

[2] As of November 2018, all but nine states and two U.S. territories require that new construction meets or exceeds ASHRAE 90.1-2004, which requires, at a minimum, automatic shutoff of lighting in commercial buildings greater than 5,000 square feet in size, with few exceptions.[http://bcapcodes.org/code-status/commercial/]

[3] Indoor Air Division prepared by U.S. Environmental Protection Agency Office of Atmospheric and Indoor Air Programs, Office of Air and Radiation, and Office of Research and Development, *Report to Congress on Indoor Air*

least of which is the uncertainty of how our typical buildings will respond to significant changes to external environmental conditions during extreme weather events, and the impact those weather events may have on the ability of our buildings to operate in the manner in which they were intended - typically relying on massive quantities of off site energy supply. In the future, lighting in buildings (new and existing) must be adaptable throughout the course of a day to: changes in the quantity and quality of daylight; to information that flows throughout a building's connected systems; and, changes in the requirements for optimal lighting for occupant comfort, health, and well being.

For over three decades researchers, practitioners, and industry have been working on integrating daylighting with electric lighting systems. These efforts have primarily emphasized energy savings and demand reduction in buildings, and have focused on optimizing the type of control with the application.[4] For thirty years, it has been estimated that controlling electric lighting in response to available daylight has the potential energy savings of 50-80%.[5,6] Despite the magnitude of these potential savings, successful integrated solutions are rarely implemented, and actual savings remain disappointingly disconnected from the estimates. "Post-occupancy studies carried out in real buildings have shown that the actual energy performance is invariably markedly worse than that predicted at the design stage." (Mardaljevic et al., 2009). In the decade since this study little has changed. Clearly this is not a new problem, but the convergence of several scientific and technical trends potentially increases the value proposition, and the chances for success, in realizing fully integrated lighting systems design and implementation. There are significantly improved capabilities for modeling the behavior of light in spaces. Spectrally tunable solid-state lighting (SSL) is available. Internet-of-things connectivity is maturing - making building systems capable of real-time data exchange. And sensors and controls technologies have advanced (including better performance, smaller size, and lower costs). In addition, there is growing scientific evidence of the importance of light on human health and well being, and these technical advances should be seen as supporting the design and delivery of the appropriate type, quality, and quantity of light to building occupants.

The myriad gaps, fractures, and discontinuities in today's daylighting and electric lighting systems research, design, implementation, and operation are identified in the following pages. While this document is not intended to be a living document, it will have several refinements and evaluations by industry partners and experts within the national laboratory ecosystem through dissemination at workshops and other meetings. It is intended to be a jumping off point for capturing R&D priorities as defined by stakeholders during dissemination efforts. This will include developing an understanding of

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Quality. : Volume 2. Assessment and Control of Indoor Air Pollution. (Final Report) (Washington, D.C. : U.S. Environmental Protection Agency, 1989., 1989), https://search.library.wisc.edu/catalog/9910010319702121.

[4] M. Alrubaih et al., "Research and Development on Aspects of Daylighting Fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505, https://doi.org/10.1016/j.rser.2012.12.057.

[5] Francis Rubinstein, Michael Siminovitch, and R. Verderber, "Fifty Percent Energy Savings with Automatic Lighting Controls," *Industry Applications, IEEE Transactions On* 29 (August 1, 1993): 768–73, https://doi.org/10.1109/28.231992.

[6] Magali Bodart and André Herde, "Global Energy Savings in Offices Buildings by the Use of Daylighting," *Energy and Buildings* 34 (June 1, 2002): 421–29, https://doi.org/10.1016/S0378-7788(01)00117-7.

why the energy savings potential from lighting systems has not been fully captured (e.g. is it a modeling, implementation, or commissioning problem, or some combination thereof). The structure of the document is divided into two primary sections. The first explores and describes the industry and professional practice and the continuing education and standards that are necessary for keeping these sectors aligned with the most recent research. The second is a description of the current state of state and future research needs for both daylight and electric lighting systems.

Finally, a general note about research needs described throughout the document. Each of the sections has a set of research needs that have been identified throughout the process of creating this document. This process has included workshops and informal surveys of stakeholders. It has been, by no means, fully comprehensive. In addition, overall priorities, coupled or linked needs, stakeholder interdependencies, and detailed timelines have not been refined. This refinement will take place during a series of stakeholder engagement sessions.

PART1 - SECTION 1: Institutional and organizational inertia working against integration of the day- and electric lighting systems.

There are persistent and wide gaps in professional knowledge and skills regarding appropriate design of lighting systems (electric and daylight) and solar control within the architectural, engineering, and construction (AEC) community. These gaps are only getting wider and deeper as requirements to achieve high performance design become increasingly complex. More detailed simulation requirements, convoluted systems hardware and software interactions, tangled code requirements, cumbersome design team organization, smaller budgets for design, and shorter timelines for construction, make addressing systematic inertia abstruse when viewed through the lens of a single profession or building system.

Professional ecosystems are fatigued by demands to do more with less, and the ambiguity of system performance and costs. Well intentioned design teams are frustrated by their ability to understand the actual performance of their designs without the proper validation of software and commissioning of completed projects. The patchwork of standards, codes, guidelines, and recommendations are inadequately curated, and trust between professions and industries atrophies in the absence of transparency. Current industry conditions make integration of day- and electric lighting systems in new buildings onerous, and virtually impossible in existing buildings. Recommendations from design practitioners and industry are to separate these systems as the controls technologies are proprietary, incompatible, and have little standardization, making current best practices supportive of disentangling lighting and shading controls new buildings (and a necessity in for existing buildings), rather than integrating them. While each of these issues are real, they do not exist in all projects for all teams. Professionals across the entire building design, construction, and occupation ecosystem are enthusiastic for higher performance (and more fully integrated), buildings, however, there are significant barriers to achieving this, including validation of savings and the persistence of contracts for design, construction, operations and maintenance that thwart holistic and long-term solutions. In addition, there is interest in the AEC community in developing a prioritization of R&D and implementation efforts to maximize traditional energy savings and leading edge non-energy benefits impacts based on an evaluation of where buildings are located, and what building types are in greatest need of improvement.

Professional and Continuing Education and Standards needs

- Improve basic education among professionals about day- and electric lighting systems;
- Develop commissioning standards for daylighting systems, and standardized education of commissioning agents;
- Create guidelines to ensure building codes are successfully implemented - from design teams to contractors to code inspectors, to reduce uncertainty in the design-construction-occupancy process;
- Develop standards for sensors and sensor locations for best controls, especially whether daylight controls and electric light controls are parasitic or integrated,
- Develop interoperability standards to address disaggregation, decentralization, and device specific controls for light systems;
- Improve functionality of interchangeable file formats for design and construction documentation and performance simulation;

- Better models for return on investment and simple payback calculations for advanced lighting control systems (ALCS);
- Validation of non-energy benefits of ALCS and impact on return on investment timeline;
- Investigation of lease structures and design and construction contracts to prevent split incentives negative long term impacts of value engineering on the selection of resilient and integrated systems.

PART 1 - SECTION 2a: Summary of Current Glare, Electric Lighting, & Daylighting Systems Literature

The literature summary was completed for the purpose of developing a more robust understanding of the current topics of research being performed by researchers at national labs and academic institutions, in professional design and construction practices, and industry. It was not intended to be, nor was it conducted as, a traditional literature review. Rather, it was viewed as a vehicle for more completely understanding the larger picture of research topics, dissemination channels, and the language used by researchers to describe their work. There is, of course, a long history of research that addresses issues of daylight and electric light systems, as well as subtopics within those fields of study. Performing a large-scale literature review of that history was not in the scope of this effort. Additionally, as an effort to understand where there are opportunities for creating a more integrated approach to the research, design, implementation, and operation of these systems, the literature evaluation was performed as a non-expert might, when unraveling the complexity of these topics.

The quality and quantity of research being undertaken at National Laboratories, in higher education, and industry is remarkable. However, in an evaluation of the dissemination and absorption of this research into professional and industry best practices, it should be noted that current dissemination pathways for this research have a narrowly focused audience. Each stakeholder group tends to focus their research and dissemination within that group's network of peers. This is an understandable process, but has its shortcomings with respect to reaching audiences outside those networks. Academic research is typically consumed by academics, industry white papers are focused on that industry's stakeholders, design and construction practitioners read about best practices in their professions. This is not to say there are not examples of cross disciplinary and cross stakeholder group work being performed and disseminated. Rather, it is an observation that additional thought is needed in the R&D process to understand why there are gaps in implementation. This should be inclusive of evaluating approaches or models to the lifecycle of R&D – from conducting basic research to understanding implementation methods that are most likely to impact professional and industry best practices. This can be extended to include better descriptions of methods presented in research articles and papers, and the tools and technique used during the research process.

Professional and Continuing Education and Standards needs

- Evaluation of publication and dissemination plans for research outcomes that proactively address the question of a target audience, and ensure the target audience is reached in the appropriate manner;
- Verify that leading edge work is consistently and appropriately moving from research to application through the development of R&D planning that targets specific impact (e.g. applied R&D);
- Develop a standard for what constitutes a minimally acceptable number of human subjects for reliable results, and transparency and clarity differentiating the number of human subjects and the number of responses to different instruments in research projects.

PART 1 - SECTION 2b: Voluntary Standards Review

There is no national building code for the United States, and, as a result, there is a chaotic network of codes for each state in the U.S. With this context in mind, an evaluation of voluntary standards could be viewed as a proxy for highlighting areas of increased emphasis on R&D outcomes, applied research, and development of professional education. This review was intended to evaluate the outcomes of voluntary standards on the coordination of building lighting systems in general. The LEED certified projects evaluation was undertaken to understand the degree to which lighting systems integration is taking place in buildings designed with voluntary standards for improved performance. LEED was the voluntary standard chose because it is the most widely used green building rating system in the world,[7] with over 140,000 projects registered or certified around the globe. Of those projects 451 projects[8] certified under standard version 3.0, LEED 2009 were evaluated to understand the degree to which projects across all certification levels were receiving credits for lighting systems (daylight and electric lights) and to what degree those projects were in a position to integrate those systems with other building mechanical, electrical, or plumbing systems. It should be noted that voluntary standards and rating systems can create situations where elements of the building are designed and constructed for the purpose of achieving specific points. This may lead to elements and building systems that are not well integrated into the overall project.

Professional and Continuing Education and Standards needs

- Understanding alignment of voluntary standards with state building codes and level of third party certification in various states by: Owner and Project Types, Organization, GrossSqFoot
- Investigation of overall rates of controllable[9] systems incorporated into high performance buildings; including evaluation of controllable systems by: State; Owner and Project Types, Organization, GrossSqFoot
- Evaluation of role of controllable systems in the design process and parameters used to determine whether inclusion in the final building design, and how this can be fostered by including supportive criteria in voluntary standards.
- Development of partnerships to examine best methods for increasing market penetration of controllable systems, in order to realize goal of increasing utilization of integrated lighting systems and their controllability.

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[7] "LEED Green Building Certification | USGBC," accessed December 19, 2019, https://new.usgbc.org/leed.
[8] The 451 projects including the following count: 112 Certified, 111 Silver, 114 Gold, and 114 Platinum. In order to catalogue at least 100 projects in each certification category it was necessary to access more than that number as not all certified projects have a completed scorecard accessible.
[9] The USGBC defines "controllable systems" for both lighting systems and thermal comfort systems (NC-2009 IEQc6.1: Controllability of systems – lighting, and IEQc6.2: Controllability of systems - thermal comfort respectively) through the intention supporting the credit. In both cases the intent is to: "Provide a high level of… system control by individual occupants or by specific groups in multi-occupant spaces (i.e. classrooms or conference areas) to promote the productivity, comfort and well-being of building occupants."

PART 1 - SECTION 2c: Critical information to lighting systems integration case studies

Case studies are critically important to the design and construction professions. The information gleaned from these records are valuable for understanding how best practices are, or are not, successful in achieving project goals and objectives, and how well research outcomes are impacting the performance of buildings. Current high performance buildings case studies form a solid backbone, but there are additional elements that would provide better depth and understanding of projects. Case study creation does tend to be limited to exceptional buildings, which is understandable given time and budget constraints. What these miss, however, is the benefits to furthering individual and collective understanding of industry practices and individual design impacts on meeting performance goals. The act of preparing a case study provides benefits to the preparer at least as much as to the eventual audience, but without the advantage of reaching that broader audience. Incentivizing preparation of case studies more broadly could be beneficial, even if they are not all outward facing. Establishing baseline criteria for case studies that include design and performance metrics, team organizational graphics, and contracts examples would be extraordinarily helpful, in order to better understand the specifics of the integration of daylighting and electric lighting systems, as well as the integration of lighting systems with other building systems. Additionally, integrated lighting in general, and specifically connected lighting, create additional streams of building data, thus greatly expanding the available data for case study projects.

Professional and Continuing Education and Standards needs for Case Studies

- Comprehensive descriptions of general project information including project team details and an overall design process and building description highlighting specific lighting systems integration efforts;
- Comprehensive descriptions of sustainability goals, historic preservation goals, and design for accessibility, and how lighting systems integration is included and impacted by these goals;
- Comprehensive descriptions of cost effectiveness goals, functional project goals, and productivity goals, and the influences of lighting integration on the outcomes of these goals;
- Comprehensive descriptions of construction activities, operations & maintenance activities, and post-occupancy evaluation activities, specifically those that directly apply to the integration of lighting systems into the project;
- Comprehensive descriptions of the information and tools used by the team, products and systems, energy issues specific to the project, the indoor environmental quality issues specific to the project, and the results specific to the project as they address the means and methods used to integrate lighting systems, and manage their long-term integration and performance.

PART 2 - SECTION 1: Visual comfort in buildings

The human visual system is able to adapt over time to a wide range of luminances, but can adapt to only a limited range of luminances at any given point in time. If the luminance range is too great, regions of the scene that are of excessively high luminance can lead to discomfort. Discomfort from glare is not well understood, and there is still no agreed model for predicting the likely presence and severity of discomfort. Furthermore, the metrics used for characterizing discomfort glare differ for daylight sources than from electric lighting sources, and the methods used for measuring both the glare-causing stimulus and the human responses vary widely.

Metrics for discomfort glare are universally based on a determination of the contrast between the luminance of the glare source and the luminance of the background to the glare source, but many different expressions have been used for computing metrics of discomfort glare. None of the glare metrics account for the spectral power distribution of the glare sources. The lighting industry has mostly settled on using the Daylight Glare Probability (DGP) metric for glare from daylight and the Unified Glare Rating (UGR) metric for glare from electric light sources.

Research Needs

- Explorations of using physiological and other measures of glare response to assess their convergence with more traditional psychophysical measures;
- Experiments to assess the alignment of the current metrics (DGP, UGR) with human responses to glare;
- Validation studies of measurement and simulation tools used to determine glare metrics to evaluate the sources of error in capturing the different elements of the metrics (luminances, geometry, size, etc.) and the impact of those errors on the metrics;
- Research towards a new glare metric based on human visual science that addresses discomfort from daylight and electric lighting systems in complex scenes;
- Exploring and delineating discomfort glare research methods that are suited for integrated daylight and electric lighting scenarios;
- Developing models for integrated lighting system controls that address energy use and visual comfort.

PART 2 - SECTION 2: Non-visual effects of lighting and possible impacts on human health

Research exploring human physiological responses to light and continued advances in SSL technology have aligned with an increasing demand for healthier buildings by building owners and occupants, including greater access to daylighting. The renewed focus on health, along with advances in SSL technology capabilities, has underscored that there is still much to learn regarding the relationship between light and human physiology. The energy implications of designing to address these possible physiological effects are not yet fully understood, but the close coordination of a tunable SSL lighting system with an integrated façade (which may include adjustable factors in glazing and shading) can enable optimization of the related energy uses.

As daylight and integrated facades designed for better daylight delivery introduce many variables into the modeling process, especially when it is desirable to account for the full spectral effects of these variables, accounting for daylight contributions can quickly add complexity to simulation models and increase the computation time. Furthermore, simulation tools have not been fully validated for this type of simulation work; simulations of physical spaces where confirmatory measurements can be taken are needed. Considering a wide range of luminaires with different form factors and color mixing strategies from different manufacturers will provide a more comprehensive non-visual metric investigation.

Research Needs

- Managing the required computation time for simulations that address the full range of daylighting-electric lighting conditions will require some documentation of the possible errors introduced by simplifying assumptions that might be needed for faster computing.
- Luminaire distribution, output, and SPD setpoints research that explores the range of errors introduced into simulations through simplifying assumptions is an important element.
- Develop more thorough consideration of building and space types along with climate effects is needed for potential national energy implications on the entire US building stock, along with the relative importance of the non-visual effects of lighting within different building types.
- More complex existing or theoretical SPDs: Access to spectral modeling tools makes it possible to vary model parameters to include theoretical SPDs that may not exist in commercial products.

PART 2 - SECTION 3: Integration of Hardware & Controls for Day- and Electric Lighting Systems

The hardware and software of daylighting and electric lighting systems have been, to date, mostly separate entities. This means there is a need for interoperability protocols development addressing facade and electric lighting controls. These algorithms are necessary for day- and electric lighting systems to manage the complexity of maximizing comfort, minimizing energy use, achieving reliable interoperability, and sustained operations and resilience to short and long-term changes. Sensing research needs include accurate prediction of workplane illuminance when sensors, or sensor networks, are usually placed remotely from the workplane or for support of other systems. The sensors and sensor networks themselves need the development of protocols that establish the appropriate levels of interaction required between electric and daylight systems controls – from fully integrated to opportunistic / parasitic. There is research required to evaluate cost-effective hardware for ubiquitous Spectral power distribution (SPD) sensing and effective sensor density and placement, determining effective sensor density and placement *per se*, implementing non-research-grade commissioning, and establishing the appropriate wavelength resolution and accuracy of sensors. Market potential research for systems integration is needed to evaluate differences between new construction vs. retrofit, space and building types (including those specific to federal government applications), regional variations in climate and other factors, and the impact on building resilience to environmental, power-supply or other disruptions. Other research directions include exploration of neuromorphic sensors that enable lighting systems to adapt to dynamic facade systems on the spectrum of daylight.

Research Needs

- Development of interoperability protocols for day- and electric lighting integration;
- Accurate work plane illuminance sensing for lighting and facade controls, including interaction and/or integration with other building systems based on their use of occupancy sensing for controls;
- Spectral power distribution (SPD) sensing, including characterizing and monitoring changes in the light output and SPD of SSL sources over their lifetime;
- Identifying potential market for electric lighting and facade integration, demonstrating value, non-energy / co-benefits of facade and electric lighting integration;
- Best control approaches for integrating electric lighting and facade, including consideration of model-predictive control techniques, sensor networks, and sensor sharing between systems;
- Hardware and software strategies are needed to simplify the installation, commission and O&M of controls to overcome complications created by bringing together already complicated systems;
- Research to enable systems to self-detect faults and operational issues and then self-correct and/or report to facility management to minimize need for facility management intervention and allow for future additions

PART 2 - SECTION 4: Simulation and Software for Integration of Day- and Electric Lighting Systems

There are a wide variety of software packages that are used to predict light distribution and intensity within the built environment. These software packages span a broad spectrum in terms of speed, ease-of-use, and accuracy, used at various stages of design. Simulation software is used for modeling at a detailed level, and the two most widely used algorithms are ray-tracing and radiosity; this software needs to be validated so that it provides accurate results for the wavelengths of daylight relevant to the non-visual effects of lighting, in addition to the accurate calculation of photopic photometric quantities. Input data commonly available for lighting simulation software - sky models, optical properties of materials, light source/luminaire characteristics - are oriented towards the computation of photopic photometric quantities, these need to be extended to encompass a fuller range of spectral data, in addition to understanding the appropriate amount and accuracy of spectral data. Development is needed of of early- and mid-design decision tools that allow quick modeling. This should start with existing tools focused on early facade design decisions, and extend to more extensively address the interactions between facades and electric lighting would facilitate design workflows for integrated facade and electric lighting systems. Development of ability to tailor tools, and their outputs, to the needs of various industry professionals as different audiences increasingly seek to justify decisions with data. Development of simulation tools that are more intuitive without losing accuracy. Substantial work remains to be done in both educating practitioners on the available software tools, their application, and successful integration into industry practices.

Research Needs:

- Software validation to ensure accurate simulation throughout relevant parts of the spectrum of daylight;
- Input data for lighting simulation software encompassing a fuller range of spectral data;
- Research on the appropriate amount and accuracy of spectral data; (source? Materials? both
- Development of tools for quick modeling for early- and mid-design decisions;
- Substantial work remains to be done in both educating practitioners on the available software tools, their application, and successful integration into industry practices.
- Development of ability to tailor tools and outputs;
- Development of simulation tools that are more intuitive without losing accuracy

-- no mention of optical properties –BSDF- especially for glare??

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PART 1 - SECTION 1: INSTITUTIONAL AND ORGANIZATIONAL INERTIA WORKING AGAINST INTEGRATION

There are pathways to integration for day- and electric lighting systems throughout the lifecycle of a building project. The design, specification, distribution, and installation of these systems hold sticking points where the integration of electric lighting and daylighting systems can be hampered. For new construction, in many cases the project size is what determines how much daylighting and lighting design is performed in-house (under the current design fee and timeline), with the possibility of some coordination with engineers using basic geometry of building for use of natural light (daylight controls for glare, internally, in coordination with passive daylight control), larger projects (with larger budgets and longer timelines) will use external consultants to create design and analysis with a greater level of detail and accuracy. For existing buildings, there are utility incentives for advanced controls for the retrofit market. However, this market lacks coordination, as each state, region, and utility sets its own priorities, and depend on how the state public benefits programs are operating. In some cases paying incentives on a per bulb or per widget basis. These programs do not take into account design and time-based impacts. It is known that advanced controls are better, but fully integrated models for calculating savings are rarely performed below a certain project size or type.

Design Practice

The current state of architectural practice is experiencing fractures and industry upheaval on a number of levels. There are wide gaps in professional knowledge and skills regarding appropriate design of lighting systems (electric and daylight) and solar control. (Solar control devices are included here, as they are relevant to the control of light, and they are part of the façade systems which must be integrated with daylighting and electric lighting systems.) Design professionals (in architecture) are operating on low design fees and rapid turnaround for projects, leaving little available budget and time to properly design lighting systems in isolation, let alone to adequately integrate the design of those same systems. Architectural design professionals in most practices are designing electric light and daylight systems based on rules of thumb. These rules of thumb are a combination of office standards, that have been implemented based on individual practitioner knowledge, from voluntary standards and guidelines, and from building codes. Rules of thumb are often applied manually through calculation of window opening to floor area ratios and window head and sill heights. There is little to no simulation occurring in most small to medium projects.

Project Development

In the development community, organizations prefer to work with a small set of architecture, engineering, and construction professionals in the development of new projects and the acquisition of existing buildings. Large firms have a national presence and can provide competitive pricing. When they cannot, those costs are outweighed by their ability to manage large, and complex, projects, and the benefits that familiarity brings. Their size gives them a wider perspective and greater depth of knowledge from which to draw for any individual project, even when working with local subcontractors with specific local knowledge that is advantageous to the project development. Building systems, in the development community, are left to the design team. Developers trust their design team to make responsible decisions based on the requirements of an RFP or contract, and within the budget and scope of the project. In general, design teams are big proponents of LEED, EnergyStar, and other third-party certification programs, as well as any new requirements to make higher performing buildings. On both the investment side and development side developers rely on the design team to drive the optimization of systems. However, in the development of new construction the big driver for building performance comes from client side – unless the client demands it, it is likely not to be included in a project. In the example the General Services Administration requirements for LEED certification, the inclusion of high-performance systems is a simple costing question for the design and development team. There is a significant difference between how industry addresses new and existing buildings, as the ability to create integrated systems and sophisticated solutions becomes limited by the *in situ* conditions for existing buildings, here a preference is for a light touch – relamping of existing luminaires, simple interior attachments, and basic controls.

Construction Specifications Documents

Construction specifications are a critical path toward integrating lighting systems. Without this critical element of contract documentation, integrating those systems is unlikely to be well coordinated or successful. As an example: in the design process for solar and glare control, one design firm described the specifications process for motorized blinds to ensure adequate controls for comfort and energy performance. In their example scenario specifications and project meeting minutes are used in conjunction to prevent unintended loss of glare and solar control through late client directed design requirements, such as when the design of the glazing system and area prevents solar and glare control through other means. This case triggers the inclusion of automated blinds as a design requirement. This added system of component hardware and controls adds first cost to the project, and is at risk of being removed without consideration for its energy and comfort impacts. Value engineering is devastating to project performance when value and cost are thought of as the same thing, in order to prevent value engineering mistakes, meeting minutes are created to for the purpose of ensuring that the motorized blinds cannot be removed without triggering design changes to replace their performance impacts. Specifications for sensors (e.g. occupancy and ambient light) are included in these requirements in order to ensure system operation and integration at the design stage.

Installation and Commissioning of Systems

Installation of lighting integration systems in small- to medium-sized projects are typically not occurring, as these types of projects are also not using building management or energy management systems. For this scale of project, when a high-performance design is undertaken, it is necessary to rely on the MEP contractor to properly zone lighting and controls systems, and to ensure those systems are carefully controlled with regard to those zones. At this point in time, due to the absence of a recognized standard for controls, daylight and electric light controls systems are simply being layered on top of each other. In order to overcome this absence, making controls work is necessarily part of the design process for building, especially as advanced lighting control systems are increasing in complexity (and controls systems are becoming more chaotic). Without a common standard (and in the absence of a regular industry design practice) current industry recommendations for control systems have leaned toward separate systems for electric light controls and daylight controls, in order to avoid this complexity.

From the developer’s perspective, project specifications and third-party certifications contract requirements are left to the contractors to meet. From a project cost perspective, adding solar photovoltaic panels (PV)is more viable and represents a lower cost, higher savings potential, and is more plug and play, than daylight controls. Robust commissioning is absolutely necessary if controls systems are expected to work at all, as daylighting controls are too fussy (and either do not work at all, or break down quickly). However, commissioning of daylighting controls systems is a skill set that is not being developed, proprietary controls systems dominate, and interoperability with other controls systems is lagging. Commissioning is expensive and often skipped even in proprietary systems as it is not included with the system itself. Open-source systems are good, but proper management and funding are needed for them to remain viable.

Design Simulation Tools

There are a variety of simulation tools being used to perform both in-house design analysis and external consultant led analysis. These rely on having a base file that is transportable and depends on the size of the firm and the project type. In many cases, each type of design analysis is using a different software, (e.g. e-quest energy modeling, DOE2 model for utility incentives, DIVA model for daylight penetration, lighting and lighting controls design). For smaller architecture firms, with clients interested in high performance buildings, the design processes might include the development of an EnergyPlus model, and the use of Safira or DIVA to model daylight availability. The degree to which this type of work is performed depends on the project and client type, the in-house skills of the design team, and the time and budget available to perform the work. When it is done in-house it is not as high quality as the work prepared by top of the line engineering or sustainability consultants.

In the high-end lighting market (both residential and commercial) there is more attention paid to the aesthetics of the electric lighting design, and therefore it is more likely there will be detailed rendering and simulation of the electric lighting system by a specialized lighting designer. Lighting designers may be unable to use digital models or drawings directly from the core architectural and engineering design team. The lighting design team may need to recreate portions of the project from the bottom up (or the entire project) based on the extent of the design services they are providing. This additional layer of model building occurs as a result of the differences in purpose for the creation of a 3D model (BIM or other) by the design team.

Commercial Buildings Integration and performance simulation technology deployment are critical for educating designers about the available software tools created by national labs. The variety of free software programs currently available through national laboratories, universities and non-profit organizations[10] have been instrumental in supporting performance analysis within small practices, where there is often not scope or fee earmarked on projects for support of high-performance design. They are simple, easy to use, trusted, and powerful. However, there are IT departments, in the design professions, restricting the acquisition and use of programs with macros that could potentially be dangerous. Currently AEC design team members, in general, have discretion as to what programs they use and how those programs are obtained. Those from known, trusted sources will likely be viewed differently than third-party software with undeclared sources. However, it may take only one cyberattack on a firm (or ransomware attacks on a firm or similar firms) for this to change for smaller firms to be unwilling to risk using freeware going forward. In addition, it is critical that these software packages are regularly updated to avoid conflicts with new operating systems and other software being

[10] https://www.buildingenergysoftwaretools.com/

used. Small firms, in the future, may simply have to stay away from these applications as they represent too large a business risk.

Available Knowledge Resources

The volume of available references makes it difficult to curate. There are cases where references and information have unknown origin or financial backing, and therefore trust is difficult to establish. Digital databases are particularly susceptible to this condition, as there are reasonable questions about the basis as sources of information available to the database users. Specifically, how is information obtained by the owner of the database? Is it directly from manufacturers, or scraped from a third-party website? Is the database comprehensive of all manufacturers, or is it curated with a special set of manufacturers (e.g. those that pay a membership fees). How is the database maintained? Revenue from advertising, membership fees, sales, etc. Resources created by national labs can have a question of audience – who is the target audience for this work, and is it reaching that audience in a way that is digestible and actionable.

Conflicting priorities between capital costs of construction and O&M costs

It is extraordinarily difficult to overcome these conflicting priorities at the institutional level. Capital costs for construction and facilities operational costs come from different budgets. Public-private partnerships, as well as other development models, allow for some improvements in how buildings are designed, constructed, and operated, however, building owners tend to be indifferent, if not antagonistic, to anything that impacts their fiscal competitiveness. Any building or retrofit program must demonstrate that the costs of any new work leads to increased profit. This is particularly acute in the difference between net and gross leases – where the incentives are split, and only one party sees the benefits of increased energy performance. What is the incentive to a property owner moving an office space from Class C office space to Class A office space if the financial burden is entirely on the owner? Currently, there is a significant premium in income between newly built Class A office space and buildings that are 10 – 20 years old. New construction is viewed as better by tenants, and they are willing to pay more for a lease. Older buildings have tenants that are more price sensitive. If tenant preference leans to new construction, how does this impact the rate and energy efficiency depth of retrofits to existing buildings?

Contracting structure for design, construction, O&M, and asset ownership

There are legitimate questions about whether standard design and construction contracts are inhibitors to delivering high-performance buildings – and the integrated systems needed to drive that performance. Design teams working on the highest performing buildings, with the most integrated systems, have changed contract structures to require certain design activities and processes that are supportive of high-performance design goals would improve overall building performance. Changing the contract structure and requirements for the design team can fundamentally change the communication, processes, and outcomes.

Confusion about responsible parties during the design process (e.g. which consultant is responsible for specifications of which systems, or where those specifications belong in the construction documents) cascade to the building trades during building construction. This leads to questions about who is responsible for installing or commissioning systems. Examples of this are frequent in the industry, where construction has become highly specialized into small subsets of the whole building. In this case, individual elements of construction can appear to cost less, but in actuality lead to cost overruns as building trades and subcontractors are unwilling to be responsible for the areas between individual contracts and the connections between different systems. In the case of automated controls at the façade (e.g. interior roll down shades, exterior operable shading, electrochromic glass), there is no industry standard for who has responsibility for the installation and operation of that control system – is it the glazing contractor, electrical contractor, or a separate systems contractor. Nor is there an industry standard for who should commission these control systems. The same is true for electric lighting controls (e.g. individually controlled lighting systems with sensors). If the sensors are going to be used by any of the systems besides the lighting, is it a specialized lighting contractor, a general electrical contractor, HVAC contractor, or a separate controls contractor who is responsible.

Lease types and asset ownership

Lease types have a significant impact on whether a landlord (or investor) will make upgrades to a property. In a triple net lease condition, where the lessee pays rent to the lessor, as well as all taxes, insurance, and maintenance expenses, there is no immediate incentive for the landlord to make energy efficiency upgrades as there will not typically be a financial return. Whereas in a gross lease condition (where the lessee pays the landlord a gross monthly amount that includes all of the utilities, taxes, insurance, and maintenance expenses), the landlord would benefit from improved energy efficiency, if the difference between the upgrade costs and the amount determined in the lease were great enough to provide a payback.

The most common work completed for a repositioning program (where a property is being moved from one class of office space to another), is that which can create maximum investment return at least cost. This work leans toward areas that have the widest public use / exposure in the building, such as lobbies, elevators, restrooms. energy efficiency, or new high-performance systems, is well down the list for investment work. Energy costs are well understood on the commercial side and are either in or out of the lease depending on the lease type. What would make the energy efficiency work jump up the list of building improvements, by affecting the investors bottom line, would be utility incentives, Federal and State tax incentives, etc. that would defray or remove costs, and assurance that either the investment put the owner at a competitive advantage, or, more likely, not at a competitive disadvantage in the market.

Role of building codes

From the developer and investment asset community perspective, changes can best be made by impacting the market as a whole, e.g. mandates that requires a particular geographic area or building type to be certified under a third-party standard. This ensures that nobody is put at a competitive disadvantage for achieving higher levels of building energy performance. The top down approach ensures a fair playing field. California is at the forefront of these performance requirements, which allows cutting edge technology to make economic sense for everyone. California is also a market leader with regard to maximizing resources at the state level, through retrofit programs with utilities that pay for costs of upgrades. Nationwide developers are seeing that most state and local governments have also adopted third-party designations / certification for their publicly funded projects. What is not known is how this impacts design and construction practices at the local and regional level, and how building codes at these levels map to the performance requirements of those third-party standards.

Manufacturing and proprietary protocols

From the building designer perspective, an interoperability application programming interface (API) standard is key to making integrated controls a reality in buildings. In addition, specifications documents need a defined section where an API or interoperability standard appears. Currently there is not adequate guidance, therefore specifications documents are not consistent, which leads to confusion and errors during design, construction, and commissioning. Having a defined Masterspec format for controls would be very helpful, as in the absence of such a definition design teams rely on inconsistent documentation for oversite of work by design consultants and contractors in the field. Other questions about interoperability and controls include the type of controls that might be required by building codes or contracts, and whether there is variability by building location (state by state) or by building type, use-type, or size type.

Voluntary Standards and Third-party Certification

Third party certification programs have progressed through several rounds of refinement. As the process for certification advances, the metrics, standards, and guidelines for achieving certification change. Professional evaluation and critique of voluntary standards is necessary for improvement. In the daylight and views portion of LEED for example, there has been a change between versions of LEED that determines how the credits are awarded for projects. In a preliminary evaluation of these two versions (LEED Version 3 and LEED Version 4), the daylight and views metrics used in LEED Version 3 were relatively easy to meet for those designers with skill and knowledge, and the Version 4 metrics are too time consuming and difficult to meet, and therefore aren't being performed. When credits are too hard to calculate it makes pursuit of these credits difficult, this has an especially harsh effect on small projects and small firms – if the requirements are too complex and/or the project is too small, the design team will not be able to use the advanced tools to analyze the design. Developing and disseminating best practices will help mitigate this, as will the creation of recognized standards for what constitutes appropriate daylight and views.

Energy and lighting are disconnected in LEED process at this time. As a result the application, or not, for daylighting credits does not seem to be related to lower energy savings that are achievable from highly efficient lighting systems. In LEED Version 4 there is no prescriptive path for daylighting design, as there is in energy efficiency. Receiving credits relies on post occupancy evaluation, however this reduces the ability to affect the daylight design during the design process. Other third-party certification systems, such as the WELL Standard, carry additional costs. Members of the AEC community currently understand that the WELL Standard certification is three to four times as expensive as LEED certification. Circadian lighting controls are upwards of 30% more expensive than typical controls, and the benefits to this added expense are unproven. In cases where there is client interest but not budget, sophisticated architecture practices can emphasize values of daylight in their projects and Circadian stimulus of daylight as a biophilic aspect of design. In this case, while the intent of the third-party standards is good, and it matches with the client's budget requirements, there currently is no accepted methods of commissioning or measuring a system for these benefits. The AEC community is very much interested in the positive impacts on wellness and health being quantified through future studies, and the development of accepted commissioning standards for new metrics.

Market Delivery

Electric lighting and facade systems are, at present, two separate industries and it is likely this will continue to be so. These two industries, which by themselves are not monolithic, consist of separate companies, with separate distribution and sales channels. As mentioned elsewhere in this section, specification, installation and maintenance of electric lighting and facade systems is usually performed by different entities as well. Successfully integrating these two types of building systems will require a degree of coordination between the two respective industries, from the more technological aspects of how to enable meaningful communication between devices in order for them to act in concert, to the more institutional ones of how these systems might be successfully bundled at the point of specification, sale, installation, commissioning, operations and maintenance.

Demonstrating value to stakeholders and industry

What are the savings associated with integrated daylight design, and what degree of confidence is there that these savings are accurately being portrayed? How accurate are recent publications examining lighting controls and savings? Any study that seeks to clarify or reduce confusion for practitioners would be welcomed. Advanced lighting control systems have potential to incorporate numerous non-energy benefits, including occupant health and safety through delivery of better lighting and therefore improved occupant satisfaction, lowered systems first costs due to wiring requirements, improved flexibility and adaptability to future spatial reconfiguration, reduced maintenance costs, increased real estate value (depending on the resolution of split incentives).

Prioritization of best practices and industry standards

Next 2-5 years:

- Address wide gaps in professional knowledge and skills regarding appropriate design of lighting systems (electric and daylight) and solar control
- Develop commissioning standards for daylighting systems; develop skill sets needed for commissioning to standardize education of commissioning agents.
- Identify need for separate lighting model export, or better results from IFC models.
- Guidelines for ensuring that requirements for new building codes are successfully implemented - from design teams to contractors, to building code inspectors.
- Mapping of predominant voluntary standards to state and local codes, and mapping of construction projects against those differences.
- Determination of integration recommendations differences for new and existing buildings; is it best to disentangle lighting and shading controls for existing buildings, new buildings?
- Development of a standard for sensors and sensor locations for best controls, especially whether daylight controls and electric light controls are parasitic or integrated, and whether controls for light systems should be disaggregated, decentralized, and device specific
- Include a broader range of organizations into the development of the circadian stimulus standards to promote trust in recommendations and avoid the appearance that they are not favoring one industry over the other.

- Develop an understanding of how facade and electric lighting industries (including manufacturers, distributors, specifiers, installers and other relevant entities) can cooperate towards effectively enabling integration of these two technologies.

- Next 5-10 years

- Better models for understanding return on investment and simple payback calculations for installation of advanced lighting control systems.
- Validating non-energy benefits that can create a lowered return on investment timeline. Asset management and systems improvements typically have a 3-5 year payback, being able to see a payback of 1.5 – 3 years would make property owners think about newer and / or better systems.
- Investigation of lease structures that can prevent the split incentive dilemma of current net and gross leases. Development of understanding of lease types by building age, geographic location, building size, use-type, etc.
- Evaluation of priorities for research and application based on an evaluation of where buildings are located, and what building types are in greatest need of improvement (e.g. ~ 50% of commercial building space is 3 stories or less, and is under 10,000 SF in size).

PART 1 - SECTION 2A: SUMMARY OF CURRENT OF GLARE, ELECTRIC LIGHTING, & DAYLIGHTING SYSTEMS LITERATURE

The literature summary was completed for the purpose of developing a more robust understanding of current research topics of at national labs and academic institutions, in professional design and construction practices, and product manufacturing. It was not intended to be, nor was it conducted as, a traditional literature review. Rather, it was viewed as a vehicle for more completely understanding the larger picture of research topics, dissemination channels, and the language used by researchers to describe their work. There is, of course, a long history of research that addresses issues of daylight and electric light systems, as well as subtopics within those fields of study. Performing a large-scale literature review of that history was not in the scope of this effort, but would provide an important documentation of past work and the ability to more completely and coherently evaluate historical research thrusts, their outcomes, and the potential for a mapping of future research thrusts that may be needed. The summary prepared here was mostly limited to publications from the last decade.

Additionally, as an effort to understand where there are opportunities for creating a more integrated approach to the research, design, implementation, and operation of these systems, the literature evaluation was performed as a non-expert might, when unraveling the complexity of these topics. The approach was to start with a simplified search for research in topic areas of “glare”, “daylighting”, “electric lighting”, and “integration of daylight and electric light systems”. A focused, key word search may well have resulted in a different set of papers.

An evaluation of the literature in the evolution of glare, day- and electric lighting systems was conducted at several levels of detail. A meta-analysis of 453 academic papers, books, guidelines, standards, and conference proceedings was conducted. Of those papers, 78 were read to understand the types of research being conducted in the area of lighting, daylighting, and glare. These papers were initially selected from a basic search of current research on daylighting and electric lighting. The 453 papers were selected from the citations of these papers. From the78 papers, 22 were analyzed for their use of specific words and phrases. While many papers were evaluated, this is not intended to be a comprehensive review of the whole field. It is an open questions about the breadth and depth to which additional meta analyses are warranted. Specifically, would there be value in understanding the nature of the language used by researchers to describe their work. Does the complexity of language used to describe research and results enhance or inhibit understanding? Does the complexity change depend on whether the research is basic or applied research? Or is it dependent on the type of research methods or research topic?

The meta-analysis revealed that a significant majority of the publications addressing glare, electric lighting, and daylighting evaluated were primarily academic – published in either an academic journal or conference proceedings.

Table 1: Distribution of published research by publication type

Type	academic journal / book	conference proceedings	industry	non-profit	codes, standards, guidelines	academic research report
Percent	75%	12%	4%	2%	2%	5%
Count	339	52	17	7	11	24

While the general increase in the overall amount of academic publications must be considered, as well as the limitations of the selection of papers used in the meta-analysis, a significant increase in the research addressing glare and lighting systems since the 1980s can still be seen.

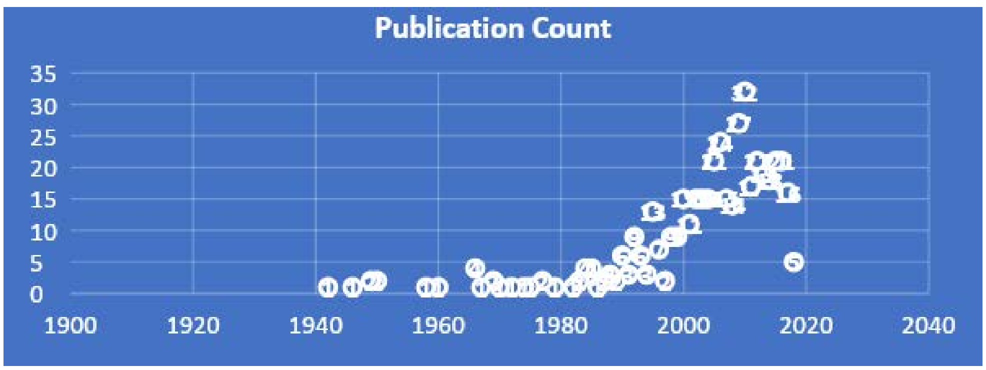

Figure 0-1: Publication count by year.

In this context it can also be seen that nearly half of all publications included in this meta-analysis were limited to just eleven publications. Those publications are: Building and Environment, Energy & Buildings, Lighting Research & Technology, Solar Energy, Journal of the Illuminating Engineering Society, Illuminating Engineering Society of North America, International Commission on Illumination (CIE), Applied Energy, Building Simulation, Renewable Energy. The remaining half of the publications were split over 126 separate publications. When it comes to dissemination of the results of research in these areas, the questions that arise from this limited, and simple, analysis include who the intended target of the research is, and whether the dissemination is reaching that intended target. How do we know if this research is reaching the intended audience, and whether that audience is the correct one? While ensuring that professionals in the current sphere of research and publication are kept abreast of the latest work is important, there is also a question about whether the application and dissemination of the research results should consider a wider range for a target audience.

The papers read for this scoping study were read for the purpose of understanding what type of research has been undertaken (both historically and contemporaneously), what the study types are, what topics were being researched, and whether that research included the use of human subjects. The first observation is that very few of the publications included information about the research type being conducted. Overall, the publications have been varied, including field studies in occupied buildings (where there are relatively uncontrolled environments, with validation by simulations being virtually impossible), and full-scale laboratory tests/evaluations, in controlled environments (where validation with simulations is possible, but difficult). The full-scale laboratory tests have included the applied type (e.g. testing how automated facades and lighting controls interact) and basic research (e.g. studying human subjects' response to glare).

The research projects described in the publications have been both qualitative and quantitative, and frequently have been mixed. The publications were approximately split between basic and applied research. The research publications included observational research (recording information about test subjects without manipulating the study environment), action research (recording information about test subjects while manipulating the study environment), longitudinal research (conducting several observations of the same test subjects over a period of time), cross-sectional research (where separate groups were compared at a single point in time). The research projects documented in the publications were evaluating glare metrics, assessing design tools, and validating simulation and software. There were a limited number of publications focused on research synthesis, review, and meta-analysis. The research subjects were all lighting focused, however approximately 40% of the publications addressed daylight specifically, 15% were specifically electric lighting focused, and 25% were addressing combined daylight and electric lighting, while 20% of the publications were agnostic to the light source.

Of the 78 papers reviewed, 42% included human subjects in the research study (human subjects were used in the research projects in laboratory tests, in situ field studies, and through post occupancy evaluation of buildings. The range in size of human subjects groups was large. The smallest group size was 3[11], while the largest group size was 842[12], with an average of 103.4 study participants. However, it was not always made clear in the publications whether the groups size was a specific number of individuals, or simply individual responses. In the case of the largest group, the authors describe the number as a study of “daylight performance and visual comfort… evaluated by a longitudinal subjective survey (842 total responses) and simulation-based metrics… during a year.” The study included a breakdown of age, gender, and academic position (all undergraduate).[13] While another study included 16 test participants, had a test procedure that was completed 21 times, where some participants completed the testing more than once, under a different sky condition or different time of day from their first participation, for a total of 156 individual survey responses.[14] Those papers that focused on simulation for the research were largely unclear about the number of simulations performed. Only 12% of the publications described a specific number of simulations. The range of specified simulations was from one to 2,160.

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[11] L. Bellia, A. Cesarano, and G.F. Iuliano, “Daylight glare: a review of discomfort indexes.,” *Semantic Scholar* (2008).
[12] Zahra S. Zomorodian and Mohammad Tahsildoost, “Assessing the effectiveness of dynamic metrics in predicting daylight availability and visual comfort in classrooms,” *Renewable Energy* 134 (April 1, 2019): 669–680.
[13] Zahra S. Zomorodian and Mohammad Tahsildoost, “Assessing the Effectiveness of Dynamic Metrics in Predicting Daylight Availability and Visual Comfort in Classrooms,” *Renewable Energy* 134 (April 1, 2019): 669–80, https://doi.org/10.1016/j.renene.2018.11.072.
[14] Andrew McNeil and Galen E. Burrell, “APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE,” 2016.

An analysis of text and word choice in twenty-two academic papers on lighting, with an emphasis on glare, was conducted. The variety in word choice and phrases used by researchers to describe their work is varied. In just one example, the topic of the use of human subjects in research, those subjects have been described as: participants, volunteers, observers, occupants, respondents, subjects, and users. While it is likely these are insignificant semantic differences, it would make comprehension of research findings easier if there were a unified manner of discussing how human subjects are described in research publications.

Descriptions of glare include **source detection methods** and **thresholds** "to assess the influence of several glare source detection methods and parameters on the accuracy of discomfort glare prediction for daylight."[15] **Glare prediction models** where user assessments combined with existing models show potential for improving glare prediction models,[16] and requiring extended laboratory studies to reassess how each of variables in discomfort glare models (Ls, ω, Lb, and P) influence, or would be required to validate the **accurate prediction of discomfort glare.**[17] In addition, there was discussion of **evaluation of glare sensation** and the "alleged precision of the glare index values from bright light sources calculated to estimate or predict the levels of visual discomfort inside buildings."[18] There was also research conducted on the necessity of establishing **criteria for discomfort glare** that account for different geographic and ethnographic users,[19] and **degree of discomfort glare** caused by source luminance as seen through a window or from an electric light, and whether there is a greater tolerance for glare from windows than from electric light sources.[20] **Daylight availability and glare** results from surveys indicate that occupants of daylit spaces are less sensitive to higher levels of daylight, and are able to adapt to excessive amount of light.[21] There was agreement that predicting **discomfort glare from daylight** through the daylight glare index (and other metrics) tend to overestimate the glare under real sky conditions and non-uniform window luminance.[22] There appears to be some disagreement on the types of glare, and whether there are two categories of glare, disability and discomfort,[23] or three categories of glare: disturbing glare, discomfort glare and disability glare.[24]

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[15] Clotilde Pierson, Jan Wienold, and Magali Bodart, "Daylight Discomfort Glare Evaluation with Evalglare: Influence of Parameters and Methods on the Accuracy of Discomfort Glare Prediction," *Buildings* 8 (July 24, 2018): 94, https://doi.org/10.3390/buildings8080094.
[16] Alrubaih et al., "Research and Development on Aspects of Daylighting Fundamentals."
[17] Pierson, Wienold, and Bodart, "Daylight Discomfort Glare Evaluation with Evalglare: Influence of Parameters and Methods on the Accuracy of Discomfort Glare Prediction."
[18] M.G. Kent et al., "Temporal Variables and Personal Factors in Glare Sensation," *Lighting Research & Technology* 48, no. 6 (October 1, 2016): 689–710.
[19] Rizki A. Mangkuto et al., "Determination of Discomfort Glare Criteria for Daylit Space in Indonesia," *Solar Energy* 149 (June 1, 2017): 151–63.
[20] L. Bellia, A. Cesarano, and G.F. Iuliano, "Daylight Glare: A Review of Discomfort Indexes.," *Semantic Scholar*, 2008.
[21] Zomorodian and Tahsildoost, "Assessing the Effectiveness of Dynamic Metrics in Predicting Daylight Availability and Visual Comfort in Classrooms."
[22] Alrubaih et al., "Research and Development on Aspects of Daylighting Fundamentals."
[23] McNeil and Burrell, "APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE."
[24] Urszula Blaszczak, "Method for Evaluating Discomfort Glare Based on the Analysis of a Digital Image of an Illuminated Interior," *Metrology and Measurement Systems* 20 (December 10, 2013): 623–634, https://doi.org/10.2478/mms-2013-0053.

Visual comfort and discomfort evaluations focused on **image based visual discomfort** models, and their accuracy and ability to be generated rapidly during the design process from architectural renderings rather than photographs of in situ spaces. Understanding the level of accuracy expected of simulations is seen as a need, as well as whether the use of image-based visual discomfort models can predict the **DGP glare classification** accurately if camera orientation in a model is not correctly aligned. In addition, relying on highly detailed and accurate duplication of the reflections occurring on real surfaces with the digital model surfaces in the simulation is a weakness without an accepted standard for modeling of objects in spaces. It was discovered that "future improvement of visual discomfort predictions will… require better tools to measure direct solar radiation and sky luminance distribution. [Jones, 2016]. **Time-based visual comfort** requires fast and accurate simulation, and "building daylighting performance in a real space is a dynamic process," yet determining comfort for long-term or time-based visual comfort evaluations has no established standard for what an appropriate time step is, or what constitutes long-term. Is it a matter of minutes or hours? Is it measured on a daily basis, or as a percentage of time over the course of a year? Is it the variation of vertical illuminance over time, or is it the frequency of glare above a certain threshold.[25]

Discomfort and comfort evaluations focused on the prediction and evaluation of discomfort glare using various methods. The **Unified Glare Rating** (UGR), the **Visual Comfort Probability** (VCP), and the **Daylight Glare Index** (DGI) ,and **Daylight Glare Probability** (DGP) are well known methods, however each has its weaknesses based on the four main factors influencing the degree of discomfort glare. The luminance of the glare source has different impacts based on whether it is from daylight or an electric light source, the solid angle of the glare source has not been evaluated for the difference in light source sizes for solid state lighting, the background luminance is affected by the size of the target viewing area, and the position of the glare source in the field of view is impacted by whether the light source is in the upper or lower visual field.[26] **Discomfort glare metrics** such as Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) have been determined to be ineffective for evaluating glare in a brightly illuminated spaces. Other factors affecting discomfort glare, including diurnal and seasonal affects, age, task difficulty and duration, and room temperature could improve the understanding of these metrics and their effectiveness for dimly illuminated spaces[27], or more generally in the extremes of available illuminance.

Daylight systems were discussed and the methods for selecting of daylighting and **daylight responsive lighting control systems**. Lighting and shading controls were assessed for their different shading control strategies, **dimming lighting control systems**, **high frequency dimming controls**, and the use of **localized controls** in over lighting systems and shading devices. This also included discussions of **automated façade shading controls** and **façade shading control algorithms**. The design of these systems of control used climate-based daylighting metrics and addressed daily and seasonal changes to available light.

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[25] Yu Bian and Yuan Ma, "Subjective Survey & Simulation Analysis of Time-Based Visual Comfort in Daylit Spaces," *Building and Environment* 131 (March 1, 2018): 63–73.

[26] Wonwoo Kim, Hyunjoo Han, and Jeong Kim, "The Position Index of a Glare Source at the Borderline between Comfort and Discomfort (BCD) in the Whole Visual Field," *Building and Environment - BLDG ENVIRON* 44 (May 1, 2009): 1017–23, https://doi.org/10.1016/j.buildenv.2008.07.007.

[27] McNeil and Burrell, "APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE."

Occupant views were discussed, including those views through a window and to the outside with respect to view type and view interest and the viewer's line of sight, however there was no evaluation of criteria for what might compose a metric for determining whether a view is low or high quality. The spatial qualities of buildings were briefly discussed, though not across all the papers reviewed. This included evaluating discomfort in open plan green buildings and those spaces with high daylight, as well as seeking to understand discomfort in daylit spaces, and the impacts of time and space distribution of daylight. There was no discussion of what design methods should be used to ensure a well daylit space.

While there is a significant quantity of literature addressing integrating daylight and electric light historically, among the recent literature evaluated only one paper explicitly addressed integrating daylight and electric light,[28] and one paper that sought to link a well daylit space with visual comfort and low energy use.[29] In general, there was little discussion linking light (daylight and electric) with energy consumption and savings. (Here keeping in mind that the publications were largely limited to work from the past decade.) One review paper summarized daylighting research, standards, and guidelines. This paper included significant reference to works completed between 1970 and 2000. It recognized that "daylighting in a building does not lead to energy savings unless it is integrated with artificial lighting systems through lighting control techniques."[30] In addition, it observed that the "daylight factor is still the most commonly used parameter to characterize the daylight situation in a building."[31] It was observed that lighting control systems are a major building systems component if daylight is to be effectively integrated with electric lighting systems, and that energy savings from electric lighting systems of between 30% - 70% can be achieved when high-frequency dimming controls are used.[32] This was countered with the additional observation that the design of daylighting systems into a building has the potential to lead to higher energy consumption if that daylighting system is not carefully integrated. It was stated that daylighting systems can be "applied at 1/20th of the cost of solar photovoltaic panels and generate the same energy savings."[33] The ability to achieve this level of electric lighting system savings through integration of with daylighting systems needs further validation, as does the cost of daylighting systems. In addition, the results and savings achieved through systems integration are highly dependent on proper sensor placement, hardware quality, and commissioning. These too, need additional validation and standards and guidelines.

While most of the research evaluations were directed toward understanding and measuring glare (for the purposes of determining discomfort from glare), the underlying purpose of that understanding - to enhance indoor environmental quality for occupant productivity and wellness - was indicated only peripherally. This is in addition to other non-energy benefits, such as environmental benefits from

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[28] Danny H. W LI, "A Review of Daylight Illuminance Determinations and Energy Implications," *Applied Energy*, no. 7 (2010): 2109.
[29] Carlos E OCHOA et al., "Considerations on Design Optimization Criteria for Windows Providing Low Energy Consumption and High Visual Comfort," *Applied Energy*, 2012, 238.
[30] M. Alrubaih et al., "Research and development on aspects of daylighting fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505.
[31] M. Alrubaih et al., "Research and development on aspects of daylighting fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505.
[32] M. Alrubaih et al., "Research and development on aspects of daylighting fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505.
[33] M. Alrubaih et al., "Research and development on aspects of daylighting fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505.

reduced energy generation needs, and the possibility that integrated lighting systems can increase occupant comfort as well as extend systems component lifecycles.[34]

Professional and Continuing Education and Standards needs*

- Evaluation of publication and dissemination plans for research outcomes to ensure the target audience is reached in the appropriate manner;
- Verify that leading edge work is consistently and appropriately moving from research to application;
- Develop a standard for what constitutes a minimally acceptable number of human subjects for reliable results, and transparency and clarity differentiating the number of human subjects and the number of responses to different instruments in research projects.

Evaluation of publication options for reaching a broader audience that cuts across disciplinary and industry boundaries;

*There are clearly additional needs based on the literature summary. These are more directly addressed by the research topics identified in Part 2 of this document.

[34] M. Alrubaih et al., "Research and development on aspects of daylighting fundamentals," *Renewable and Sustainable Energy Reviews* 21 (May 1, 2013): 494–505.

PART 1 - SECTION 2B: VOLUNTARY STANDARDS REVIEW

This section has reviewed only one voluntary standard, in an effort to not become bogged down in the larger discussion of voluntary standards, guidelines and certification programs. In addition, this section was specifically prepared without detailed evaluation or discussion of building and zoning codes. There are better sources of comprehensive information pertaining to evaluation of voluntary design, construction, and operations standards. Several of these sources are listed below. There is no national building code for the United States, and, as a result, there is a chaotic network of codes for each state in the U.S., and often times this cascades down to localized codes within states, including major metropolitan areas, regions, and other jurisdictions responsible for construction oversight. Rather this review was intended to evaluate the outcomes of voluntary standards on the coordination of building lighting systems in general. To this end a subset of U.S. Green Building Council, Leadership in Energy and Environmental Design (LEED) certified projects were selected for review.

The LEED certified projects evaluation was undertaken to understand the degree to which lighting systems integration is taking place in buildings designed with voluntary standards for improved performance. LEED was the voluntary standard chose because it is the most widely used green building rating system in the world,[35] with over 140,000 projects registered or certified around the globe. Of those projects 451 projects[36] certified under standard version 3.0, LEED 2009[37] [38] were evaluated to understand the degree to which projects across all certification levels were receiving credits for lighting systems (daylight and electric lights) and to what degree those projects were in a position to integrate those systems with other building mechanical, electrical, or plumbing systems. (The USGBC launched LEED v3 on April 27, 2009. The USGBC allowed LEED users to register projects under the LEED 2009 rating system until Oct. 31, 2016, the last day projects can submit for certification, also called the sunset date is June 30, 2021.) The version 3.0 LEED 2009 for New Construction was chosen for the number of projects certified, and the simplicity of the categorization of the NC category. While version 4.0 and 4.1 of LEED should also be evaluated, this would require a different level of evaluation as there are as many as twenty-three separate certification categories for version 4.0 that can be extracted from the U.S. Green Building Council database. In addition, the methods required to qualify for daylighting credits in the current LEED versions are in flux. Below is an example of how the total project list was filtered in order to retrieve information from the USGBC website. It is understood that these projects will have

[35] "LEED Green Building Certification | USGBC."
[36] The 451 projects including the following count: 112 Certified, 111 Silver, 114 Gold, and 114 Platinum. Approximately 125 projects from the list of certified projects were accessed from the USGBC website. In order to catalogue at least 100 projects in each certification category it was necessary to access more than that number as not all certified projects have a completed scorecard accessible. In addition, using the website filtering criteria, projects were only filtered as shown in the screen captured image above.
[37] "USGBC Announces Extension of LEED 2009 | U.S. Green Building Council," https://www.usgbc.org/articles/usgbc-announces-extension-leed-2009.
[38] "USGBC: LEED Version 3," February 25, 2010, https://web.archive.org/web/20100225022230/http://www.usgbc.org/DisplayPage.aspx?CMSPageID=1970.

been designed in the year(s) prior to certification, and do not represent the current state-of-the-shelf in technology and design methods.

Multiple scoring criteria in v3 – LEED 2009 have the potential to impact the manner and type of lighting system and systems controls incorporated into a building design – from site selection to design and construction innovations. However, there are several specific scoring criteria targeting these systems, which fall in the Indoor Environmental Quality section of the standard. These criteria explicitly discuss whether thermal comfort or lighting systems: have the capacity for occupant controllability, have been designed with occupant well-being and productivity in mind, and have been implemented with the ability to assess the performance of those systems over time. These Indoor Environmental Control criteria are in the table below.

Table 2: U.S. GBC LEED criteria explicitly addressing daylight and electric lighting systems.

Criteria Number	Criteria Title	Criteria Subtitle
EQc6.1	Controllability of systems	lighting
EQc6.2	Controllability of systems	thermal comfort
EQc7.1	Thermal comfort	design
EQc7.2	Thermal comfort	verification
EQc8.1	Daylight and views	daylight
EQc8.2	Daylight and views	views

Controllability of Systems

The USGBC defines "controllable systems" for both lighting systems and thermal comfort systems (NC-2009 IEQc6.1: Controllability of systems – lighting, and IEQc6.2: Controllability of systems - thermal comfort respectively) through the intention supporting the credit. In both cases the intent is to: "Provide a high level of… system control by individual occupants or by specific groups in multi-occupant spaces (i.e. classrooms or conference areas) to promote the productivity, comfort and well-being of building occupants."[39] [40]

These controls come in a variety of forms. For lighting systems specifically the requirements are to provide individual lighting controls for 90% (minimum) of the building occupants to enable adjustments

[39] "IEQc6.1," *LEEDuser*, 6, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc6.1.
[40] "IEQc6.2," *LEEDuser*, 6, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc6.2.

to suit individual task needs and preferences, and to provide lighting system controls for all shared multi-occupant spaces to enable adjustments that meet group needs and preferences.[41]

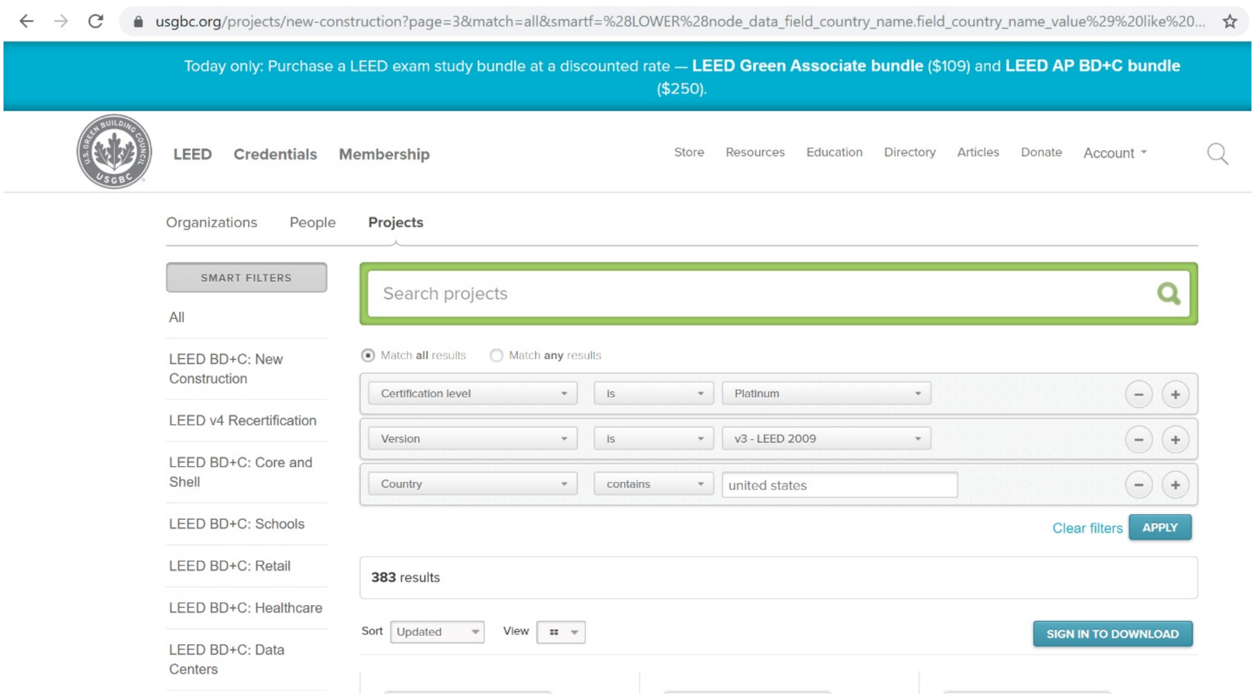

Figure 0-1: U.S. GBC LEED projects selection filter for buildings in the U.S., that are certified Platinum under the v3 LEED 2009 standard.

LEED and Daylight

The table below shows that the projects receiving EQc8.1 for daylight. The U.S. Green Building Council (USGBC) emphasizes the use of daylit spaces as important elements of an overall sustainability goal as well as being critical to occupant well-being and productivity. In order to receive the credit for daylight it must be demonstrated that greater than 75% of all regularly occupied spaces receive daylight illuminance levels between 25 fc and 500 fc, under a clear sky condition on a representative autumnal equinox (September 21) between 9:00 a.m. and 3:00 p.m. Those areas that do not meet these criteria are not in compliance.[42] There are three options for demonstrating that the standard has been met under v3.0 LEED 2009, they are: Simulation, Measurement, Combination of any of the above methods. (Originally there was a fourth method, however the prescriptive option was removed in 2009.) The calculation methods (either simulation or prescriptive path evaluation) provide a low threshold for

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[41] "IEQc6.1," *LEEDuser*, 6, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc6.1.
[42] U.S. Green Building Council., "LEED 2009 for New Construction and Major Renovations," 2010, https://www.usgbc.org/ShowFile.aspx?DocumentID=5546.

achieving the daylight illuminance range over the stated time frame. Despite this, it can be seen that of the certified projects reviewed only 5% received the "EQc8.1: Daylight and views – daylight" credit. Silver and Gold certified projects received the credit at a higher rate (14% and 15% respectively), but only in the teens. Platinum certified projects only received the credit at 38%. The average for all the projects evaluated was only 18%. This was consistent with the percentage of all projects in the U.S. that have received LEED certification, where the achievement rate for this credit was 17%.[43]

For those projects receiving credit for EQc8.2 for views, where the intent of the credit is to provide building occupants with visual connection to the exterior through glazing. This credit has occupant well-being and satisfaction with the interior building environment. And requires a direct line of sight to the outdoor environment through clear glazing that is between 2.5 feet and 7.5 feet above the finish floor surface. In order to receive this credit, greater than 90% of all regularly occupied areas must meet this threshold. Meeting this threshold requires minimal effort to calculate the direct line of sight through diagrams (in building plan or section view), for all the calculated area that is within sight lines drawn. This includes views through interior glazing.[44] With this relatively low threshold for compliance, the table shows that certified projects reviewed only 28% received the "EQc8.2: Daylight and views – views" credit. Silver and Gold certified projects received the credit at a higher rate (40% and 41% respectively). Platinum certified projects only received the credit at 57%. The average for the projects evaluated was only 41%. This was consistent with the percentage of all projects in the U.S. that have received LEED certification, where the achievement rate for this credit was 37%.[45]

Table 3: Percent of LEED NC v2009 projects receiving credits for Indoor Environmental Quality by certification level.

INDOOR ENVIRONMENTAL QUALITY		Certified	Silver	Gold	Platinum	All
EQc6.1	Controllability of systems - lighting	61%	72%	65%	76%	69%
EQc6.2	Controllability of systems - thermal comfort	37%	41%	39%	43%	40%
EQc7.1	Thermal comfort - design	82%	88%	85%	92%	87%
EQc7.2	Thermal comfort - verification	53%	64%	65%	82%	66%
EQc8.1	Daylight and views - daylight	5%	14%	15%	38%	18%
EQc8.2	Daylight and views - views	28%	40%	41%	57%	41%

[43] "NC-2009 IEQc8.1: Daylight and Views - Daylight | LEEDuser," accessed December 19, 2019, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc8.1#tab-credit-language.
[44] "NC-2009 IEQc8.2: Daylight and Views - Views | LEEDuser," accessed December 19, 2019, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc8.2#tab-credit-language.
[45] "NC-2009 IEQc8.2: Daylight and Views - Views | LEEDuser."

LEED and Systems Controllability

Systems controllability for lighting systems, as a percentage of projects, receives more credits than does thermal comfort. (The percent increase in systems controllability for lighting systems over thermal comfort systems by certification level is: Certified 66%; Silver 74%; Gold 68%; Platinum 78%; All 71%.) Clearly it is considered easier and more cost effective to provide control of lighting systems than thermal comfort systems, however the peak controllability for platinum projects is only three quarters of all platinum projects. When it comes to the thermal comfort systems themselves, there is relatively little difference across all of the certification levels for design of thermal comfort for occupants (meeting the requirements of ASHRAE standard 55-2004 for U.S. projects)[46], however there is a significant drop when it comes to the verification of that thermal comfort. Most notably those platinum certified projects only experience a 10% drop in credit achievement for EQc 7: Thermal Comfort. (Percent change for credits received for EQc7.1: Thermal comfort – design; EQc7.2: Thermal comfort – verification by certification level is: Certified (-36%); Silver (-27%); Gold (-23%); Platinum (-10%); All (-24%).) In this case it is clear that for lower certification levels it is considered too difficult and/or expensive to "provide a permanent monitoring system to ensure that building performance meets the desired comfort criteria as determined by IEQ Credit 7.1: Thermal Comfort—Design."[47]

Table 4: Percent of LEED NC v2009 projects receiving lighting systems credits in combination with other building systems credits by certification level.

INDOOR ENVIRONMENTAL QUALITY	Certified	Silver	Gold	Platinum	All
EQc8.1, EQc8.2	2.7%	10.5%	11.5%	28.9%	13.5%
EQc6.1, EQc8.1	2.7%	10.5%	10.6%	33.3%	14.4%
EQc6.1, EQc8.1, EQc8.2	1.8%	8.8%	8.0%	26.3%	11.3%
EQc6.1-2, EQc7.1-2, EQc8.1-2	0.0%	3.5%	2.7%	13.2%	4.9%

EQc6.1: Controllability of systems – lighting; EQc6.2: Controllability of systems - thermal comfort; EQc7.1: Thermal comfort – design; EQc7.2: Thermal comfort – verification; EQc8.1: Daylight and views – daylight; EQc8.2: Daylight and views – views

LEED Projects Areas of Impact

LEED projects have numerous areas where focused effort could impact the integration of light systems. In order to understand more completely how this could happen, the projects certified in the U.S. under

[46] "NC-2009 IEQc7.1: Thermal Comfort - Design | LEEDuser," accessed December 20, 2019, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc7.1#tab-credit-language.
[47] "NC-2009 IEQc7.2: Thermal Comfort—Verification | LEEDuser," accessed December 20, 2019, https://leeduser.buildinggreen.com/credit/NC-2009/IEQc7.2#tab-credit-language.

version 3.0, LEED 2009 were parsed for a variety of characteristics. This included: type of ownership, type of project, and type of ownership organization. In addition, these characteristics were then evaluated with the area of the projects and their location (by state).

Owner Types

Nine essential types of ownership were derived from the LEED scorecards and LEED project database, out of a total of thirty-eight unique ownership type descriptors. Those ownership types are below:

- Business Improvement District
- Community Development Corporation or Non-Profit
- Corporate
- Educational
- Government
- Investor
- Main Street Organization
- Non-Profit (that do not fit into other categories)
- Religious

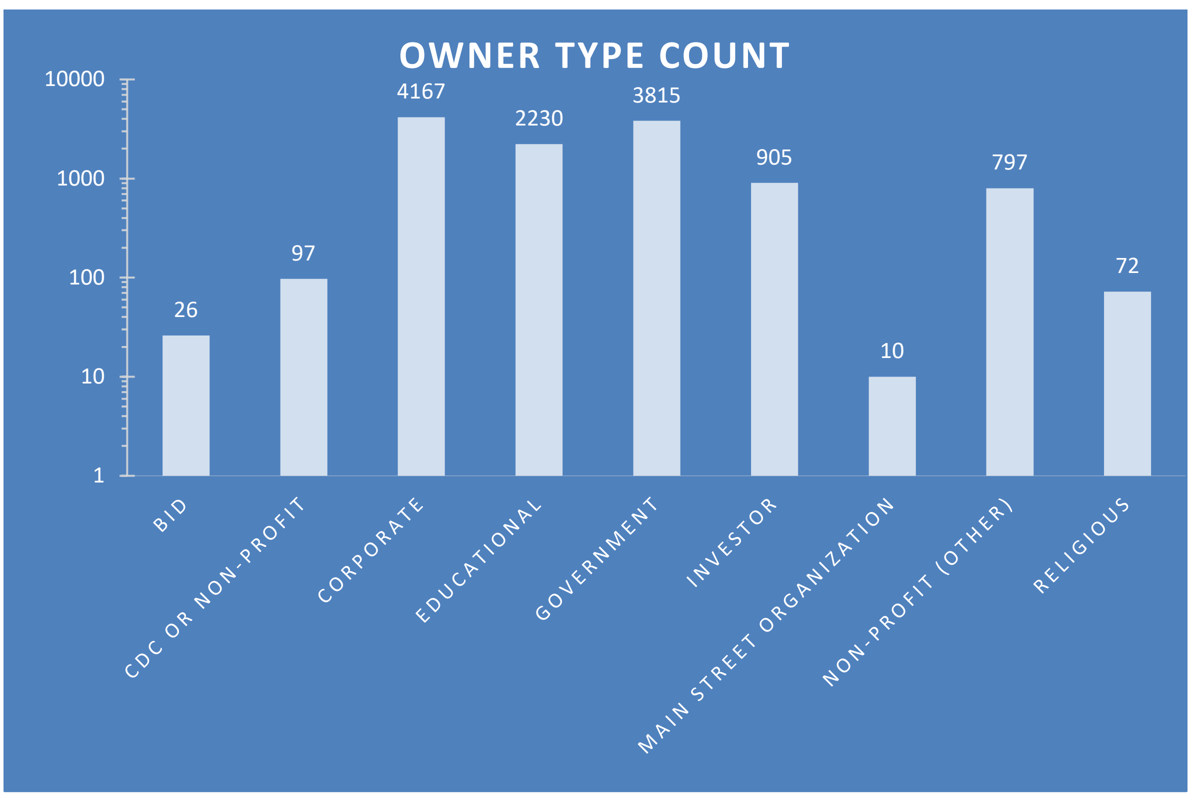


Figure 0-2: Count of v3 LEED 2009 projects by owner type, and the nine essential types of ownership were derived from the LEED scorecards and LEED project database.

Project Types

There are thirty-six distinct types of project, out of a total of 104 project titles. Those project types are below. These project types need to be evaluated against the basic occupancy types defined in building codes to understand if they can be reduced

Table 5: Distinct project types included in documentation from the U.S. Green Building Council and the project teams.

Distinct Project Types			
Airport	**Daycare**	**Library**	**Religious Worship**
Animal Care	Financial & Commercial	Lodging	Restaurant
Assembly	Health Care	Military Base	Retail
Campus (corp/school)	Higher Education	Multifamily Res.	Service
Circulation Space	Hotel/Resort	Office	Single-Family Res.
Commercial Office	Industrial	Other	Special Needs
Comm. Dev. Corp.	Industrial Manuf.	Public Assembly	Stadium/Arena
Core Learning Space	Interpretive Center	Public Order & Safety	Transit
Data Center	Laboratory	Recreation	Warehouse & Dist. Cntr

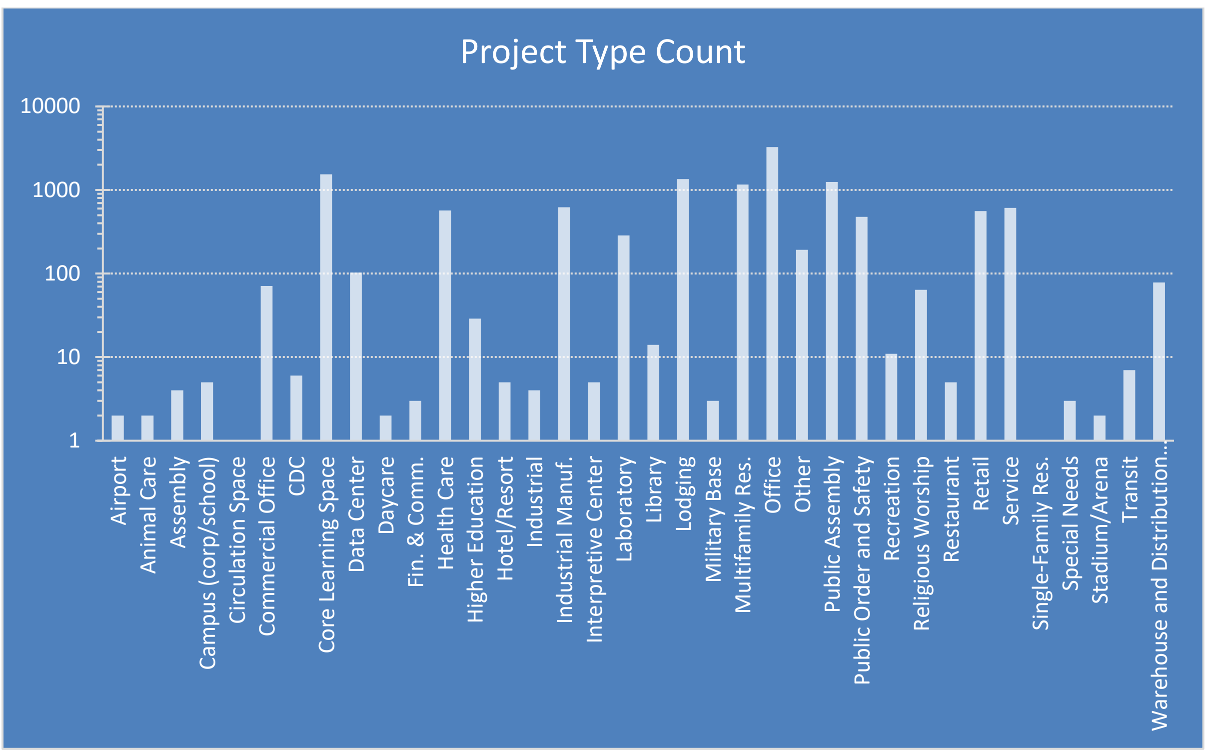


Figure 0-3: Count of projects by type derived from the LEED scorecards and LEED project database

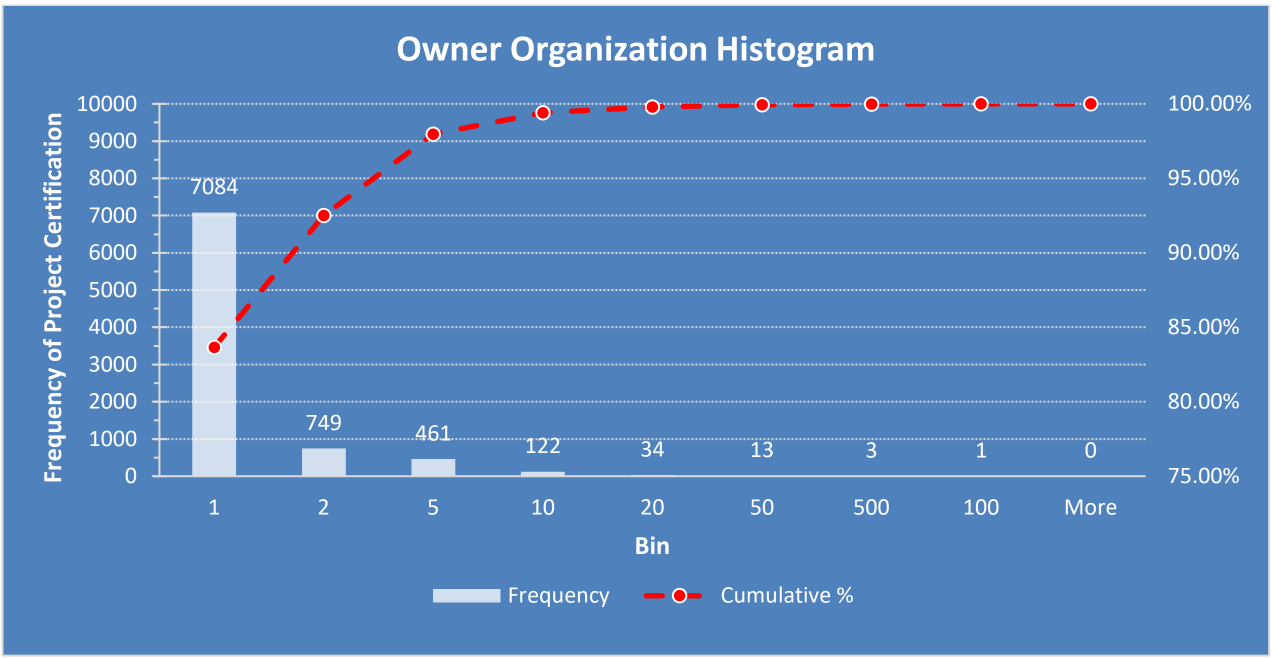
Ownership Organization

Determining the essential ownership organization names is a far more difficult exercise than determining the essential ownership type or project type. The Ownership Organization is the name of the organization that owns the property, and as such there are a virtually unlimited number of unique organization names. However, what is possible to do is to distill the number of organizations by evaluating whether the organization itself has been inadvertently made to appear unique. Without reviewing the entirety of the U.S.-based projects, a number of discrepancies and errors in the cataloguing of the project ownership names can be observed. Below are examples of how seemingly inconsequential changes to the ownership name can change the nature in which data analysis can be performed when sorting, filtering or grouping projects by the organizational name.

- Shortening of the owner name by one or more words (e.g. Z* U* Investment Group G* to Z* U* Investment Group)
- Same organization parent, but local control and management (e.g. YWCA, YMCA)
- Changes in capitalization of organization name (e.g. Group vs. group)
- Different parts of the same organization or corporate structure that have autonomy (e.g. University Facilities, College, or School)
- Variable use of punctuation describing organization structure (e.g. Co., LTD. Vs. Co. LTD)
- Variable use of the organization name, including abbreviations (e.g. XYZ Capital Planning & Development vs. XYZ)
- Simple misspellings of organization name (e.g. Michigan vs. Michgan)
- Inclusion or absence of whitespace in organization name (e.g. XYZPartners vs. XYZ Partners)
- Inconsistent use of organization name abbreviations or unintended abbreviations based on number of characters allowed for input (e.g. State Dept Of Transportation vs. State Department Of Transpor)
- Different divisions of same parent organization (e.g. Parent Group USA vs. Parent Group Europe, Asia, etc.)
- Variable spelling of organization name (healthcare v. health care, etc.)
- Variable use of organization title and sub organization level (USDA; USDA Forest Service; USDA Forest Service, Tongass National, etc.)
- Unknown organizational relationship between owner organizations (is US Government and US General Services Adminstration considered to be the same, for example)
- Use of various organizational name and lower tier organization structures (the U.S. Army Corps of Engineers has at least 42 separate entries, with a total of 276 projects after reviewing fewer than 650 of the approximately 8,500 version 3.0 LEED 2009 certified projects in the U.S.)

There are approximately 8,500 version 3.0 LEED 2009 certified projects in the U.S. Performing a histogram analysis of these projects without evaluating the database for errors or discrepancies as observed above shows that of those 8,500 projects greater than 7,000 of them are certified by unique organizations. This would indicate that a vast majority of the U.S.-based projects are completed without the eventual owner having experienced the rigors of applying a voluntary standard to their projects. However, what a cursory review of the ownership organization shows, is that there are likely a statistically significant number of ownership organizations that have, in fact, seen more than one project through the LEED process. This may represent an opportunity to improve the likelihood that future projects by those organizations could have integrated lighting systems if a pathway to that integration was made clearer. It should be noted here that the LEED system, as with all voluntary standards, is susceptible to the building design and construction being tuned to achieving certain credits, or a count of credits, which may not lead to the best building energy performance, and may also not be representative of a more typical design process where third party certification is not a project objective.

Table 6: Histogram of the distribution of owner organizations and the number of projects each organization has had certified through the version 3.0 LEED 2009 process.



Professional and Continuing Education and Standards needs

- Understanding alignment of voluntary standards with state building codes and level of third party certification in various states by: OwnerTypes; ProjectTypes, OwnerOrganization; GrossSqFoot;
- Investigation of overall rates of controllable systems incorporated into high performance buildings; including evaluation of controllable systems by: State; OwnerTypes; ProjectTypes, OwnerOrganization; GrossSqFoot;
- Defining more clearly the terms controllable systems and integrated lighting systems;
- Evaluation of role of controllable systems in the design process and what parameters are used to determine whether they are included in the final building design, and how this can be fostered by including supportive criteria in voluntary standards;
- Development of partnerships to examine best methods for increasing market penetration of controllable systems, in order to realize goal of increasing utilization of integrated lighting systems and their controllability.

Additional Resources

- U.S. Green Building Council projects database: https://www.usgbc.org/projects/
- U.S. Green Building Council credits database: https://www.usgbc.org/credits/
- Building Green LEED User database: https://leeduser.buildinggreen.com/
- The Green Building Information Gateway: http://www.gbig.org/
- U.S. Green Building Council EQC8.1 credit history: https://www.usgbc.org/credits/new-construction/v2009/eqc81
- International WELL Building Institute: https://www.wellcertified.com/certification/v1/
- International Living Future Institute: https://living-future.org/

PART 1 - SECTION 2C: CRITICAL INFORMATION TO LIGHTING SYSTEMS INTEGRATION CASE STUDIES

What information should be included in a case study in order to understand the lighting integration story?[48] Case studies are critically important to the design and construction professions, as such, the story a case study tells needs to include much more than just the quantitative information about area, volume, number of occupants, construction costs and energy use. The information gleaned from these records are valuable for understanding how best practices are, or are not, successful in achieving project goals and objectives.[49] How the introduction of new standards and guidelines are implemented. How requirements from new building codes impact the process and teams. And, how well current research (and its outcomes) are impacting the performance of buildings. While most of the requirements for buildings, and their performance, are objective, how those requirements are met is dictated by the subjectivity of the relationships of the design team and the comfort of the occupants. Therefore, it is essential that the qualitative and subjective elements of the process – from pre-design through post occupancy – are captured.[50] Like the process of making high performance buildings, individual and institutional processes focused on the development of a case study is cumulative.

Current high-performance buildings case studies form a solid backbone, but there are additional elements that would provide better depth and understanding of projects. Case study creation does tend to be limited to exceptional buildings, which is understandable given time and budget constraints. What this excludes, however, is the benefits to furthering individual and collective understanding of industry practices and discrete design impacts on meeting performance goals. The act of preparing a case study provides benefits to the preparer at least as much as to the eventual audience. It is an opportunity for reflection on how teams individually and collectively respond to goals, codes, and requirements. It is an opportunity that is infrequently provided in practice. The simple act of revisiting the process and outcomes of making a building reveals those areas where improvements can be made individually and collectively across a team, and changes how a team and its members approach the design of the next project. Establishing baseline criteria for case studies that include design and performance metrics, as well as team organizational graphics, examples of contract language, and surveys of the team would be extraordinarily helpful. In each case, these should include specific details about lighting systems integration. Project descriptions should be comprehensive, including project team details, design process and building description need to emphasize lighting systems integration efforts. Project goals (including energy, sustainability, resilience, historic preservation, and design for accessibility), should

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[48] "Case Studies | WBDG - Whole Building Design Guide," accessed December 19, 2019, https://www.wbdg.org/additional-resources/case-studies.

[49] "Federal Center South Building 1202 | WBDG - Whole Building Design Guide," accessed December 19, 2019, https://www.wbdg.org/additional-resources/case-studies/federal-center-south-building-1202.

[50] "Governor George Deukmejian Courthouse (Long Beach Court Building) | WBDG - Whole Building Design Guide," accessed December 19, 2019, https://www.wbdg.org/additional-resources/case-studies/governor-george-deukmejian-courthouse-long-beach-court-building.

indicate how lighting systems integration is inherent to the development of these goals. Metrics for cost effectiveness, project function, and occupant productivity goals need to be evaluated for the influence of lighting integration on the realization of these goals. Construction, operation and maintenance, and post-occupancy should be assessed through the lens of lighting systems integration, and the degree to which that integration impacted those activities. Perhaps most importantly, a comprehensive description should be generated that characterizes the information and tools used by the team, as they address the means and methods used to integrate lighting systems and manage their long-term integration and performance.

Each of the sections and bullet points in the appendices below can be generically applied to a building case study. An expansive case study would accurately document the entirety of a project. In the early stages of lighting systems integration, projects having a achieved integration should be as comprehensive as possible. This is an unrealistic expectation for all case studies, however it is not unrealistic to expect that this could be achieved for a select subset of projects.

Each of the elements below can also be explicitly applicable to lighting integration. General project information should include descriptions of how the lighting systems integration design was facilitated, and who were the team members who led the integration efforts. There should be a complete description of the specific software tools used by the team to perform the design and installation integration. It should answer any questions about how the design and implementation processes were shaped by changes in project occupation (e.g. from owner-occupied to tenant occupied).

The project team details should include a complete description of how the finance mechanism of the project affected the type and degree of integration, and how community outreach and engagement is impacted by addressing lighting systems integration? How does this engagement address the topics of energy benefits, and non-energy benefits?]

The overall building description should include details and graphics describing the passive lighting systems – daylighting. There should be details and graphics describing how integrated lighting systems improve building resilience. It should include a table or graphic showing the how lighting systems integration impact project goals and implementation, and how capital and operations and maintenance (O&M) expenditures are affected by lighting systems integration. It should include an outline of how the lighting systems integration play a role in any financial incentives. Including any additional design budget required to fully design the integrated systems.

Sustainability goals should include descriptions of any post occupancy performance evaluations and energy consumption targets or metrics used to verify lighting-based design targets for energy consumption. It should answer questions about integration of daylighting and electric lighting systems compliance with other third-party certifications, guidelines, or standards employed for the purposes of achieving sustainability goals should also be included. Including whether third-party certifications are applicable to lighting systems integration. If not, what are new certifications, guidelines, and standards that might need to be created.

Functional project goals should include a description of the design development methods or criteria used during project design for describing how lighting systems integration improves lifecycle flexibility. There should be a description of occupational metrics showing design responsiveness to owner / tenant lighting design criteria (e.g. employee productivity, satisfaction, health and wellness), and whether those metrics are validated for lighting systems integration that track productivity, satisfaction, and well-being. Additionally, a description of design flexibility for occupant reorganization and tenant changes, should be created. This will address how integrated lighting systems address present and future design flexibility, and what standards for lighting integration are needed to provide seamless systems reorganizations for retrofits.

Design for Accessibility should include a description of the design metrics and goals created to provide accessibility for workforces with various abilities, and how those goals (and workforce abilities) are impacted by integrated lighting systems.

Cost effectiveness goals should include descriptions of integrated lighting area and systems construction costs compared to typical costs. It should answer questions about how lighting systems integration can change the return on investment calculation for the full building design, how integrated lighting systems affect the lifespan of other building systems, whether daylighting and electric lighting integration alone change individual system lifespan, and what system are the anticipated lifespans of lighting systems that are integrated into other building systems. The case study should define what an appropriate timeline for understanding return on investment and simple payback for integrated lighting systems is, and what are the metrics needed to adequately assess investments (e.g. energy, health, satisfaction).

Historic preservation goals should include an assessment of the historic lighting systems used in the original building and preserved during renovation. There should be specific descriptions of the criteria used to adapt integrated lighting systems adapt to historic buildings and their passive systems of lighting.

Recent investigations related to lighting and workforce productivity should be addressed by describing the project goals related to this issue, including what metrics are needed for understanding how integrated lighting systems lead to changes in occupant productivity. Metrics for health and wellness should include integrated lighting systems metrics for views (interior and exterior). If there is no accepted standard for quantifying views, how are project specific view metrics developed for integrated lighting systems? Are daylighting and electric lighting metrics disaggregated? Are they separated from lighting altogether? Other metrics for satisfaction and comfort should show what portion of satisfaction and comfort can be attributed to integrated lighting systems.

Additional significant project aspects should provide a description or examples of contract language used during the project design, construction, and occupancy that provide for integrated lighting systems. This should include details regarding systems provisioning with discrete contract language or embedded in existing contracts. Design team processes for lighting systems integration developed in support of the contract language should be clarified, especially to the degree these processes are specified in the contract language. A description of Minimum Performance Criteria (MPC) for lighting systems integration should include the extent to which daylighting and electric lighting, views, and their associated wellness contributions are addressed independently, or as part of an overarching set performance criteria that captures all subcategories.

Wholistic design processes should be described in a design team flowchart and organizational chart, clearly identifying lighting systems design team members. A description of Pre-Design/Planning Activities that support successful achievement of integrated lighting systems metrics, and the extent they are impacted by upstream activities, and whether those activities lead to better integration. A comprehensive description of methods used for verification of integrated lighting systems cost and performance models prior to construction and matching with post construction and occupation metrics. And the characterization of lighting systems integration benchmarks throughout design, construction, and post occupancy stages. Team integration (e.g. knowledge-sharing models, lessons learned) should be evaluated specifically as they address lighting systems integration. Project-based incentives (financial or otherwise) used for meeting total project goals should identify specifically their support of lighting systems integration within incentive structures. Additionally, identifying details of payments for achieving lighting systems integration goals are balanced against other project goals, as well as identifying how energy and non-energy benefits are weighted to achieve lighting systems goals separately and in their fully integrated configuration.

Construction activities specific to lighting systems integration should include a complete description of the use of construction mockups. It should answer questions about lighting systems integration mock-ups being created separately or in combination with other building assemblies. It should clarify the proportion of mock-up cost related to lighting integration and explain impacts on the final construction costs and timelines. Establishment of a metric for describing value of elevated early design scope and increased overall design fee with respect to lighting systems elements where no field modifications could be made. The case study should identify and describe elements of the integrated lighting systems that required full design, and at which phase, as a proof of concept.

Documentation of financial and performance impacts of early integration of the general contractor, architect, engineering, and all sub-contracting parties and the influence this had on the design, construction, and commissioning of the integrated lighting systems. This documentation should include a description of process by which BIM is used as a common tool for field trades to communicate and resolve questions and issues specific to the integrated lighting systems during construction, the frequency of updates to the model, and accuracy of the model at completion of construction, and how BIM documentation describe the lighting systems integration. A description of the methods used for real-time corrections and coordination to the lighting systems integration, and how this is enforced by the team (e.g. contractually or other process).

Integrated lighting systems operations and maintenance activities should be described, including details of design team training activities and costs for training facilities personnel to ensure the lighting systems operate at optimal performance (e.g. contract example and project budget dedicated to this activity). The case study should include metrics showing the impact of occupant and facilities staff training on the integrated lighting systems performance. A discrete metric that identifies the specialized lighting systems integration training is needed for facilities staff and occupants focused exclusively on understanding of how long, and at what cost, the training takes, including: time dedicated annually to make renew facilities staff and occupants knowledge, and to train new staff and building occupants.

There should be a description of how many and what kinds of information and training sessions are used to adequately acquaint building occupants with the specifics of how the integrated lighting systems function, to what extent are operations and maintenance staff involved in these information sessions (delivery of information and attendance, or are they conducted by a third party), and how many, and how frequently, are new staff members and occupants trained in the lighting systems operations. There should be a discrete identification of the specialized efforts needed for knowledge transfer between the design team and the building operations and maintenance staff. Specific costs associated with this knowledge, and any recurring training, and lighting systems specific descriptions, and any measures used to quantify learning objectives from pre-occupation educational programming to apprise occupants about the features and interrelationships between the integrated lighting systems and other building systems. A description of the relationship between occupants and facilities operational staff to highlight the link between integrated lighting systems operation (passive and active) and employees' enjoyment of the workplace environment. This should include documentation of the integrated lighting systems specific feedback systems between occupants and facilities staff, the means and methods used to solicit feedback and information exchange to ensure the proper function of the lighting systems as designed, specified, and commissioned. Finally, a description of BMS, BEMS, integration specific to the Integrated lighting systems, including the subsystems, sensors, meters, and system flexibility, and occupant controls.

A description of post-occupancy evaluation activities should include specific categories relating to integrated lighting systems, how they are measured, what corrective actions are regularly applied, a description of means and methods used to commission the lighting systems, and how they are evaluated after occupancy through a POE evaluation to identify user behavior that is positively and negatively affecting lighting system performance. Documentation of formal measurement and verification process including types and quantities of updates to energy model assumptions to reflect the actual operation. A description and identification of receptacle loads that can be categorized as part of the lighting system, how they are integrated with the permanent building lighting system, and the various types and modes of operation, occupant schedule dependent or other supervisory control methods. A description of how the integrated lighting system is documented in the as-built condition. Identification of qualitative and quantitative changes to the integrated lighting system during and after construction and occupancy. Identification and description of the granularity of the control and data collection specifically dedicated to the integrated lighting system. Creation of a specific integrated lighting systems organizational structure, workflow diagrams, and mechanisms used to both document adherence to the organizational structure and workflow, and make appropriate updates to both. Highlighting of specific contract clauses and sections dedicated to the integrated lighting systems performance and targets.

A Description of the information and tools used by the team should include those specific to integrated lighting systems design used during the design and construction of the project, and recommendations from improvements to workflow and tools. Documentation of interoperability of various tools used, time and fee impact of model building separately to primary models, etc. A description of the specific tools used by the design and construction teams for designing and evaluating the integrated lighting systems, and their impacts on fee with regard to software and hardware interoperability. Should there be interoperability between design and installation software and hardware.

A description of the products and systems used in the project should include the specific decision-making systems used regarding integrated lighting systems that describe how trade-offs in energy use and costs, construction costs, and environmental impact are made. What is the structure of the control systems for lighting integration, how are the specified in the construction documents, what is the basis of design and the sequence of operations needed for these systems.

A description of the energy issues specific to the project should include documentation of the parts of the integrated lighting systems (and to what extent are those systems, or subsystems) are engaged in grid services. A description of the integrated lighting system relative to the minimal building standards defined by the governing codes for the building.

A description of the indoor environmental quality issues specific to the project should include the degree and types of occupant control of the visual environment, and the prediction and confirmation of indoor environmental quality issues that are specific to integrated lighting systems, such as occupant control, feedback mechanisms, and control strategies used to ensure visual comfort. There should be a metric to describe the complexity and count of integrated lighting system zones, and how they are developed relative to occupancy, use-type, and location within the building.

Details of the visual environment should include graphic, tabular, and written descriptions of how lighting levels vary by space use type in the building. Schedules of electric lighting systems that documents system spectrum controls. Operations and maintenance practices describing how replacement systems and lamps will be matched to in situ systems and existing conditions (in existing buildings), or matched to as-built conditions (in recently constructed or renovated buildings). Operations and maintenance practices for documenting occupant satisfaction levels with the visual environment.

A description of the project results specific to the integrated lighting systems should include a publicly viewable dashboard of metrics described above [Specific documentation and display of tabular, graphic, and written descriptions of the integrated lighting systems.

References

- https://sftool.gov/learn/agency-practices/446/iswg-case-studies
- https://sftool.gov/learn/10129/agency-practices
- https://www.nibs.org/page/outcomebasedpathways
- https://newbuildings.org/code_policy/outcome-based-energy-codes/
- https://buildingdata.energy.gov/cbrd/energy_based_acquisition/
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PART 2 - SECTION 1: VISUAL COMFORT IN BUILDINGS

Glare is defined by the International Commission on Illumination (CIE) as a phenomenon that is caused by unsuitable luminances in the field of view, either from a range of luminances that is too broad or from a distribution of luminances that creates extreme contrasts. Such luminance patterns can cause discomfort or can reduce the ability to see details or objects. Discomfort glare is further defined by the CIE as “glare that causes discomfort without necessarily impairing the vision of objects.” Discomfort glare thus describes a subjective sensation (discomfort from glare) that may or may not impair visual performance (disability from glare). For integrated daylight / electric lighting system considerations, discomfort glare from any of the sources of illumination is an important concern.

The human visual system is able to adapt over time to a wide range of luminances, through changes in pupil size and through slower changes in the sensitivity of the rod and cone photoreceptors. Because adaptation takes time, the visual system can adapt to only a limited range of luminances at any given point in time. If the luminance range is too great, regions of the scene that are of excessively high luminance can lead to discomfort. Common examples of such situations include the headlights of oncoming vehicles when driving after dark and direct sunlight through windows in daytime.

Discomfort from glare is not well understood. Despite the existence of many experimental studies of discomfort from glare in various contexts, there is still no agreed model for predicting the likely presence and severity of discomfort. Furthermore, the metrics used for characterizing discomfort glare differ for daylight sources than from electric lighting sources, and the methods used for measuring both the glare-causing stimulus and the human responses vary widely. As a result, the reliability of the metrics in predicting human response remains an open question. This section reviews these topics and outlines possible research needs related to discomfort glare in buildings.

Metrics

Metrics for discomfort glare are universally based on a determination of the contrast between the luminance of the glare source and the luminance of the background to the glare source. The metrics also typically account for the size of the source(s), the location of the source(s), and the number of sources. Within those broad descriptions, though, there are many different expressions that have been used historically for computing metrics of discomfort glare. The full-page chart at the end of this section shows details of different glare metrics that have been derived over the years.

Of the glare metrics shown, the industry has mostly settled on using the Daylight Glare Probability (DGP) metric for glare from daylight and the Unified Glare Rating (UGR) metric for glare from electric light sources. These metrics are reviewed fully by Eble-Hankins and Waters, and Ashdown [51,52]. The UGR has a value between 5 and 30, with a higher value meaning more glare. The DGP has a value between 0 and 1, with a higher number meaning more glare. Importantly, none of the glare metrics account for the spectral power distribution of the glare sources.

Test procedures for discomfort glare research

Experimental designs for studying discomfort glare can be categorized by whether the subject has an external reference for comparison (i.e. absolute or relative measurement), and whether the subject is a passive or an active participant in the experiment, in terms of direct control of the stimulus conditions.[53] Fotios and Kent reported four possible approaches as shown in Table 1; they also detail the measurement issues involved in each approach as summarized below.

Table 7: Basic procedures for explicit quantitative measurement (Fotios and Kent, 2019)

Interaction with the visual scene	**ABSOLUTE MEASUREMENT** **(no external reference present)**	**RELATIVE MEASUREMENT** **(presence of an external reference)**
PASSIVE **(No Interaction)**	Category Rating	Discrimination
ACTIVE **(Interaction Required)**	Adjustment	Matching

Note: *External reference*: a second relevant visual scene is presented whilst assessment of the test scene is made, although not necessarily simultaneously. *Interaction*: within the trial, the visual scene itself can be changed by the actions of the participant. In brightness studies this interaction is limited to one dimension – variation in quantity, such as luminance or illuminance, at a calibration point.

Category Rating is usually a single interval task in which the participant is required to describe the degree of discomfort experienced when observing a visual scene by allocating it to one of a series of categories. There is no consensus as to the number of response points nor the labels of each category and hence these vary between studies. In discomfort from glare studies, category rating is typically used

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[51] Michelle Eble-Hankins, "VCP and UGR Glare Evaluation Systems: A Look Back and a Way Forward," *Leukos* 1 (October 1, 2004): 7–38, https://doi.org/10.1582/LEUKOS.2004.01.02.001.
[52] Ian Ashdown, "Sensitivity Analysis of Glare Rating Metrics," *LEUKOS The Journal of the Illuminating Engineering Society of North America* 2 (October 1, 2005): 115–22, https://doi.org/10.1582/LEUKOS.2005.02.02.003.
[53] Michael Kent and Steve Fotios, "The Effect of a Pre-Trial Range Demonstration on Subjective Evaluations Using Category Rating of Discomfort Due to Glare," *LEUKOS*, July 23, 2019, 1–16, https://doi.org/10.1080/15502724.2019.1631177.

as a single-interval task in which different visual scenes are presented and evaluated individually, in succession. Potential experimental biases introduced by the category rating method include: stimulus range bias, pre-trial demonstration, order effects, response scale design (including the number of response categories, number of rating items, category labels, language translation, and common understanding). In addition, statistical analyses of category rating data must address whether parametric or non-parametric statistics are appropriate.

Discrimination requires the participant to report which of two scenes presents the greater degree of discomfort (also known as pair comparison). The two scenes are presented in spatial or temporal juxtaposition and the conditions of both are fixed for a given trial. Discrimination has been rarely used in discomfort studies.

Adjustment is a single-interval task in which only a single visual scene is observed; judgements are made against an internal (memory) reference: a two-interval task is one in which two visual scenes are observed, the scene being judged and a visual comparison. Potential experimental biases introduced by the adjustment method include: stimulus range bias, anchor effects, order effects, direct versus indirect control, visual task, and effect sizes of different factors. Experimental projects using the method of adjustment must consider these biases during the planning process.

Matching presents participants with two scenes in spatial or temporal juxtaposition. One scene is the reference and remains unchanged. Participants are instructed to vary the glare source luminance of the second (test) scene until it matches as near as possible the degree of discomfort portrayed by the reference scene. Matching has been rarely used in discomfort studies.

Measurement of glare response: Physiological and other measures

In addition to the subjective psychophysical approaches that have been common in discomfort glare research, advances in various physiological and other measurement techniques show promise for documenting the effect of glare sources on humans.[54] Fotios and Kent provide a summary of past studies that have measured discomfort using methods other than subjective psychophysical procedures. [55] Such methods include measuring changes in pupil size, electrograms using techniques such as electromyography (EMG) , extent of eye opening, brain activity such as measured through functional magnetic resonance imaging (fMRI), gaze behavior, and behavioral responses such as closing window blinds or changing seating positions and view direction.

Measurement of glare conditions (stimulus)

Discomfort glare is fundamentally an issue of luminance contrasts. Consequently, characterizing the stimulus conditions that may create discomfort depends on measuring luminances in realistic settings. Historically, these measurements have been conducted using hand-held “spot” luminance meters to capture the luminance values of multiple points within the field of view. Since a full characterization of the elements of the field of view that may contribute to glare requires many measurements, and since the accuracy of each measurement depends on careful aiming and focusing of the luminance meter,

[54] Michael Kent and Steve Fotios, “The Effect of a Pre-Trial Range Demonstration on Subjective Evaluations Using Category Rating of Discomfort Due to Glare,” *LEUKOS* (July 23, 2019): 1–16.
[55] Steve Fotios and Michael Kent, “Measuring discomfort from glare: Recommendations for good practice. (Draft paper prepared for PNNL and submitted for publication in LEUKOS.)” (2019).

data collection is very labor intensive. As a result, many of the past studies on glare had limited characterizations of the luminance distributions within the space of interest.

More recently, high dynamic range imaging (HDRI) devices have been used for luminance measurement in architectural applications. For example, the development and initial evaluations of the Daylight Glare Probability (DGP) metric were based on images using a scientific-grade CCD camera.[56] More recently, other researchers have used luminance data derived from HDRI using commercial cameras for glare evaluations and the development of potential new metrics for glare[57,58,59,60,61,62]

Many remaining questions about how to identify and measure the luminance of the glare source(s) and of the background to the glare source(s) are still unresolved. Furthermore, the sources and magnitude of errors in luminance measurement through HDRI are an active current topic of research. [63]

Research needs

- Explorations of using physiological and other measures of glare response to assess their convergence with more traditional psychophysical measures;
- Experimental research to assess the alignment of the current metrics (DGP, UGR) with human responses to glare;
- Validation studies of measurement and simulation tools used to determine glare metrics to evaluate the sources of error in capturing the different elements of the metrics (luminances, geometry, size, etc.) and the impact of those errors on the metrics;
- Research towards a new glare metric based on human visual science that addresses discomfort from daylight and electric lighting systems in complex scenes

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[56] Jan WIENOLD and Jens CHRISTOFFERSEN, "Evaluation Methods and Development of a New Glare Prediction Model for Daylight Environments with the Use of CCD Cameras," *Special Issue on Daylighting Buildings*, no. 7 (2006): 743.
[57] Hongyi Cai, "High Dynamic Range Photogrammetry for Synchronous Luminance and Geometry Measurement," *Lighting Research and Technology* 45 (April 1, 2013): 230–57, https://doi.org/10.1177/1477153512453273.
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[59] Jae Yong Suk, Marc Schiler, and Karen Kensek, "Development of New Daylight Glare Analysis Methodology Using Absolute Glare Factor and Relative Glare Factor," *Energy and Buildings* 64 (June 7, 2013), https://doi.org/10.1016/j.enbuild.2013.04.020.
[60] Kevin Van den Wymelenberg and Mehlika Inanici, "A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight," *LEUKOS* 10, no. 3 (July 3, 2014): 145–64, https://doi.org/10.1080/15502724.2014.881720.
[61] Kevin Van Den Wymelenberg and Mehlika Inanici, "Evaluating a New Suite of Luminance-Based Design Metrics for Predicting Human Visual Comfort in Offices with Daylight," *LEUKOS* 12, no. 3 (2016): 113–38, https://doi.org/10.1080/15502724.2015.1062392.
[62] Kevin Van den Wymelenberg, Mehlika Inanici, and Peter Johnson, "The Effect of Luminance Distribution Patterns on Occupant Preference in a Daylit Office Environment," *LEUKOS* 7, no. 2 (October 2010): 103–22, https://doi.org/10.1582/LEUKOS.2010.07.02003.
[63] Sarah Safranek and Robert G. Davis, "HDRI for Luminance measurement: A literature review of four sources of error. (Draft paper prepared by PNNL and submitted for publication in LEUKOS.)," 2019.

- Exploring and delineating test procedures and methods that are suited for integrated daylight and electric lighting scenarios.
- Developing models for integrated lighting system controls that address energy and visual comfort.

PART 2 - SECTION 2: NON-VISUAL EFFECTS OF LIGHTING AND POSSIBLE IMPACTS ON HUMAN HEALTH

Research exploring human physiological responses to light and continued advances in SSL technology have aligned with an increasing demand for healthier buildings by building owners and occupants, including greater access to daylighting. Interest in WELL™ [64] certified spaces, where the wellness of building occupants is the primary focus of architectural design, has increased rapidly in the past few years. The renewed focus on health, along with advances in SSL technology capabilities, has underscored that there is still much to learn regarding the relationship between light and human physiology. The energy implications of designing to address these possible physiological effects are not yet fully understood. Beyond the fact that the basic metric of luminous efficacy (lumens per watt) does not apply to light's stimulation of non-visual physiological effects, the emerging science seems to indicate that addressing a holistic view of the human needs in most applications may mean a need for increased light exposure. This increase in light has an associated increase in energy use if it is met only by electric lighting systems. Consequently, the energy use intensity for lighting may exceed levels predicted by luminous flux-based analyses for traditional applications which are based solely on visual task performance.

Metrics

While the full relationship between light and human biological functioning is not fully understood, several techniques have emerged to estimate the possible relative effects of different light sources based on their spectral content, usually characterized as the spectral power distribution (SPD). For example, the equivalent melanopic lux (EML) metric was derived from a journal paper and spreadsheet toolboxpublished by Lucas et al. [65] . This method determines the melanopic illuminance (EML) by weighting the SPD of the light source by the spectral efficiency function of the photoreceptors that have the most direct influence on non-visual effects of light, the intrinsically photosensitive retinal ganglion cells (ipRGCs). A ratio of the EML to the standard visual illuminance, determined by weighting the source SPD by the photopic visual efficiency function, V(λ), can then be calculated for each light source.

The EML metric as defined in the Lucas et al. paper is not compliant with the International System of Units (SI), because illuminance and its unit of lux are defined only in terms of the standard visual response in the SI system and EML uses a different response function. As a result, the International Commission on Illumination (CIE) has approved an alternate, SI-compliant method for evaluating melanopic content, referred to as melanopic equivalent daylight illuminance (EDI)[66].

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[64] International WELL Building Institute. WELL v2, 2018. https://v2.wellcertified.com/v/en/overview. Accessed 09/05/2019.

[65] Robert Lucas et al., "Measuring and Using Light in the Melanopsin Age," *Trends in Neurosciences* 37 (November 25, 2013), https://doi.org/10.1016/j.tins.2013.10.004.

[66] CIE S 026:2018. CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. Vienna, Austria: CIE Central Bureau; 2018.

The EML metric is based solely on the ipRGC response without including separate contributions from other photoreceptors. However, Lucas et al.[67] explained that the biological effects of light in humans, such as the suppression of melatonin, are influenced by all of the photoreceptors, not just the ipRGCs,. Furthermore, the relationship between different levels of EML and biological responses such as melatonin suppression is not known.

An alternative metric which purports to address these shortcomings, circadian stimulus (CS), has been proposed by Rea and Figueiro[68,69,70]. The CS metric was designed to be proportional to the suppression of nocturnal melatonin production and depends first on a determination of circadian light (CL_A). The underlying math for CL_A and thus for CS considers the spectral composition of the light at the eye as weighted by relative contributions of all five photoreceptor types (ipRGCs, rods, and three types of cones), in part by incorporating the blue-yellow (b-y) opponent processing mechanisms associated with the short-, medium-, and long-wavelength sensitive cones. If the b-y calculation indicates "blue" then the output of the cones modifies the ipRGC response in determining CL_A; if the b-y calculation does not indicate "blue" then the ipRGC response alone determines CL_A and thus CS. This technique for including the possible role of all photoreceptors in melatonin suppression had not been widely accepted by the medical community at the time of this paper.

Analytic tools are readily available for calculating the EML, melanopic irradiance, and CS values for a given SPD and illuminance at the eye. But to implement these new metrics, target criteria are needed for different applications and desired outcomes. Establishing criteria for non-visual goals is complicated because our understanding of these processes is still emerging, as Lucas explains[71]:

> "Although melanopsin phototransduction is only engaged at moderate to high irradiance, ipRGCs and their downstream responses can be responsive to much lower levels of illumination. For example, it was originally thought that illuminance of 2500 lux was required to suppress nocturnal melatonin in humans[72], but later studies have shown that under certain conditions, as little as 1 lux or less can suppress melatonin in humans[73]."

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[67] Lucas et al., "Measuring and Using Light in the Melanopsin Age."
[68] Mark Rea and Mariana Figueiro, "Light as a Circadian Stimulus for Architectural Lighting," *Lighting Research and Technology* 50 (December 6, 2016), https://doi.org/10.1177/1477153516682368.
[69] Mark Rea et al., "Circadian Light," *Journal of Circadian Rhythms* 8 (February 1, 2010): 2, https://doi.org/10.1186/1740-3391-8-2.
[70] Mark Rea, "Toward a Definition of Circadian Light," *Journal of Light & Visual Environment* 35 (January 1, 2011): 250–54, https://doi.org/10.2150/jlve.35.250.
[71] Robert Lucas et al., "Measuring and using light in the melanopsin age," *Trends in neurosciences* 37 (November 25, 2013).
[72] Alfred Lewy et al., "Light Suppresses Melatonin Secretion in Humans," *Science (New York, N.Y.)* 210 (January 1, 1981): 1267–69, https://doi.org/10.1126/science.7434030.
[73] Gena Glickman et al., "Inferior Retinal Light Exposure Is More Effective than Superior Retinal Exposure in Suppressing Melatonin in Humans," *Journal of Biological Rhythms* 18 (February 1, 2003): 71–79, https://doi.org/10.1177/0748730402239678.

Recommendations for practice

Recommendations for appropriate levels of EML or CS have not been adopted by a recognized industry standards organization. However, there are currently three primary organizations with documents that recommend methods for designing lighting to account for the human non-visual system: The International WELL Building Institute ™ (IWBI ™), Underwriters Laboratory (UL), and the Collaborative for High Performance Schools (CHPS). The IWBI maintains WELL, also known as The WELL Building Standard™. In 2014 the first WELL document was published with the goal of defining design features that support and advance human health and wellness. The WELL v2 pilot was released by IWBI in the first half of 2018, with quarterly updates continuing through the second half of 2019. CHPS operates on the same foundational concepts as WELL (including water and thermal comfort, etc.) and has a point-based system with both required and flexible design strategies for compliance.

UL 24480, "Recommended Practice and Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People" is solely focused on circadian-effective lighting. The document describes how circadian-effective lighting designs are to be accomplished and verified, based on the circadian stimulus (CS) metric.

The initial WELL standard refers to a single non-visual metric, equivalent melanopic lux (EML). However, revised WELL standard v2 includes the circadian stimulus (CS) metric as an alternative path. UL RP 24480 only provides guidance for implementing CS. CHPS mentions CS and EML metrics in their latest update but lacks guidance on how to apply these metrics. No authoritative body, including the Illuminating Engineering Society (IES) and International Commission on Illumination (CIE), has standardized or promoted the use of either of these metrics. Although EML was originally developed through consensus, there is no agreement regarding how to use the metric, and there are now variations of the original metric[74]. Despite the uncertainty and lack of consensus, these metrics are continuing to gain increasing attention in lighting, healthcare, and education industries.

Software tools

Widely used lighting software programs, such as AGi32 and Radiance, rely on simplifying assumptions about surfaces and light sources. AGi32 is commercial software with a user-friendly interface but it does not account for any spectral properties of the light source or the surface reflectances. Radiance is open-source software that lacks a user-friendly interface and that considers a simple three-channel (RGB) spectral model for light sources and surfaces; these three channels provide roughly 130nm of spectral resolution. The growing interest in designing spaces that consider the human non-visual responses to light combined with the emergence of tunable SSL systems as a design strategy has motivated the development of software tools capable of predicting both the intensity and spectrum of light at the eye, with greater spectral resolution needed to account for the narrow band nature of SSL sources and of the different human response functions of interest. Accounting for the spectral interaction of light with

[74] CIE S 026:2018. CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light. Vienna, Austria: CIE Central Bureau; 2018.

objects and materials in the built environment requires complex computations, especially as tunable LED lighting systems allow more dynamic control of the spectrum from a single luminaire.

Common practice for calculating non-visual metrics includes simulating or measuring the illuminance at the eye and then using the rated SPD of the luminaire to calculate EML or CS. Valuable information pertaining to the viewing direction, architectural surfaces, furnishing, and location of luminaires is not considered when using this method. There can be a significant difference between the SPD of the luminaires and the SPD measured vertically at the eye, caused by spectral absorption and reflection of optical radiation as it moves throughout space and interacts with surfaces and objects, as well as by the possible mixture of daylight and multiple electric light sources.

One new software tool capable of such computations is Adaptive Lighting for Alertness (ALFA), commercially available through Solemma, LLC. ALFA is built on the Radiance calculation engine but improves upon it, by considering SRDs for all surfaces and SPDs for all light sources, both of which are discretized into 81 values, 5 nm increments, across the visible spectrum. Although researchers are using this new tool for preliminary electric lighting simulations, the software has yet to be fully validated, and the developers have not yet included the many additional variables introduced by integrated building facades and daylighting.

Energy consequences

The energy consequences associated with meeting the current recommendations for EML and CS are not addressed by WELL, UL RP 24480, or CHPS Core Criteria 3.0. Previous GATEWAY field evaluations[75] [76] [77] found that current IES illuminance recommendations are too low to meet EML and CS recommendations. One evaluation found that the illuminance levels had to be doubled to meet CS recommendations. The results of the ALFA simulations of electric lighting conducted Safranek et al.[78] support the results of previous GATEWAY reports: meeting current IES illuminance recommendations will not satisfy current EML and CS recommendations.

For some simulations that met non-visual metric recommendations, average illuminance was more than double the IES recommendations along with high CCTs, beyond what is typically considered acceptable for office and classroom settings. In the case of simulations for an office, only one set of parameters (6200K CCT luminaires with horizontal illuminance of over 800 lx and high reflectance room and desk surfaces) was able to meet the requirement of EML ≥ 240 at all seated view positions to earn 3 points by the WELL v2 2019 Q2 Circadian Lighting Design feature. This simulation condition increased energy use

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[77] SF Safranek and RG Davis, *Evaluating Tunable Lighting in Classrooms,* PNNL-27806, Sept 2018.

[78] Sarah Safranek et al., “Energy impact of human health and wellness lighting recommendations for office and classroom applications,” in press for publication in *Energy and Buildings,* July 2020.

by 30% even at the minimum suggested duration. No classroom simulation conditions were able to meet the CHPS Core Criteria 3.0 recommendations of EML ≥ 250 or CS ≥ 0.3 at 75% of seated view positions. The highest average EML and CS values in the classroom, 288 EML and 0.34 CS, were achieved at 6200 K and 100% light output, resulting in greater energy consumption and likely an undesirable visual environment due to the high CCT and light output.

The variables considered for the office and classroom ALFA simulations were limited to specifically compare intensity and SPD of electric light in the built environment. Additional variables, like those discussed in the following section, have not yet been considered in detail. Still, it seems clear that, the emerging demands for higher intensities of light in buildings may significantly affect the energy-saving possibilities of SSL lighting systems, if those systems alone must meet the new requirements.

Research needs

According to the current non-visual metric models, it is important to increase lighting stimulus in intensity and short wavelength spectral content during the day and reduce light levels and short wavelength spectral content in the evening and at night to support healthy sleep. While these changes in lighting spectrum and intensity can be accomplished through implementation of tunable SSL systems, the close coordination of a tunable electric lighting system with an integrated façade (which may include adjustable factors in glazing and shading) can enable optimization of the related energy uses. But this coordination is not currently feasible without further research.

Research in the following topics is suggested for optimizing the energy use of future buildings designed to meet a holistic set of human needs. (The authors note that some of this work is included in a multi-year PNNL-LBNL collaborative research project funded by DOE.)

- **Daylight contributions**: The WELL v2 2019 Q2 Circadian Lighting Design feature has different circadian metric recommendations if daylight is considered. It is possible to model daylight and electric light simultaneously in ALFA; however, given that ALFA is a new software tool, the full implications of using it for complex modeling of an integrated daylight-electric light system over the course of a year have not yet been explored. As daylight and integrated facades designed for better daylight delivery introduce many variables into the modeling process, especially when it is desirable to account for the full spectral effects of these variables, accounting for daylight contributions can quickly add complexity to simulation models and increase the computation time. Managing the required computation time will require some documentation of the possible errors introduced by simplifying assumptions that might be needed for faster computing. Furthermore, ALFA and other simulation tools have not been fully validated for this type of simulation work; simulations of physical spaces where confirmatory measurements can be taken are needed.

- **Luminaire distribution, output, and SPD setpoints**: Considering a wide range of luminaires with different form factors and color mixing strategies from different manufacturers will provide a more comprehensive non-visual metric investigation. Given that many tunable luminaires are capable of full 0-100% dimming and fine-tune color control, careful consideration will be needed of the trade-offs between the number of simulated conditions desired and the required computation time. Again, research that explores the range of errors introduced into simulations through simplifying assumptions is an important element.

- **Space types**: The preliminary electric lighting simulations described above focused on specific open office and classroom space types. To better understand the potential national energy implications on the entire US building stock, a more thorough consideration of building types is needed, along with the relative importance of the non-visual effects of lighting within different building types.

- **Climate effects**: In considering the potential effects of daylighting on non-visual responses, it seems likely that certain climates will rely more on electric lighting than daylight to satisfy non-visual requirements. Full analysis of energy implications will need to address the differential effects of climate and physical location.

- **More complex existing or theoretical SPDs:** Access to spectral modeling tools like ALFA makes it possible to vary model parameters to include theoretical SPDs that may not exist in commercial products. These simulations may help demonstrate the potential advantages and drawbacks of these theoretical SPDs that have been optimized for balancing considerations related to efficacy and non-visual metrics.

PART 2 - SECTION 3: INTEGRATION OF HARDWARE & CONTROLS FOR DAY- AND ELECTRIC LIGHTING SYSTEMS

Integrating facades and electric lighting systems has significant implications for the hardware and control algorithms of both types of systems. At present, several relevant issues are evident:

- Facade and electric lighting automated systems are, with rare exceptions, separate, with control hardware and software that are not set up to communicate with the other system.
- Automated systems may have the capability to communicate using generic protocols (e.g., BACnet) but don't necessarily have the algorithms to act in accordance to other systems' status or behavior. This can technically be achieved but usually requires an extensive effort by highly skilled personnel to design, implement and, often, also to maintain; at present, this may not be a practicable option for most buildings.
- Where direct communication between facade and electric lighting isn't present (the overwhelming majority of cases), lighting control systems aren't able to deal optimally with changes in the facade - especially the case for light-redirecting systems - because sensing alone isn't able to ascertain whether changes in the daylit environment are due to changes in outdoor conditions or changes in the fenestration; at present, facade or electric lighting systems are also not able to sense the intensity distribution of daylight entering the space.
- At present, sensing for lighting controls and automated facade systems infers interior light levels from secondary measurements of light levels at other locations (usually, but not always, the ceiling). This often results in suboptimal lighting system behavior which can cause both occupant dissatisfaction and increased energy use.
- While the technical capability to sense the color of the ambient light exists, sensing for lighting controls and automated facade systems is usually geared toward photopic illuminance - i.e., has no ability to sense the non-visual stimulus provided by daylight. This is appropriate when the principal concern is to provide an adequate amount of light but does not have the capability to address the potential impact of provided light levels on the circadian rhythm of the building occupants. Characterizing the spectral quality of light in a daylit space requires accurate sensing of both the spectrum of available daylight as well as the spectrum of the electric light sources, which may vary throughout the lifetime of the lighting system. It may also require sensing of the spectrum of the light reflected by the space itself, which depends on the spectral optical properties of the surface finishes present in the space.

In order to address these issues and enable the successful integration of electrical lighting and facade hardware and controls in a wide variety of building types and throughout design, installation, commissioning and operations, research on the following topics is needed:

- Two-way communication between lighting and facade controls. Several technology standards for building system interoperability already exist (e.g., BACnet, Modbus) and others are in development (e.g., an interoperability standard for lighting controls is in development by ANSI/NEMA). Specifically for the integration of facades and electric lighting, research is needed on topics that include:

  - o The types of communication protocols that are appropriate for facade/electric lighting integration.
  - o The manner in which facade and control algorithms should act in concert to maximise comfort and minimize energy use.
  - o How to achieve appropriate interoperability and sustained operation quickly at installation and commissioning time.

- Accurate work plane illuminance sensing for lighting and facade controls. (Note: “work plane” is used here in a general sense and can be taken to mean the traditional horizontal desk plane or other points of interest such as computer monitor or occupant’s eye.) This can include:
  - o Accurately predicting workplane illuminance from sensors or sensor networks placed remotely (e.g., on ceiling or walls at some distance from the workplane).
  - o Integrating workplane-mounted sensors into lighting/facade control systems.
  - o Sensing changes in daylight distribution due to changes at the facade.
  - o Sensing intensity distribution of daylight from windows.
  - o Privacy implications of sensing for facade and lighting systems.
- Spectral power distribution (SPD) sensing. Research needs include:
  - o Cost-effective hardware for SPD sensing.
  - o Effective sensor density and placement. This is analogous to the topic above, but for SPD sensing. It also includes determining effective sensor density and placement *per se* and also how to implement in a non-research-grade commissioning situation.
  - o Appropriate wavelength resolution and accuracy of sensors.
- Identifying potential market for electric lighting and facade integration, including consideration of:
  - o New construction vs. retrofit
  - o Space and building types, including those specific to government applications
  - o Occupancy model – owner occupied vs lease/rental
  - o Regional variations in climate and other factors

- Benefits to building resilience to environmental, power-supply or other disruptions

- Identifying potential for interaction and/or integration with other building systems, including:
  - Heating, ventilation, and air conditioning (HVAC)
  - Other building sensors (e.g., CO2 air quality sensors to enhance accuracy of occupancy sensing)
  - Building automation and energy management systems

- Characterizing and monitoring changes in the actuation and effect of dynamic facades, such as blinds or shades or smart glazing, over their lifetime:
  - Early Fault Detection and Diagnostics (FDD) using shared sensors
  - Modeling and monitoring of daylighting and solar gains over time
  - Monitoring/control of daylight-redirecting devices and autonomous adjustment over time (e.g., in response to aging of components), using sensors shared between different building systems.

- Characterizing and monitoring changes in the light output and SPD of SSL sources over their lifetime, including:
  - Models for light output and SPD of SSL sources over their lifetime
  - Procedures for the experimental characterization of light output and SPD of SSL sources over time
  - Sensing strategies for in situ monitoring of light output and SPD changes throughout the lifetime of SSL sources

- Similarly to the above topic, characterizing and monitoring the impact of facade systems on the SPD of daylight, or the ability of the façade to control such SPD.

- Appropriate control approaches for integrating electric lighting and façade in order to achieve energy efficiency, resilience, comfort and well-being, including consideration of:
  - Model-predictive control techniques
  - Sensor networks; sensor sharing between systems

- Demonstrating value and non-energy co-benefits of facade and electric lighting integration, including:
  - Cost-effectiveness (including upfront and O&M costs; also financial benefits from increased productivity and/or desirability of the space)

- Resilience/adaptability
- Thermal and visual comfort
- Health and wellness
- Aesthetics

- Other research directions
  - Neuromorphic sensors: sensors that act like the human visual system have the promise of sensing the luminous environment in a way that emulates human response [Indiveri 2000]. This could lead to more reliable sensing of glare and spectral effects of lighting.
  - Lighting systems that can adapt to the impact of facade systems (shading devices, chromogenic windows) on the spectrum of daylight. Facade systems can change the spectrum of daylight admitted to buildings. This may or may not be appropriate to the time of the day/year; with adequate sensing and interoperability capabilities, spectrally-tunable lighting systems have the potential to address this issue. While the beginnings of such systems already exist, additional research is needed, including how to evaluate their effectiveness at meeting human needs and how to control them to best meet such needs.
  - Both active facade and SSL systems rely on direct current (DC) power. The potential to integrate these systems at the level of a DC power grid needs to be explored. This would allow deeper integration between them as well as enabling potential integration with local photovoltaic (PV) power generation. This would in turn enable autonomous, resilient operation.
  - Separately from the facade, lighting controls themselves are still complex to install and commission. Integrating them with facade systems will only add to this challenge. Hardware and software strategies are needed to simplify the installation, commissioning and O&M of integrated electric lighting and facade systems.
  - Integration of building systems can add complexity. Research is needed on ways to enable these systems to self-detect faults and operational issues and then self-correct and/or report to facility management ways that:
    - Minimize need for facility management intervention
    - Are flexible enough to allow for future additions

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PART 2 - SECTION 4: COMPUTER SIMULATION AND SOFTWARE FOR INTEGRATION OF DAY- AND ELECTRIC LIGHTING SYSTEMS

There are a wide variety of software packages that are used to predict light distribution and intensity within the built environment. These software packages span a broad spectrum in terms of speed, ease-of-use, and accuracy, used at various stages of design. Simulation software is used for modeling at a detailed level, and the two most widely used algorithms are ray-tracing and radiosity. Radiosity algorithms are based on the rasterization concept. Light distribution is calculated by dividing room surfaces into small patches and tracking how much light is emitted from the source to each patch, and, subsequently, the amount of light leaving this patch to other patches that are in the field of view. One of the most common software packages that utilize this method is AGI32 [Lighting Analysts, 2020], which is popular among the lighting designers in the U.S. Some of the shortcomings of the radiosity method include challenges with non-perfectly-diffuse surfaces and non-scalability as geometric complexity increases. Ray-tracing is another simulation method that addresses both of the disadvantages discussed. Light is traced from the viewpoint into and bounced around in the environment, reflected, absorbed, and in the end reaching the light source (backwards ray-tracing), or from light sources into the environment (forward ray-tracing). Backwards ray-tracing is efficient in the sense that, of all light 'rays' in an environment, we only care about the ones that are important to the interested viewpoint. However, this method by itself faces challenges when the light sources are difficult to find through optically complex geometry and materials, such as light redirecting films and specularly reflective blinds; in these cases forward-raytracing is more efficient. As explained in Part 2 Section 2, current simulation software using any of these approaches provides limited capabilities for spectral modeling..

One of the most popular physically-driven[79] ray-tracers is Radiance. [Ward Larson, 1998]. Radiance is an open source, physically-based ray-tracing engine mainly for lighting and daylighting simulation, whose development started in 1984 at Lawrence Berkeley National Lab. It consists of a series of source code libraries and around 100 command-line tools, which are widely used by the R&D community. Radiance uses a combination of deterministic and stochastic (Monte Carlo) ray-tracing: it is deterministic when dealing with direct sun and specular reflections and stochastic when trying to figure out the diffuse interreflection between the objects, which allows for physically accurate global illumination. Another advantage of a backward ray-tracer such as Radiance is that it scales computationally well as geometry gets more complicated, which is a critical advantage when predicting luminance-based visual comfort metrics as the state-of-the-art luminaires and window systems are optically/geometrically complex. Radiance is commonly used in daylighting design, although it was originally designed for electric lighting calculation. Rendering an image using a backward ray-tracer can take a considerably longer time than when using rasterization. However, there are R&D efforts on both the software (Matrix-based simulation) and hardware side (e.g., Graphical Processing Units) to address these limitations. Also,

[79] I.e., aimed at rendering images and calculating quantities in a manner consistent with the physics of light, rather than merely rendering images that appear realistic.

photon-mapping is a forward-raytracing module recently added to Radiance to complement its backward-raytracing method [Schregle, 2015].

When simulating visible light as part of the solar spectrum, the common practice is to divide the calculation into three channels, commonly referred to as red, green, and blue. As part of the foundation of color science developed in the 20th century, RGB is used ubiquitously to display color in devices such as TVs and cell phones. RGB channels are weighted individually to the human visual response to calculate the perceived 'brightness' of the object. For the non-visual aspect of the human eye, the sensitivity response shifts to a lower-wavelength part of the spectrum. For predicting metrics such as circadian stimulus, the division of spectrum will need to be reconsidered as to how many channels and how to divide them. Existing tools are attempting to address this need by evenly dividing the 380nm to 780nm into 81 channels (ALFA [Solemma, 2020a]), or dividing the existing RGB channels into thirds to a total of nine channels (LARK [University of Washington, 2020]).

Several tools exist that allow Radiance to be used through a graphical user interface. For example, DIVA [Solemma, 2020b] can be used to iterate daylighting and energy modeling and uses Radiance for lighting calculations. It has a graphical user interface that allows users to perform complex lighting calculations without having to write code. Both as a standalone tool and as an engine, Radiance is capable of performing accurate and fast simulations of optically complex fenestration systems (e.g., venetian blinds). More recently, the extension of these capabilities to fenestration systems not in the plane of the window (e.g., awnings) has been developed and validated.

In order to perform accurate daylighting calculations, lighting software packages need accurate data on the optical properties of window materials. WINDOW [Mitchell, 2019a] and OPTICS [LBNL, 2020] and their associated glazing and shading databases are software packages that enable the generation of optical data that can be used by some lighting software (e.g., Radiance) to correctly characterize the way facade systems interact with incident daylight.

The outputs from the array of software tools that is available to simulate the lighting behavior of facade and electric lighting systems mainly include light levels across the space, surface brightness maps , quantitative glare metrics, and rendered images of spaces. The tools that can address the spectral effects of daylight on the human visual system also can output specific metrics related to these effects. The more complex tools, such as DIVA, that allow the combination of lighting simulation engines with energy simulation and optimization capabilities can output space or building designs optimized according to parameters set by the user. These tools can be used to compute the effects of both daylight and electric lighting on lighting energy use and overall energy performance. While they currently offer an impressive array of capabilities, several research gaps are evident on the path to further integration of electric lighting and facades.

The increased relevance of the non-visual effects of lighting has led to the development of software, such as ALFA or LARK mentioned above, that can perform simulation for an extended range of visible wavelengths. However, at the moment these pose several issues. One is that this software has not gone through the extensive experimental validation process that is required for ensuring that results reflect physical reality. Another is that the kind of input data that are commonly available for lighting simulation software – sun and sky models, optical properties of materials, light source/luminaire characteristics - are oriented towards the computation of photopic photometric quantities. All these still need to be extended so that they encompass a more appropriate range of spectral data; research on the appropriate amount and accuracy of spectral data is also needed.

Another important research and development gap are software tools specifically aimed at facade/electric lighting integration. The most advanced existing tools can already be - and are, by the most sophisticated practitioners - used to achieve space designs that make the best of the interactions between electric lighting and the facade. However, mostly for reasons of cost and/or complexity, this is not practicable in the majority of new buildings or deep retrofits that take place due to budget constraints, time constraints and/or design team skill limitations. Tools that allow quick modeling in order to make early- and mid-design decisions are therefore needed. Tools focused on early facade design decisions already exist (e.g., COMFEN [Mitchel, 2019b]) and extending this category of software to more extensively address the interactions between facades and electric lighting would facilitate design workflows for integrated facade and electric lighting systems.

Additionally, substantial work remains to be done in both educating practitioners on the available software tools. Conversely, as different audiences increasingly seek to justify decisions with data, there is a need for tailoring tools and their outputs to the needs of practitioners like architects and engineers, as well as contractors who are involved in installing and commissioning products installed in buildings. Some of these audiences may be happy to invest significant effort on expert tools, while others may prefer tools with intuitive, easy to learn user interfaces. If simulation tools can be made more intuitive without losing accuracy, their user base will be broadened and it will be more likely that they are used to aid in the early stage of building design.

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APPENDICES

PART 1 - SECTION 1: INSTITUTIONAL AND ORGANIZATIONAL INERTIA WORKING AGAINST INTEGRATION

Table 8: Research priorities by scoping study section, year, and focus of research effort.

	1.1: Institutional and organizational inertia working against integration	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Primary Focus	Secondary Focus
1.1a	Address professional knowledge and skills gap											Education, Professional	Simulation Tools
1.1b	Skillsets and standardize education of CX agents											Education, Professional	Standards & Guidelines
1.1c	Commissioning standards for daylighting systems											Standards & Guidelines	Education, Professional
1.1d	Mapping voluntary standards to state and local codes											Standards & Guidelines	Benefits, Energy
1.1e	Guidelines for implementation of building codes											Standards & Guidelines	Education, Professional
1.1f	Broadly based TAC to promote trust in recommendations and guidelines											Standards & Guidelines	Education, Industry
1.1g	Develop better BIM lighting model export (IFC or other)											Simulation Outcomes	Education, Professional
1.1h	Evaluation of priorities for R&D based on buildings climate zone											Case Studies	Research Outcomes
1.1i	Integration recommendations for new/existing buildings controls											Sensors & Controls	Case Studies
1.1j	Controls recommendations (disaggregated, decentralized, or device specific)											Sensors & Controls	Case Studies
1.1k	Standard for sensor types and locations for best controls											Sensors & Controls	Standards & Guidelines

1.1l	ROI and SPB models for ALCS based on new project delivery types	Benefits, Energy	Sensors & Controls
1.1m	Validating non-energy benefits for ROI and SPB investment timeline	Case Studies	Benefits, Non-Energy
1.1n	Lease types by building age, geographic location, building size, use-type, etc.	Finance & Real Estate	Case Studies
1.1o	Mapping of construction projects against lease type differences	Finance & Real Estate	Standards & Guidelines
1.1p	Lease structures to disrupt split incentive dilemma	Finance & Real Estate	Benefits, Energy
	1.2: Literature Review of Glare, Day- & Electric Lighting Systems		
1.2a	Publication outcomes of research projects at national labs	Research Outcomes	Education, Professional
1.2b	Evaluation of moving research results into industry best practices	Education, Industry	Research Outcomes
1.2c	Establish standards for minimal accepted number of human subjects	Research Standards	Standards & Guidelines
1.2d	Establish standards to clearly define research types in publications	Research Standards	Standards & Guidelines
1.2e	Verify results of publication outcomes of research projects at national labs	Research Outcomes	Education, Professional
1.2f	Verify results of information transfer into industry best practices	Education, Industry	Research Outcomes
1.2g	Verify application of standards / guidelines to clearly define research types	Research Standards	Standards & Guidelines

1.2h	Verify application of standards / guidelines for minimal number of human subjects	Research Standards	Standards & Guidelines
	1.3: Critical information for systems integration case studies		
1.3a	Establish baseline criteria for case studies that include metrics, graphics, contracts examples	Case Studies	Education, Professional
1.3b	Verify impact of new case study criteria on dissemination and AEC best practices	Education, Professional	Case Studies
	2.1: Visual comfort in buildings		
2.1a	Explorations of physiological glare response to assess convergence with psychophysical measures	Simulation Background	Benefits, Non-Energy
2.1b	Assess alignment of current metrics (DGP, UGR) with human responses to glare	Simulation Background	Benefits, Non-Energy
2.1c	Validation studies of measurement and simulation tools used to determine glare metrics	Simulation Validation	Benefits, Non-Energy
2.1d	Unified glare metric based on human visual science to addresses discomfort	Simulation Background	Standards & Guidelines
	2.2: Non-visual effects of lighting / possible impacts on human health		

2.2a	Understanding peak of complex modeling for full spectral effects for circadian stimulus	Simulation Background	Research Outcomes
2.2b	Document errors introduced by simplifying assumptions for managing computation time	Simulation Background	Research Outcomes
2.2c	Document simulation error range from simplifying assumptions for managing computation time	Simulation Outcomes	Research Outcomes
2.2d	Criteria for modeling processes for full spectral effects / computation time for circadian stimulus	Simulation Background	Standards & Guidelines
2.2e	Simulating wide range of luminaires with different form factors and color mixing strategies	Simulation Outcomes	Research Outcomes
2.2f	National energy implications for entire US building stock by building typology	Benefits, Energy	Finance & Real Estate
2.2g	Characterize importance of non-visual effects within different building types and climate zones	Benefits, Non-Energy	Simulation Background
2.2h	Validation of software for simulation of complex lighting systems with full spectral effects	Simulation Validation	Benefits, Energy
2.2i	Simulations of physical spaces with confirmatory measurements	Simulation Validation	Research Outcomes
2.2j	Documentation of trade-offs for simulations and required computation time for advanced luminaires	Simulation Outcomes	Research Outcomes
2.2k	Exploration of use of spectral modeling tools to vary model parameters for theoretical SPDs	Simulation Outcomes	Research Outcomes

	2.3: Integration of Hardware / Controls for Day- and Electric Lighting Systems		
2.3a	Development of interoperability protocols for integration of facades and electric lighting	Standards & Guidelines	Standards & Guidelines
2.3b	Predicting workplane illuminance from sensors without regard for placement of other systems	Simulation Background	Sensors & Controls
2.3c	Identifying potential market for ALCS / facade integration for new vs. existing space / building types	Finance & Real Estate	Sensors & Controls
2.3d	Identifying potential market for ALCS / facade integration for climate and regional variations	Finance & Real Estate	Sensors & Controls
2.3e	Identifying potential market for ALCS / facade integration for impact on building resilience	Finance & Real Estate	Sensors & Controls
2.3f	Identifying potential for interaction and/or integration with occupancy sensing for controls	Sensors & Controls	Simulation Background
2.3g	Characterizing and monitoring changes in light output and SPD of SSL sources over their lifecycle	Simulation Background	Case Studies
2.3h	Demonstrating value of non-energy / co-benefits of facade and electric lighting integration.	Benefits, Non-Energy	Simulation Background
2.3i	Development of interaction level between controls – fully integrated to opportunistic / parasitic.	Sensors & Controls	Simulation Background

2.3j	Achieve interoperability and sustained operation over full system life cycle		Systems Interoperability	Sensors & Controls
2.3k	Cost-effective hardware for ubiquitous SPD sensing and effective sensor density and placement		Sensors & Controls	Standards & Guidelines
2.3l	Implement non-research-grade CX / establish appropriate wavelength resolution / accuracy of sensors		Sensors & Controls	Standards & Guidelines
2.3m	Best control approaches for integrating electric lighting and façade		Standards & Guidelines	Sensors & Controls
2.3n	Develop systems that adapt to impact of facade systems on spectrum of daylight.		Sensors & Controls	Simulation Outcomes
2.3o	Potential to integrate active facade and SSL systems at the level of a DC power grid		Benefits, Non-Energy	Sensors & Controls
2.3p	Develop Hardware / software strategies to simplify install, CX, and O&M of controls		Standards & Guidelines	Sensors & Controls
2.3q	Enabling systems to self-detect faults / operational issues and self-correct and/or report		Systems Interoperability	Sensors & Controls
	2.4: Simulation and Software for Integration			
2.4a	Develop accurate (cross-platform compatible) data on optical properties of window materials		Simulation Outcomes	Education, Professional
2.4b	Understand appropriate amount and accuracy of spectral data		Simulation Background	Standards & Guidelines

2.4c	Develop experimental validation process to ensure that results reflect physical reality	Simulation Validation	Research Outcomes
2.4d	Input data for lighting simulation software extended to encompass spectral data	Simulation Background	Research Outcomes
2.4e	Development of tools for quick modeling for early- and mid-design decisions	Simulation Outcomes	Education, Professional
2.4f	Extend existing tools to focus on early facade design decisions	Simulation Tools	Education, Professional
2.4g	Educating practitioners on successful integration into industry practices.	Education, Professional	Simulation Tools
2.4h	Development of ability to tailor tools and outputs to various industries	Simulation Tools	Education, Professional
2.4i	Facilitate design workflows for integrated facade and electric lighting systems	Simulation Tools	Education, Professional
2.4j	Development of simulation tools that are more intuitive without losing accuracy	Simulation Tools	Education, Professional

PART 1 - SECTION 2A: LITERATURE REVIEW OF GLARE, ELECTRIC LIGHTING, & DAYLIGHTING SYSTEMS

Below are the articles, theses, dissertations, standards, guidelines, and other publications read for the scoping study.

Word and Phrase Analysis Articles

Twenty-two separate articles had a word and phrase analysis performed on the text of the documents. Those articles are listed below.

	Articles Analyzed
1	Andrew McNeil and Galen E. Burrell, “APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE,” 2016.
2	Anna Maria Atzeri, Francesca Cappelletti, and Andrea Gasparella., “Comparison of Different Glare Indices through Metrics for Long Term and Zonal Visual Comfort Assessment.,” in Proceedings of the 15th IBPSA Conference (IBPSA 2017, San Francisco, CA, USA, 2017), 1194–1203, https://doi.org/10.26868/25222708.2017.311.
3	Christoph F REINHART and Jan WIENOLD, “The Daylighting Dashboard: A Simulation-Based Design Analysis for Daylit Spaces,” Building and Environment, no. 2 (2011): 386.
4	Clotilde Pierson, Jan Wienold, and Magali Bodart, “Daylight Discomfort Glare Evaluation with Evalglare: Influence of Parameters and Methods on the Accuracy of Discomfort Glare Prediction,” Buildings 8 (July 24, 2018): 94, https://doi.org/10.3390/buildings8080094.
5	Clotilde Pierson, Jan Wienold, and Magali Bodart, “Discomfort Glare Perception in Daylighting: Influencing Factors,” Energy Procedia 122 (September 1, 2017): 331–36.
6	Iason Konstantzos and Athanasios Tzempelikos, “Daylight Glare Probability Measurements and Correlation with Indoor Illuminance in a Full-Scale Office with Dynamic Shading Controls,” July 1, 2014.
7	Jeff Shuster, “Addressing Glare in Solid-State Lighting,” Ephesus, January 2014.
8	Kevin Van den Wymelenberg and Mehlika Inanici, “A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” LEUKOS 10, no. 3 (July 3, 2014): 145–64, https://doi.org/10.1080/15502724.2014.881720.
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11	M. Alrubaih et al., “Research and Development on Aspects of Daylighting Fundamentals,” Renewable and Sustainable Energy Reviews 21 (May 1, 2013): 494–505, https://doi.org/10.1016/j.rser.2012.12.057.
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13	Michael Kent, Steve Fotios, and Sergio Altomonte, “Discomfort Glare Evaluation: The Influence of Anchor Bias in Luminance Adjustments,” Lighting Research & Technology, October 13, 2017, 147715351773428, https://doi.org/10.1177/1477153517734280.
14	Nathaniel Jones and C. Reinhart, “Experimental Validation of Ray Tracing as a Means of Image-Based Visual Discomfort Prediction,” Building and Environment 113 (February 15, 2017): 131–50, https://doi.org/10.1016/j.buildenv.2016.08.023.
15	Rizki A. Mangkuto et al., “Determination of Discomfort Glare Criteria for Daylit Space in Indonesia,” Solar Energy 149 (June 1, 2017): 151–63.
16	Sian Kleindienst and Marilyne Andersen, “The Adaptation of Daylight Glare Probability to Dynamic Metrics in a Computational Setting” 2009 (January 1, 2009).
17	T. Porsch et al., “MEASUREMENT OF THE UNIFIED GLARE RATING (UGR) BASED ON USING ILMD,” n.d.
18	Urszula Blaszczak, “Method for Evaluating Discomfort Glare Based on the Analysis of a Digital Image of an Illuminated Interior,” Metrology and Measurement Systems 20 (December 10, 2013): 623–634, https://doi.org/10.2478/mms-2013-0053.
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20	Yu Bian and Yuan Ma, “Subjective Survey & Simulation Analysis of Time-Based Visual Comfort in Daylit Spaces,” Building and Environment 131 (March 1, 2018): 63–73.
21	Yu Bian, Tianxiang Leng, and Yuan Ma, “A Proposed Discomfort Glare Evaluation Method Based on the Concept of ‘Adaptive Zone,’” Building and Environment 143 (October 1, 2018): 306–17.
22	Zahra S. Zomorodian and Mohammad Tahsildoost, “Assessing the Effectiveness of Dynamic Metrics in Predicting Daylight Availability and Visual Comfort in Classrooms,” Renewable Energy 134 (April 1, 2019): 669–80, https://doi.org/10.1016/j.renene.2018.11.072.

Research Typology Analysis

Seventy-eight separate articles, reports, and presentations were analyzed for the type of research, number of research subjects, and other research details relevant to understanding how lighting systems are evaluated. Those articles, reports, and presentations are listed below.

	Articles Analyzed
1	A. Mahi, K. Galicinao, and K. Van Den Wymelenberg, “A Pilot Daylighting Field Study: Testing the Usefulness of Laboratory-Derived Luminance-Based Metrics for Building Design and Control,” Building & Environment 113 (2017): 78–91.
2	Alfonso Gago-Calderon et al., “Evaluation of Uniformity and Glare Improvement with Low Energy Efficiency Losses in Street Lighting LED Luminaires Using Laser-Sintered Polyamide-Based Diffuse Covers,” Energies 11 (April 2, 2018): 816, https://doi.org/10.3390/en11040816.
3	Amin Alah Ahadi, Mahmoud Reza Saghafi, and Mansoureh Tahbaz, “The Study of Effective Factors in Daylight Performance of Light-Wells with Dynamic Daylight Metrics in Residential Buildings q,” Solar Energy 155 (January 14, 2019): 679–697, https://doi.org/10.1016/j.solener.2017.07.005.
4	Andrew McNeil and Galen E. Burrell, “APPLICABILITY OF DGP AND DGI FOR EVALUATING GLARE IN A BRIGHTLY DAYLIT SPACE,” 2016.

5	Andrew McNeil, Eleanor S. Lee, and Jacob C. Jonsson, “Daylight Performance of a Microstructured Prismatic Window Film in Deep Open Plan Offices,” Building and Environment 113 (February 2017): 280–97, https://doi.org/10.1016/j.buildenv.2016.07.019.
6	Anna Maria Atzeri, Francesca Cappelletti, and Andrea Gasparella., “Comparison of Different Glare Indices through Metrics for Long Term and Zonal Visual Comfort Assessment.,” in Proceedings of the 15th IBPSA Conference (IBPSA 2017, San Francisco, CA, USA, 2017), 1194–1203, https://doi.org/10.26868/25222708.2017.311.
7	Apiparn Borisuit, Jean-Louis Scartezzini, and Anothai Thanachareonkit, “Visual Discomfort and Glare Rating Assessment of Integrated Daylighting and Electric Lighting Systems Using HDR Imaging Techniques.,” Architectural Science Review 53, no. 4 (December 2010): 359–73.
8	Carlos E OCHOA et al., “Considerations on Design Optimization Criteria for Windows Providing Low Energy Consumption and High Visual Comfort,” Applied Energy, 2012, 238.
9	Cheng Sun et al., “A Longitudinal Study of Summertime Occupant Behaviour and Thermal Comfort in Office Buildings in Northern China,” Building and Environment 143 (October 1, 2018): 404–20.
10	Christoph F REINHART and Daniel A WEISSMAN, “The Daylit Area — Correlating Architectural Student Assessments with Current and Emerging Daylight Availability Metrics,” Building and Environment, 2012, 155.
11	Christoph F REINHART and Jan WIENOLD, “The Daylighting Dashboard: A Simulation-Based Design Analysis for Daylit Spaces,” Building and Environment, no. 2 (2011): 386.
12	Clotilde Pierson, Jan Wienold, and Magali Bodart, “Daylight Discomfort Glare Evaluation with Evalglare: Influence of Parameters and Methods on the Accuracy of Discomfort Glare Prediction,” Buildings 8 (July 24, 2018): 94, https://doi.org/10.3390/buildings8080094.
13	Clotilde Pierson, Jan Wienold, and Magali Bodart, “Discomfort Glare Perception in Daylighting: Influencing Factors,” Energy Procedia 122 (September 1, 2017): 331–36.
14	D. Sawicki and A. Wolska, “Discomfort Glare Prediction by Different Methods.,” Lighting Research & Technology 47, no. 6 (October 2015): 658–71.
15	Dalia Hafiz, “Daylighting, Space, and Architecture: A Literature Review,” Enquiry, The ARCC Journal for Architectural Research, Applied Effects, 12, no. 1 (December 2015), https://doi.org/10.17831/enq:arcc.v12i1.391.
16	Danny H. W LI, “A Review of Daylight Illuminance Determinations and Energy Implications,” Applied Energy, no. 7 (2010): 2109.
17	Doris A. Chi, David Moreno, and Jaime Navarro, “Correlating Daylight Availability Metric with Lighting, Heating and Cooling Energy Consumptions,” Building and Environment 132 (March 15, 2018): 170–80.
18	Fabio SICURELLA, Gianpiero EVOLA, and Etienne WURTZ, “A Statistical Approach for the Evaluation of Thermal and Visual Comfort in Free-Running Buildings,” Energy and Buildings, 2012, 402.
19	Gene-Harn Lim et al., “Daylight Performance and Users’ Visual Appraisal for Green Building Offices in Malaysia,” Energy & Buildings 141 (April 15, 2017): 175–85.
20	Gyeong Yun, Kap Yoon, and Kang Kim, “The Influence of Shading Control Strategies on the Visual Comfort and Energy Demand of Office Buildings,” Energy and Buildings 84 (December 1, 2014): 70–85, https://doi.org/10.1016/j.enbuild.2014.07.040.
21	Hiroshi Takahashi et al., “Position Index for the Matrix Light Source,” Journal of Light & Visual Environment 31 (January 1, 2007): 128–33, https://doi.org/10.2150/jlve.31.128.
22	Iason Konstantzos and Athanasios Tzempelikos, “Daylight Glare Evaluation with the Sun in the Field of View through Window Shades,” Building and Environment 113 (February 15, 2017): 65–77.

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24	Ing Liang Wong, “A Review of Daylighting Design and Implementation in Buildings,” Renewable and Sustainable Energy Reviews 74 (July 1, 2017): 959–68.
25	J. Alstan Jakubiec and Christoph F. Reinhart, “A Concept for Predicting Occupants’ Long-Term Visual Comfort within Daylit Spaces,” LEUKOS 12, no. 4 (2016): 185–202, https://doi.org/10.1080/15502724.2015.1090880.
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27	Jae Yong Suk, “Luminance and Vertical Eye Illuminance Thresholds for Occupants’ Visual Comfort in Daylit Office Environments,” Building and Environment 148 (January 1, 2019): 107–15, https://doi.org/10.1016/j.buildenv.2018.10.058.
28	Jeff Shuster, “Addressing Glare in Solid-State Lighting,” Ephesus, January 2014.
29	Joon-Ho Choi, Vivian Loftness, and Azizan Aziz, “Post-Occupancy Evaluation of 20 Office Buildings as Basis for Future IEQ Standards and Guidelines,” September 1, 2012, https://doi.org/10.1016/j.enbuild.2011.08.009.
30	K.A. Kurnia et al., “Visual Comfort Assessment Using High Dynamic Range Images under Daylight Condition in the Main Library Building of Institut Teknologi Bandung,” Procedia Engineering 170 (December 31, 2017): 234–39, https://doi.org/10.1016/j.proeng.2017.03.056.
31	Kevin Van den Wymelenberg and Mehlika Inanici, “A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight,” LEUKOS 10, no. 3 (July 3, 2014): 145–64, https://doi.org/10.1080/15502724.2014.881720.
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33	L. Bellia, A. Cesarano, and G.F. Iuliano, “Daylight Glare: A Review of Discomfort Indexes.,” Semantic Scholar, 2008.
34	Laura Bellia, Francesca Fragliasso, and Emanuela Stefanizzi, “Daylit Offices: A Comparison between Measured Parameters Assessing Light Quality and Users’ Opinions,” Building and Environment 113 (February 15, 2017): 92–106.
35	Line Karlsen, Per Heiselberg, and Ida Bryn, “Occupant Satisfaction with Two Blind Control Strategies: Slats Closed and Slats in Cut-off Position,” Solar Energy 115 (May 31, 2015), https://doi.org/10.1016/j.solener.2015.02.031.
36	Lisa Heschong, “Daylighting in Schools An Investigation into the Relationship Between Daylighting and Human Performance Condensed Report,” August 20, 1999, https://doi.org/10.13140/RG.2.2.31498.31683.
37	M. Alrubaih et al., “Research and Development on Aspects of Daylighting Fundamentals,” Renewable and Sustainable Energy Reviews 21 (May 1, 2013): 494–505, https://doi.org/10.1016/j.rser.2012.12.057.
38	M. B HIRNING et al., “Post Occupancy Evaluations Relating to Discomfort Glare: A Study of Green Buildings in Brisbane,” Building and Environment, 2013, 349.
39	M. B HIRNING, G. L ISOARDI, and I COWLING, “Discomfort Glare in Open Plan Green Buildings,” Energy and Buildings, 2014, 427.

40	M.B. Hirning, G.L. Isoardi, and V.R. Garcia-Hansen, “Prediction of Discomfort Glare from Windows under Tropical Skies,” Building and Environment 113 (February 15, 2017): 107–20.
41	M.G. Kent et al., “Temporal Variables and Personal Factors in Glare Sensation,” Lighting Research & Technology 48, no. 6 (October 1, 2016): 689–710.
42	Mahsan Mohsenin and Jianxin Hu, “Assessing Daylight Performance in Atrium Buildings by Using Climate Based Daylight Modeling,” Solar Energy 119 (September 1, 2015): 553–60.
43	Marie-Claude Dubois et al., Monitoring Protocol for Lighting and Daylighting Retrofits A Technical Report of IEA SHC Task 50 Subtask D, Report T50.D3, 2016.
44	Marilyne Andersen, “Unweaving the Human Response in Daylighting Design,” Building and Environment 91 (March 1, 2015), https://doi.org/10.1016/j.buildenv.2015.03.014.
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46	Mark Rea, “Lighting Simply Made Better: Providing a Full Range of Benefits without Much Fuss,” Building and Environment 144 (July 1, 2018), https://doi.org/10.1016/j.buildenv.2018.07.047.
47	Matt Jungclaus et al., “Deep Energy Retrofits in Federal Buildings: The Value, Funding Models, and Best Practices,” ASHRAE Transactions 123, no. Part 1 (2017): 55–70.
48	Mehlika Inanici and Alireza Hashemloo, “An Investigation of the Daylighting Simulation Techniques and Sky Modeling Practices for Occupant Centric Evaluations,” Building and Environment 113 (February 15, 2017): 220–31.
49	Michael B. Hirning, “The Application of Luminance Mapping to Discomfort Glare : A Modified Glare Index for Green Buildings” (PhD, 2014), https://eprints.qut.edu.au/72926/.
50	Michael Kent, Steve Fotios, and Sergio Altomonte, “Discomfort Glare Evaluation: The Influence of Anchor Bias in Luminance Adjustments,” Lighting Research & Technology, October 13, 2017, 147715351773428, https://doi.org/10.1177/1477153517734280.
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53	Nuanwan Tuaycharoen., “The Reduction of Discomfort Glare from Windows by Interesting Views.” (Dissertation, University of Sheffield, 2006).
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55	R. D. Clear, “Discomfort Glare: What Do We Really Know?,” Lighting Research and Technology 45, no. 2 (2013): 141–158.
56	R. G. Hopkinson, “Evaluation of Glare,” Illuminating Engineering 52 (1957): 305–16.
57	Rizki A. Mangkuto et al., “Determination of Discomfort Glare Criteria for Daylit Space in Indonesia,” Solar Energy 149 (June 1, 2017): 151–63.
58	Roberto German Rodriguez, Julieta A. Yamín Garretón, and Andrea E. Pattini, “An Epidemiological Approach to Daylight Discomfort Glare,” Building and Environment 113 (February 15, 2017): 39–48.
59	Seyed Amir Sadeghi et al., “Occupant Interactions with Shading and Lighting Systems Using Different Control Interfaces: A Pilot Field Study,” Building and Environment 97 (February 15, 2016): 177–95, https://doi.org/10.1016/j.buildenv.2015.12.008.

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64	View, Inc., "Visual Comfort and Energy Benefits of View Smart Windows in Workplaces," View, Inc, September 2019.
65	Wonwoo Kim, Hyunjoo Han, and Jeong Kim, "The Position Index of a Glare Source at the Borderline between Comfort and Discomfort (BCD) in the Whole Visual Field," Building and Environment - BLDG ENVIRON 44 (May 1, 2009): 1017–23, https://doi.org/10.1016/j.buildenv.2008.07.007.
66	Y. Huang and Tsung-Hsien Wang, Automatic Calculation Of A New China Glare Index, 2016.
67	Ying-Chieh CHAN and Athanasios TZEMPELIKOS, "Efficient Venetian Blind Control Strategies Considering Daylight Utilization and Glare Protection," Solar Energy, 2013, 241.
68	Ying-Chieh Chan, Athanasios Tzempelikos, and Iason Konstantzos, "A Systematic Method for Selecting Roller Shade Properties for Glare Protection," Energy & Buildings 92 (April 1, 2015): 81–94.
69	Yu Bian and Tao Luo, "Investigation of Visual Comfort Metrics from Subjective Responses in China: A Study in Offices with Daylight," Building and Environment 123 (October 1, 2017): 661–71
70	Yu Bian and Yuan Ma, "Analysis of Daylight Metrics of Side-Lit Room in Canton, South China: A Comparison between Daylight Autonomy and Daylight Factor," Energy & Buildings 138 (March 1, 2017): 347–54.
71	Yu Bian and Yuan Ma, "Subjective Survey & Simulation Analysis of Time-Based Visual Comfort in Daylit Spaces," Building and Environment 131 (March 1, 2018): 63–73.
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73	Yulia I. Tyukhova, "DISCOMFORT GLARE FROM SMALL, HIGH LUMINANCE LIGHT SOURCES IN OUTDOOR NIGHTTIME ENVIRONMENTS." (PhD dissertation, University of Nebraska–Lincoln, 2015).
74	Yulia Tyukhova and Clarence Waters, "Discomfort Glare from Small, High-Luminance Light Sources When Viewed against a Dark Surround," LEUKOS, April 5, 2018, 1–16, https://doi.org/10.1080/15502724.2018.1434415.
75	Yulia Tyukhova, "Comparison of Discomfort Glare Metrics for Small, High-Luminance Light Sources in Outdoor Nighttime Environments" (2016 SSL Technology Development Workshop, November 16, 2016).
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77	Zahra S. Zomorodian and Mohammad Tahsildoost, "Assessing the Effectiveness of Dynamic Metrics in Predicting Daylight Availability and Visual Comfort in Classrooms," Renewable Energy 134 (April 1, 2019): 669–80, https://doi.org/10.1016/j.renene.2018.11.072.

78	Zhe Kong et al., "The Impact of Interior Design on Visual Discomfort Reduction: A Field Study Integrating Lighting Environments with POE Survey," Building and Environment 138 (April 1, 2018), https://doi.org/10.1016/j.buildenv.2018.04.025.

Publisher type, publication date, and audience analysis

453 separate articles, standards, guidelines, reports, conference proceedings, books, and other publications were analyzed for their publication date, publisher, and perceived audience. Those documents are below.

	First Author	Title	Publication	Year
1	Abbaszadeh	Occupant satisfaction within door environmental quality in green buildings	Proceedings of Healthy Buildings	2006
2	Akaike	A new look at the statistical model identification	IEEE	1974
3	Altomonte	Visual task difficulty and temporal influences in glare response	Building and Environment	2016
4	Altomonte	Task Difficulty, Temporal Variables and Glare Response	Proceedings of PLEA Conference on Passive and Low Energy Architecture	2016
5	Alwaer	Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings	Solar Energy & Environment	2010
6	Ander	Daylighting performance and design	J Wiley & Sons	2003
7	ANSI/ASHRAE/USGBC/IES	189.1 Standard for the design of high-performance green buildings	ASHRAE	2010
8	Aries	Windows, view, and office characteristics predict physical and psychological discomfort	Journal of Environmental Psychology	2010
9	Aries	Windows, view, and office character-istics predict physical and psychological discomfort	Journal of Environmental Psychology	2010
10	Arnal	Consideration of glare from daylight in the control of the luminous atmosphere in buildings	IEEE	2011
11	Aschehoug	Daylight In Buildings: A Source Book on DaylightingSystems and Components	IEA SHC Task 21 / ECBCS Annex 29	2000
12	ASHRAE	ASHRAE/ANSI Standard 55–2013: Thermal Environmental Conditions for Human Occupancy	ASHRAE	2013
13	ASHRAE	Performance Measurement Protocols for Commercial Buildings	ASHRAE	2010

14	Asif	Energy supply its demand and security issues for developed and emerging economies	Renewable and Sustainable Energy Reviews	2007
15	Atzeri	Comfort metrics for an integrated evaluation of buildings performance	Energy & Buildings	2016
16	Badan Standardisasi Nasional	(BSN) SNI 03–2396-2001: 2009. Guidelines for designing daylighting system in buildings: Application of automated blind for daylighting in tropical region	Energy Conversion and Management	2009
17	Baker	Daylight design of buildings	Earthscan / James & James	2002
18	Baker	We are all outdoor animals: Architecture City Environment	Proceedings of PLEA Conference on Passive and Low Energy Architecture	2000
19	Baker	Daylight Design of Buildings: a Handbook for Architects and Engineers	Routledge	2014
20	Bargary	Proceedings of Building Simulation	Neuropsychologia	2015
21	Bell	Designing buildings for daylight	Building Research Establishment	1995
22	Bellia	Daylit offices: a comparison between measured parameters assessing light quality and users' opinions	Building and Environment	2017
23	Bellia	Daylight Glare: A Review of Discomfort Indexes	Università degli Studi di Napoli Federico II	2008
24	Bennett	The demographic variables of discomfort glare	Lighting Design and Application	1977
25	Berman	The Influence of Spectral Composition on Discomfort Glare for Large-Size Sources	Illuminating Engineering Society of North America	1995
26	Bian	Investigation of visual comfort metrics from subjective responses in China : a study in of fi ces with daylight	Building and Environment	2017
27	Bian	Investigation of visual comfort metrics from subjective responses in China: a study in offices with daylight	Building and Environment	2017
28	Bian	Subjective survey & simulation analysis of time-based visual comfort in daylit spaces	Building and Environment	2018
29	Bian	Analysis of daylight metrics of side-lit room in Canton, south China: a comparison between daylight autonomy and daylight factor	Energy & Buildings	2017
30	Bian	Optimization of building daylighting design on the basis of reference sky luminance distribution model	Journal S. China Univ. Technol	2015
31	Blackwell	Contrast thresholds of the human eye	Journal of the Optical Society of America	1946

32	Bordass	Daylight use in open-plan offices: the opportunities and the fan-tasies	Chartered Institution of Building Services Engineers National Lighting Conference	1992
33	Borisuit	Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood	Lighting Research & Technology	2014
34	Borisuit	A new device for dynamic luminance mapping and glare risk assessment in buildings	Proceedings. SPIE 8485	2012
35	Boubekri	Effect of window size and sunlight presence on glare	Lighting Research & Technology	1992
36	Bourassa	Mechanism of binocular increase of discomfort to high luminance	Nature	1966
37	Bourgeois	A standard daylight coefficient model for dynamic daylighting simulations	Building Research & Information	2008
38	Boyce	The benefits of daylight through windows	Lighting Research Center	2003
39	Brembilla	Influence of Input Reflectance Values on Climate- Based Daylight Metrics Using Sensitivity Analysis	Journal of Building Performance Simulation	2018
40	Brotas	The Average Total Daylight Factor	Light & Engineering	2006
41	Brotas	Daylight in urban canyons: planning in Europe	Proceedings of PLEA Conference on Passive and Low Energy Architecture	2006
42	BSI	BS EN 15251 indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.	BSI Group	2007
43	Burton	Passive solar energy as a fuel Energy Conservation in Building—the achievement of 50% energy savings (1990–2000)	Proceedings of the NORTHSUN	1990
44	Busch	Energy-efficient lighting in Thai commercial buildings	Energy	1993
45	Cabus	Luminous efficacy of daylighting in inter tropical region: an analysis for toplighting systems	Renewable Energy	1996
46	Cai	Improving the quality of high dynamic range images	Lighting Research & Technology	2011
47	Cantin	Daylighting metrics based on illuminance distribution glare and directivity	Lighting Research & Technology	2011
48	Cauwerts	Comparison of the vignetting effects of two identical fisheye lenses	Journal of the Illuminating Engineering Society	2012

49	Chaiwiwatworakul	Evaluation of sky luminance and radiance models using data of north Bangkok	Journal of the Illuminating Engineering Society	2004
50	Chan	A systematic method for selecting roller shade properties for glare protection	Energy & Buildings	2015
51	Chan	Real-world measurements for call of duty: advanced warfare	Physically Based Shading in Theory and Practice	2015
52	Chan	A hybrid ray-tracing and radiosity method for calculating radiation transport and illuminance distribution in spaces with venetian blinds	Solar Energy	2012
53	Chan	Eff. venetian blind control strat. considering daylight util. and glare protection	Solar Energy	2013
54	Chauvel	Daylight as a source of visual discomfort: Daylighting Atlas, vol 2	Joule	1995
55	Chauvel	Glare from windows: current view of the problem	Lighting Research & Technology	1982
56	Chel	A modified model for estimation of daylight factor for skylight integrated with dome roof structure of mud-house in New Delhi (India)	Applied Energy	2010
57	Chendo	Hourly global and diffuse radiation of Lagos, Nigeria – correlation with some atmospheric parameters	Solar Energy	1994
58	Chi	Optimization method for perforated solar screen design to improve daylighting using orthogonal arrays and climate-based daylight modelling	Journal Building Performance Simulation	2017
59	China National Standard	Standard for daylighting design of buildings [S].	China National Standard (GB 50033-2013):	2013
60	China National Standard	Evaluation standard for green building [S].	China National Standard (GB 50378-2016):	2016
61	Chirarattananon	Daylight availability and models for global and diffuse horizontal illuminance and irradiance for Bangkok	Renewable Energy	2002
62	Chirarattananon	Daylight availability and models for global and diffuse horizontal illuminance and irradiance for Bangkok	Renewable Energy	2002
63	Chou	Predicted simulation on the lighting energy saving in a classroom using the sun shading as the daylight-introducing device	Proceedings of PLEA Conference on Passive and Low Energy Architecture	2004
64	Christoffersen	The New European Standard (PrEN 17037) in Buildings e a Brighter Future ? Part 2	Chartered Institution of Building Services Engineers	2016

65	Chung	A study of luminous efficacy of daylight in Hong Kong	Energy & Buildings	1992
66	CIBSE	CIBSE Lighting Guide 10: Daylighting and Window Design	Chartered Institution of Building Services Engineers	1999
67	CIBSE	C Code for interior lighting	The Chartered Institute of Building Services Engineers	1994
68	CIBSE	Energy efficiency in buildings, CIBSE guide F	The Chartered Institute of Building Services Engineers	2004
69	CISE	Environmental design	Chartered Institution of Building Services Engineers	1999
70	CLC	Occupational Safety & Health	Butterworths, PartII	1991
71	Clear	Discomfort glare: what do we really know?	Lighting Research & Technology	2013
72	Cohen	Passive solar design of a Montessori primary-school: Energy Conservation in Building—the achievement of 50% energy savings	Proceedings of the NORTHSUN	1990
73	Collaborative for High Performance Schools	Best practices manual	http://www.chps.net/	2010
74	Commission Internatiónal e de l'Éclairage (CIE)	Spatial Distribution of Daylight e CIE Standard General Sky	Joint ISO/CIE Standard ISO	2003
75	Commission Internatiónal e de l'Éclairage (CIE)	Spatial Distribution of Daylight e CIE Standard Overcast Sky and Clear Sky	Joint ISO/CIE Standard ISO	1996
76	Commission Internatiónal e de l'Éclairage (CIE)	CIE 117-1995: Discomfort Glare in Interior Lighting	International Commission on Illumination (CIE)	1995
77	Commission Internatiónal e de l'Éclairage (CIE)	CIE 117–1995: Discomfort glare in interior lighting	International Commission on Illumination (CIE)	1995

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337	Reinhart	Development and validation of a radiance model for a translucent panel	Energy & Buildings	1999
338	Reinhart	Dynamic RADIANCE-based daylight simulations for a full-scale test office with outer venetian blinds	Energy & Buildings	1991
339	Reinhart	Findings from a survey on the current use of daylight simulations in building design	Energy & Buildings	2013
340	Reinhart	The simulation of annual daylight illuminance distributions e a state-of-the-art comparison of six RADIANCE-based methods	Energy & Buildings	1990
341	Reinhart	Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds	Energy & Buildings	2010
342	Reinhart	Daysim version 3.0	http://daysim.com	2003
343	Reinhart	Glare Analysis of Daylit Spaces: Recommendations for Practice. Online	http://web.mit.edu/tito/www/Projects/Glare/GlareRecommendationsForPractice.html	1996
344	Reinhart	Dynamic daylight performance metrics for sustainable building design	Journal of the Illuminating Engineering Society	1995
345	Reinhart	Experimental validation of 3ds Max design 2009 and Daysim 3.0	Journal of the Illuminating Engineering Society	1995

346	Reinhart	Experimental validation of Autodesk® 3ds Max® design 2009 and daysim 3.0	Journal of the Illuminating Engineering Society	1995
347	Reinhart	Predicting the daylit area—a comparison of students assessments and simulations at eleven schools of architecture	Journal of the Illuminating Engineering Society	1995
348	Reinhart	Monitoring manual control of electric lighting and blinds	Lighting Research & Technology	1995
349	Reinhart	Effects of interior design on the daylight availability in open plan offices; 2010	National Research Council of Canada Institute for Research in Construction	1983
350	Reinhart	Tutorial on the use of daysim simulations for sustainable design	National Research Council of Canada Institute for Research in Construction	1987
351	Reinhart	LIGHTSWITCH 2002: a model for manual and automated control of electric lighting and blinds	Solar Energy	1970
352	Reinhart	Simulation-based daylight performance predictions: Building performance simulation for design and operation	Taylor & Francis	2008
353	Robbins	Daylighting, Design and Analysis	Van Nostrand Reinhold	1988
354	Robertson	Estimation-theoretic approach to dynamic range enhancement using multiple exposures	Journal of Electronic Imaging	2013
355	Roche	Occupant reactions today light in offices	Lighting Research & Technology	2009
356	Roche	Summertime performance of an automated lighting and blinds control system	Lighting Research & Technology	2010
357	Rockcastle	Human perceptions of daylight composition in architecture: a preliminary study to compare quantitative contrast measures with subjective user assessments in HDR renderings	Proceedings of the 14th International Conference of IBPSA	2011
358	Rodriguez	An epidemiological approach to daylight discomfort glare	Building and Environment	2008
359	Rodriguez	Glare and cognitive performance in screen work in the presence of sunlight	Lighting Research & Technology	2005
360	Rogers	Daylighting metric development using daylight autonomy calculations in the sensor placement optimization tool (http://www.archenergy.com/SPOT/download.html)	Architectural Energy Corporation	2001
361	Ruck	Daylight in buildings: a sourcebook on daylighting systems and components	Lawrence Berkeley National Laboratory	2011

362	Ruppertsberg	Rendering complex scenes for psychophysics using RADIANCE: how accurate can you get?	Journal of the Optical Society of America	2011
363	Rushmeier	Comparing real and synthetic images: some ideas about metrics	National Institute of Standards and Technology	1995
364	Sabry	Smart windows: thermal modelling and evaluation	Solar Energy	2012
365	Saridar	The impact of applying recent facade technology on daylighting performance in buildings in eastern Mediterranean	Building and Environment	1983
366	Saur	Influence of physiological factors on discomfort glare level	Optometry & Vision Science	2001
367	Selkowitz	High performance glazing systems: architectural opportunities for the 21st century	Glass Procesessing Days	2010
368	Shehabi	The lightharvesting potential of dynamic daylighting windows	Energy & Buildings	1969
369	Shen	Energy and visual comfort analysis of lighting and daylight control strategies	Building and Environment	1979
370	Shen	Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading	Building and Environment	2015
371	Shin	View types and luminance effects on discomfortglare assessment from windows	Energy & Buildings	2005
372	Singh	Illuminance estimation and daylighting energy savings for Indian regions	Renewable Energy	2009
373	Sivak	Discomfort glare is task dependent	UMTRI	2001
374	Sp€ath	Fitting affine and orthogonal transformations between two sets of points	Math. Commun. 9 (2004) 27e34.	1966
375	Speed	The effect of adaptation levels and daylight glare on office workers' perception of lighting quality in open plan offices	Architectural Science Review	2013
376	Stein	Mechanical and electrical equipment for buildings	J Wiley & Sons	2003
377	Stringham	Macular Pigment and Visual Performance in Glare: Benefits for Photostress Recovery, Disability Glare, and Visual Discomfort	Investigative Ophthalmology & Visual Science	1990
378	Stringham	Spatial Properties of Photophobia	Investigative Ophthalmology & Visual Science	1999
379	Stumpfel	Direct HDR capture of the sun and sky	Proceedings of the 3rd International Conference on Computer Graphics	1999

380	Sudan	Dynamic analysis of daylight metrics and energy saving for rooftop window integrated flat roof structure of building	Solar Energy	2002
381	Suk	Investigation of existing discomfort glare indices using human subject study data	Building and Environment	2015
382	Suk	Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor	Energy & Buildings	2009
383	Suk	Investigation of Evalglare software, daylight glare probability and high dynamic range imaging for daylight glare analysis	Lighting Research & Technology	1975
384	Sze	Indoor environmental conditions in New York City public school classrooms e a survey	Harvard University, Master in Design Studies Thesis	2015
385	Tennessen	Views to nature: effects on attention	Journal of Environmental Psychology	2002
386	Thomas	Evaluating design strategies, performance and occupant satisfaction: a low carbon office refurbishment	Building Research & Information	2008
387	Tokura	Experimental study on discomfort glare caused by windows: Development of a method for evaluating discomfort glare from a large light source	Journal of Architecture, Planning and Environmental Engineering	2006
388	Tregenza	Guide to recommended practice of daylight measurement	International Commission on Illumination (CIE)	2006
389	Tregenza	Subdivision of the sky hemisphere for luminance measurements	Lighting Research & Technology	2005
390	Tregenza	The design of lighting	Taylor & Francis	2005
391	Trzaski	Energy labeling of windows – possibilities and limitations	Solar Energy	2006
392	Tsikaloudaki	A study on luminous efficacy of global radiation under clear sky conditions in Athens	Renewable Energy	1984
393	Tuaycharoen	Windows are less glaring when there is a preferred view	Built-Environment Sri Lanka	2013
394	Tuaycharoen	Discomfort glare from interesting images	Lighting Research & Technology	1997
395	Tuaycharoen	Discomfort glare from interesting images	Lighting Research & Technology	1989
396	Tuaycharoen	View and discomfort glare from windows	Lighting Research & Technology	1966
397	Tzempelikos	Editorial: advances on daylighting and visual comfort research	Building and Environment	1958

398	Ubbelohde	Comparative evaluation of four daylighting software programs	ACEEE Summer Study on Energy Efficiency in Buildings	2009
399	United Nations	World Population Prospects: The 2015 Revision	Department of Economic and Social Affairs, Population Division	2002
400	US National Grid	Managing Energy Costs in Colleges and Universities	https://www9.nationalgridus.com	2016
401	US-DOE	US-DOE. EnergyPlus V5.0. from. US Department of Energy	US DOE Building Technologies Program	2003
402	USGBC	USGBC. LEED 2009 for schools. Washington DC	US Green Building Council	Year
403	USGBC	USGBC. LEED-NC (Leadership in energy and environmental design) version 3.0. from	US Green Building Council	2006
404	USGBC	LEED 2009 for New Construction and Major Ren-ovations. Reference guide	USGBC	1974
405	Van Bommel	Non-visual biological effect of lighting and the practical meaning for lighting for work	Applied Ergonomics	2016
406	Van den Berg	Dependence of intraocular straylight on pigmentation and light transmission through the ocular wall	Vision Research	2016
407	Van den Wymelenberg	Evaluating Human Visual Preference and Performance in an Office Environment Using Luminance-Based Metrics [Dissertation]	http://www.idlboise.com/papers/KevinVanDenWymelenberg-phd.pdf	2010
408	Van den Wymelenberg	A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight	Journal of the Illuminating Engineering Society	2003
409	Van den Wymelenberg	A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight	Journal of the Illuminating Engineering Society	2010
410	Van den Wymelenberg	Evaluating a new suite of luminance based design metrics for predicting human visual comfort in offices with daylight	Journal of the Illuminating Engineering Society	2010
411	Van den Wymelenberg	The effect of luminance distribution patterns on occupant preference in a daylit office environment	Journal of the Illuminating Engineering Society	2010
412	Van den Wymelenberg	The effect of luminance distribution patterns on occupant preference in a daylit office environment	Journal of the Illuminating Engineering Society	2011
413	Van den Wymelenberg	Visual comfort, discomfort glare, and occupant fenestration control: developing a research agenda	Journal of the Illuminating Engineering Society	2000
414	Van den Wymelenberg	Visual Comfort, Discomfort Glare, and Occupant Fenestration Control: Developing a Research Agenda	Journal of the Illuminating Engineering Society	2013

415	Veitch	Quantifying lighting quality based on experimental investigations of end user performance and preference	Proceedings of Right Light Three	2010
416	Velds	User acceptance studies to evaluate discomfort glare in a daylit room	Solar Energy	2007
417	Velds	User acceptance studies to evaluate discomfort glare in daylit rooms	Solar Energy	2016
418	Velds	Assessment of lighting quality in office rooms with daylighting systems	Technische Universiteit Delft (TUD)	2009
419	Vine	Office worker response to an automated venetian blind and electric lighting system: a pilot study	Energy & Buildings	2002
420	Vos	Disability glare – a state of the art report	Computers in Entertainment Journal	2000
421	Walkenhorst	Dynamic annual daylight simulations based on one-hour and one-minute means of irradiance data	Solar Energy	2014
422	Wang	An efficient GPU-based approach for interactive global illumination	ACM SIGGRAPH	2015
423	Ward	Radiance Visual Comfort Calculation	https://radsite.lbl.gov	1995
424	Ward	A new technique for computer simulation of illuminated spaces	Journal of the Illuminating Engineering Society	2017
425	Ward	Rendering with radiance: The art and science of lighting visualization	Morgan Kaufmann	2008
426	Ward	JPEG-HDR: a backwards-compatible, high dynamic range extension to JPEG	Proceedings of SIGGRAPH ’06	1977
427	Webb	Non-visual effects of light	Energy & Buildings	1995
428	White	Effect of iris pigmentation and latitude on chronotype and sleep timing	Chronobiology International 20	2017
429	Wienold	Dynamic daylight glare evaluation	Building Simulation	2017
430	Wienold	Dynamic simulation of blind control strategies for visual comfort and energy balance analysis	Building Simulation	2018
431	Wienold	Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras	Energy & Buildings	2017
432	Wienold	Evaluation methods and development of a newglare prediction model for daylight environments with the use of CCD cameras	Energy & Buildings	2015
433	Wienold	Daylight glare: Age effects and their impact on glare evaluation.	Energy Forum	1946
434	Wienold	Evalglare version 0.9f	Fraunhofer Institute for Solar Energy Systems (ISE)	1992

435	Wienold	Evalglare,Version 1.08	Fraunhofer Institute for Solar Energy Systems (ISE)	2014
436	Wienold	Evalglare – a new RADIANCE based tool to evaluate daylight glare in office spaces	https://www.radianceon line. org	2012
437	Wienold	New features of Evalglare	Oral presentation at the 11th International Radiance Workshop	1992
438	Wienold	Daylight Glare in Offices	PhD Thesis	1966
439	Wienold	New features of evalglare. Online	Presented at the 11thInternational Radiance Workshop	2008
440	Wienold	Dynamic daylight glare evaluation	Proceedings of Building Simulation	2003
441	Wienold	Dynamic simulation of blind control strategies for visual comfort and energy balance analysis	Proceedings of Building Simulation	2018
442	Wienold	Towards a New Daylight Glare Rating	Proceedings of Lux Europa	2006
443	Wienold	Dynamic daylight glare evaluation	Proceedings of the 11th International IBPSA Conference	2006
444	Wong	Total building performance evaluation of academic institution in Singapore	Building and Environment	2007
445	Xiong	Model-based shading and lighting controls considering visual comfort and energy use	Solar Energy	1990
446	Xue	The effects of daylighting and human behavior on luminous comfort in residential buildings: a questionnaire survey	Building and Environment	1993
447	Yamin Garreton	A global evaluation of discomfort glare metrics in real office spaces with presence of direct sunlight	Energy & Buildings	1996
448	Yamin Garretón	Effects of perceived indoor temperature on daylight glare perception	Building Research & Information	2011
449	Yoon	Development of annual daylight simulation algorithms for prediction of indoor daylight illuminance	Energy & Buildings	2011
450	Yun	The influence of shading control strategies on the visual comfort and energy demand of office buildings	Energy & Buildings	2012
451	Yun	Influence of window views on the subjectiveevaluation of discomfort glare	Indoor and Built Environment	2004
452	Zain-Ahmed	Daylighting as a passive solar design strategy in tropical buildings: a case study of Malaysia	Energy Conversion and Management	2015

453	Zomorodian	Assessment of window performance in classrooms by long term spatial comfort metrics	Energy & Buildings	2015

PART 1 - SECTION 2B: VOLUNTARY STANDARDS REVIEW

Table of LEED projects reviewed under v3 – LEED 2009, BD+C: NC. The USGB database is in a constant state of flux as projects are updated during the review and certification processes. The table below is a record of the projects evaluated for this document.

Table 9: Table of LEED projects reviewed under v3 – LEED 2009, BD+C: NC, with certification level awarded.

Project Name	LEED ID	City	State	Level
AFPLS L007 - Metropolitan Library	1000031556	Atlanta	GA	SILVER
Fulton County Milton Library	1000031672	Milton	GA	SILVER
South Fulton Library	1000051690	Union City	GA	SILVER
Human Health & Performance Laboratory	1000016689	Houston	TX	SILVER
Asian American Resource Center	1000002997	Austin	TX	SILVER
Fulton County Alpharetta Library	1000033570	Alpharetta	GA	SILVER
Wolf Creek Library	1000021659	Atlanta	GA	SILVER
Rotunda Rehabilitation	1000042609	Charlottesville	VA	SILVER
Argyros Girl Scout Leadership Center	1000030830	Newport Beach	CA	SILVER
Palmetto Branch Library	1000024308	Palmetto	GA	SILVER
Independence Park Library	1000006615	Baton Rouge	LA	SILVER
Austin Animal Center Kennel Addition	1000069546	Austin	TX	SILVER
Public Safety Training Facility	1000000199	Austin	TX	SILVER
Lancaster City Hall	1000021579	Lancaster	PA	SILVER
Loma Linda Univ Health San Bernardino	1000045726	San Bernardino	CA	SILVER
Henrico County Varina Area Library	1000026475	Henrico	VA	SILVER
Morris Williams Pro Shop	1000010106	Austin	TX	SILVER
UND School of Education	1000003166	Grand Forks	ND	SILVER
Demonstration	1000019722	Arlington	VA	SILVER
West Springfield Public Library	1000034685	West Springfield	MA	SILVER
Franklin and Marshall Shadek Stadium	1000070757	Lancaster	PA	SILVER
OSU Schottenstein Center North Addition	1000070559	Columbus	OH	SILVER
BTC Fisheries and Aquaculture Science	1000022589	Bellingham	WA	SILVER
UASOF at Camp Ripley	1000017634	Little Falls	MN	SILVER
Cannon Place: Danville Veterans Housing	1000054120	Danville	IL	SILVER
College North Residence Hall	1000026237	Washington	DC	SILVER
Bay Area Chinese Bible Church	1000011641	Alameda	CA	SILVER
Tracy Aviary Avian Health Center	1000029317	Salt Lake City	UT	SILVER
Henrico County Libbie Mill Library	1000026474	Henrico	VA	SILVER
Central Hall II	1000024816	Lexington	KY	SILVER
Salisbury University Choptank Hall	1000022014	Salisbury	MD	SILVER
New Belgium AVL DC	1000043801	Candler	NC	SILVER
Central Hall I	1000024741	Lexington	KY	SILVER

College South Residence Hall	1000026238	Washington	DC	SILVER
Tractor Supply Co - Store Support Center	1000027597	Brentwood	TN	SILVER
TSC Distribution Center-Casa Grande, AZ	1000052611	Casa Grande	AZ	SILVER
VCU West Grace Street Housing - South	1000007173	Richmond	VA	SILVER
Tucson Modern Streetcar Maint Facility	1000005681	Tucson	AZ	SILVER
Mission Linen	1000055818	Newark	CA	SILVER
ArtHouse	1000025549	Portland	OR	SILVER
Outpost Natural Foods - Mequon	1000033318	Mequon	WI	SILVER
Mercedes-Benz Headquarters	1000065902	Atlanta	GA	SILVER
CSJTC-Field Shop Add/Alt	1000020296	Chillicothe	OH	SILVER
UC Davis Trinchero Family Estates Bldg.	1000000578	Davis	CA	SILVER
CVCC Workforce Solutions Complex	1000048559	Hickory	NC	SILVER
1315 Clifton	1000070545	Washington	DC	SILVER
LancasterHistory org	1000001032	Lancaster	PA	SILVER
ABIA Terminal East Infill	1000032868	Austin	TX	SILVER
BMS Biologics Development Building	1000039353	Devens	MA	SILVER
Sarasota National Guard Armory	1000021209	Sarasota	FL	SILVER
The Nic on Fifth	1000030208	Minneapolis	MN	SILVER
Traffic Management/Emergency Ops Center	1000002608	Shoreline	WA	SILVER
UMD Phase IX Sorority Bldg 171	1000011769	College Park	MD	SILVER
The Penfield	1000009852	Saint Paul	MN	SILVER
Woodruff Electric Cooperative Corp	1000034433	Forrest City	AR	SILVER
UMD Phase IX Sorority Bldg 176	1000011770	College Park	MD	SILVER
Riverdale Country School Natatorium	1000057567	Bronx	NY	SILVER
City of Raleigh Fire Station 12	1000041168	Raleigh	NC	SILVER
Van Nuys Fire Station 39	1000035472	Van Nuys	CA	SILVER
Mason - CSP - Residences	1000014516	Front Royal	VA	SILVER
MSU - School of Communication & Media	1000057722	Montclair	NJ	SILVER
Signet Residential	1000052450	Mclean	VA	SILVER
Fairfax Bldg V Noman Cole Jr PCP	1000043807	Lorton	VA	SILVER
NAS Meridian Dining Facility	1000040788	Meridian	MS	SILVER
Fairfield Inn and Suites Springfield, MO	1000071164	Springfield	MO	SILVER
UA Pat Walker Health Center addition	1000077573	Fayetteville	AR	SILVER
Ohio Reformatory for Women Lincoln Bldg	1000085224	Marysville	OH	SILVER
710 Wilshire	1000078459	Santa Monica	CA	SILVER
NCSU CCSH - Building 1	1000003845	Raleigh	NC	SILVER
USAF Holloman AFB Clinic Replacement	1000057938	Holloman AFB	NM	SILVER
Ada County Paramedics Admin Facility	1000004344	Boise	ID	SILVER
NCSU Talley Student Center	1000011172	Raleigh	NC	GOLD
Academic West Building	1000010878	Lewisburg	PA	SILVER
Pepperdine Outer Precinct Residence Hall	1000073235	Malibu	CA	SILVER
Facilities Maintenance	1000075735	Durant	OK	SILVER

Clinic	1000075733	Durant	OK	SILVER
NYCHH - Carter	1000018724	New York	NY	SILVER
STACK - Atlanta 01 - Shell	1000013401	Alpharetta	GA	SILVER
BMW of Mountain View - Showroom Addition	1000074733	Mountain View	CA	SILVER
Tupper Hall Renovation	1000034067	Athens	OH	SILVER
Ohio University Sook Academic Center	1000087726	Athens	OH	SILVER
Avora at Port Imperial	1000047629	Weehawken	NJ	SILVER
Beacon	1000071156	Tampa	FL	SILVER
Dublin Road Water Treatment Upgrade	1000026367	Columbus	OH	SILVER
P-240 Armory	1000065388	Yigo	GU	SILVER
Biosciences Facility - Bessey Addition	1000053665	AMES	IA	SILVER
USTA Armstrong	1000062384	Flushing	NY	SILVER
National Harbor Block W - Building A	1000069462	Oxon Hill	MD	SILVER
Mississippi & Fremont Apartments	1000071275	Portland	OR	SILVER
P424 LCS Mission Module Readiness Center	1000085490	NAS Mayport	FL	SILVER
SKYCTC Building L Instructional Complex	1000059482	Bowling Green	KY	SILVER
Kirkpatrick West Public Safety Center	1000074361	Aldie	VA	SILVER
TMI	1000078238	Fort Collins	CO	SILVER
100 East 53rd Street	1000041582	New York	NY	SILVER
OSU Lima - New Student Life Building	1000034166	Lima	OH	SILVER
Chevy Chase Lakes	1000064264	Chevy Chase	MD	SILVER
14th Civil Support Team Ready Building	1000087171	Windsor Locks	CT	SILVER
723 Pacific Ave Office Building	1000085228	Salt Lake City	UT	SILVER
Eskenazi Museum of Art Renovation	1000081179	Bloomington	IN	SILVER
VA TNC Maintenance Building	1000039539	Tallahassee	FL	SILVER
St. of Illinois, SIUE Science Bldg Renov	1000040011	Edwardsville	IL	SILVER
Kaktus Life MUD	1000072571	Las Vegas	NV	SILVER
Oak Harbor Administration - Maintenance	1000075424	Oak Harbor	WA	SILVER
SFCC Gymnasium Renovation	1000074365	Spokane	WA	SILVER
Unity Care NW - Ferndale	1000066689	Ferndale	WA	SILVER
CoorsTek Center	1000054941	Golden	CO	SILVER
CHP Fresno	1000054940	Fresno	CA	SILVER
P562 TBS Student Officer Quarters	1000036167	Quantico	VA	SILVER
Recycling and Resource Center	1000015861	Dayton	OH	SILVER
1400 W Peachtree - Hotel	1000067189	Atlanta	GA	SILVER
UT Graduate & Health Studies Building	1000091660	Tampa	FL	SILVER
1411 Key Blvd	1000053224	Arlington	VA	SILVER
UNC Campus Commons	1000063983	Greeley	CO	GOLD
Vet Med-Primary Care & Dentistry Clinic	1000095217	Gainesville	FL	GOLD
West Village Residences LLC	1000017897	New York	NY	GOLD
Geiger Office Wing	1000075921	Lewiston	ME	GOLD
Columbia Precast Products	1000069929	Woodland	WA	GOLD

Sealaska Heritage Institute	1000013937	Juneau	AK	GOLD
San Rafael Replacement Fire Station 52	1000066342	San Rafael	CA	GOLD
UW - Maple and Terry Halls	1000024675	Seattle	WA	GOLD
UC Davis Cage Wash	1000081234	Davis	CA	GOLD
Apartment Tower at Confluence Park	1000054987	Denver	CO	GOLD
Butler University Lacy Business School	1000074501	Indianapolis	IN	GOLD
SAS Building A	1000020565	Cary	NC	GOLD
Hoxton Hotel	1000070486	Chicago	IL	GOLD
VITA	1000062147	Littleton	CO	GOLD
Operation Coordination Center	1000058684	Riverside	CA	GOLD
MSU Rendezvous Dining Pavilion	1000069764	Bozeman	MT	GOLD
Mission Hills/Hillcrest Library	1000085739	San Diego	CA	GOLD
625 Division Street	1000036004	Chicago	IL	GOLD
Administration Building	1000058683	Riverside	CA	GOLD
Towson University Residence Tower	1000071545	Towson	MD	GOLD
MCTC -Postsecondary Center of Excellence	1000060156	Morehead	KY	GOLD
Tarrant County Dionne Phillips Bagsby So	1000068058	Fort Worth	TX	GOLD
Lafourche Parish Correctional Complex	1000066134	Thibodaux	LA	GOLD
VA TNC Administration Building	1000039534	Tallahassee	FL	GOLD
Advanced Teaching & Research Bldg	1000053673	Ames	IA	GOLD
SPU - Watershed Headquarters	1000065984	North Bend	WA	GOLD
Life Sciences Building	1000077163	Logan	UT	GOLD
USM CPS Building B	1000060264	Hattiesburg	MS	GOLD
USM CPS Building C	1000060265	Hattiesburg	MS	GOLD
CNM J Building Renovation & Addition	1000073533	Albuquerque	NM	GOLD
Rutgers Weeks Hall School of Engineering	1000067858	Piscataway	NJ	GOLD
Everitt Laboratory Renovation	1000049999	Urbana	IL	GOLD
GBMSD R2E2 Project	1000042305	Green Bay	WI	GOLD
Minnewaska Hall - Formerly Bevier	1000057393	New Paltz	NY	GOLD
USM CPS Building A	1000060263	Hattiesburg	MS	GOLD
Principal Financial Group - Corporate 1	1000042096	Des Moines	IA	GOLD
COH- Central Permitting Center	1000001355	Houston	TX	GOLD
Metro Bellevue Public Library	1000026598	Nashville	TN	GOLD
Concordia College Integrated Science	1000056550	Moorhead	MN	GOLD
W&M Integrative Wellness Center	1000064657	Williamsburg	VA	GOLD
The Museum of the American Revolution	1000044681	Philadelphia	PA	GOLD
The Patton College - McCracken Hall Reno	1000044521	Athens	OH	GOLD
Lakeland CC Healthcare Tech Addition	1000078480	Kirtland	OH	GOLD
Vanderbilt E. Bronson Ingram College	1000055826	Nashville	TN	GOLD
CU Biotech Academic Wing	1000061760	Boulder	CO	GOLD
MHCD Dahlia Campus for Health&Well-Being	1000045627	Denver	CO	GOLD
Miami U Ohio - Scott Hall	1000077747	Oxford	OH	GOLD

Minnesota Multi-Purpose Stadium	1000030223	Minneapolis	MN	GOLD
TRI-C - Metro Campus Center	1000066931	Cleveland	OH	GOLD
POM FY11 Barracks	1000067623	Monterey	CA	GOLD
610 Beacon Street - 30 Bay State Road	1000065764	Boston	MA	GOLD
Miami U Ohio - Minnich Hall	1000077731	Oxford	OH	GOLD
Woburn Public Library	1000090588	Woburn	MA	GOLD
SUNY University at Albany Herkimer Hall	1000062634	Albany	NY	GOLD
CIC The Trailhead Visitor Center	1000045877	Avalon	CA	GOLD
Manhattan College Student Commons	1000016876	Bronx	NY	GOLD
Jeffco Family Health Services Clinic	1000016282	Wheat Ridge	CO	GOLD
Bay Terrace Community and Education Cent	1000023990	Tacoma	WA	GOLD
Central Station of Evanston	1000022814	Evanston	IL	GOLD
AACC Ludlum Hall Admin Building	1000023743	Arnold	MD	GOLD
NLR Electric Administration Building	1000014016	North Little Rock	AR	GOLD
Saint Lukes Manor	1000004294	Cleveland	OH	GOLD
First Congregational Church - UCC	1000011353	Atlanta	GA	GOLD
CCU Academic Office/Classroom Building 2	1000058722	Conway	SC	GOLD
Washington Canal Park	1000007420	Washington	DC	GOLD
USU Student Recreation and Wellness Ctr	1000036139	Logan	UT	GOLD
UALR Student Services One Stop	1000008266	Little Rock	AR	GOLD
SCPPA	1000017712	Glendora	CA	GOLD
North Extension Center	1000023449	Bradley	IL	GOLD
New Student Housing	1000022315	Richmond	KY	GOLD
Treasures of the Rainforest	1000044599	Salt Lake City	UT	GOLD
California Democratic Party Headquarters	1000035403	Sacramento	CA	GOLD
Miramar College Administration Building	1000018124	San Diego	CA	GOLD
Jewish Studies Center Addition	1000039728	Charleston	SC	GOLD
Ovation	1000012375	McLean	VA	GOLD
Lawrence Public Library	1000027316	Lawrence	KS	GOLD
Black Gold Corporate Headquarters	1000013135	Grand Forks	ND	GOLD
Chicago Children's Theatre	1000065942	Chicago	IL	GOLD
UALR - Honors Housing	1000006099	Little Rock	AR	GOLD
Washburn Center for Children	1000027665	Minneapolis	MN	GOLD
New Academic and Laboratory Building	1000015773	New Haven	CT	GOLD
SF MoMA Expansion	1000018682	San Francisco	CA	GOLD
Auburn Avenue Research Library	1000030758	Atlanta	GA	GOLD
Plain Green TTEC	1000006518	Plain	WI	GOLD
UMass Research and Education Greenhouse	1000003634	Amherst	MA	GOLD
Johnson Co Ambulance & Medical Examiner	1000065154	Iowa City	IA	GOLD
CoA African Amer Cultural/Heritage Faci	1000003544	Austin	TX	GOLD
Lunder Arts Center at Lesley University	1000013859	Cambridge	MA	GOLD
The Pennovation Center	1000073217	Philadelphia	PA	GOLD

Pompano Beach Library/Cultural Center	1000033830	Pompano Beach	FL	GOLD
ABIA-GTSA Relocation and Renovation	1000010698	Austin	TX	GOLD
ROCK CREEK REG PARK MAINTENANCE YARD	1000023834	DERWOOD	MD	GOLD
San Bernardino Transit Center	1000030131	San Bernardino	CA	GOLD
NAU Student Academic Services Building	1000044601	Flagstaff	AZ	GOLD
Jackson Laboratory for Genomic Medicine	1000023017	Farmington	CT	GOLD
San Diego Rental Car Center	1000028736	San Diego	CA	GOLD
Montclair State University CELS	1000011995	Montclair	NJ	GOLD
Spring Lake Fire Station No. 1	1000062394	Spring Lake	MI	GOLD
Washington Gas - Fleet Facility Addition	1000056105	Rockville	MD	GOLD
Cielo	1000028775	Seattle	WA	GOLD
Downtown Commons Medical Offices	1000065868	Sacramento	CA	GOLD
East Roswell Branch Library	1000023242	Roswell	GA	GOLD
The Bryant School Redevelopment	1000012538	Great Barrington	MA	GOLD
MGM National Harbor	1000040012	Oxon Hill	MD	GOLD
Byron Rogers FOB Modernization	1000000981	Denver	CO	GOLD
Valley Health Center Downtown San Jose	1000019817	San Jose	CA	GOLD
CU Sustainability Energy and Env Complex	1000034039	Boulder	CO	GOLD
Tippet Rise LLC - Olivier Barn	1000055410	Fishtail	MT	GOLD
DPW Office	1000007610	Baton Rouge	LA	GOLD
Sheldon Community Fire Station NO 3	1000004906	Houston	TX	GOLD
Walden Pond Visitor Center	1000057463	Concord	MA	GOLD
Center for Health and Well-Being	1000051659	Columbia	SC	GOLD
SUNY New Paltz - Wooster Building	1000019528	New Paltz	NY	GOLD
1A/3B Granite Pass	1000078723	Merced	CA	PLATINUM
UCDH North Addition	1000056686	Sacramento	CA	PLATINUM
Millikan	1000033057	Claremont	CA	PLATINUM
Whitman Residence Hall	1000087928	Walla Walla	WA	PLATINUM
Bentley University Arena	1000069093	Waltham	MA	PLATINUM
WSU Elson S. Floyd Cultural Center	1000067928	Portland	OR	PLATINUM
Burr and Burton Academy Mountain Campus	1000022071	Peru	VT	PLATINUM
Petzl America Headquarters	1000028420	West Valley City	UT	PLATINUM
San Ysidro Land Port of Entry - Phase 1B	1000032755	San Diego	CA	PLATINUM
CSHQA Office Building	1000029926	Boise	ID	PLATINUM
Mitchell Park Library Community Center	1000002397	Palo Alto	CA	PLATINUM
ESF Gateway	1000001022	Syracuse	NY	PLATINUM
UC Davis Vet Med 3B	1000009588	Davis	CA	PLATINUM
Hillman Hall, Brown School, WUSTL	1000033733	Saint Louis	MO	PLATINUM
Architectural Nexus Design Center	1000001601	Salt Lake City	UT	PLATINUM
UCI COB	1000087875	Irvine	CA	PLATINUM
Grossman Hall	1000066542	Waterville	ME	PLATINUM
UCLA La Kretz Garden Pavilion	1000052803	Los Angeles	CA	PLATINUM

Las Positas College-Academic Building	1000062544	Livermore	CA	PLATINUM
Cincinnati Zoo - Gorilla World	1000072818	Cincinnati	OH	PLATINUM
North Coastal HHSA Facility	1000078242	Oceanside	CA	PLATINUM
Facebook MPK 21	1000065796	Menlo Park	CA	PLATINUM
One-Toyota Georgetown	1000069668	Georgetown	KY	PLATINUM
Roux Center for the Environment	1000075514	Brunswick	ME	PLATINUM
MGM Daycare	1000078901	Springfield	MA	PLATINUM
ASU Student Pavilion	1000066381	Tempe	AZ	PLATINUM
Benton Hall	1000071215	Hamilton	NY	PLATINUM
Center for Nature Based Learning	1000077192	San Antonio	TX	PLATINUM
Unisphere	1000056187	Silver Spring	MD	PLATINUM
CLC Science and Engineering Building	1000022808	Grayslake	IL	PLATINUM
MACP Expansion	1000041928	Eden Prairie	MN	PLATINUM
WU Loop Living Phase 1	1000025935	Saint Louis	MO	PLATINUM
Building 110 Net Zero Energy North Wareh	1000062546	Research Triangle Park	NC	PLATINUM
Key West City Hall at Glynn Archer	1000032917	Key West	FL	PLATINUM
Vans Headquarters	1000069268	Costa Mesa	CA	PLATINUM
PA - Snyder Center	1000067793	Andover	MA	PLATINUM
REI DC3	1000057035	Goodyear	AZ	PLATINUM
Liberty Wildlife Rehabilitation Center	1000066359	Phoenix	AZ	PLATINUM
Colorado State University Chemistry	1000065368	Fort Collins	CO	PLATINUM
Redford Conservancy for Sustainability	1000071284	Claremont	CA	PLATINUM
MU Patient-Centered Care Learning Center	1000039168	Columbia	MO	PLATINUM
Land O'Lakes Headquarters Building C	1000069969	ARDEN HILLS	MN	PLATINUM
USF St. Petersburg Poynter Laboratory	1000093489	St Petersburg	FL	PLATINUM
Fort Irwin Hospital	1000012692	Fort Irwin	CA	PLATINUM
Federal Bldg 50 UNP	1000001946	San Francisco	CA	PLATINUM
SBCC West Campus Center	1000032076	Santa Barbara	CA	PLATINUM
BRC1001 DC1 New Tech and Learning Ctr	1000043653	Fall River	MA	PLATINUM
Chinatown Branch Library	1000038245	Chicago	IL	PLATINUM
CityScape at Belmar	1000024272	Lakewood	CO	PLATINUM
PSU Karl Miller Center	1000060801	Portland	OR	PLATINUM
Johnson County Criminalistics Laboratory	1000001456	Olathe	KS	PLATINUM
M E Group Office Building	1000001499	Omaha	NE	PLATINUM
Norm Asbjornson Hall	1000054942	Bozeman	MT	PLATINUM
Evergreen Valley College Fitness Center	1000029342	San Jose	CA	PLATINUM
RMI Innovation Center	1000032625	Basalt	CO	PLATINUM
Engine House No 5	1000003485	Denver	CO	PLATINUM
777 Main Street	1000033576	Hartford	CT	PLATINUM
Metro Nashville Fire Station No 19	1000053650	Nashville	TN	PLATINUM
UF Institute on Aging Clinical Tran Res	1000006005	Gainesville	FL	PLATINUM
Posty Cards Expansion	1000002303	Kansas City	MO	PLATINUM

Packard Foundation 343 Second St Project	1000004074	Los Altos	CA	PLATINUM
Exploratorium at Piers 15/17	1000002338	San Francisco	CA	PLATINUM
Unilever Project Unify	1000073546	Englewood Cliffs	NJ	PLATINUM
NSP	1000035585	Atlanta	GA	PLATINUM
Alfandre Architecture Office Building	1000002593	New Paltz	NY	PLATINUM
SWA WTE Admin and Visitors Center	1000018926	West Palm Beach	FL	PLATINUM
Lands End Lookout	1000019323	San Francisco	CA	PLATINUM
OHSU Knight Cancer Research Building	1000060924	Portland	OR	PLATINUM
Firestation 14	1000089330	Madison	WI	PLATINUM
NREL Research Support Facility II	1000007345	Golden	CO	PLATINUM
Milken Institute School of Public Health	1000011236	WASHINGTON	DC	PLATINUM
Perkins and Will Atlanta Office	1000002307	Atlanta	GA	PLATINUM
Banfield Corporate Campus	1000052457	Vancouver	WA	PLATINUM
Engine Company 16	1000006729	Chicago	IL	PLATINUM
Method	1000034052	Chicago	IL	PLATINUM
La Kretz Innovation Campus	1000027827	Los Angeles	CA	PLATINUM
VMware Phase 4 - CSG	1000029756	Palo Alto	CA	PLATINUM
Lane Community College - Academic	1000018271	Eugene	OR	PLATINUM
Sebastian Coe Building	1000052760	Beaverton	OR	PLATINUM
MRB1	1000073434	Riverside	CA	PLATINUM
WU Fitness Recreation Athletic Addition	1000035947	Saint Louis	MO	PLATINUM
Springline Architects Office	1000016821	Charlotte Amalie	VI	PLATINUM
San Jose Environmental Innovation Center	1000002922	San Jose	CA	PLATINUM
VMWare Phase 4 - HTG	1000052617	Palo Alto	CA	PLATINUM
Group14 Engineering / Reilly Law Office	1000000112	Denver	CO	PLATINUM
MedImmune Childcare Center	1000058188	Gaithersburg	MD	PLATINUM
ASU BioDesign Institute Building C	1000066888	Tempe	AZ	PLATINUM
Emory Student Center	1000095412	Atlanta	GA	PLATINUM
Home2 Hillandale	1000065121	Silver Spring	MD	PLATINUM
FPDCC Rolling Knolls Pavilion	1000040364	Elgin	IL	PLATINUM
Stony Brook Millstone Watershed Associat	1000016899	Hopewell	NJ	PLATINUM
Wedgewood Academic Center	1000024615	Nashville	TN	PLATINUM
UND Gorecki Alumni Center	1000015510	Grand Forks	ND	PLATINUM
CU Boulder - VCDCC	1000055997	Boulder	CO	PLATINUM
Mission College - MBR Phase II	1000040805	Santa Clara	CA	PLATINUM
Harris County Burnett-Bayland Gym	1000028605	Houston	TX	PLATINUM
Delta Americas Headquarters	1000026416	Fremont	CA	PLATINUM
Early Learning and Job Training Center	1000025514	Helena	MT	PLATINUM
1212 Bordeaux	1000074146	Sunnyvale	CA	PLATINUM
PG and E - San Francisco	1000004730	San Francisco	CA	PLATINUM
Five Rivers EEC	1000000373	Delmar	NY	PLATINUM
New Kellogg School of Management	1000029267	Evanston	IL	PLATINUM

New Addition to Sartorius Stedim	1000013020	Yauco	PR	PLATINUM
Rebekah Scott Hall	1000068798	Decatur	GA	PLATINUM
Novato Fire Station 64 Replacement	1000025823	Novato	CA	PLATINUM
Seattle Fire Station 22	1000051465	Seattle	WA	PLATINUM
Market One	1000041742	DesMoines	IA	PLATINUM
Williams College Bookstore	1000065236	Williamstown	MA	PLATINUM
Princetel	1000011757	Hamilton	NJ	PLATINUM
TCCD Energy Technology Center	1000025887	Fort Worth	TX	PLATINUM
AV 128 Winery Group	1000057822	Healdsburg	CA	PLATINUM
Sierra Nevada Brewing Co.	1000035924	Mills River	NC	PLATINUM
New Central Library	1000014205	Austin	TX	PLATINUM
Kresge Centennial Hall Renovation	1000036363	Evanston	IL	PLATINUM
Cubesmart Chamblee Dunwoody	1000070647	Chamblee	GA	CERTIFIED
AEP Ardmore Service Center	1000069666	FortWayne	IN	CERTIFIED
Art Place at Fort Totten	1000061731	District of Columbia	DC	CERTIFIED
Marriott Full Service Hotel	1000034246	Bellevue	WA	CERTIFIED
Xcel Energy: Hudson Service Center	1000077685	Hudson	WI	CERTIFIED
Altis Pembroke Gardens	1000062128	Pembroke Pines	FL	CERTIFIED
Colgate Mfg Facility - South Carolina	1000039671	Hodges	SC	CERTIFIED
FGCU North Lake Village Dining	1000057400	Fort Myers	FL	CERTIFIED
Rockville Evangelical Mission Church	1000061633	Gaithersburg	MD	CERTIFIED
Fuchs North America	1000046711	Hampstead	MD	CERTIFIED
AEP Spy Run Service Center	1000074582	Fort Wayne	IN	CERTIFIED
AC by Marriott Chapel Hill	1000064198	Chapel Hill	NC	CERTIFIED
Crestview Station Phase III	1000094915	AUSTIN	TX	CERTIFIED
Twelve Twelve	1000030258	Nashville	TN	CERTIFIED
Xcel Energy: Phillips Service Center	1000077678	Phillips	WI	CERTIFIED
Florida Avenue Self Storage	1000066202	Washington	DC	CERTIFIED
The Main Norfolk	1000051342	Norfolk	VA	CERTIFIED
FedEx Express CHSA	1000076594	Charleston	SC	CERTIFIED
Renaissance Hotel at Westar Place	1000059439	Westerville	OH	CERTIFIED
Rainbow LIght Headquarters	1000029875	Santa Cruz	CA	CERTIFIED
CRS Maple	1000070990	Dallas	TX	CERTIFIED
UCA Conway Corp Center for Sciences	1000056633	Conway	AR	CERTIFIED
FTCH Michigan City	1000093253	Michigan City	MI	CERTIFIED
IUOE Int'l Training & Conference Center	1000070374	Crosby	TX	CERTIFIED
Touchstone Common House	1000050514	Ann Arbor	MI	CERTIFIED
GRCC Early Childhood Learning Lab	1000065301	Grand Rapids	MI	CERTIFIED
Viceroy Hotel Chicago	1000058656	Chicago	IL	CERTIFIED
Two Light Tower	1000068718	Kansas City	MO	CERTIFIED
Ames Water Treatment Plant	1000031130	Ames	IA	CERTIFIED
oneC1TY - The Shay Apartments	1000055728	Nashville	TN	CERTIFIED

Curl Hall	1000036284	Columbus	OH	CERTIFIED
North Recreation Center	1000036287	Columbus	OH	CERTIFIED
Rogers County Sheriff's Office	1000074904	Claremore	OK	CERTIFIED
Union Tower West	1000052742	Denver	CO	CERTIFIED
Los Fresnos Service Center	1000080982	Los Fresnos	TX	CERTIFIED
SCIP - Phase I and II	1000031656	Greer	SC	CERTIFIED
Penn Eleven	1000069587	Washington	DC	CERTIFIED
Maintenance Building - BCAG	1000040059	Chico	CA	CERTIFIED
BATO Aiken County Off Road Tire Plant	1000021313	Trenton	SC	CERTIFIED
NICoE Satellite - Fort Belvoir	1000027576	Fort Belvoir	VA	CERTIFIED
Optima Signature	1000060622	Chicago	IL	CERTIFIED
Drury Plaza Hotel Santa Fe	1000020115	Santa Fe	NM	CERTIFIED
26 Ann Street Hotel	1000058305	New York	NY	CERTIFIED
GAF Triple Crown	1000039135	Parsippany	NJ	CERTIFIED
Educare Lincoln	1000017035	Lincoln	NE	CERTIFIED
PG and E Santa Rosa - Back Building	1000014163	Santa Rosa	OR	CERTIFIED
Bakersfield Service Center Renovations	1000009963	Bakersfield	CA	CERTIFIED
Conway Federal Plaza	1000010547	Conway	AR	CERTIFIED
element Bozeman	1000055995	Bozeman	MT	CERTIFIED
FedEx White Mountain	1000086965	Draper City	UT	CERTIFIED
GSU Indian Creek Lodge	1000023367	Stone Mountain	GA	CERTIFIED
Mankato MN Courtyard by Marriott	1000000711	Mankato	MN	CERTIFIED
PG&E Rocklin DCC AGCC	1000051077	Rocklin	CA	CERTIFIED
UPR Comprehensive Cancer Center	1000016274	San Juan	PR	CERTIFIED
Bucknell University Carnegie Building	1000052597	Lewisburg	PA	CERTIFIED
PG&E Vacaville Primary Grid Control	1000054049	Vacaville	CA	CERTIFIED
PG&E Willows Service Center	1000059412	Willows	CA	CERTIFIED
WKU Augenstein Alumni Center	1000011170	Bowling Green	KY	CERTIFIED
Courtyard Marriott Redwood City	1000055985	Redwood City	CA	CERTIFIED
AC Hotel Spartanburg	1000061265	Spartanburg	SC	CERTIFIED
Smith Wagner Building	1000058638	Chesterfield	VA	CERTIFIED
Courtyard Marriott Bowie	1000097662	Bowie	MD	CERTIFIED
Wheeling Town Center	1000070558	Wheeling	IL	CERTIFIED
Harbor Center	1000029141	Buffalo	NY	CERTIFIED
GSPH Parran and Crabtree Halls Phase 1	1000006278	Pittsburgh	PA	CERTIFIED
Lake Nona USTA Tennis Center - Office	1000057058	Orlando	FL	CERTIFIED
Yellowstone Club Golf Clubhouse	1000050756	Big Sky	MT	CERTIFIED
GMIA Baggage Claim Building	1000016044	Milwaukee	WI	CERTIFIED
USTA Transportation Building	1000039574	Flushing	NY	CERTIFIED
Pinellas County Public Safety Building A	1000017425	Largo	FL	CERTIFIED
ESI PA Pharmacy	1000051079	North Huntington	PA	CERTIFIED
PG and E Santa Rosa - Front Building	1000008771	Santa Rosa	CA	CERTIFIED

The Heritage Group - The Center	1000057392	Indianapolis	IN	CERTIFIED
El Paso Regional Communications Center	1000062543	El Paso	TX	CERTIFIED
SWA Wings	1000069202	Dallas	TX	CERTIFIED
Camden Shady Grove	1000020756	Rockville	MD	CERTIFIED
DFW Jaguar Land Rover	1000057121	DFW Airport	TX	CERTIFIED
90 Columbus	1000057988	Jersey City	NJ	CERTIFIED
400 K Street NW	1000046278	Washington	DC	CERTIFIED
CBU New School of Business	1000014233	Riverside	CA	CERTIFIED
Porsche Grapevine	1000070249	Grapevine	TX	CERTIFIED
Camden Washingtonian	1000067061	Gaithersburg	MD	CERTIFIED
HISD South Early College High School	1000049843	Houston	TX	CERTIFIED
Legacy Kincaid	1000094767	Plano	TX	CERTIFIED
Youth Center Renovation	1000060799	US Army Base Fort Hood	TX	CERTIFIED
1250 Taylor Street NW	1000073826	Washington	DC	CERTIFIED
MCN Eufaula Indian Health Center	1000056757	Eufaula	OK	CERTIFIED
San Benito Service Center	1000074955	San Benito	TX	CERTIFIED
Vehicle Maintenance Shop	1000053546	Valley City	ND	CERTIFIED
YMCA of the Rockies - Mountain Center	1000045022	Estes Park	CO	CERTIFIED
Maker's Mark 46 Storage Facility	1000074343	Loretto	KY	CERTIFIED
Goodwill Decatur Office	1000053996	Decatur	GA	CERTIFIED
Ralph Wilson Stadium - Commissary	1000032285	Orchard Park	NY	CERTIFIED
Tysons Corner Hotel	1000023556	Tysons Corner	VA	CERTIFIED
Grace Farms - BD+C	1000026959	New Canaan	CT	CERTIFIED
Kroc Center- South Hampton Roads	1000026119	Norfolk	VA	CERTIFIED
ECHO PARK - Monterrey Village	1000074621	San Antonio	TX	CERTIFIED
United Pacific - Corporate Headquarters	1000069659	Long Beach	CA	CERTIFIED
AC Hotel - the Cove at Oyster Point	1000056719	South San Francisco	CA	CERTIFIED
Element Downtown Denver East	1000076753	Denver	CO	CERTIFIED
NDSCS Horton Hall Renovation	1000002054	Wahpeton	ND	CERTIFIED
Symphony Honolulu	1000061767	Honolulu	HI	CERTIFIED
Simulator Center	1000087157	Camp Lejeune	NC	CERTIFIED
B31 SPD Addition	1000030573	Chillicothe	OH	CERTIFIED
Buncombe County New Courts Building	1000015860	Asheville	NC	CERTIFIED
ECHO PARK - New Braunfels	1000074643	New Braunfels	TX	CERTIFIED
Sunstar Headquarters and Manufacturing	1000034003	Schaumburg	IL	CERTIFIED
MODE Logan Square	1000064231	Chicago	IL	CERTIFIED
Pullman Community Center	1000076105	Chicago	IL	CERTIFIED
Nordhaus	1000061557	Minneapolis	MN	CERTIFIED
VCSU Rhoades Science Center	1000024500	Valley City	ND	CERTIFIED
DRTA Fed Ex	1000052436	Del Rio	TX	CERTIFIED

PART 1 - SECTION 2C: CRITICAL INFORMATION TO LIGHTING SYSTEMS INTEGRATION CASE STUDIES

The list below is meant to start the conversation about what elements of a case study are must haves, nice to have, and nice extras. The list will need to be evaluated in this context and with the understanding that not all of the elements are of equal value. This will include addressing the purpose of case studies, where there are varying focii - design process, technology, etc. Prioritization should start with “What is the objective of this case study”, in order to make recommendations about which elements to include or not.

General project information should include:

- Design, construction, operations, ownership, occupant organizational chart as well as examples of contract types that lay out the design and construction team decision making in a flowchart to understand how decisions were made, and who had final decision-making authority. Including a post construction facilities decision making diagram.

- Diagrams and descriptions of the tools used by the designer and construction team to make performance decisions.

- A description of the building occupants, whether owner-occupied or tenant occupied, in order to understand the performance difference between an owner-occupied building, and one occupied by a tenant.

The project team details should include:

- Information about the financing of the project, whether public, private or a combination.

- Community Outreach and engagement is a critical element of any project, members of the team engaged in outreach to the community in which the building will be constructed should be included, as well as a diagram showing how that community outreach was conducted.

The overall building description should include:

- Details and graphics describing the passive systems of environmental control included in the building.

- Details and graphics describing resilience measures included in the building, in addition to their function.

- A table or graphic showing the range of project goals, implementation, construction budget, and operations and maintenance (O&M) plans.

- An outline of any financial incentives for the design-build team, which team members benefit from incentive, whether the incentives were successfully met, as well as an evaluation of whether incentives were a replacement for regular fee, or in addition to it. An evaluation of how incentives impacted team communication or affected internal consultant practices.

Sustainability goals should include descriptions of:

- Any post occupancy performance evaluations and energy consumption targets used to verify design energy targets.
- Any compliance with other third-party certifications, guidelines, or standards employed for the purposes of achieving sustainability goals should also be included.

Functional project goals should include a description of:

- Design development methods or criteria used during project design and development for creating lifecycle flexibility.
- Any occupational metrics showing design responsiveness to owner / tenant design criteria (e.g. employee productivity, satisfaction, health and wellness)
- A description of design flexibility for occupant reorganization and tenant changes, such as open building systems and controls that allow for program and work group subdivisions without need for systems retrofits.

Design for Accessibility should include a description of:

- Design metrics and goals to provide accessibility for workforces with various abilities.

Cost effectiveness goals should include descriptions of:

- Area Cost Compared to Typical: construction costs for similar building type, with possible cost breakdown by different construction elements (e.g. HVAC, Lighting (Day- and Electric), Structure, Passive Systems, Resilience Measures)
- Building Design Lifespan: the building lifespan designed to for evaluating Return on Investment and Simple Payback.
- System Design Lifespan: design lifespan of building systems
- Return on Investment and Simple Payback Timelines.
- Building Lifecycle Evaluation: breakdown of the lifecycle impact of primary building materials and elements.

Historic preservation goals should include:

- An assessment of the historic passive systems of environmental control used in the original building and preserved in the renovation.

Productivity goals should include:

- Metrics for Productivity: details for calculating improvements in occupant productivity

- Metrics for Health & Wellness: Metrics for Views (Interior and Exterior)
- Metrics of satisfaction and comfort.

Additional significant project aspects should include:

- Description or examples of contract language used during the project design, construction, and occupancy that provide for implementation of performance goals and requirements.
- Description of design team processes used to support the contract language, and whether any of these processes were described in the contract language.
- Description of Minimum Performance Criteria (MPC) for energy efficiency and subcategories (lighting, views, wellness, etc.)

A description of the design process should include:

- Design team flowchart and organizational chart.
- Description of Pre-Design/Planning Activities that support project metrics
- Description of methods used for verification of cost and performance models prior to construction and matching with post construction and occupation metrics.
- Evaluation of team integration - knowledge-sharing models, lessons learned
- Description of incentives used for meeting total project goals.
- Details of payments for achieving goals
    - Total project cost
    - Energy efficiency
    - Community goals

A description of construction activities should include:

- Description of use of construction mockups
    - Documentation of construction time and cost savings associated with mock-ups to refine approach and increase productivity during construction.
    - Use of construction mock-ups to prove viability and performance
    - Budget amounts dedicated to mock-up construction
- Metric for describing value of elevated early design scope and increased overall design fee.

- With respect to building elements where no field modifications could be made.
- Identification and description of elements that required full design, and at which phase, as a proof of concept.
- Documentation of financial and performance impacts of early integration of the general contractor, architect, engineering, and all sub-contracting parties.

- Description of process by which BIM is used as a common tool for field trades to communicate and resolve questions and issues during construction
  - Frequency of updates to model and accuracy of model and completion of construction.
  - Description of methods used for real-time corrections and coordination and how this is enforced contractually.

A description of operations & maintenance activities should include

- Description of design team training activities and costs for training facilities personnel to ensure building systems operated at optimal performance – contract example and project budget dedicated to this activity.
  - Metrics showing impact of occupant and facilities staff training on overall building performance, occupant satisfaction, and LCA impacts – impact per hour of training, per employee trained, etc.
  - Description of the means and methods used to identify and implement manageable behavioral shifts for the users that will result in lower energy consumption.
  - Description of post occupation contact between design and construction team and facilities personnel for systems performance issues (Description of costs in time and fees for conducting this work, contract example and budget dedicated to this activity.)
  - Description of pre-occupation educational programming to train occupants to understand sustainability features including interrelationships between systems, and the necessity of engaging the users to achieve energy efficiency goals, contract example and budget dedicated to this activity.
  - Description of the relationship between occupants and facilities operational staff to highlight the link between building systems operation (passive and active) and employees' enjoyment of the workplace environment.
- Description of BMS, BEMS, integration – numbers of systems included, sensors and meters in use, level of control/interaction by occupants, level of flexibility by system and zone.

A description of post-occupancy evaluation activities should include

- Table or description of the corrective actions and impacts made during POE evaluation and O&M targets.

- Description of types of POE studies used to commission occupant behavior and metrics used or created as a result

- Description of formal measurement and verification process including types and quantities of updates to energy model assumptions to reflect the actual operation.

  - Description or metric showing impact on building energy use from building receptacle controls (various types and modes of operation, occupant schedule dependent or other supervisory control methods).

  - Description of process for notification of variations and adoption of revised energy targets used to correlate to an updated and accurate operation profile.

  - Description of the type and quantity of meters and sub-meters and evaluation of whether the type and quantity are appropriate.

- Description of how specific roles and responsibilities for the design team, building owner, and tenant are established, and mechanisms used to carry out compliance and ensure optimal operation of the new workplace.

- Contract samples that create a shared responsibility and accountability for EUI targets: responsibilities and information provided.

A Description of the information and tools used by the team should include:

- Design-build team recommendations and lessons learned from the use of the various tools

- Documentation of interoperability of various tools used, time and fee impact of model building separately to primary models, etc.

A description of the products and systems used in the project should include:

- Design Decision Making Diagram for Minimizing Building Costs, Embodied Carbon, etc.

- Graphics Showing Design Decision Financial-Performance-Environmental Impact Trade Offs

- Control Systems Description and Diagrams for Electric Light and Daylight Systems

- Specification for Lighting Control Systems – Including Description of System Software

- Description of Basis of Design and Sequence of Operations

A description of the energy issues specific to the project should include: Participation in Demand Response, Automated Demand Response Programs

- Description of impacts of program energy requirements above local code requirements

A description of the indoor environmental quality issues specific to the project should include:

- Occupant Control of Thermal, Acoustic, Visual Comfort
  - Occupant Feedback to Modify Thermal, Acoustic, Visual Comfort
  - Means and methods used to control indoor environment to align with project goals
- Metric to describe systems with regard to the number of zones, zone complexity (number of spaces, occupants, use-types, etc.), zone volumes, exposure to exterior conditions.
- Visual environment details
  - Lighting Levels by use type,
  - schedule, use of tunable spectrum lights, lighting spectrum modeling,
  - O&M practices that will ensure replacement of lamps with correct color spectrum and output.
  - O&M practices that document occupant satisfaction with visual environment

A description of the project results specific to the project should include:

- Publicly viewable dashboard of metrics described above

PART 2 - SECTION 1: VISUAL COMFORT IN BUILDINGS

Metric		A.K.A.	Variables (all metric units)	Equation	Scales	Limitations	Additional Notes
	Discomfort Glare		L_s - Luminance of glare source L_b- luminance of general field w_i - solid angle subtended by source ψ- Angular displacement of source from observer's line of sight	$G = \left(\frac{L_{si}^{e}\omega_{si}^{f}}{L_b^{g} f(\Psi)}\right)$			•Glare that produces discomfort. Does not necessarily interfere with visual performance or visibility
IESNA Metrics	Visual Comfort Probability	VCP	L_s - Luminance of glare source Q- 20.4ws+1.52ws 0.02-0.075 w_s- solid angle subtended at eye by glare source P- index of position of glare source with respect to line of sight calculated for any interior luminaire within FOV, limited to 53degs above horizontal line of sight	For single source: $M = 0.50 L_{si} Q / P_i F^{0.44}$ For multiple sources: $DGR = [\sum_{i=1}^{n} M_i]^{n^{-0.0914}}$ From DGR to VCP: $VCP = 100/\sqrt{2\pi} \int_{-\infty}^{6.374-1.3227\ln(DGR)} e^{-t^2/2} dt$	imperceptible: 80-100 perceptible: 60-80 disturbing: 40-60 intolerable: < 40	• Not intended for daylit environments • Not intended for small sources • Not intended for large sources • Not intended for nonuniform sources • Does not accurately model discomfort caused by parabolic fluorescent luminaires •Only used in North America	•1963 - Formula proposed by Guth •Recommended by IESNA with considerations to its limitations
European Metrics	British Glare Index	BGI BRS IES Glare Index	L_s- Luminance of glare source L_b- Average luminance of FOV excluding glare source w_s- solid angle subtended at eye by glare source P- index of position of glare source with respect to line of sight as derived by Luckiesh and Guth			• Not intended for daylit environments • Limited to small sources (solid angle < 0.027 sr) • Does not accurately predict glare from larger and wider sources • Does not take into account the effect of adaptation	• 1950 - Developed by Petherbridge and Hopkinson • Validity of equation put into question by work done by Einhorn • 1967 - IES-London published BGI • 2002 - CIBSE recommended using UGR instead of BGI

	CIE Glare Index	CGI	E_d - direct vertical illuminance at eye due to all sources E_i - indirect illuminance at eye L- luminance of luminous parts of each luminaire in direction of the observer's eye w-solid angle of luminous parts of each luminaire in direction of the observer's eye P-Guth position index for each luminaire (displacement from the line of sight)	$CGI = 8log_{10}((\frac{2\left(1+\frac{E_d}{500}\right)}{E_d+E_i})\sum_{i=1}^{n}\frac{L_{si}^2\omega_{si}}{P_i^2}$	imperceptible: < 13 perceptible: 13-22 disturbing: 22-28 intolerable: > 28	• Not intended for daylit environments • Increased calculation time due to Ed component	•1979 - Metric developed by Einhorn • Developed to correct mathematical inconsistency of BGI equation for multiple glare sources • Developed to combine best points of VCP, BGI and the Glare Limiting System
	Unified Glare Rating	UGR	L_b - background luminance (can be derived from illuminance at eye of observer) L_i - luminance of luminaire i w_i - solid angle of luminaire i P_i - Guth position index of luminaire i	$UGR = 8log_{10}(\frac{0.25}{L_b})\sum_{i=1}^{n}\frac{L_{si}^2\omega_{si}}{P_i^2}$	imperceptible: < 13 perceptible: 13-22 disturbing: 22-28 intolerable: > 28	• Not intended for daylit environments • Restricted to sources with solid angle of 3 x 10^-4 to 10^-1 • Not intended for sources smaller than 0.005 m2 • Not intended for sources larger than 1.5 m2 • May not be accurate for complex sources such as specular luminaires • Has been found to over-estimate glare •Does not explicitly allow for co-variance nor the direct component of adaptation	• 1995 - CIE published UGR as a refinement of CGI • Based on CGI with omission of Ed due to its increase on calculation time without significant impact on accuracy • 2002 - UGR extension equations available for: small sources, large sources, non-uniform indirect lighting and complex sources.

Daylight Metrics	Daylight Glare Index	DGI Cornell Glare Eq.	L_s - luminance of each glaring light source in FOV L_b - average luminance of visual field w - solid angle of glare source at eye pos - angle between direction of light source and direction of viewing	$DGI = 10log_{10}(0.4784\sum_{i=1}^{n}\frac{L_{si}^{1.6}\omega_{si}^{0.8}}{(L_b + 0.07\omega^{0.5}L_{win}P_i^{1.6})})$	imperceptible: < 18 perceptible: 18-24 disturbing: 24-31 intolerable: > 31	• Outperformed by DGP	• 1982 - Modification of BGI by Chauvel • DGI = 2/3 x (IES glare index +14)
	Daylight Glare Probability	DGP	E_v - vertical eye illuminance L_s - luminance of source w_s - solid angle of source P - position index	$DGP = 5.87 \times 10^{-5}E_v0.0918log_{10}(1 + \sum_{i}\frac{L_{si}^2\omega_{si}}{E_v^{1.87}P_i^2}) + 0.16$	imperceptible: < 0.3 perceptible: 0.3 -0.35 disturbing: 0.35-0.4 intolerable: > 0.45	• Not defined for Ev <320 lux • Developed only using clear sky conditions • Has not proven to be adequate as standalone metric due to low vertical illuminance values	• 2006 - Developed by Wienold and Christoffersen • The percentage that occupant will be disturbed by glare as opposed to magnitude • Binary measurement(comfortable or uncomfortable)

PART 2 - SECTION 2: NON-VISUAL EFFECTS OF LIGHTING AND POSSIBLE IMPACTS ON HUMAN HEALTH

PART 2 - SECTION 3: INTEGRATION OF HARDWARE & CONTROLS FOR DAY- AND ELECTRIC LIGHTING SYSTEMS

PART 2 - SECTION 4: SIMULATION AND SOFTWARE FOR INTEGRATION OF DAY- AND ELECTRIC LIGHTING SYSTEMS