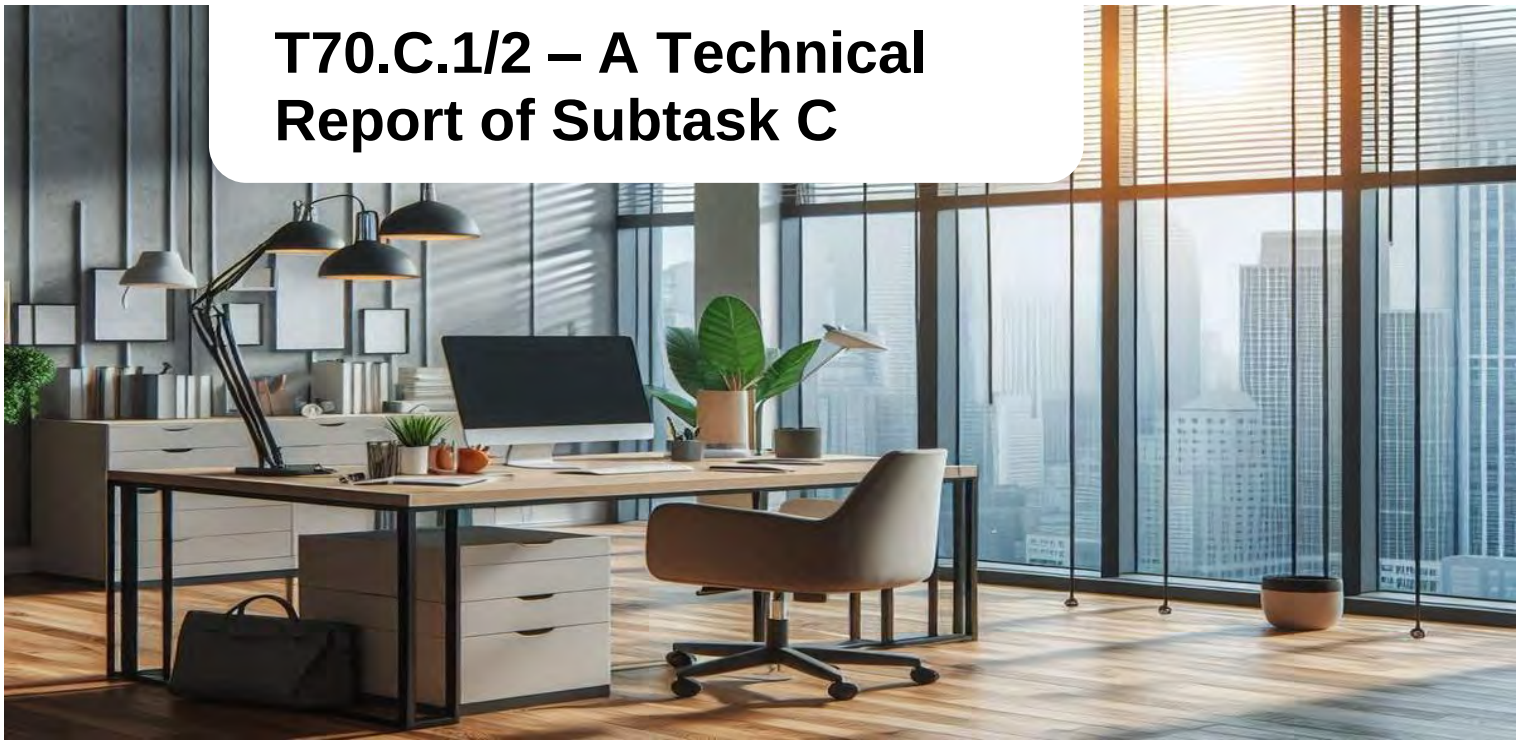
SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Integrated lighting solutions and controls: Market and literature state-of-the-art

T70.C.1/2 – A Technical Report of Subtask C



IEA SHC TASK 70 | EBC Annex 90: LOW CARBON, HIGH COMFORT INTEGRATED LIGHTING

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Solar Heating & Cooling Technology Collaboration Programme (IEA SHC)

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

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- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
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SOLAR HEATING & COOLING PROGRAMME
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Integrated lighting solutions and controls: Market and literature state-of-the-art

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PREFACE

Lighting accounts for 15% of the global electrical energy consumption and 5% of global CO_2 emissions. Thus, widening the rating perspective of lighting solutions to a more holistic view of its impact on CO_2 emissions, encompassing the whole life cycle chain also in the context of regional energy markets aspects, interaction with other building trades, etc. is urgently deemed necessary. This goes far beyond the pure LED lamp-driven energy efficiency gains.

The aim of IEA SHC Task 70 / EBC Annex 90 “Low Carbon, high comfort integrated lighting” is to identify and support implementing the potentials of lighting (electric, façade: daylighting and passive solar) in the decarbonization on a global perspective while aligning the new integrative understanding of humans’ light needs with digitized lighting on a building and a building related urban scale. This includes the following activities:

- Actively support broadening the view on lighting solutions as a whole in the context of decarbonization. Help bridge the gap between a component view (manufacturer’s focus) and design-oriented system approaches. Support the transition from a rather pure energy focused view so far to a life cycle assessment (LCA) perspective. On this basis, identify key impact factors, and develop the most effective strategies and roadmaps while including regional specifics.
- Contextualize this with the fast-developing digitization of buildings/lighting installations on the technology, design and operational side. Add to selected open points in the digital chain like better design processes.
- Align this with the still growing understanding of user needs; here specially build upon results from earlier IEA projects (e.g., IEA SHC Task 61 / EBC Annex 77).
- Integrate competencies: Bring the different involved players (electric lighting, façade, industry, controls) so far not connected on low carbon solutions together in workshops and specific projects. Create added value also by transferring into standardization, regulations and building certificates.
- Foster the broad implementation of low carbon solutions, also and especially in developing countries, by promoting tailored “Low Tech – High Impact Solutions” through demonstration, design guidelines, and workshops.

To accomplish these objectives, the work plan of IEA SHC Task 70 / EBC Annex 90 is organized according to the following four main subtasks.

Subtask A: Low Carbon Lighting and Passive Solar: Scenarios, Strategies, Roadmaps.

Subtask B: Visual and non-visual User Requirements.

Subtask C: Digitalized Lighting Solutions (Technology & Design Tools / Process).

Subtask D: Application and Case Studies.

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1 Executive Summary

If we survey today's market and garner an understanding of the state of the lighting industry from those in leadership positions, we find that there are strong, competing global market forces at play that influence the uptake of innovative technologies in buildings and shape R&D priorities. Regional directives advocating rapid decarbonization and increased transparency of the environmental footprint of lighting products are driving near term developments of certified sustainable, quality products. Looking beyond cost competitiveness as the sole driver of choice, industry trends are focused on delivering holistic solutions that reflect a balanced view of architecture and aesthetics, a keen awareness of the criticality of environmental concerns, and a growing understanding of the multi-dimensional aspects of how light influences physiological and psychological health and well-being.

The objective of this report is to provide an overview of the current state of technological innovation as a resource for key stakeholders seeking professional development, increased consumer awareness, formulating policy, or developing best practices. The report enables stakeholders to assess generally where we are today and where we need to go to achieve stated goals of increased energy efficiency, demand flexibility, comfort, health, and well-being. The overview was compiled from industry product data, peer-review scientific publications, reports from public institutions, amongst others, with analysis and synthesis to identify R&D trends.

Detailed descriptions of technological innovations are given in three chapters with targeted conclusions and references provided within each chapter. Summary conclusions are as follows.

Daylighting and shading systems: With integrative lighting, daylighting and shading technologies have shifted from a singular focus on delivering glare-free, controlled daylight to reduce lighting and HVAC energy use to more qualitative daylighting that supports human health and well being (yet still satisfies decarbonization objectives). Given the broad variation in visual and non-visual responses to light amongst humans, solutions include those tailored to individual preferences and more general solutions that celebrate the natural aspects of daylight (i.e., spectral content, diurnal variability, colour temperature) with personal control satisfied via complementary means (e.g., local shading to mitigate discomfort glare, design for workplace and task flexibility). At the leading edge of R&D, dynamic technologies (i.e., chromogenic glazings, kinetic shading structures) are combined with architectural strategies (zoned window walls) and controlled using user-adaptive algorithms, advanced sensor networks, and linked to whole building and grid-integrated, interoperable controls. Solutions will likely (and hopefully) evolve with new R&D findings in chronobiology and neuroscience.

Electric lighting core technologies: Impressive advancements in solid state lighting (SSL) luminous efficacy have been accomplished over the past two decades with smaller incremental improvements projected through 2050. The R&D focus is now on improving source and luminaire optics, colour rendering, and spectral properties for superior lighting quality and also on meeting challenging non-visual requirements for melanopic lux levels at the eye without incurring the two- to three-fold increase in lighting energy use seen in earlier installations and case studies. Holistic design and engineering practices are critical to maintaining the efficiency gains accomplished to date by LED replacement of non-SSL inefficient sources.

Integrated lighting controls: Digitalisation of lighting has transformed the industry with its potential to adapt control of individual lighting, shading, and daylighting components to the changing site, regional, and global context and maintain high performance over the 10-to-50-year life of the installation. Forward looking R&D has focused on improving the "intelligence" of systems through sensor fusion, control integration with other building systems, and forecasted, predictive, adaptive modeling that encompasses user-centric and decarbonization goals throughout the operations phase of the life cycle. Considerable work on the underlying infrastructure is underway to reduce complexity and the hands-on engineering and implementation costs via BIM, semantic modeling, interoperable components, machine learning, and digital twins.

2 Introduction

There continues to be increased regulatory and societal pressure to reduce energy consumption and CO_2 emissions as we collectively strive to meet zero-carbon and sustainability goals in the near-term future. The means for increasing efficient use of resources in lighting encompasses: (i) product level improvements, (ii) integrated design processes, and (iii) improved commissioning and maintenance processes over the life of the installation.

The scope of this report focuses on identifying innovative technological advancements that engage these three aspects to reduce energy, demand, and life cycle environmental impacts of indoor lighting applications, yet satisfy user-centric comfort, health and well-being requirements as the global context evolves.

An in-depth review of the state-of-the-art daylighting and shading systems, electric lighting systems, and integrated control systems was performed by collecting inputs from key stakeholders (industry, standardization bodies, research, public institutions, design and engineering community), reviewing commercially available product offerings, and reviewing and analyzing recent peer-reviewed scientific literature. The review is presented with detailed descriptions of core technologies and includes, in the area of electric lighting systems, a comprehensive review of thirteen key application areas with associated technological strategies and solutions. For each technological area, conclusions regarding challenges, needs, and future trends are given.

Digitalization is a cross-cutting technology that enables systems integration between lighting systems (e.g., daylight+electric light) and across systems (e.g., HVAC, lighting, grid) over the building lifecycle. This aspect is covered within each of the technological areas at varying levels of abstraction. Note that from the integrated design perspective, the report is divided into the traditional siloed industries but is not intended to discourage consideration of solutions that cross trade boundaries. Such integration must be addressed at the architectural and engineering design level using advanced software tools[1], through the use of interoperable components and systems and adaptable controls, and extending design intent into the operations phase with supporting fault detection and diagnostic tools.

The review cannot claim to be comprehensive as there are many technological solutions that are existing and under development by industry for a wide range of purposes. However, the review does seek to focus on potential solutions for the recent challenge presented by integrative, non-visual lighting requirements which has the potential to increase lighting energy use and demand significantly (e.g., by a factor of 2 to 3) due to the much higher flux requirement at the eye (i.e., melanopic lux on vertical surfaces), with all of its attendant problems such as discomfort glare, solar heat gains/ HVAC energy use (if supplemented with daylight), and temporal restrictions on demand flexibility. To address this challenge at scale, improvements in source (lm/W with LED, OLEDs) and optical efficiency are likely the simplest turnkey solutions for both indoor and outdoor lighting but given the relatively nascent stage of non-visual research, daylighting solutions should not be dismissed despite their inherent complexity. Similarly, advancements in digitalization have similar tradeoffs in benefit and complexity. Look towards rapid developments in advanced control systems that combine equation-based modeling, machine learning, and digital twins to enable sustained, reliable high performance over the 10-to-50-year lifetime of our built solutions.

[1] D. Geisler-Moroder, E.S. Lee, X. Guo, M. Scorpio (Eds.). Simulation Tools for Low Carbon, High Comfort Integrated Lighting. T70.C.4.1. A Technical Report of Subtask C, IEA SHC Task 70 / EBC Annex 90. 2026.

3 Daylighting / Shading Systems

Vincent van Karsbergen and Stephan Moser

3.1 Industry Overview: Current Trends and Innovations

3.1.1 State-of-the-Art

Sun shading products for windows and glass facades play a crucial role in energy efficiency, indoor comfort, and modern architecture, seamlessly blending functionality with aesthetics. This overview includes a state-of-the-art review of existing sun shading systems with a focus on industrialized solutions. Generally, the market offers a diverse range of solutions, from traditional blinds to advanced automated shading systems. These products effectively regulate light and heat, contributing to energy savings and enhanced climate control.

The growing demand for sustainable and energy-efficient solutions is driving the development of new materials and innovative automation strategies. E.g., zoned control strategies have the potential to improve building performance by dividing windows or spaces into independently managed sections. This allows systems to simultaneously block eye-level glare while redirecting daylight deeper indoors, reducing both cooling and lighting loads. Despite this potential, fine-grained zoning is not widely applied yet due to high initial costs, complex integration with building management systems, and unpredictable manual overrides. Other advancements such as AI-driven shading systems, photovoltaic-integrated blinds, and smart films are shaping product innovation with the aim of optimizing energy performance while improving comfort of the building occupants.

To better understand the current landscape, a general classification of daylighting systems and their integration with zoned control strategies have been detailed below:

Sun Shading Products

- **Dynamic Shading Systems:** These represent the most widespread industrialized solutions, relying on physical movement to block or filter light. This category includes motorized exterior and interior blinds, roller textiles, and systems integrated directly between glazing panes. By adjusting slat angles or fabric deployment, these systems provide a flexible, cost-effective balance between thermal protection and outside views.
- **Smart Glazing Technologies:** Moving beyond physical barriers, smart glass alters its own optical properties to dynamically control solar transmission. Unlike applied films, these active materials are manufactured directly into the glass matrix or permanently sealed within an Insulated Glass Unit (IGU), making them a premium solution best suited for new construction or major renovations. This includes electrochromic glass, which darkens when an electrical voltage is applied, and thermochromic glass, which reacts passively to heat. These technologies are particularly valuable for maintaining unobstructed exterior views while dynamically managing glare and solar heat gain in real-time.
- **Films and Coatings:** Designed to selectively filter the solar spectrum, window films (whether reflective, tinted, or actively switchable “smart films”) are superficial layers applied directly onto the interior or exterior surface of the glass. In contrast to the built-in, capital-intensive nature of smart glazing, films and coatings offer a lightweight, highly accessible, and cost-effective retrofitting solution. While some smart films can change state, most conventional films or coatings provide static, passive filtering to reduce heat transmission and ultraviolet exposure without the need for bulky mechanical hardware or, in the case of adhesive films, even without full window replacement.
- **Daylight Redirecting Systems:** Rather than simply blocking light, these systems, such as light shelves, reflective louvers, and tubular skylights, are designed to actively reflect or refract sunlight deeper into a building's core. They are highly effective in deep-plan offices where perimeter zones suffer from glare while interior zones suffer from gloom.
- **Adaptive and Kinetic Facade Technologies:** This cutting-edge category encompasses multi-functional building envelopes. It includes Building-Integrated Photovoltaics (BIPV) that generate energy while providing shade, as well as kinetic facades featuring special, often biomimetic, geometries that physically morph or rotate in real-time response to the sun's trajectory.

Control Strategies

To unlock the full potential of the physical products listed above, often sophisticated control strategies are required to orchestrate them:

- **Sensor-Based Automated Control:** These systems utilize localized photo-sensors and pyranometers to deploy shading automatically when sunlight or temperature thresholds are exceeded, removing the reliance on unpredictable occupant behaviour.
- **Smart Home and User-Centric Integration:** Providing occupants with simple, intuitive interfaces (via smartphones or smart home ecosystems) allows for manual overrides. Studies show that giving users a degree of control over their immediate zone significantly increases overall satisfaction with the automated system.
- **Subdivision with Motorized Multi-Zone Systems:** Also known as “split-control”, this strategy divides a single window into upper and lower zones that operate independently. For instance, the lower blinds can close to prevent glare on VDUs of occupants, while the upper blinds remain open or tilted to allow sufficient daylighting, potentially even redirecting it into deeper room areas by bouncing daylight off the ceiling. Pairing these zoned facades with interior spatial data, such as desk layouts or occupancy sensors, allows the control system to prioritize visual comfort in occupied areas while maximizing energy efficiency in unoccupied zones.
- **AI-Control Strategies Based on Pre-Simulation:** The most advanced tier of control utilizes machine learning and pre-calculated daylight simulations. These AI systems continuously analyse variables like sun position, weather forecasts, and historical occupant preferences to predictively adjust shades, optimizing the delicate balance between visual comfort and energy consumption before glare even occurs.

3.1.2 References to IEA Reports

This section summarizes key findings from existing IEA reports, providing an overview of the analysed solar shading products. *IEA Task 56* includes a SWOT analysis of various building-integrated solar envelope systems for HVAC and lighting. However, this section places a stronger emphasis on the lighting aspect, and different shading systems are compared based on their SWOT analysis.

Smart glazing solutions can provide a sleek, modern facade suitable for urban architecture, with low maintenance and quiet operation due to the absence of moving parts. However, uncertainties regarding their long-term performance, the need for specialized framing, and high initial costs present challenges. Additionally, their lighting value relies on intangible benefits like occupant comfort and daylighting, which can be difficult to quantify for decision-makers (where HVAC benefits are considered separately). Dynamic shading systems, classified into motorized venetian blinds, roller shutters, and textile screens, are the most popular sun protection systems in Central Europe. This is due to their flexibility in balancing daylight, glare control, outside view, and solar protection. Their widespread use makes them highly cost-effective compared to specialized shading solutions (e.g., facade technologies integrated into the IGU like Okalux Okasolar 3D).

Relevant IEA Tasks include:

- Task 56: SWOT Analysis of different solar building systems/products
- Task 50: A source book for daylighting
- Task 61: Review of lighting and daylighting control systems

3.1.3 Industry Trends

One key trend driven by enhanced control mechanisms is the finer zoning of window areas and individual room levels. Textile shading plays a crucial role in modern architecture in this context and is widely used. Buildings with large window areas can create a visually harmonious exterior while maintaining strict interior climate control. Some examples from the field are listed below.

3.1.3.1 Shading Systems with Integrated PV

Various companies have recognized the potential of combining shading solutions directly with photovoltaics to not only shield sunlight but also simultaneously use it and generate electricity. Moving beyond static shading, adaptive systems with PV are gaining traction:

- *Colt Shadovoltaik*: External facade system with glass slats with integrated photovoltaics. Automatic adjustment to the solar position improves shading and solar power generation (Colt, n.d.).
- *SolarGaps*: External venetian blinds made of aluminium equipped with solar panels on the single slats. Smart blinds automatically adjust to the solar position (SolarGaps, n.d.).
- *solarnova*: PV models integrated into cold, warm, or double facades as BIPV solutions. Moving slat systems balance daylight and solar power generation (solarnova, n.d.).
- *SolarStoren*: External venetian blinds with carbon slats equipped with solar panels that align to the solar position (SolarStoren, n.d.).

3.1.3.2 Glazing Trends

The industry is seeing rapid advancements in the physical properties of the glass itself, moving toward thinner, more highly insulative products:

- Thin Triple Glazing: Insulated Glass Units (IGU) with ultra-thin middle glass layers (Glaston, n.d.).
- Vacuum Glazing: Products like *Pilkington Spacia* (Pilkington, n.d.), *Passivglas* (Passivglas, n.d.), *VacuMax* (Vitro Architectural Glass, n.d.), and *FINEO glass* (FINEO, n.d.), which offer the thermal performance of thick double or triple glazing in a fraction of the width.

3.1.3.3 ShadeMe Controller

ShadeMe, a Swiss start-up, provides an advanced smart controller for venetian blinds both commercial and residential buildings (ShadeMe, n.d.). Designed as a decentralized system, it optimizes daylight provision and solar gain control while ensuring a comfortable, glare-free environment. Equipped with an embedded camera, it continuously monitors sky and ground luminance distribution, calculating daylight provisions in rooms, and dynamically adjusting blinds to the ideal position and tilt angle based on real-time weather conditions. By intelligently managing daylight, *ShadeMe* ensures:

- Optimal natural lighting by maintaining sufficient daylight on work surfaces, reducing reliance on artificial lighting.
- Energy efficiency by minimizing cooling costs by blocking excessive solar heat while maximizing natural illumination.
- Visual comfort by preventing glare and enhancing indoor ambiance.
- It supports multiple smart home ecosystems (Tuya, MI, KNX, RS485, Casambi) and is applicable for a wide range of commercial applications.

3.1.3.4 Trends in integrated systems and controls

In the field of integrated electric lighting and daylighting systems – particularly integrated control systems – there are also various trends in the industry. In some cases, even large companies from different sectors are joining forces to best support this integration. One example for this is *Wellumic*, which is formed by *Warema* (shading, daylighting) and *Trilux* (electric lighting). These trends are described below in Section 5.2.

3.2 Scientific Research

In recent years, scientific research on daylighting systems has advanced significantly, driven by the dual mandates of building energy efficiency and occupant well-being. Researchers are aggressively exploring innovative materials, dynamic control systems, and advanced modelling tools to harness natural light more effectively. Following are several core thematic pillars revealed in current scientific discourse based on a comprehensive literature survey on occupant-centric daylighting systems.

3.2.1 Innovative Materials and Smart Glazing

There is a profound shift toward dynamic, switchable materials that alter their optical properties in response to environmental stimuli or electrical currents.

- Electrochromic (EC) and Thermochromic Glazing: Research heavily investigates EC glass for its ability to reduce discomfort glare without sacrificing the outside view, performing favourably against traditional fritted glass and standard blinds (Ardakan et al., 2017). However, studies note that the control strategy significantly impacts EC performance; optimized model-predictive controls are required to balance cooling loads, visual comfort, and the relatively high embodied energy of these glazings (Kheybari et al., 2022; Favoino et al., 2016, Gehbauer et al. 2023). Furthermore, empirical tests indicate that while EC glass reduces glare, specific visible light transmittance thresholds (as low as 0.14%) are required to achieve true visual comfort when the sun is directly in the field of view (Jain et al., 2022).
- Polymer-Dispersed Liquid Crystal (PDLC) and Photoelectrochromic (PEC) Devices: Smart windows like PDLC can switch from translucent to transparent, effectively rejecting near-infrared radiation and reducing cooling loads in summer (Hemaida et al., 2020). However, it is important to note that PDLCs are always powered when in the clear state, a factor that must be taken into account in an energy efficiency / life cycle analysis. PEC devices combine electrochromic materials with dye-sensitized solar cells to create self-powered, adaptive transparent films, offering significant energy savings particularly in cooling-dominated climates (Fiorito et al., 2020; Leftheriotis et al., 2010).

3.2.2 Integration of AI and Machine Learning

The complexity of balancing thermal loads, daylight autonomy, and glare has led researchers to integrate Machine Learning (ML) and Artificial Intelligence (AI) into control systems.

- Occupant-Centric AI: Traditional systems rely on static thresholds, but humans have subjective, time-varying tolerances for glare. Researchers are utilizing ML to build personalized preference profiles. For instance, Bayesian classification and Dirichlet Process priors have been used to infer occupant visual preferences from limited data, shifting control from a generalized model to a deeply personalized one (Sadeghi et al., 2018; Xiong et al., 2020).
- Predictive Control and Automation: Support Vector Machines, Extreme Gradient Boosting (XGB), and Random Forest algorithms are increasingly used to predict glare and optimize blind tilt angles in real-time. By utilizing pre-simulated daylight data and real-time solar irradiance, ML models can actuate shading systems to prevent up to 96.9% of glare while saving over 80% in lighting energy use (Xie & Sawyer, 2021; Takhmasib et al., 2023).

3.2.3 Comprehensive Daylighting Models and Metrics

Accurate simulation is the backbone of modern daylighting design. Current research is refining metrics and reducing the computational cost of annual simulations.

- Glare Evaluation: The Daylight Glare Probability (DGP) metric has become a standard, but researchers are finding nuances. For instance, DGP can underestimate glare in specific educational settings where contrast on a focal point (like a blackboard) is more critical than overall illuminance (Bian et al., 2023). Furthermore, tolerance to glare is not static; it has been proven to increase as the day progresses, suggesting that variable set-points for automated controls are necessary (Bian et al., 2020). For small glare sources in the field of view, an adaptation of the DGP – the so-called “Daylight Glare Metric” (DGM) – has been introduced (Geisler-Moroder and Knoflach, 2025).
- Simulation Efficiency: Assessing dynamic facades annually requires immense computational power. Studies have developed simplified methods, such as the five-phase matrix method and tensor-tree Bidirectional Scattering Distribution Functions (BSDF), to accurately model complex fenestration systems (CFS) and specular transmission without unreasonable CPU time (Ward et al., 2021; Sepulveda et al., 2021).

3.2.4 Adaptive and Occupant-Centric Systems

A major consensus in the literature is that fully automated, rigid systems often lead to occupant dissatisfaction and subsequent manual overrides.

- Behavioural Modelling: Incorporating accurate Blind Control Occupant Behaviour Models (BC-OBMs) into simulations is critical. Assuming blinds are always open or optimally controlled creates a massive “performance gap” between simulated and actual building energy use (Verma & Gopalakrishnan, 2025; Correia da Silva et al., 2014).
- Split-Control and Zoning: To satisfy both daylight penetration and glare protection, researchers highly recommend “split-controlled” blinds. By operating the upper and lower sections of a blind independently, direct sunlight can be blocked at eye level while daylight is redirected to the back of deep-plan offices via the ceiling, significantly improving Useful Daylight Illuminance (UDI) (Olbina & Hu, 2012; Alsukkar et al., 2022).
- User Interaction: Providing occupants with a degree of manual override or expressive feedback interfaces increases their acceptance of automated adjustments, thereby securing the anticipated energy savings (Bakker et al., 2014; Meerbeek et al., 2016).

3.2.5 Multi-functional and Kinetic Building Elements

Architectural geometry and dynamic movement are merging to create “kinetic facades”.

- Kinetic and Bio-inspired Design: Moving away from traditional louvers, researchers are testing pneumatically adaptive polydimethylsiloxane (PDMS) arrays (Hinz et al., 2018), shape memory alloys for bistable kinetic screens (Vazquez & Duarte, 2022), and even biomimetic designs inspired by the Gazania flower (Sommese et al., 2024). These systems dynamically morph to filter daylight hierarchically based on sun position and occupant location.
- Daylight Redirecting Systems (DRS): Micro-prism films, active sunlight redirection systems with sun-tracking mirrors, and laser-cut panels are being integrated into the upper clerestory zones of windows. These systems redirect luminous flux deep into the space, effectively doubling the daylighting zone while keeping the lower window zone free of glare (Kontadakis et al., 2017; Fang et al., 2022, McNeil et al. 2017).
- Parametric and Performance-driven Kinetic Façades: Parametric kinetic façade concepts were investigated that combine responsive shading elements with computational optimization to improve daylight distribution, reduce cooling loads, and enhance visual comfort. The research demonstrates how adaptive façade geometries can balance multiple performance objectives by integrating climate-responsive design, daylight simulation, and energy analysis during the early design stages (Hosseini et al., 2019; Hosseini et al., 2024; Hosseini et al., 2026).

3.3 Challenges and Needs

Despite the impressive technological strides demonstrated in the literature, there remains a distinct gap between state-of-the-art research and widespread industry implementation.

3.3.1 Identified Gaps

- Technology Adoption & Economic Factors: There is a significant lag in adopting cutting-edge findings (like AI-driven kinetic facades or EC glass) into commercial practices, primarily due to high initial capital costs, complex installation, and the difficulty of quantifying “intangible” benefits like visual comfort for return-on-investment (ROI) calculations.
- Integration Issues: Integrating sophisticated daylighting systems with existing Building Management Systems (BMS) remains a technical hurdle. Advanced Model Predictive Control (MPC) algorithms require heavy computational integration that most standard HVAC/lighting controllers cannot natively support.
- Performance Measurement & Behavioural Unpredictability: There is a lack of standardized metrics for real-world assessments. As highlighted by Nezamdoost et al. (2018) and Verma and Gopalakrishnan (2023), human behaviour is unpredictable; occupants often leave manual blinds closed for weeks, negating the architectural daylighting design and skewing energy performance predictions.

- Awareness and education: Many architects and clients lack awareness of the long-term energy and productivity benefits of advanced daylighting, hindering demand.

3.3.2 Key Needs for the Future

- Enhanced research collaboration: Partnerships between academia, industry, and policymakers are needed to scale down the costs of advanced materials (like chromogenic glazings and BIPV) and facilitate knowledge transfer.
- User-centric design: Systems must prioritize the user experience. The literature proves that systems allowing manual overrides or employing ML to learn individual occupant preferences result in higher productivity and satisfaction (Choi et al., 2019).
- Holistic integration: Shading cannot be designed in a vacuum. Integrated design approaches that couple dynamic facades directly with HVAC and dimmable artificial lighting networks are necessary to achieve Net Zero Energy Building (NZEB) targets.
- Regulatory frameworks and education: Building codes should evolve to mandate the inclusion of OBMs in energy compliance simulations. Furthermore, training programs for practitioners are vital to ensure daylighting systems are properly commissioned and calibrated post-occupancy.

3.4 Conclusion

The field of daylighting and shading systems is undergoing a transformation from static, purely mechanical solutions to dynamic, intelligent, and occupant-centric building envelopes. As detailed in the preceding sections, innovations in electrochromic glazing, split-louver redirection, AI-driven predictive controls, and kinetic architectures offer unprecedented opportunities to balance the often-conflicting goals of maximizing natural light, mitigating glare, and minimizing HVAC energy loads.

However, while scientific research continues to push the boundaries of what these systems can achieve, a significant gap remains between theoretical potential and practical, widespread application. Overcoming the barriers of high initial costs, complex BMS integration, and unpredictable occupant behaviour will require enhanced multi-disciplinary collaboration. By prioritizing user-centric designs, standardizing real-world performance metrics, and updating regulatory frameworks, the industry can successfully translate these technological innovations into everyday practice, ultimately delivering highly sustainable buildings that actively enhance occupant health, comfort, and productivity.

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4 Electric Lighting Systems

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4.1 Introduction

Modern electric lighting has undergone a remarkable transformation, evolving from traditional incandescent and fluorescent lighting to highly efficient solid-state lighting (SSL) technologies, primarily light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs). This shift has been driven by the need for greater energy efficiency, sustainability, and enhanced user experience. LED technology, now the dominant form of lighting, has paved the way for further innovations, including smart lighting systems and human-centric lighting.

Besides technological innovations, state-of-the art lighting technology puts the user in the centre, thus advanced lighting controls based on IoT technologies or enhanced controls including daylight harvesting systems towards integral lighting systems are becoming increasingly popular. These controls automatically adjust lighting levels based on occupancy and natural light availability, thus enhancing energy savings and user comfort.

Electrical lighting consumes about 13.7% of global electricity and strongly affects human vision, well-being, health, and safety. It also influences environmental resources and ecosystems. After many years of limited progress in older lighting technologies, solid-state lighting (SSL) - especially LEDs - has emerged as the most efficient option available today. This shift is often considered the third major revolution in lighting. LED technology is now mature and is rapidly taking over a market valued at more than US$120 billion [5].

Although innovation in LEDs has slowed somewhat recently, new large-area, flexible organic emitters are creating fresh scientific and design opportunities. At the same time, a fourth revolution is approaching: intelligent, sustainable lighting systems that merge illumination with information technology, Internet of Things (IoT) connectivity, and other digital tools reshaping daily life [5]. Key improvements in electric lighting technologies include enhancing light source efficiency, better controlling intensity, and ensuring light is only used where needed. Increasing the proportion of light that directly supports visual functions could further amplify energy savings beyond efficiency gains alone [14].

The following major trends led to innovations in the last years in the electric lighting field:

1. Smart Lighting Systems: smart lighting has transitioned from a futuristic concept to a present-day reality. By integrating with the IoT, these systems offer enhanced convenience and energy efficiency. Users can remotely control lighting via smartphones or voice assistants, allowing for customizable schedules and ambiance settings. Features such as automation enable lights to operate based on specific times or occupancy, and integration with other smart home devices creates a seamless experience.

2. Energy-Efficient Solutions: the drive for sustainability has led to advancements in energy-efficient lighting. LED technology continues to evolve, providing higher efficiency, longer lifespans, and improved light quality. Innovations in solar-powered lighting reduce reliance on the grid, making these solutions ideal for various applications. Adopting energy-efficient lighting can lead to significant reductions in electricity bills and carbon footprints.

3. Human-Centric Lighting: human-centric lighting (HCL) emphasizes the impact of light on well-being, aiming to improve mood, productivity, and sleep patterns by mimicking natural light cycles. HCL supports natural circadian rhythms by adjusting light intensity and colour temperature throughout the day. Proper lighting can reduce eye strain, enhance concentration, and promote better sleep, making HCL particularly beneficial in workplaces, schools, and healthcare facilities.

LED technology dominates the market with approximately 40-45% penetration as of recent assessments, while emerging technologies like OLEDs, quantum dot LEDs, and micro-LEDs promise new form factors and capabilities [1][2]. The transition to next-generation SSL systems coupled with intelligent controls could reduce global illumination energy use substantially by 2030, with field deployments demonstrating energy savings of up to 73% through occupancy and daylight harvesting controls [3][4].

This chapter of the report will give an overview of the current state of the art in electric lighting systems, starting with the core technologies in the field of modern lighting systems, and followed by their application area and

corresponding industrial solutions. Technical innovations on optical and photometric concepts will be highlighted as relevant aspect as a basis for modern lighting design to reach highest standards in optical efficiency and energy standards. Technologies in lighting control and automation will bridge the gap to human interaction, their efficient integration into overall building controls, up to future concepts based on machine learning algorithms.

Finally, the chapter will give an insight also into current sustainability and regulatory trends, which are becoming higher relevance since the last years through new upcoming standards also in the electric lighting field, initiated by the Ecodesign guideline or the European initiative “Fit for 55”, which defines a set of new EU-Directives to achieve the European “Green Deal” and gives a summarizing outlook on the upcoming trends. [13]

4.2 Core Technologies in Modern Lighting

4.2.1 LED technology – Efficiency, colour rendering and lifetime improvements

Lighting technology has evolved significantly over the past few decades, with Light-Emitting Diodes (LEDs) leading the shift toward energy-efficient and sustainable illumination. Light-emitting diodes represent the dominant technology in modern electric lighting, serving as the backbone of solid-state lighting (SSL) across virtually all application sectors. LEDs are semiconductor devices that emit light through electroluminescence when current passes through a p-n junction. Unlike traditional incandescent bulbs that produce light through thermal radiation or fluorescent lamps that rely on gas discharge, LEDs convert electrical energy directly into photons with significantly higher efficiency [6].

LEDs based solid-state lighting is one of the predominant general illumination technologies. They use semiconductor materials to produce light more efficiently, resulting in lower energy consumption, longer lifespans, and reduced environmental impact. Today, LEDs dominate the lighting market, offering various applications ranging from residential and commercial lighting to automotive and smart lighting systems and whether used for indoor or outdoor lighting.

Key Technical Characteristics:

- **Luminous Efficacy**: Modern white LEDs achieve luminous efficacies exceeding 150-200 lm/W in laboratory conditions, with commercial products typically delivering 100-150 lm/W [1][6]
- **Lifetime**: LED systems offer operational lifetimes of 50,000-100,000 hours (L70 rating), far exceeding traditional sources [2]
- **Colour Rendering**: Contemporary LEDs provide colour rendering indices (CRI) of 80-95+, with tuneable spectrum options for specialized applications [7]
- **Controllability**: Instant on/off, dimmability without colour shift, and compatibility with digital control protocols [8]

Two common technologies for generating white light exists: PC-LED based on a blue LED pumping yellow and red wavelength optical down-converters (typically phosphors) to produce white light and the CM-LED approach using primary colours that compose a red, green, blue, and amber (RGBA) LED combined to produce white light.

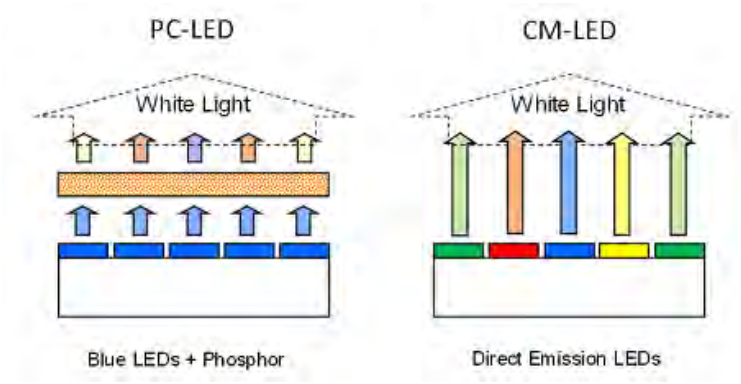


Figure 4.1: Schematics of the two main white LED architectures, Source: [14]

The PC-LED architecture is the dominant white light architecture used for LED lighting today.

Recent developments in LED technology include:

- **High-Power LEDs**: Devices capable of handling higher current densities for applications requiring high luminance, such as automotive headlamps and stadium lighting [9].
- **Chip-on-Board (COB) LEDs**: Multiple LED chips mounted directly onto a substrate to create high-density light sources with improved thermal performance and more uniform illumination [1].
- **Chip-Scale Package (CSP) LEDs**: Miniaturized packages approaching the size of the LED die itself, enabling ultra-compact luminaire designs and improved optical control [9].
- **Matrix and Segmented LED Arrays**: Individually addressable LED elements enabling adaptive lighting patterns, particularly important for automotive applications where beam shaping must respond to traffic and road conditions [9].

4.2.2 Organic Light-Emitting Diodes (OLEDs)

Organic light-emitting diodes represent a fundamentally different approach to solid-state lighting, using thin films of organic semiconductor materials sandwiched between electrodes (see Figure 4.2). When voltage is applied, electrons and holes recombine in the organic emissive layer to produce light. Unlike LEDs, which emit light from a single point source, OLEDs are made from organic compounds that create thin, flexible, and evenly diffused light panels. This allows for innovative lighting designs, including bendable, transparent, and ultra-thin displays.

With OLEDs, light is created within thin organic layers by the formation of excitons through electron-hole recombination and emission of radiation. OLEDs with state-of-the-art phosphorescent emitters can be very efficient. Internal quantum efficiency levels approaching 100% have been demonstrated. However, the stability of phosphorescent blue emitters is insufficient for commercial panels. Fluorescent emitters are more stable, but these lead to radiation only from singlet excitations, so that well over 50% of the energy is lost. The structure of a conformable OLED lighting panel made of ultra-thin glass. The organic layers are encapsulated to prevent the ingress of water and oxygen while allowing the supply of current through flexible electrical contacts.



Figure 4.2: Construction of an OLED, Source: [14]

OLEDs offer several distinctive advantages for lighting applications. As natural large-area emitters, they produce diffuse, low-glare light without the need for secondary optics. Their structure also allows fabrication on flexible substrates, making curved or conformable lighting panels possible. Because OLED panels can be extremely thin—often under 2 mm—they open up new opportunities for integrated architectural and design concepts.

But despite their potential, OLEDs still face several hurdles that limit their broader use in general lighting. Their luminous efficacy, though improving, remains below that of inorganic LEDs, with typical white panels reaching only about 60–100 lm/W at practical luminance. Lifetime and stability also pose challenges: organic materials and electrode interfaces degrade over time, restricting operational lifetimes to roughly 10,000–30,000 hours at higher brightness levels. Production costs remain comparatively high as well, since OLED manufacturing depends on specialized materials and equipment. Efficiency is further constrained by light trapped inside the device due to total internal reflection, making advanced extraction strategies necessary. Finally, OLEDs are extremely sensitive to moisture and oxygen, requiring robust encapsulation that increases both cost and complexity. [10], [11]

4.2.3 LED Luminous Efficacy

Over the last decade, luminous efficacy has more than doubled from approximately 85 lm/W to 185 lm/W at a standard operating current density of 35 A/cm². This growth has been primarily driven by improvements in blue LED efficiency, along with advancements in phosphor performance - enhancing both efficiency and spectral optimization - and better package efficiency through reduced optical scattering and absorption.

The efficiency of white LEDs has slowly reached a saturation point and is unlikely to see major improvements in the future. Currently, phosphor-based mid-power LEDs achieve operational efficiencies of over 200 lm/W. According to projections from the U.S. Department of Energy (DOE), the potential for phosphor-based LED types is around 250 lm/W. Even higher efficiencies could theoretically be achieved through spectral mixing of specific wavelengths.

Metric	Type	2020	2025	2030	2035	2050
LED Package Efficacy (lm/W)	PC Cool White	185	228	246	249	250
	PC Warm White	165	210	231	241	250
	Color Mixed	138	204	245	281	336

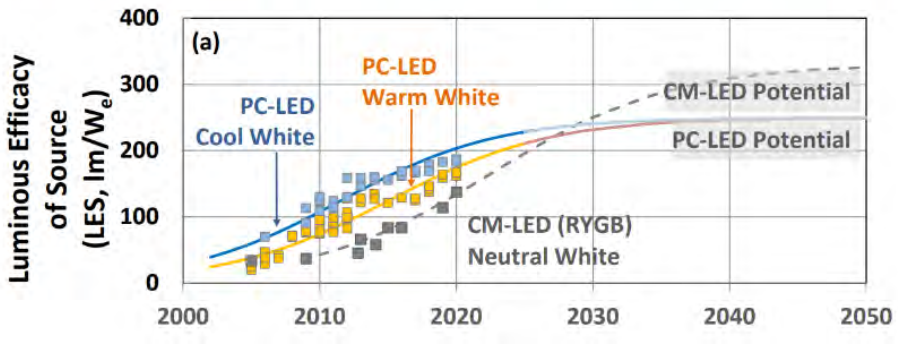


Figure 4.3: Historical and targeted efficacy levels of LEDs, Source: [14]

As indicated by the saturation points of the blue and yellow curves in Figure 4.3, PC-LEDs are expected to achieve luminous efficacies of approximately 250 lm/W under the specified operating conditions. For the colour-mixed architectures, an upper limit of 325 lm/W is considered achievable with greater breakthroughs in the technology advancements. While LED emitter materials have improved rapidly over the past decade, there are still key technological challenges that are limiting further improvement, e.g., the impact of droop in LEDs limits performance at higher operating currents and temperatures.

Another possibility to improve the performance are new LED device architectures tailored for different lighting applications, e.g., improvement performance including designs to circumvent current density droop and LED devices scaled down to a few microns in size. Advanced LED device architecture can improve efficiency or

improve the device operating ranges. These can lead to improvements in current density drop or provide desirable device performance, such as high luminance, that is not achieved with conventional LEDs.

4.2.4 Optical Delivery Efficiency

Significant energy reduction gains are still possible through the optimization of light delivery and light distribution. While improving the LED source efficiency has been a strong focus in the LED industry, how that light is delivered to the lighting application is equally as important. Advances in optical delivery are needed to use light most efficaciously for the application at hand. Understanding the application needs from both a visual acuity perspective, as well as the non-visual benefits, is essential to know how to best deliver the ideal light.

Improvement in the optical delivery from the source to the user can enable tailoring the optical distribution for the application while minimizing light that does not contribute to the application. Light intensity distributions that can be engineered in space and time and would reduce the over-illumination and under-illumination of spaces and spectral regions. Such engineered light could thus simultaneously reduce energy use and improve the effectiveness of lighting.

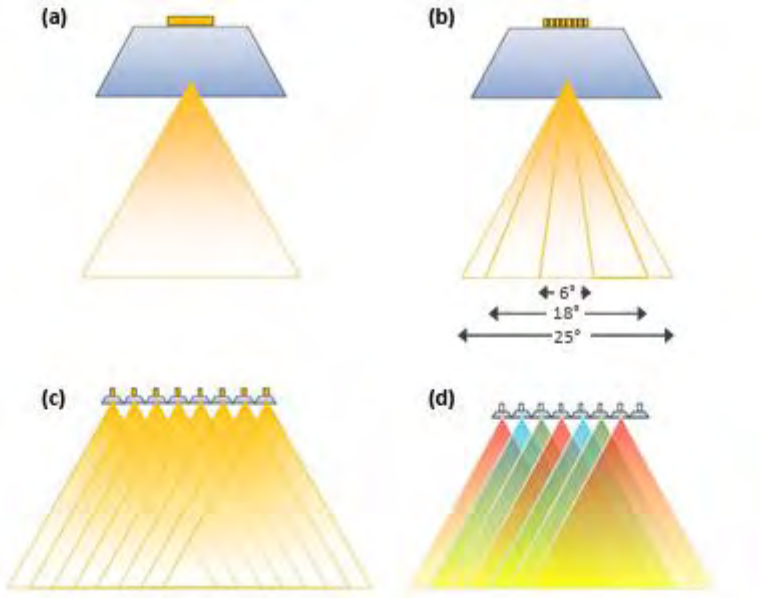


Figure 4.4: Illustrations of different approaches to optical control

In Figure 4.4, illustrations of different approaches for an optical control of the delivery efficiency are shown. A conventional static lens (a) is the traditional solution with a fixed beam angle or illumination pattern. New dynamic lenses can allow for changing the beam spread dynamically (b) by using liquid crystal electro-optic technology. Projection optics using many overlapping LEDs can enable more optical distribution patterns (c) and also allow for further spectral tuning along with the optical tuning (d).

Currently, less than 1% of the light generated by luminaires reaches an occupant's eye, indicating substantial room for efficiency gains. By doubling the proportion of light that directly supports visual functions, additional dramatic energy savings could be realized. These advancements will not only improve energy efficiency but also contribute to more sustainable, cost-effective, and user-friendly lighting solutions.

4.2.5 Human-Centric Lighting (HCL) – Circadian lighting, biological impact

General illumination meets two critical needs for human health and productivity: it allows humans to see their surroundings and supports the regulation of circadian, behavioural, and endocrine responses. While research related to light and melatonin suppression has been occurring since the 1970s, it was the discovery twenty years ago of another class of photoreceptors in the eye, ipRGCs, that has spurred recent research on the physiological impacts of light. Since then, more has been learned about the two primary neural pathways that transmit light information for these needs, as shown in Figure 4.5, with some interaction between the pathways.

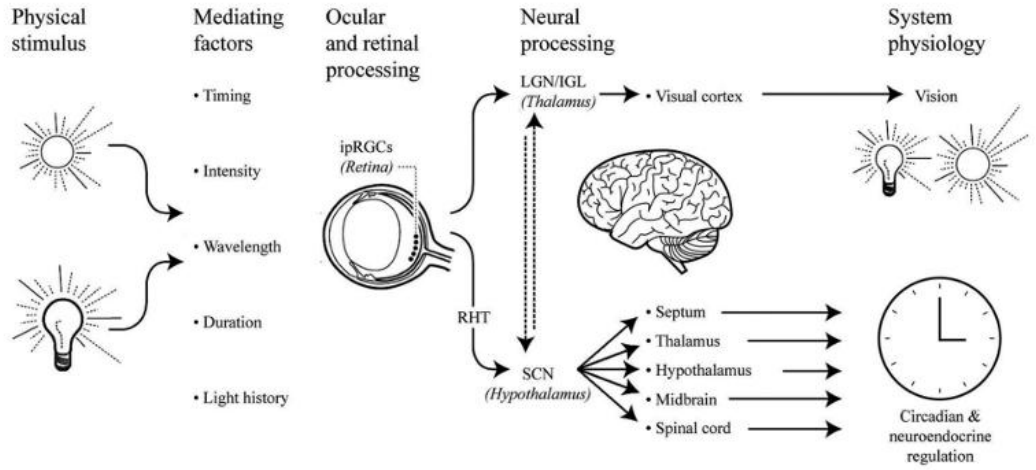


Figure 4.5: Schematic illustration of the neuroanatomical underpinnings of physiological effects of light, Source: [15].

In Figure 4.5, the schematic illustration of the neuroanatomical underpinnings of physiological effects of light. The ipRGCs transmit environmental light information via the Retin hypothalamic tract (RHT) to the central clock in the brain (SCN, suprachiasmatic nuclei); other direct projections of ipRGCs include thalamic and other brain regions. The response will depend on the light characteristics and/or mediating factors [15].

Much of the research on non-visual responses has been focused on laboratory settings where the lighting stimulus and human behaviour can be carefully controlled. While further understanding of the basic non-visual responses to light is helpful and necessary, it is also necessary to understand and optimize light spectrum and intensity to support non-visual physiological responses in realistic lighting settings with less controlled human behaviours and external factors. The link between real world exposure with real world outcomes requires studies in naturalistic settings where objective responses can be measured and related to light exposure and other potential factors. For example, in workplaces, quantitative outcomes related to health, productivity, and absenteeism can be evaluated and related to light exposure and other potential factors.

4.2.6 Smart and Connected Lighting – IoT-based control, sensor-driven automation

Smart lighting represents the integration of solid-state light sources with sensors, communication networks, and intelligent control algorithms to create adaptive, responsive, and multifunctional lighting systems. This paradigm shift transforms lighting from a passive utility into an active, data-driven service that optimizes energy use, enhances user comfort, and provides additional capabilities beyond illumination [5][8].

A smart lighting system is built up on following core components [8][12]

1. **Sensing**: Occupancy detection, daylight harvesting, environmental monitoring (temperature, humidity, air quality)
2. **Communication**: Wired (DALI, PoE, PLC) and wireless (Zigbee, Bluetooth Mesh, Wi-Fi, LoRaWAN) networking
3. **Intelligence**: Local and cloud-based algorithms for control optimization, predictive maintenance, and service delivery
4. **User Interface**: Mobile apps, voice control, gesture recognition, and automated scene programming
5. **Integration**: Interoperability with building management systems, smart home platforms, and IoT ecosystems

Modern smart lighting systems use a range of control strategies to improve efficiency, comfort, and user experience. Occupancy-based control relies on sensors - such as PIR, ultrasonic, or computer vision - to adjust lighting automatically based on whether a space is in use. Daylight harvesting uses photosensors to measure natural light and dim or switch off electric lighting accordingly. Task tuning tailors illumination to the minimum level

needed for specific activities, avoiding unnecessary brightness. Personal control lets users fine-tune lighting to their own preferences while still benefiting from networked energy management. Finally, circadian or human-centric lighting dynamically adapts colour temperature and intensity throughout the day to support natural biological rhythms and overall well-being.

4.2.7 Conclusion

The electric lighting industry has undergone a fundamental transformation over the past two decades, transitioning from traditional incandescent and fluorescent technologies to solid-state lighting based primarily on LEDs. This shift has delivered substantial improvements in energy efficiency, controllability, and functionality, with LED technology now dominating new installations across virtually all application sectors.

The transformation of electric lighting from traditional sources to solid-state technology represents one of the most successful energy efficiency transitions of the 21st century. LED technology has proven its superiority across virtually all performance dimensions - efficiency, lifetime, controllability, and environmental impact. The integration of smart controls and IoT connectivity is now enabling lighting systems to deliver value far beyond simple illumination, contributing to energy management, occupant comfort, smart building and city services.

However, realizing the full potential of modern lighting technology requires attention to system design, commissioning quality, user acceptance, and ongoing performance verification. As the industry moves toward "Lighting 4.0," success will depend not just on advancing component technologies but on creating integrated systems that are reliable, interoperable, and genuinely beneficial to the humans they serve.

The future of electric lighting is bright - efficient, intelligent, and increasingly human-centric. Continued innovation in materials, devices, controls, and system integration will further enhance lighting's contribution to sustainability, comfort, and quality of life in the built environment.

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4.3 Application Areas & Industry Solutions

This section provides a comprehensive review of application areas and industry solutions in the field of electric lighting systems. It explores the evolution of lighting technologies from traditional illumination to advanced, intelligent systems that integrate human-centric design, energy efficiency, and smart infrastructure capabilities. The content covers diverse domains including workplaces, retail, education, healthcare, residential environments, cultural spaces, outdoor and public areas, transportation hubs, industrial facilities, sports, museums and heritage, as well as sectors such as agriculture and connected infrastructure. Through an examination of state-of-the-art practices, technological innovations, and market trends, this document highlights how lighting systems contribute to visual comfort, operational performance, sustainability, and user well-being. The review emphasizes the role of adaptive controls, IoT integration, and dynamic lighting strategies in shaping modern environments, offering insights for designers, engineers, and decision-makers seeking to implement effective and future-ready lighting solutions.

This review is structured around thirteen key application areas and industry solutions that reflect the breadth of modern lighting practices. Each section highlights emerging trends, technological strategies, and solutions that shape lighting design, implementation, and performance. The table below provides a clear outline of the covered domains:

Office & Workplace Lighting	Outdoor & Public Lighting
Retail & Hospitality Lighting	Transportation Hubs & Mobility Infrastructure Lighting
Educational Facilities Lighting	Agricultural & Horticultural Lighting
Residential Lighting	Museums, Heritage & Monument Lighting
Healthcare & Hospital Lighting	Sports & Recreation Lighting
Industrial & Warehouse Lighting	Data, Connectivity & Smart Infrastructure Lighting
Art, Culture & Performance Lighting	

4.3.1 Office & Workplace Lighting

Modern office and workplace lighting has evolved to support not only visual comfort but also employee well-being and productivity. Lighting systems today are designed to align with circadian rhythms, reduce glare, and adapt to hybrid work environments. Dynamic and tuneable lighting solutions, integrated with occupancy and daylight sensors, are increasingly adopted to enhance energy efficiency and user experience.

Recent advancements focus on human-centric lighting strategies that support alertness, mood, and sleep quality. These systems are particularly beneficial for night shift workers and flexible workspaces, where lighting must adapt to varying schedules and tasks.

Key Drivers & Objectives	**Technological Solutions & Strategies**
Productivity-focused, low-glare task lighting & uniformity	High efficacy luminaires with UGR-controlled optics; layered ambient-task-accent schemes; maintained illuminance and uniformity per EN 12464-1; continuous dimming with task tuning and high-end trim.

Dynamic lighting for well-being & circadian support	Tuneable-white spectra scheduled to meet daytime melanopic EDI and reduce evening exposure; daylight-linked scenes; validation with light-dosimetry and user feedback.
Night-shift / extended hours alertness & sleep protection	Time-locked blue-enriched exposures during shift (≥5000 K where appropriate), pre-/post-shift melanopic reduction; blackout/rest areas with very low melanopic EDI.
Integration with occupancy & daylight sensors	Occupant-centric NLCs using PIR/vision/BLE beacons, daylight harvesting, shade coordination, and analytics (fault detection, optimization) to save energy while maintaining visual/circadian targets.

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4.3.2 Retail & Hospitality Lighting

Retail and hospitality environments increasingly rely on advanced lighting strategies to shape customer experiences, reinforce brand identity, and enhance product presentation. Accent and ambient lighting are used to create inviting atmospheres, while tuneable white and RGB systems allow dynamic adaptation to seasonal themes and promotional events. High-quality colour rendering ensures accurate product visualization, and immersive lighting technologies contribute to memorable customer journeys.

Integration of interactive lighting systems, such as responsive RGB and adaptive ambiance controls, supports branding and emotional engagement. These innovations are driven by developments in LED technology, IoT-based controls, and perceptual light art, enabling retailers and hospitality venues to transform their spaces into experiential environments.

Key Drivers & Objectives	**Technological Solutions & Strategies**
Enhance customer experience	Implementation of layered ambient–accent–task lighting systems with adaptive illuminance and CCT modulation (tuneable-white or multi-channel LED arrays) to influence dwell time, visual comfort, and emotional appraisal.
Branding and ambiance adaptation	Deployment of spectrally tuneable LED platforms and programmable control protocols to deliver brand-specific lighting signatures. Dynamic scenes support brand storytelling through light colour and intensity.
Product presentation accuracy	Use of high colour rendering luminaires with narrow-beam optics and tailored SPD to enhance material texture and colour perception. Precision accent lighting enables visual hierarchy and supports visual merchandising strategies.

Seasonal and event-based scene setting	Pre-program seasonal/event looks (spectral + spatial distribution); pixel-addressable lines/spotlights for quick re-themes; synchronize with window displays and façade lighting.
Immersive and interactive experiences	Integration of sensor-driven lighting systems (e.g., vision, LiDAR, BLE, or IoT triggers) with adaptive scene control and interactive media.

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4.3.3 Educational Facilities Lighting

Lighting in educational facilities plays a critical role in supporting student well-being, focus, and performance. Modern lighting systems are increasingly designed to align with circadian rhythms, reduce visual discomfort, and adapt to diverse learning activities. Dynamic lighting scenes and daylight harvesting strategies are being integrated to enhance both energy efficiency and cognitive outcomes.

Key Drivers & Objectives	Technological Solutions & Strategies
Support circadian rhythms and focus	Tuneable white LED systems (2700K–6500K) with automated schedules; daylight optimization for melanopic stimulus.
Visual comfort and non-flickering illumination	Flicker-free LED luminaires, glare control via UGR <19, high CRI (>90) for colour accuracy.
Dynamic lighting for varied activities	IoT-enabled controls for scene-based presets (lecture, group work, exams); adaptive CCT and intensity.
Energy efficiency and daylight integration	Daylight harvesting sensors, dimming algorithms, and integration with blinds; LED retrofits reducing energy use by up to 50%.

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4.3.4 Residential Lighting

Residential lighting has evolved significantly with the integration of human-centric and smart technologies. Modern systems aim to support circadian rhythms, enhance visual comfort, and provide personalized lighting experiences. Flicker-free and low-glare solutions are essential for visual health, while smart home integration enables automation and voice control. Aging-in-place lighting solutions are increasingly relevant for elderly users, promoting safety and well-being.

These innovations are driven by advancements in LED and OLED technologies, IoT-based controls, and adaptive lighting strategies. The following table summarizes key drivers, technological solutions, notable projects and products, and research findings in residential lighting.

Key Drivers & Objectives	Technological Solutions & Strategies
Circadian rhythm support	Dynamic tuneable white LEDs (2700K–6500K), automated schedules simulating daylight progression.
Visual comfort	Flicker-free LED drivers, glare control (UGR <19), high CRI (>90) for colour fidelity.
Smart home integration	IoT-enabled lighting (Zigbee, Matter), voice assistants, app-based scene control.
Personalized lighting scenes	Scene presets for reading, relaxation, entertainment; adaptive dimming and colour tuning.
Aging-in-place support	Layered lighting, motion sensors in hallways, adjustable brightness and colour temperature for visual acuity.

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4.3.5 Healthcare & Hospital Lighting

Healthcare and hospital lighting plays a critical role in enhancing patient recovery, supporting staff performance, and ensuring safety and hygiene. Modern lighting systems are increasingly designed to align with circadian rhythms, reduce glare and flicker, and integrate with smart controls for adaptive illumination. Specialized lighting solutions are essential in surgical rooms, ICUs, and neonatal care units, where precision and reliability are paramount.

Furthermore, lighting technologies now support infection control through touchless interfaces and UV-C disinfection. Tuneable lighting systems are being deployed in dementia care and mental health wards to improve

therapeutic outcomes. The integration of circadian-friendly lighting ensures optimal conditions for 24/7 operations in healthcare environments.

Key Drivers & Objectives	Technological Solutions & Strategies
Patient recovery & staff performance	Circadian lighting systems (tuneable white LEDs, 2700K–6500K), daylight access, dynamic scheduling to support biological rhythms and alertness.
Precision lighting for critical care	High-CRI (>90) LED luminaires, adjustable beam angles, task-specific lighting zones for surgical and diagnostic accuracy.
Infection control	Sealed, smooth-surface luminaires with IP65 rating; UV-C disinfection systems integrated into lighting for pathogen reduction.
Therapeutic lighting for mental health	Adaptive colour temperature and intensity controls; biophilic design with daylight simulation; patient-controlled dimming for autonomy.
24/7 operational efficiency	Networked LED systems with occupancy sensors, daylight harvesting, and centralized controls; energy-efficient retrofits reducing costs by up to 50%.

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4.3.6 Industrial & Warehouse Lighting

Industrial and warehouse lighting plays a critical role in ensuring safety, productivity, and operational efficiency. Modern solutions focus on high-efficiency luminaires, robust designs for harsh environments, and intelligent controls. Lighting systems are increasingly integrated with sensors and visual management tools to support precision tasks and streamline workflows.

Key Drivers & Objectives	Technological Solutions & Strategies
Safety and productivity in large-scale operations	LED high-bay luminaires with uniform distribution; CRI ≥80 for accurate colour rendering; compliance with OSHA and EN 12464-1 standards.
Durability in harsh or hazardous environments	IP65+ rated LED fixtures, corrosion-resistant housings, vibration-proof designs; tri-proof lights for dust, moisture, and chemical resistance.
Energy efficiency and automation	Smart lighting systems with IoT controls, occupancy sensors, daylight harvesting; predictive maintenance via AI-based platforms.
Precision task lighting	Adjustable LED task lights with high colour accuracy (CRI >90), glare-free optics; localized lighting for assembly and inspection zones.
Visual management and signalling	Andon light towers, color-coded LED indicators, integrated visual alarms for workflow status and safety alerts.

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4.3.7 Art, Culture & Performance Lighting

Lighting in art, cultural, and performance environments plays a pivotal role in shaping visitor experience, enhancing visual impact, and supporting conservation efforts. Modern lighting solutions in these domains focus on interactivity, precision, and immersive engagement. Technologies such as RGB tuneable lighting, adaptive control systems, and synchronized audio-visual setups are increasingly integrated into museums, galleries, theatres, and concert halls.

Key Drivers & Objectives	Technological Solutions & Strategies
Enhance visitor engagement	Interactive RGB lighting, motion sensors
Conservation and display accuracy	High CRI LEDs, tuneable white systems
Immersive performance environments	DMX-controlled lighting, synchronized AV systems
Adaptive control for venues	Scene presets, automated dimming
Synchronized shows	Integration with audio and motion

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4.3.8 Outdoor & Public Lighting

Outdoor and public lighting systems are evolving to meet the demands of smart cities, sustainability, and urban safety. Modern solutions focus on adaptive brightness, energy efficiency, and integration with sensor networks to enhance functionality and reduce environmental impact. Dynamic lighting strategies are increasingly used to support pedestrian and vehicular zones, while also enabling urban storytelling and interactive public experiences.

Key Drivers & Objectives	Technological Solutions & Strategies
Smart city integration	Sensor-based adaptive lighting, IoT connectivity
Energy efficiency & light pollution reduction	LED retrofits, dimming controls, spectral tuning

Safety and security	Motion-activated lighting, surveillance integration
Adaptive lighting for mobility zones	Zonal brightness control, pedestrian detection
Urban storytelling & public engagement	RGB dynamic lighting, programmable scenes

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4.3.9 Transportation Hubs & Mobility Infrastructure Lighting

Lighting in transportation hubs and mobility infrastructure plays a critical role in ensuring safety, operational efficiency, and passenger experience. Modern systems incorporate dynamic and adaptive technologies to support wayfinding, security, and emergency response across diverse environments such as airports, train stations, tunnels, and parking areas. Integration with real-time control and sensor networks enables intelligent lighting that responds to traffic flow, environmental conditions, and user needs.

Key Drivers & Objectives	**Technological Solutions & Strategies**
Wayfinding and safety	LED signage, adaptive brightness, sensor integration
Passenger flow and security	Dynamic lighting control, surveillance-linked illumination
Tunnel and bridge lighting	High-output luminaires, weather-resistant fixtures
Emergency systems integration	Touchless controls, evacuation lighting protocols
Operational efficiency	IoT-based real-time control, predictive maintenance

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4.3.10 Agricultural & Horticultural Lighting

Agricultural and horticultural lighting has evolved significantly with the advent of LED technology and smart control systems. Modern solutions focus on optimizing plant growth through controlled spectrum lighting, managing seasonal and photoperiod cycles, and integrating lighting with climate and irrigation systems. These innovations not only enhance crop yield and quality but also contribute to energy efficiency and automation in agricultural operations.

Key Drivers & Objectives	Technological Solutions & Strategies
Optimize plant growth and yield	Controlled spectrum LED lighting tailored to growth phases.
Seasonal and photoperiod control	Automated lighting schedules with dynamic shading and adaptive control.
Energy efficiency	High-efficiency LED fixtures with spectral tuning and dimming.
Integration with climate systems	IoT-based integration with HVAC, CO_2, and irrigation systems.
Automation and monitoring	Sensor-driven monitoring for predictive control and adaptive lighting.

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4.3.11 Museums, Heritage & Monument Lighting

Lighting in museums, heritage sites, and monuments plays a critical role in both conservation and visitor engagement. Preservation-focused lighting minimizes UV exposure and controls intensity to protect sensitive artifacts, while dynamic and adaptive lighting enhances storytelling and cultural experiences. Modern systems integrate with tourism flows and adjust based on time of day and visitor presence, ensuring both sustainability and immersive engagement.

Key Drivers & Objectives	Technological Solutions & Strategies
Artifact preservation	Low UV, controlled intensity LED systems with advanced spectral tuning for delicate materials
Nighttime heritage visibility	Directional lighting with low light pollution and precise beam control for enhanced facade detailing
Visitor engagement	Dynamic RGB lighting and projection mapping for immersive storytelling and guided experiences
Adaptive control	Sensor-based lighting adjustment responsive to occupancy, daylight, and event scheduling

References

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4.3.12 Sports & Recreation Lighting

Lighting for sports and recreation facilities must meet stringent performance and visual standards to ensure player safety, spectator experience, and broadcast quality. High-illuminance, glare-controlled systems are essential for arenas and sports halls, providing uniform lighting that complies with international standards (EN 12193, IES RP-6). For televised and streamed events, broadcast-ready lighting ensures proper colour rendering and flicker-free operation at high frame rates.

Adaptive lighting systems allow venues to switch between different sports and event modes, optimizing energy use and visual comfort. Integration with RGB dynamic lighting shows enhances fan engagement, creating immersive experiences synchronized with music and live action. These solutions combine advanced LED technology, IoT-based controls, and DMX protocols for precision and flexibility.

Key Drivers & Objectives	Technological Solutions & Strategies
High-illuminance, glare-controlled lighting for arenas and sports halls	LED floodlights with high lumen output, glare control optics, compliance with EN 12193 and IES RP-6 standards.
Broadcast-ready lighting for TV and streaming	Flicker-free LED systems, CRI ≥90, TLCI compliance, adjustable colour temperature for camera optimization.
Adaptive lighting for different sports and events	Scene-based presets via IoT or DMX control; tuneable intensity and distribution for multi-sport venues.
Integration with spectators' experience (RGB dynamic lighting shows)	RGBW LED fixtures, DMX/Art-Net protocols for synchronized effects; integration with AV systems for immersive shows.

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4.3.13 Data, Connectivity & Smart Infrastructure Lighting

Lighting systems are increasingly integrated into smart infrastructure frameworks, enabling real-time control, data transmission, and performance optimization. IoT-based platforms allow for seamless communication between lighting and other building systems, enhancing operational efficiency and user experience. Advanced sensor integration and Li-Fi technology are transforming lighting into a multifunctional component of connected environments.

Key Drivers & Objectives	Technological Solutions & Strategies
Real-time monitoring and control	IoT-enabled lighting platforms
Performance optimization via sensors	Occupancy, daylight, and environmental sensors
Data transmission through lighting	Li-Fi technology

References

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4.4 Optical and Photometric Concepts

Modern, high-quality lighting solutions must be optimally adapted to human needs. Features such as application-specific, optimally defined light distribution with clean cut-off behaviour without structural or colour defects are essential for meeting the different needs of users, maximizing visual comfort and performance, and minimizing visual fatigue. In addition, the topics of spectral quality and application-specific, dynamic white lighting throughout the day have become increasingly important, as these can be implemented very well with modern LED lighting systems and offer noticeable added value for the user. There are also physiological influences to consider: the health effects of the suppression of melatonin secretion during the night, which is aggravated by cold white light, must be considered as well as the general influence of light on the human circadian rhythm.

Using innovative calculation and manufacturing methods as for example 3D free-form surfaces with microfacets, it is possible to meet the requirements for optimal, structure-free light distribution with perfect colour mixing. In addition, these optical components are highly efficient, as colour mixing is achieved purely through defined light redirection, eliminating the need for diffusers, scattering layers, or covers. The optical components can be used in downlights, projectors, or asymmetrical lighting system solutions such as wall washers or framers [Föger, 2023].

4.4.1 Optical Elements in Luminaires

Types of optical elements

- Lenses: Modern luminaires use Total Internal Reflection (TIR) lenses, Fresnel lenses, and batwing lenses to shape and distribute light efficiently.
- Reflectors: Innovations include free-form surfaces with high-reflectivity coatings and faceted surfaces to maximize efficiency and control beam shape.
- Hybrid and multi-layer lens systems are increasingly common, combining refractive and reflective elements for tailored distributions and improved colour mixing in demanding applications
- Prismatic Diffusers: Micro-prismatic and surface-structured diffusers scatter light at controlled angles, enhancing uniformity and reducing glare. Advances in polymer science and precision moulding have enabled the production of complex, durable diffusers for slim and edge-lit luminaires.

Performance Metrics

- Optical Efficiency: Measured as the ratio of emitted to input light, with advanced elements achieving >90% efficiency.
- Beam Angle Control: Modern optics allow for precise beam shaping, from narrow spotlights to wide-area illumination.
- Glare Reduction: Micro-faceting and prismatic structures are specifically designed to limit high-angle light and reduce glare ratings.

Research Projects, Case Studies

- Micro and nano optical structures for highly efficient technical emergency and general lighting [MINALEM, 2019]
- Re-usable and re-configurable parts for sustainable LED-based lighting systems [Repro-light, 2020]
- Innovative solutions in the field of optical applications [Opt_Solutions, 2023]

Influence of changes in lamps on luminaire development

Classical light sources like tungsten halogen or metal halide lamps emit radiation (visible light, infrared and ultraviolet) in all directions whereas most LEDs primarily generate visible light in hemisphere.



Figure 4.6: Classical light sources (tungsten halogen, metal-halide) and LED (CSP)

This facilitates the implementation of highly efficient lighting concepts tailored to specific requirements. This can be achieved by specifically redirecting the light through reflection (reflectors), refraction and total internal reflection TIR (lenses), or a combination of both (hybrid concepts).



Figure 4.7: Reflectors, lenses and hybrid systems / bartenbach.com

Targeted faceting (micro-facets with complex surfaces) prevents unwanted artifacts, and additional optical components such as mixing chambers can compensate for colour defects of the lamp (colour over angle, colour over space).

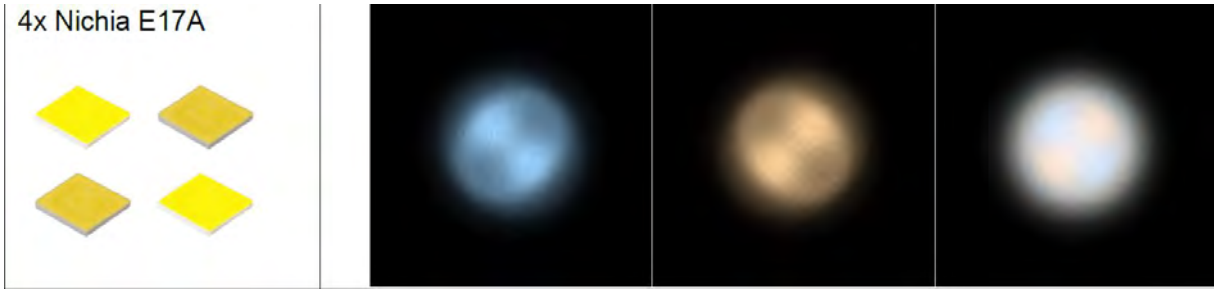


Figure 4.8: Adapting colour and colour temperature by multiple LEDs (RGBW, ww + cw, …; tuneable white)

A mixing chamber consists of diffuse surfaces with a high reflectance to minimize absorption of light during multiple reflections. A light guide also ensures good mixing of the light through many total reflections during light transport.

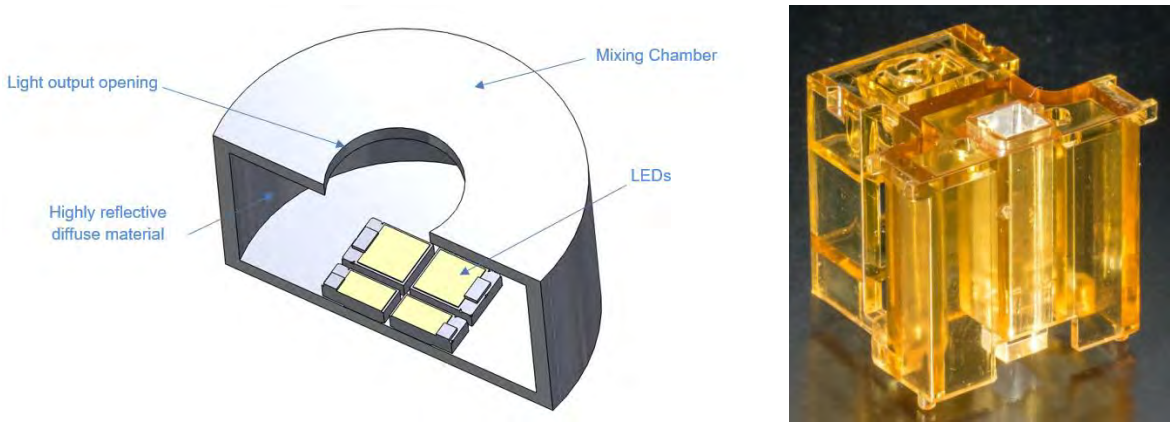


Figure 4.9: Colour Mixing: Mixing chamber and mixing light guide

LEDs with an integrated dome change radiation for example, to achieve a narrower beam. In comparison, a mixing dome minimizes unwanted colour effects that occur, for example, in LED arrays with different colour temperatures. The structure of this dome must be thoroughly designed to achieve optimal colour mixing.

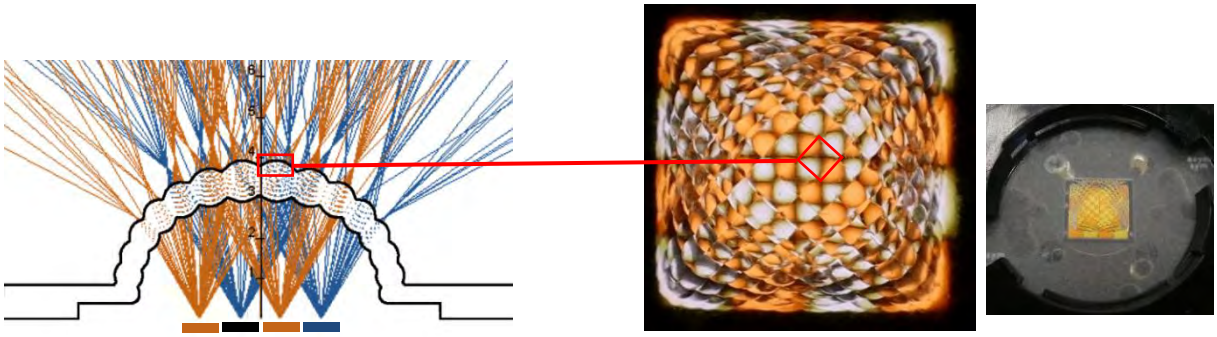


Figure 4.10: Colour Mixing: Mixing dome

Current high-end lighting components are typically manufactured industrially using plastic injection moulding and have the ability to capture all or part of the light emitted by one or more LEDs and redirect it in a targeted manner via optically active free-form surfaces, resulting in application-specific, advantageous, and efficient far-field light distributions.

In order to reduce both the costs of mould tooling and structural imaging of the optical components, products on the market (even in the high-end segment) often have a diffusing surface. However, this approach has significant disadvantages in terms of visual perception (glare due to higher scattered luminous intensities) and photometry (reduction in efficiency due to incorrect light guidance).

However, these disadvantages can be avoided through specific developments by replacing scattering surfaces with specially calculated surface structures (microfacets in the range of 0.2 x 0.2 mm - 2.0 x 2.0mm) with a high-gloss surface finish (arithmetic mean roughness value Ra < 40nm). These microfacets lead to a defined light beam expansion and are themselves free-form surfaces, which are determined by the lighting technology target field requirements.

The realization of such components requires the highest standards in terms of optical development, manufacturing, and industrialization, and thus covers a wide range of disciplines, e.g., optical design methods, the technology for manufacturing the moulding tools, the transfer to injection-moulded components: processes for minimizing tolerances, micro/nano mould transfer, surface quality, and even material properties such as long-term component durability. [Föger, 2023]

4.4.2 Light Distribution Strategies

Recent Research and Best Practices

- Direct vs. Indirect Lighting: Direct lighting delivers light straight from the luminaire to the horizontal task area, while indirect lighting reflects light off surfaces (typically ceilings or walls) to create a softer, more diffuse illumination on all surfaces, including at the eye, which can satisfy melanopic lux requirements. Recent studies show that a higher proportion of indirect lighting and more uniform ceiling distribution are generally preferred by occupants, enhancing room appraisal and visual comfort. However, preferences can vary, highlighting the need for adaptable lighting solutions.
    - Uniformity Metrics: Uniformity is typically quantified using the uniformity ratio ($U_0 = E_{min}/E_{avg}$), where E_{min} is the minimum illuminance and E_{avg} is the average illuminance across a space. High uniformity ratios are associated with improved visual comfort and reduced eye strain.
- Simulation Tools: Lighting simulation software such as DIALux, ReluxDesktop and AGi32 are widely used to model and optimize light distribution, allowing designers to predict uniformity, glare, and energy consumption before installation. See the IEA SHC Task 70 C4.1 report reviewing 26 simulation tools.
    - Industry Standards: EN 12464 as well as the IES Lighting Library emphasize the importance of uniform illuminance and minimizing glare, recommending careful coordination with architectural constraints.

Case Studies

- Real-world projects demonstrate that strategic use of direct and indirect lighting, combined with photometric analysis and full cut-off fixtures, can achieve regulatory compliance, uniformity, and visual comfort.

To optimize utilization factor different types of direct light distributions of downlights can be precisely realized.



Figure 4.11: Reflector components for direct-beam luminaires / bartenbach.com

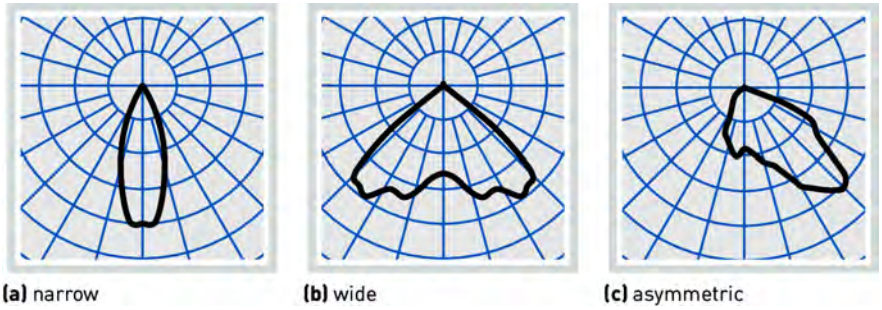


Figure 4.12: Exemplary luminous intensity distribution curves of direct-distribution luminaires / trilux.com

A balanced distribution of brightness in the field of vision can be achieved using additional indirect luminaires or luminaires with an indirect component for ceiling illumination. The decisive factors for the visual quality of a room are not the illuminance distributions on work surfaces, but the luminance distribution throughout the entire environment with corresponding highlighting of important areas and visual tasks.



Figure 4.13: Different illumination concepts by downlight (direct light), downlight + indirect, downlight + wallwasher, wallwasher (diffuse light)

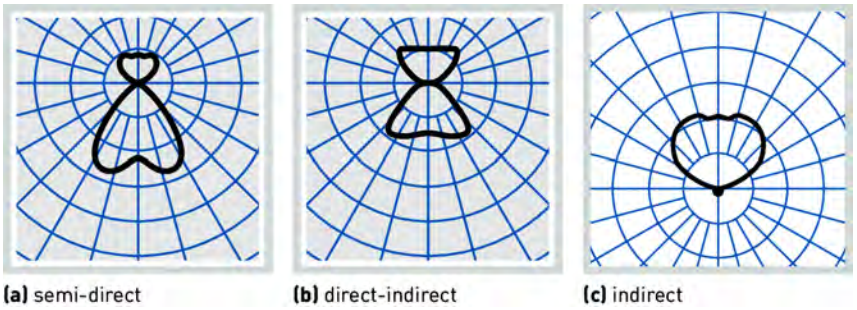


Figure 4.14: Exemplary luminous intensity distribution curves with indirect portion / trilux.com

Freeform lenses: Complex surfaces as entrance and exit surface allow for non-symmetric light patterns.

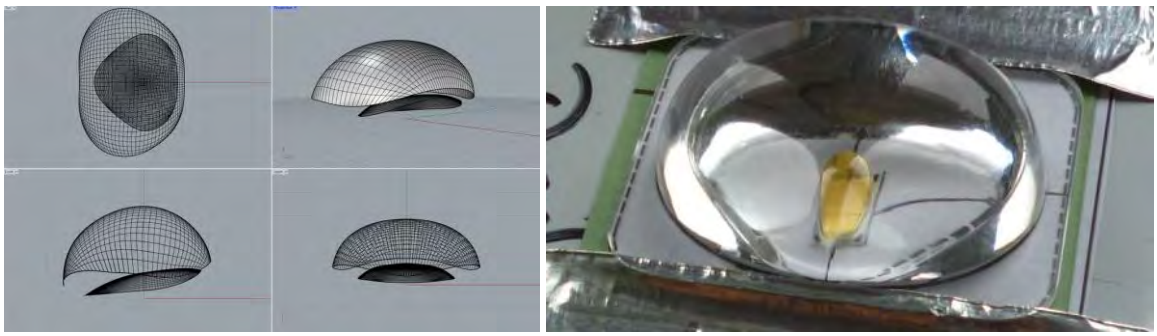


Figure 4.15: Freeform lenses, complex surfaces / bartenbach.com

Thanks to the development of 3D free-form reflectors manufactured with maximum precision and their correct positioning and orientation in practical applications, such systems stand out by the precision of their light distribution as well as the possibility of integrating them into projects in a barely visible manner. [Spielberger, 2016]

The appearance of the room is determined by the architecture and the lighting concept, rather than by dominant and distracting luminaires. Post-occupancy optimization of user-centred lighting applications offers great potential for overcoming previous design limitations and subsequently reduces performance gaps. [Hammes, 2024]

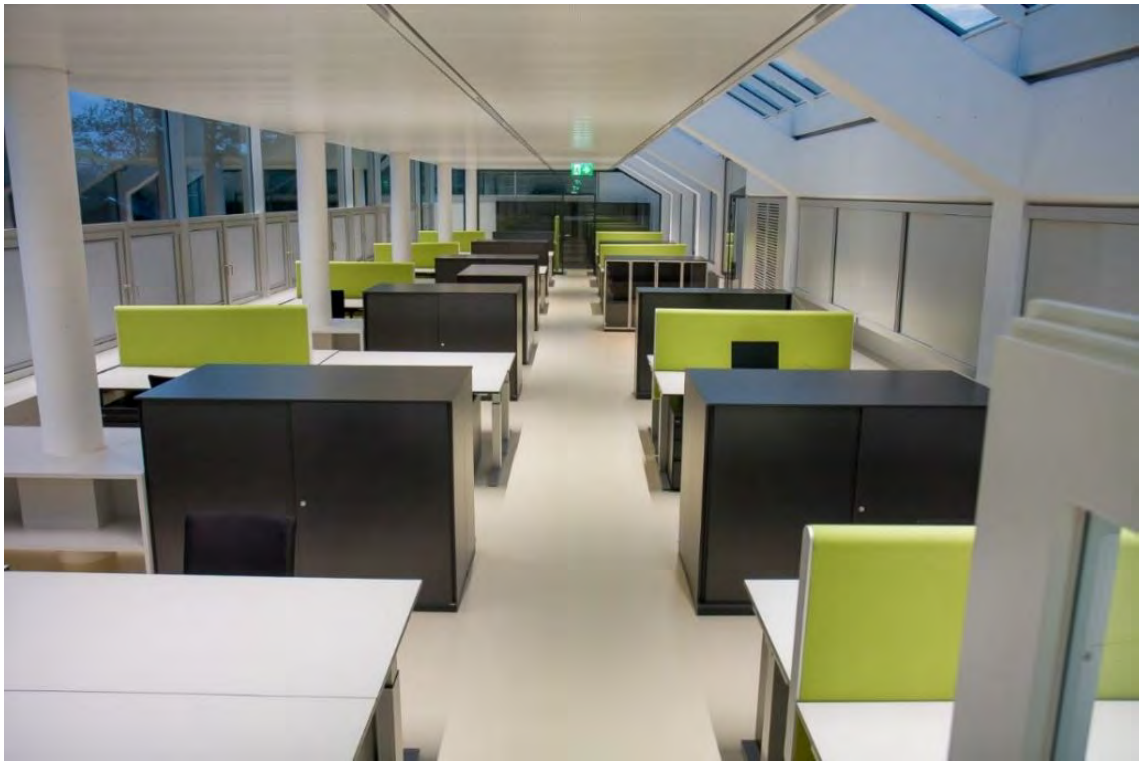


Figure 4.16: Seamless integration of lighting into room architecture (Bartenbach GmbH in Aldrans, Austria)

4.4.3 Colour Temperature & Rendering

Updated Standards and Metrics

- CRI Limitations: The traditional Colour Rendering Index (CRI) uses only 8 colour samples and measures only fidelity, not preference or vividness. It is less accurate for modern LED sources.
- TM-30 Standard: The IES TM-30 standard uses 99 colour samples and provides multiple metrics:
    - Fidelity Index (R_f): Measures colour accuracy.
    - Gamut Index (R_g): Measures colour saturation.

- Colour Vector Graphic: Visualizes hue and saturation shifts.
- Design Intents: TM-30-20 introduces preference, vividness, and fidelity as design priorities, allowing for tailored lighting solutions.

- Dynamic White (Tuneable White) Lighting: Allows adjustment of colour temperature (e.g., 2700K–6500K) to support circadian rhythms, task adaptation, and aesthetic flexibility. Implemented using multi-channel LEDs and advanced optical mixing to ensure uniform colour.

Practical Implications

- Application-Specific Design: TM-30 enables designers to specify lighting for retail (preference), healthcare (fidelity), or entertainment (vividness) environments.
- Case Studies: Projects using dynamic white solutions in offices and healthcare settings report improved occupant satisfaction and well-being.

Colour fidelity of light source compared to reference illuminant: Standard Colour Rendering Index CRI uses the average value for 8 colour samples (TCS 01 to TCS 08) and is based on outdated colorimetry (CIE 1964 U*V*W*).



Figure 4.17: CIE 13.3-1995: Method of measuring and specifying colour rendering properties of light sources (CRI, Ra)

Especially for scientific use it is essential to use more recent colorimetry to specify colour fidelity R_f and colour gamut R_g. TM-30 is based on 99 colour samples thoroughly chosen from real-world materials covering uniform colour space and uses CAM02-UCS (CIECAM02).

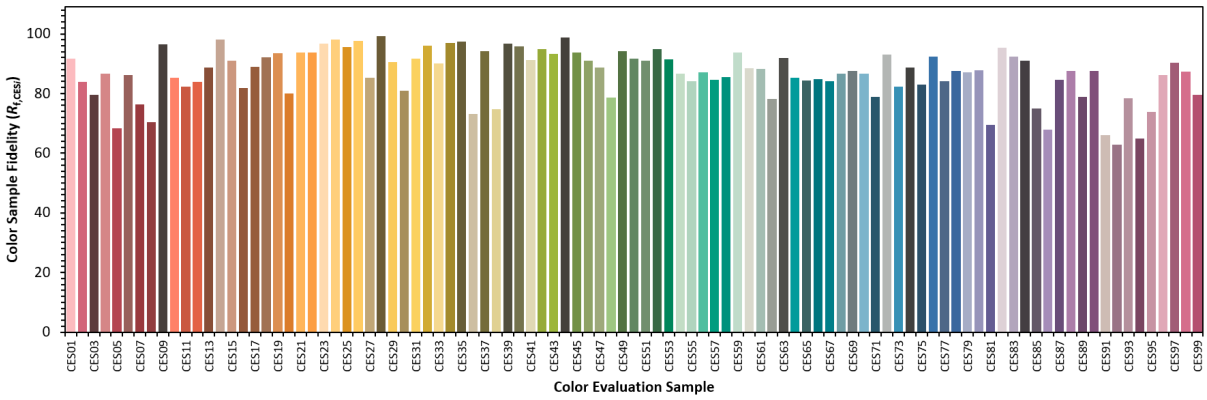


Figure 4.18: Fidelity Index R_f (TM-30) based on Colour Sample Fidelity for 99 colour samples: Example LED 4000 K, R_f = 87

Several Technical Committees of the CIE have dealt with colour rendering and colour quality in recent decades:

- TC 1-62 Colour rendering of White LED Light Sources (CIE 177:2007)
- TC 1-69 Colour Rendition by White Light Sources (established 2006)
- TC 1-90 Colour Fidelity Index
- TC 1-91 New Methods for Evaluating the Colour Quality of White-Light Sources

Various metrics have been proposed and investigated [Bhusal, 2017], [Royer, 2018]. IES has approved TM-30 in 2015. This new method was adopted with slight modifications as “CIE 2017 Color Fidelity Index for accurate scientific use” [CIE 224:2017].

Recently ANSI/IES TM-30-24 “IES Method for Evaluating Light Source Colour Rendition” and CIE 253:2024 “Overview of Methods for Evaluating Colour Rendition of White-Light Sources beyond Colour Fidelity” have been published.



Figure 4.19: CIE 224-2017: CIE 2017 Colour Fidelity Index for accurate scientific use. Based on IES TM-30 (R_f)

4.4.4 Glare Control and Visual Comfort

Latest Research and Standards

- UGR (Unified Glare Rating): Quantifies discomfort glare on a scale where 10 implies no discomfort and values greater than 28 are not used in recommendations for glare limitations (glare too high). EN 12464-1:2021-08 and CIE 117 provide updated guidelines and recommended UGR limits for various environments (e.g., UGR ≤ 19 for offices/classrooms, ≤ 16 for technical drawing).
- Modern Diffusion Techniques:
  - Micro-prismatic Diffusers: Achieve UGR values as low as ≤16, suitable for sensitive environments.
  - Hybrid Optical Systems: Combine lenses, reflectors, and diffusers for optimal light distribution and minimal glare.
  - Indirect Lighting: Reduces direct glare by reflecting light off ceilings/walls.
- Fixture and Material Innovations: Low-UGR LED fixtures, adjustable beam angles, and low-gloss interior surfaces further reduce glare and enhance comfort.

Measurement and Simulation

- Simulation Tools: DIALux, Relux, and imaging luminance meters are standard for predicting and validating UGR in design phases.

Case Studies

- Healthcare and Office Environments: Use of micro-prismatic diffusers and indirect lighting strategies has been shown to maintain UGR below 19, supporting productivity and reducing eye strain.

An unsuitable distribution or range of luminance, or extreme luminance contrasts can cause discomfort or a reduction in the ability to see details or objects. These effects are described as glare, whereby a distinction is made between discomfort glare and disability glare. In artificial lighting discomfort glare is typically modelled by Unified Glare Rating UGR

$$UGR = R_{UG} = 8\log(\frac{0.25}{L_B}\sum_i \frac{L_{s,i}^2\,\omega_i}{P_i^2})$$

where $L_B[cd/m^2]$ is the background luminance, $L_{s,i}[cd/m^2]$ is the luminance of glare source i, $\omega_i[sr]$ is the solid angle of glare source i, and P_i is the position index for glare source i. This is restricted to sources which have a maximum subtense at the eye of 0.1 sr (cone with aperture 2 x 10.2°) and the UGR system should not be used for sources smaller than 0.0003 sr (cone with aperture 2 x 0.56°). In practice, this is usually ignored. The standard EN 12464-1 specifies the usage of UGR – tables which are calculated without considering these restrictions for solid angles. The latest version of this standard EN 12464-1:2021-08 now allows for the usage of direct UGR calculations but in this case no limits are defined, only guidelines. For luminaires with smaller or larger luminous areas outside the scope of the UGR-formula there is a reference to CIE 147-2002 “CIE Collection on Glare 2002. Glare from Small, Large and Complex Sources”. Reference is also made to the CIE Technical Report CIE 232-2019 “Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance”. Up to now these hints in Annex A (an informative part of the standard) have not been implemented in lighting design software.

Glare Evaluation According to UGR

ρ Ceiling		70	70	50	50	30	70	70	50	50	30
ρ Walls		50	30	50	30	30	50	30	50	30	30
ρ Floor		20	20	20	20	20	20	20	20	20	20
Room Size X	Y	Viewing direction at right angles to lamp axis					Viewing direction parallel to lamp axis				
2H	2H	18.6	19.2	18.8	19.4	19.6	18.7	19.3	18.9	19.5	19.7
	3H	18.5	19.0	18.7	19.3	19.5	18.6	19.1	18.8	19.4	19.6
	4H	18.4	18.9	18.7	19.2	19.4	18.5	19.0	18.8	19.3	19.5
	6H	18.3	18.8	18.6	19.1	19.4	18.4	18.9	18.7	19.2	19.5
	8H	18.3	18.8	18.6	19.1	19.4	18.4	18.9	18.7	19.2	19.5
	12H	18.2	18.7	18.6	19.0	19.3	18.4	18.8	18.7	19.1	19.4
4H	2H	18.4	18.9	18.7	19.2	19.4	18.5	19.0	18.8	19.3	19.5
	3H	18.2	18.7	18.6	19.0	19.3	18.3	18.8	18.7	19.1	19.4
	4H	18.2	18.6	18.5	18.9	19.2	18.3	18.7	18.6	19.0	19.3
	6H	18.1	18.4	18.5	18.8	19.2	18.2	18.5	18.6	18.9	19.3
	8H	18.1	18.4	18.5	18.7	19.1	18.2	18.5	18.6	18.8	19.2
	12H	18.0	18.3	18.5	18.7	19.1	18.1	18.4	18.6	18.8	19.2
8H	4H	18.1	18.3	18.5	18.7	19.1	18.2	18.4	18.6	18.8	19.2
	6H	18.0	18.2	18.4	18.6	19.1	18.1	18.3	18.5	18.7	19.2
	8H	17.9	18.1	18.4	18.6	19.0	18.0	18.2	18.5	18.7	19.1
	12H	17.9	18.0	18.4	18.5	19.0	18.0	18.1	18.5	18.6	19.1
12H	4H	18.0	18.3	18.4	18.7	19.1	18.1	18.4	18.5	18.8	19.2
	6H	17.9	18.1	18.4	18.5	19.0	18.0	18.2	18.5	18.6	19.1
	8H	17.9	18.0	18.4	18.5	19.0	18.0	18.1	18.5	18.6	19.1
Variation of the observer position for the luminaire distances S											
S = 1.0H		+5.6 / -15.3					+5.6 / -15.2				
S = 1.5H		+8.4 / -15.9					+8.4 / -15.8				
S = 2.0H		+10.4 / -16.3					+10.4 / -16.3				
Standard table		BK00					BK00				
Correction Summand		-0.4					-0.3				
Corrected Glare Indices referring to 1000lm Total Luminous Flux											

Figure 4.20: Downlight, UGR table for Spacing-to-Height-Ratio = 0.25

In offices at a workplace designed for writing, typing, reading and data processing the UGR according to EN 12461-1 shall not exceed 19 (R_{UGL} = 19 for Ref. no. 34.2 in table 34). Frequently it is suggested to look at the UGR table at the values at 4H / 8H for $\rho_{ceiling}$ = 70%, ρ_{walls} = 50% and ρ_{floor} = 20%. In this case these UGR values are 18.1 and 18.2 for the viewing directions contained in the table and both values are smaller than the limit R_{UGL} = 19. For technical drawing R_{UGL} = 16 is specified which is not met in this example.

Table 4.1: EN 12464-1, Table 34 - Offices

Ref. no.	Type of interior, task or activity	R_{UGL}
34.2	Writing, typing, reading and data processing	19
34.3	Technical drawing	16

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4.5 Lighting Control and Automation

Lighting control and automation represents a rapidly evolving field that integrates advanced sensor technologies, IoT connectivity, and intelligent algorithms to optimize illumination systems for energy efficiency, occupant comfort, and operational flexibility. This section provides an overview of the field, examines the current state-of-the-art in scientific literature, and explores industrial applications and market trends.

4.5.1 Definition and Components

The primary objectives of lighting control and automation systems are centred on achieving operational efficiency, user comfort, and system intelligence within built environments. These systems contribute significantly to energy conservation by implementing intelligent dimming algorithms and occupancy-based control strategies that minimize unnecessary energy consumption. In parallel, they enhance occupant comfort through adaptive and personalized lighting environments that respond to user preferences and contextual requirements. Furthermore, they support the implementation of human-centric lighting (HCL) principles, ensuring illumination conditions align with circadian rhythms to promote health and productivity. Integration with comprehensive building management

systems (BMS) enables coordinated operation across multiple subsystems, facilitating centralized monitoring and control. Finally, advanced diagnostics and data-driven analytics within these systems support maintenance optimization and early fault detection, thereby improving reliability and reducing operational costs.

Lighting control and automation refers to hardware and software systems that sense occupancy, daylight, and user intent and then adjust luminaires (on/off, dimming, colour) automatically to meet visual, comfort, and energy objectives [1][2]. The field encompasses automatic switching, dimming, colour temperature control, scheduling, and emergency lighting functions integrated with building management systems.

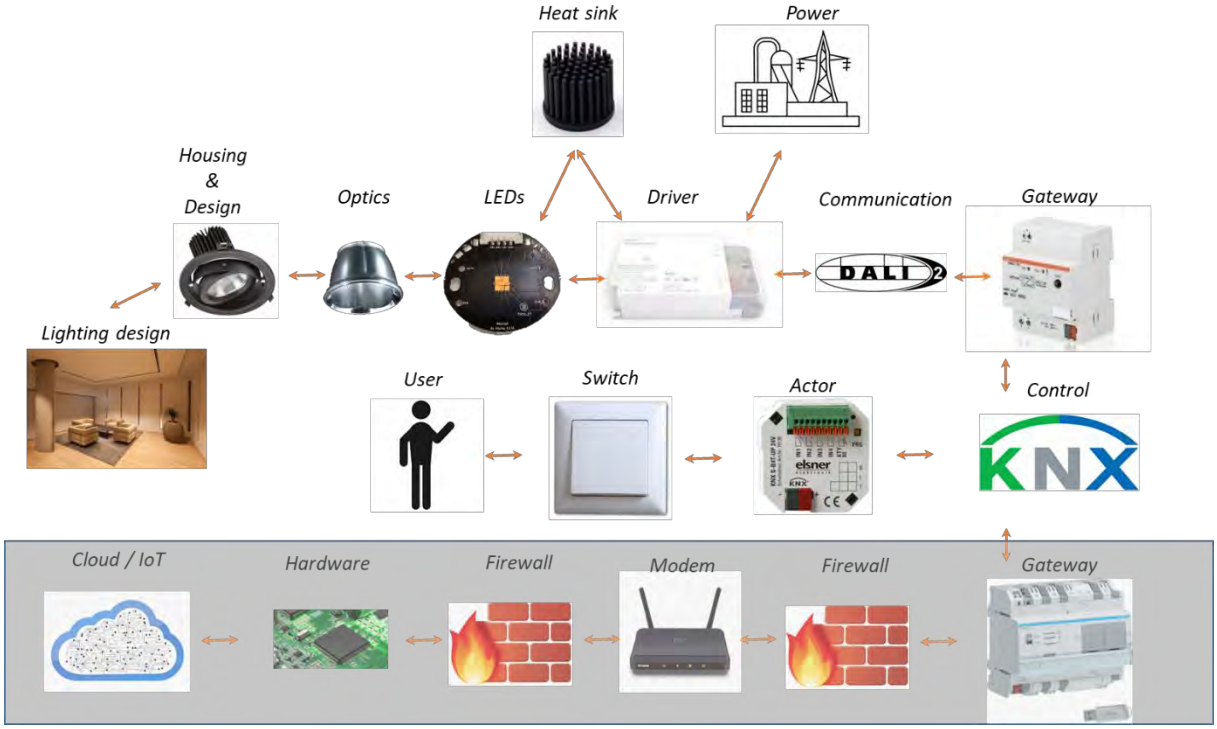


Figure 4.21: Components of an artificial lighting control system

Modern lighting control systems typically comprise:

- **Sensors**: Occupancy detectors, daylight sensors, and environmental monitors
- **Controllers**: Embedded processors or cloud-based control systems
- **Communication Networks**: Wired (DALI, KNX) or wireless (ZigBee, WiFi) protocols
- **Actuators**: LED drivers, dimming ballasts, and smart switches
- **User Interfaces**: Mobile apps, wall panels, and web-based dashboards

State-of-the-art lighting control blends wired standards (DALI, PoE) and wireless stacks (Bluetooth Mesh, 802.15.4-based) with advanced daylight harvesting, adaptive dimming, and AI-driven predictive controls to cut lighting energy and improve comfort while posing new integration and interoperability challenges. The following table compares leading wired and wireless lighting control technologies and connects technical traits to practical pros/cons for industry deployment. The table compares DALI, Bluetooth Mesh, Zigbee/802.15.4, and PoE across interface type, topology, strengths and weaknesses.

	Interface and topology	Key advantages	Key disadvantages	Deployment notes
DALI / DALI-2	Wired digital bus, addressable ballasts/drivers; centralized	Deterministic control with standardized device interoperability and mature human-centric features	Wiring cost for retrofits; requires compatible drivers and controllers	DALI-2 controllers and low-power DALI daylight systems have been prototyped and validated for building daylight control and human-centric lighting applications
Bluetooth Mesh	Wireless mesh over Bluetooth LE; many-to-many relaying	Flexible wiring-free installs, mobile commissioning and user interfaces; suitable for retrofit and occupant control	Mesh range depends on relay density; potential RF congestion in dense sites	Bluetooth smartphone commissioning and mesh garage/parking designs have been demonstrated in prototypes and lab studies
Zigbee / IEEE 802.15.4 family	Low-power wireless stack (PHY/MAC: 802.15.4) enabling mesh networks	Low-power sensor networks and mature vendor ecosystem for lighting sensors/controls	Fragmentation between stacks and gateways; need for gateway to BMS	Wireless sensor networks using IEEE 802.15.4 have been used to extend DALI systems into IoT scenarios
PoE lighting	Power and data over Ethernet to luminaires; Ethernet topology	Single-cable power+control, predictable QoS, easier BMS integration and centralized management	Requires Ethernet infrastructure and PoE switches sized for lighting loads; standards and UL/IEC rules evolving	PoE/IoT lighting assessed as enabling next-generation building lighting with 3–5 year payback expectations in techno-economic analyses

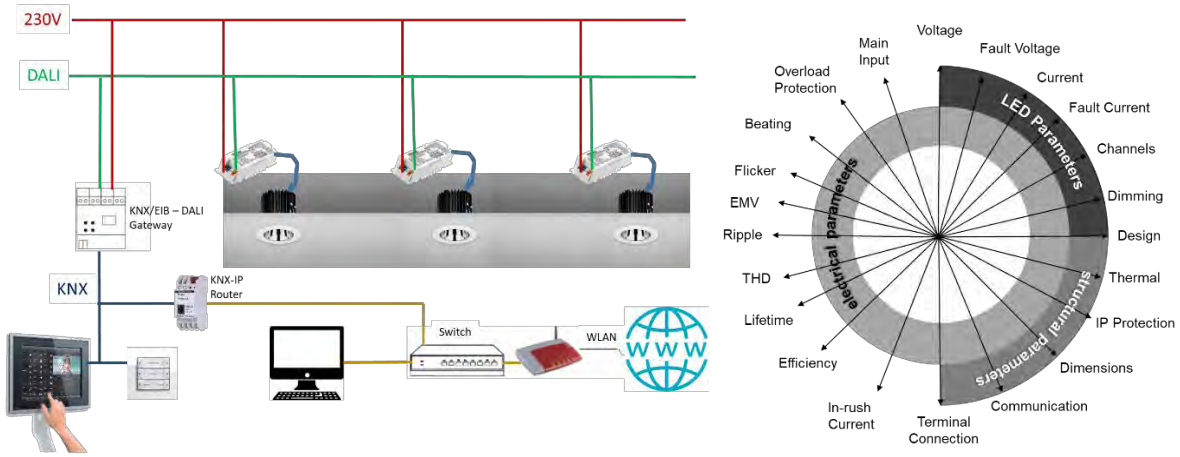


Figure 4.22: Exemplarily integration scheme of DALI into a building management system (left) and different aspects to be considered in lighting controls (right)

In modern lighting control, different technological fields are involved in order to achieve a proper connection to other building technologies involved towards smart lighting as well as artificial intelligence lighting:

- Internet of Things (IoT) and Cloud Computing

IoT platforms provide device addressing, remote monitoring, over-the-air updates, and cloud analytics for large-scale deployments [4][5]. Modular IP-to-luminaire architectures have demonstrated readiness for commercial lighting applications, enabling luminaire-level IP connectivity, cloud services, and extended IoT use cases.

- Wireless Sensor Networks (WSNs)

Wireless sensor technologies enable low-cost occupancy and daylight sensing, distributed control, and retrofit capabilities without extensive rewiring [6][7]. ZigBee and other WSN implementations in pilot studies have demonstrated energy savings of 36-45% using occupancy detection and daylight harvesting algorithms.

- LED Technology and Driver Electronics

Advanced LED drivers support precise dimming, colour tuning, and integration of sensors at the fixture level [8]. Recent developments include SIMO (Single-Input Multiple-Output) topologies and magnetic control systems that enable RGB control and efficient power conversion.

- Smart Building Integration

Lighting control systems increasingly integrate with Building Energy Management Systems (BEMS) to coordinate lighting with HVAC, shading, and overall energy management [9]. Hybrid BEMS architectures and multi-agent approaches have reported 20-40% energy improvements in studied implementations.

- Artificial Intelligence and Machine Learning

AI technologies are being applied for predictive control, occupancy pattern learning, and optimization of lighting schedules. Advanced algorithms compute direct illuminance contributions and use fuzzy logic to deliver improved energy-comfort trade-offs [11][12].

4.5.2 Emerging Sensing Technologies

Emerging sensing technologies are transforming lighting control systems by enabling richer environmental awareness, real-time adaptability, and decentralized intelligence. The convergence of multi-modal sensing, biometric feedback, and advanced communication infrastructures supports a new generation of lighting systems that go beyond simple occupancy detection to deliver comprehensive, context-sensitive control.

- **Next-Generation Sensing:** Modern research and development focus on integrating diverse sensor types to enhance spatial and behavioural understanding within buildings.
- **Multi-Modal Sensors:** Combine occupancy, daylight, air quality, and acoustic sensing for holistic environmental monitoring.
- **Computer Vision:** Employ camera-based detection and activity recognition to distinguish between user behaviours and space utilization patterns.
- **Biometric Integration:** Use physiological signals such as heart rate and stress level data to enable wellness-oriented lighting adjustments.

In parallel, advancements in edge computing and 5G connectivity facilitate ultra-low-latency communication and decentralized processing, allowing control algorithms to operate locally within luminaires or sensor nodes. This evolution toward distributed intelligence enables mesh networks of self-organizing, decision-capable lighting units, paving the way for scalable, real-time, and context-aware lighting ecosystems that align with the broader vision of smart and adaptive building infrastructures.

4.5.3 Market Overview and Key Industry Players

The global lighting control systems market is experiencing sustained expansion, driven by increasing energy efficiency regulations, the rise of smart building initiatives, and the integration of IoT technologies. Valued at several billion dollars, the market is projected to grow annually by approximately 12–15%, with particularly strong

adoption across North America, Europe, and the Asia-Pacific region. Growth is further supported by trends emphasizing workplace wellness and intelligent building management. Leading industry players include Signify (Philips Lighting) with its Hue and professional IoT-enabled systems, Osram focusing on digital and smart city lighting solutions, Schneider Electric through its EcoStruxure automation platform, Acuity Brands offering integrated lighting and management technologies, and Lutron, known for advanced dimming and control systems across residential and commercial applications.

4.5.4 State-of-the-Art in Scientific Literature

The state of the art in current scientific literature highlights significant progress in sensor-driven control systems, advanced algorithmic management, and human-centric lighting (HCL) integration. Modern lighting control frameworks increasingly leverage distributed wireless sensor networks, utilizing communication protocols such as ZigBee and other low-power wireless standards. Field evaluations have demonstrated substantial energy savings across various application domains, including reductions of 36–45% in transit and office environments through rule-based dimming and occupancy detection [7], up to 90% savings in low-traffic zones via master-slave IoT configurations [16], and approximately 28% in office setups. [9]

Advanced control algorithms:
Contemporary lighting control architectures employ increasingly sophisticated algorithms to achieve precise, adaptive, and user-responsive operation. A published concept named Direct Illuminance Contribution Lighting Control Algorithm (DIC-LCA) exemplifies this progress by continuously calculating the individual illuminance contributions of each luminaire, thereby enabling fine-grained dimming regulation and optimized trade-offs between visual comfort and energy efficiency [13]. Fuzzy-logic controllers extend these capabilities by managing the inherent uncertainty of real-world environments. Through rule-based reasoning, they adjust lighting parameters dynamically in response to variations in occupancy, daylight availability, and environmental context [12]. More recently, artificial-intelligence-driven personalization techniques have emerged as a major innovation. Systems employing user-trajectory prediction and behavioural modelling can forecast occupant movement and preferences, allowing the lighting environment to adapt proactively to anticipated needs [14]. Collectively, these algorithmic advances mark a transition from static, rule-based control toward intelligent, data-driven frameworks that continually refine performance, ensuring both energy optimization and enhanced occupant satisfaction.

Human-Centric Lighting Integration:
Recent research in lighting control has increasingly emphasized human-centric lighting (HCL) principles, aiming to enhance occupant well-being, comfort, and performance by aligning artificial illumination with natural circadian rhythms. Modern systems incorporate adaptive control strategies that dynamically adjust colour temperature, intensity, and spectral composition based on the time of day, ambient daylight availability, and occupancy patterns. This temporal adaptation supports biological processes such as alertness during working hours and relaxation in the evening, contributing to improved health and productivity. Furthermore, the integration of biometric and environmental sensors enables real-time monitoring of parameters such as stress levels, fatigue, and visual comfort. By processing this physiological feedback, lighting systems can fine-tune their operation to better suit the occupant's current state. Complementing these features, personalized lighting profiles are increasingly employed to accommodate individual preferences, visual tasks, and user-defined comfort thresholds. Together, these developments mark a transition from purely energy-driven control strategies toward holistic, occupant-centred solutions that combine physiological, psychological, and environmental factors to create optimized and adaptive lighting environments.

As a novel control concept addressing multiple of these aspects the IndiLight Module (ILM) was developed at the University of Innsbruck's Energy-Efficient Buildings research unit to enable truly individualized workplace lighting (see Figure 4.23). The ILM captures the spatial position and behavioural patterns of occupants and dynamically adjusts both daylighting elements (e.g., tracking shading louvres) and artificial illumination systems accordingly. By coordinating multiple façade zones and luminaire groups, it provides fine-tuned responses to individual preferences and task demands. The module architecture supports threshold-based personalization, enabling each user to define their desired lighting environment while the system continuously adapts in real time. In practical implementations the ILM can act as a central, simulation-based control unit, combining day-and artificial lighting control with minimization of primary energy loads for heating and cooling while enhancing the occupant comfort.

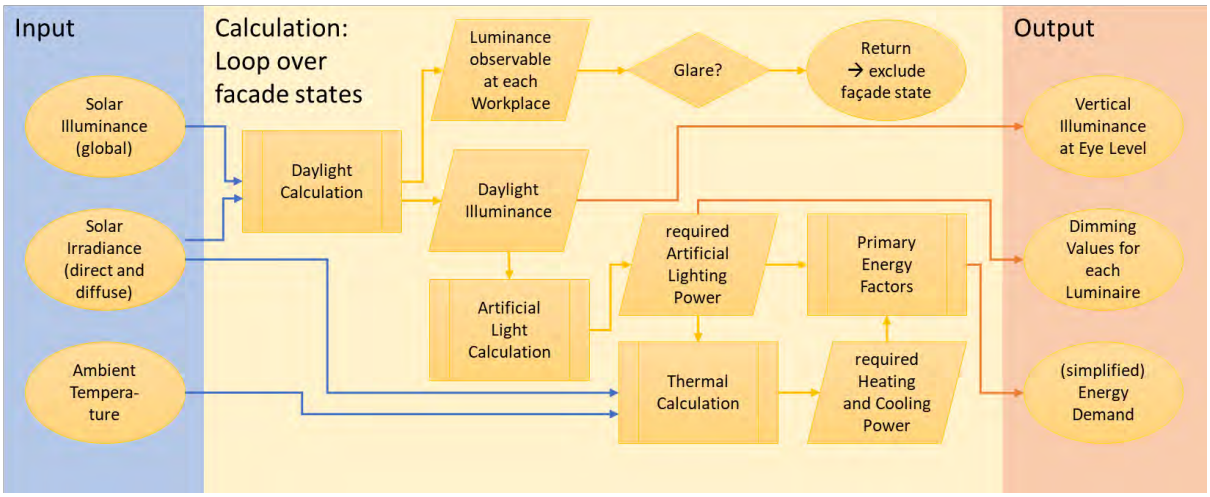


Figure 4.23: Control logic of the IndiLight-module

In ongoing research investigations, the ILM also serve as a “teacher” system for autonomous machine-learning frameworks in follow-on research (e.g., reinforcement learning) and is envisaged for deployment in smart-home and building-automation scenarios. This approach aligns with the trend toward occupant-centric, adaptive lighting control and underscores the transition from static, one-size-fits-all lighting regimes to responsive, data-driven systems.

Summary:

Lighting control and automation represent a rapidly maturing field that combines advances in sensor technology, IoT connectivity, artificial intelligence, and human-centric design principles. The scientific literature demonstrates significant potential for energy savings (20-90% in various implementations) while improving occupant comfort and well-being.

Current industrial applications span from simple occupancy-based controls to sophisticated AI-driven systems that learn and adapt to user preferences. Major manufacturers are investing heavily in IoT-enabled platforms and smart building integration, driving market growth and technological advancement.

Key challenges remain in standardization, security, and user acceptance. Future developments will likely focus on improved interoperability, advanced AI integration, and human-centric design approaches that prioritize both energy efficiency and occupant wellness.

The field is positioned for continued growth as smart building initiatives expand globally and energy efficiency regulations become more stringent. Success will depend on addressing current technical and market barriers while maintaining focus on practical, user-friendly implementations that deliver measurable benefits.

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4.6 Sustainability and Regulatory Trends

The lighting industry is undergoing a transformative shift towards sustainability, driven by evolving regulatory frameworks, technological innovations, and growing environmental consciousness. This report examines the latest trends in lighting sustainability, focusing on three critical areas: energy efficiency regulations, lifecycle and circular economy approaches, and carbon footprint reduction strategies.

Key findings reveal that regulatory frameworks are expanding beyond traditional energy efficiency metrics to encompass comprehensive lifecycle considerations, circular economy principles, and embodied carbon requirements. The widespread adoption of LED technology, combined with smart controls and IoT systems, is delivering significant energy savings while enabling new business models such as Lighting-as-a-Service (LaaS). Meanwhile, lifecycle assessment methodologies are becoming increasingly sophisticated, supporting more informed decision-making in lighting system design and procurement.

The convergence of technological advancement, regulatory evolution, and sustainability imperatives is creating unprecedented opportunities for carbon footprint reduction while establishing new compliance requirements that industry stakeholders must navigate.

4.6.1 Regulatory trends

The European Union aims to cut carbon emissions 80-95% from 1990 by 2050 [1] with the buildings sector contributing to one-third of the total global energy consumption and 34% of related carbon emissions [2]. The rapid increase in the global floor area coupled with rising affluence has significantly amplified the demand for thermal and visual comfort among building occupants. Consequently, this has led to a substantial rise in energy consumption, CO_2e emissions, and the capital costs of building operations [3]. Therefore, it is important to design and construct buildings that are both energy-efficient and conducive to occupant health [4]. Building energy consumption encompasses various factors such as lighting, heating, domestic hot water, air conditioning, and cooling [5]. Renovating the service systems in existing buildings presents significant opportunities to reduce energy consumption and carbon emissions [6]. Notably, electric lighting constitutes a significant portion of this consumption, accounting for approximately 11% and 4% of total electricity use in the commercial and residential sectors, respectively, in the U.S.A [7].

A review of the relevant literature on electric lighting energy consumption reveals that many recent studies focus on integrated lighting systems [8,9]. These systems combine various daylighting strategies with conventional and smart lighting technologies [10] to optimize energy efficiency. For instance, a study by Iatauro and Zinzi [11] reveals that using dynamic climate-based simulations instead of the EN15193-1:2017 standard can reduce annual lighting energy consumption by 62–78%, highlighting the importance of climate-based assessments. A similar study by Hosseini et al. [12] investigates the integration of LED dimming control with interactive kinetic louvers, utilizing occupant detection and estimation to enhance visual comfort, daylight performance, and electric energy consumption simultaneously. The results indicate that this parametric approach reduces electric lighting energy consumption by approximately 99% compared to the lighting occupancy profile of the ASHRAE 90.1 standard. In a related study, Lee and Kang [13] demonstrate that the implementation of daylight-concentrating indoor louvers, integrated with LED-linked dimming control, results in an 85% reduction in electric lighting energy consumption, particularly during the transitional season. In a study by Mesloub et al. [14], it was found that vertical tubular daylighting devices (TDDs), combined with LED and a dimming control system, can reduce electric lighting energy consumption by up to 21% in deep-plan office buildings located in hot desert climates.

However, excluding daylighting systems and focusing solely on lighting types and systems, there are few studies that consider the impacts of lighting system renovation on electric energy use in buildings, and its environmental impacts in relation to different types of lighting. It is possible to divide the studies into smart and conventional lighting systems. The first category of research investigates various lighting types and employs both occupancy detection and sensor-based optimization to significantly reduce electric energy consumption. Notably, there is substantial potential for energy savings in electric lighting, with approximately 30% achievable by replacing compact fluorescent lamps (CFLs) with smart light-emitting diodes (LEDs). Additionally, the integration of smart lighting systems with LEDs can further reduce energy consumption by up to 40% in residential buildings in Sweden [10]. This study does not account for the contribution of lighting to the overall building's energy use intensity and its environmental impacts.

The second category mostly focused on conventional lighting systems by replacing different types of lights with high performance LEDs. Studies conducted in various countries, including China, Malaysia, Turkey, Bangladesh, and Brazil, across educational, residential, and industrial sectors, confirm the effectiveness of replacing traditional lighting types. These studies demonstrate significant reductions in light energy consumption and carbon emissions. A study conducted in China investigated the impact of replacing incandescent light bulbs with compact fluorescent lights (CFLs) on household lighting electricity usage. The research considered various factors, including different room types, daily lighting usage patterns, the number of light bulbs per household and per room, and seasonal variations. The findings revealed that this intervention led to a reduction in lighting energy consumption by 23% to 27% for the years 2010 and 2020, respectively. Notably, targeting the replacement of light bulbs in bedrooms resulted in a potential reduction of over 38% in CO_2e emissions for households [15]. Another study examined the energy benefits of LED adoption in Malaysia by reviewing relevant research papers and conducting a life cycle assessment evaluation. The findings indicate that replacing 62% of incandescent lamps with LEDs in residential buildings could result in an 80% reduction in carbon emissions and an 82% to 88% reduction in electricity bills [16]. A similar intervention in an industrial building in Bangladesh demonstrated a decrease in lighting energy usage from 15% to 7.5%, resulting in a 50% reduction in CO_2e emissions [17]. Enhancing conventional lighting systems in historical and educational buildings in Turkey by replacing incandescent, halogen lamps, and fluorescent tube lights with LEDs resulted in significant energy savings. Specifically, this intervention led to a 78% reduction in electric energy consumption in historical buildings [18] and a 68% reduction in educational buildings [19]. Moreover, a research study conducted in Brazil investigates the reduction of electric energy consumption in an educational building through the retrofitting of fluorescent tube lights with LEDs. The results from life cycle assessment (LCA) evaluations and field study measurements indicate a 34% reduction in lighting energy consumption and a 33% decrease in CO_2e emissions [20].

A recent study by Hoxha et al. [21] analysed the environmental impacts of lighting systems through a detailed review of 101 environmental product declarations (EPDs) encompassing 753 LED-based products. The research evaluated the ecological footprint of these lighting solutions across all 27 European Union countries, focusing on both embodied emissions and emissions from electricity use. Additionally, the study examined the application of these systems in a timber building in Denmark. The analysis revealed that luminous efficacy varied from 30 to 171 lm/W across the products studied. Using a functional unit of 1,000 lumens provided over 35,000 hours, the study found that in countries such as Poland, Cyprus, Estonia, Malta, Czechia, Bulgaria, Germany, Italy, the Netherlands, Ireland, and Greece, electricity consumption accounted for over 95% of the environmental burden. This underscores the need to prioritize energy efficiency and low-carbon energy sources. In contrast, in other EU countries, material-related emissions were more significant, contributing up to 60% of the total impact and

highlighting the importance of strategic lighting solutions with low-carbon material choices. The study also identified an exponential decline in system impacts as luminous efficacy increased, suggesting that selecting high-efficacy lighting is a more effective way to reduce environmental impacts than relying solely on passive design or grid decarbonization. In the Danish case study, lighting accounted for 10–30% of the building's total climate impact. However, it is worth noting that even advanced technologies significantly contribute to building emissions. To meet future climate goals, including those of the Paris Agreement, both operational (6–24%) and embodied (up to 12.5%) impacts must be addressed through holistic improvements across the life cycle of lighting systems. In summary, research on lighting types and systems has primarily focused on energy efficiency and the resulting reduction of carbon emissions associated with electricity use. Although the publication of this study reviewing EPDs for lighting provides valuable insights, further in-depth analyses are required to strengthen the assessment of the environmental impacts of buildings. Future studies could be enhanced by integrating dynamic assessments of energy demand for artificial lighting, as well as considering different building shapes and typologies.

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Lifecycle and Circular Economy Approaches

The lighting industry is increasingly embracing circular economy principles to minimize waste, maximize resource efficiency, and establish closed-loop material flows. These strategies aim to extend product lifecycles, reduce environmental impact, and integrate sustainability throughout the design, production, and end-of-life phases. Circular economy approaches in lighting not only support environmental goals but also create economic value through resource optimization and innovative business models.

Design for Circularity

Modern lighting products are being designed with end-of-life considerations to facilitate recycling, refurbishment, and material recovery. Design for disassembly principles is implemented through modular construction, reversible fasteners, and material marking, while reducing material diversity simplifies recycling processes [1]. Material selection and efficiency emphasize the use of recyclable or renewable materials, minimizing material usage, eliminating hazardous substances, and incorporating recycled content where feasible [2]. Together, these practices ensure that products are inherently more sustainable and easier to reintegrate into the material lifecycle.

As the manufacturing of LED lighting is considered, the environmental impact of today's system designs and production processes should be considered. Developing a sustainable supply chain that feeds into the circular economy is an opportunity for lighting industry to model the transformation needed for a sustainable future. Manufacturers need to design differently by using more sustainable materials and to deconstruct differently by creating intentional designs for disassembly and recycling of luminaire materials.

A sustainable lighting future requires the creation of eco-friendly designs with minimized component count, and the use of low-embodied energy materials, recycled materials, or bioderived materials. Most SSL luminaires use aluminium and other energy-dense structural and thermal materials in their designs and manufacturing processes. The use of recycled materials can help save energy and repurpose items from the landfill. Extracting

and processing raw resources to make usable materials requires a lot of energy, whereas recycling often requires much less processing to turn previous products into usable materials.

Embodied Carbon Management

While operational energy remains the dominant contributor to lighting system carbon footprints, embodied carbon - associated with the manufacture, transport, and material composition of lighting products - is increasingly recognized as a critical sustainability metric, particularly for LED systems with complex electronic components. Strategies for manufacturing impact reduction focus on improving material efficiency, optimizing semiconductor production processes, minimizing packaging and auxiliary components, sourcing materials locally to reduce transportation emissions, and integrating renewable energy within manufacturing facilities [7]. Enhancing product longevity further mitigates embodied carbon intensity by implementing robust design practices for durability, modular architectures that allow component-level replacement, optimized thermal management to extend LED lifespans, and rigorous quality assurance systems that maintain consistent performance [8]. Collectively, these approaches support a comprehensive strategy for reducing the total carbon footprint of lighting systems across their entire life cycle.

Business Model Innovation and Implementation Strategies

The adoption of service-based and remanufacturing business models further advances circularity in the lighting sector. Concepts such as Lighting-as-a-Service (LaaS) allow manufacturers to retain system ownership, incentivize efficiency through performance-based contracts, and ensure proper end-of-life material recovery [3]. Remanufacturing and refurbishment strategies extend product lifespans via component upgrades, quality assurance systems, and reverse logistics networks [4]. Effective implementation also requires supply chain transformation, including sustainable material sourcing, collaboration with recycling partners, and integration of circularity metrics into procurement decisions [5]. Comprehensive data collection and transparency, supported by material composition databases, predictive performance monitoring, and digital product passports, are essential for optimizing recycling and enabling industry-wide adoption of circular principles [6].

The approach of sustainable supply chains and the circular economy can create a local economic advantage by embracing the concept of upgradable or repairable fixtures and allowing for more maintenance and servicing local revenue streams. Additionally, maintaining more bio-friendly materials and an emphasis on reducing transportation waste can help improve the local supply chains. If a sustainable design rating was a competitive barrier, then categories such as reduction in transport waste, sustainable materials use, and efficient recycling could be differentiators in rating.

Additional information on the Life Cycle Assessment (LCA) of lighting systems can be found in the IEA SHC Task 70 / EBC Annex 90 Subtask A.1 report. The report presents a detailed review of LCA methodologies, relevant environmental impact categories, system boundary considerations, and key assumptions for evaluating the sustainability performance of lighting products and installations.

Technological Innovations Supporting Sustainability

Efficiency and Performance Improvements

Recent advances in LED technology continue to enhance both energy efficiency and system performance in modern lighting applications. Luminous efficacy has reached new heights, with laboratory demonstrations exceeding 300 lumens per watt and commercial products routinely achieving 150–200 lumens per watt, all while maintaining improved colour rendering and extended operating temperature ranges that enhance system reliability. In parallel, spectral optimization enables precise control of light characteristics to support energy savings and human-centric lighting objectives. Tuneable white LEDs facilitate circadian rhythm alignment, narrow-band LEDs optimize photopic-to-scotopic ratios for visual comfort, and horticultural lighting is tailored to maximize photosynthetic efficiency. Additionally, UV-free formulations mitigate material degradation, extending fixture lifetimes and maintaining performance. Together, these developments illustrate a continued trend toward highly efficient, versatile, and human-aware lighting systems that combine peak energy performance with advanced functional capabilities (refer in this context also to the previous subchapters 4.1.2 about Core Technologies in Modern Lighting and 4.1.4 on Optical and Photometric Concepts).

But beside LED-innovations, also operational improvements in terms of advanced control strategies (refer to subchapter 4.1.5 on Lighting Control and Automation) in terms of adaptive dimming systems (e.g., Occupancy-based dimming, Daylight harvesting, Task-specific lighting and Predictive algorithms to optimizing energy consumption).

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4.7 Future Trends and Conclusion

4.7.1 Continued LED Advancement

Recent developments in LED technology have focused on increasing luminous efficacy, improving colour quality and spectral tunability, enabling greater miniaturization, and reducing system costs. Advances in chip design, phosphor technologies, packaging concepts, and optical control have expanded the performance range and application potential of solid-state lighting while supporting more efficient and compact lighting solutions.

Looking ahead, further progress is expected from both the optimization of existing LED technologies and the exploration of novel material systems. Improvements in the yellow, amber, and red spectral regions may require alternatives to current III-V semiconductor materials. Computational modelling and materials discovery are likely to play an increasingly important role in identifying promising compounds, predicting device performance, and accelerating the development of next-generation solid-state lighting technologies.

4.7.2 OLED Development Emerging Emitter Technologies

OLED lighting development has focused on improving efficacy, lifetime, manufacturing scalability, and optical performance while expanding design possibilities through flexible and transparent form factors. Advances in materials, device structures, and production technologies continue to enhance the competitiveness of OLEDs for architectural and human-centric lighting applications.

In here, further progress can be expected from both the refinement of OLED technology and the emergence of new emissive platforms such as quantum dot LEDs, micro-LEDs, and perovskite LEDs. In parallel, highly integrated semiconductor-based lighting architectures could transform future lighting systems by combining light generation, control, communication, and power management at the chip level. Although significant technical and materials challenges remain, these developments offer the potential for higher efficiency, greater functionality, scalable manufacturing, and new opportunities for lighting integration within buildings and products.

4.7.3 Sustainability and Circular Economy

Sustainability considerations are becoming increasingly important in the development of future lighting solutions. Beyond delivering substantial energy savings, modern solid-state lighting technologies can contribute to reducing greenhouse gas emissions while supporting more resource-efficient lighting systems. At the same time, growing attention is being paid to product durability, material efficiency, and the environmental impacts associated with the entire lifecycle of lighting products.

Looking ahead, circular economy principles are expected to play a central role in lighting design and manufacturing. Future trends include improved recyclability, the recovery of valuable materials, modular and upgradeable product architectures, and service-based business models that encourage responsible lifecycle management. Combined with the elimination of hazardous substances and more sustainable end-of-life strategies, these developments have the potential to further enhance the environmental performance of next-generation lighting systems.

4.7.4 Recommendation of stakeholders

To fully realize the potential of modern lighting technologies, stakeholders across the industry must take coordinated action. Building owners and facility managers should prioritize comprehensive LED retrofits paired with smart controls to maximize energy savings. Ensuring proper commissioning and ongoing performance verification is essential to maintain system efficiency and reliability. Adopting lighting-as-a-service models can help overcome upfront cost barriers, while engaging occupants in system design promotes acceptance and encourages proper use.

Policymakers play a crucial role by strengthening building energy codes to require efficient lighting and control systems. Developing standardized performance metrics and verification protocols, along with utility incentive programs that encourage full-system upgrades, can accelerate adoption. Additionally, funding research into human-centric lighting, interoperability, and emerging technologies will support continued innovation in the sector.

Manufacturers should focus on developing open and interoperable systems to prevent vendor lock-in, while simplifying commissioning processes and providing effective tools and training to support adoption. Addressing the limitations of OLED technology will expand its applications, and implementing circular economy strategies can promote sustainable lifecycle management of lighting products.

Finally, researchers are essential for advancing knowledge and technology in the field. Rigorous studies are needed to quantify the benefits of human-centric lighting and identify optimal design strategies. Developing better commissioning tools and performance verification methods will enhance reliability, while improving OLED efficiency and lifetime is critical for competitive general lighting solutions. Exploring emerging technologies, including quantum dots, micro-LEDs, and perovskites, will help identify the next generation of high-performance lighting opportunities.

5 Integrated Lighting Controls

By David Geisler-Moroder, Sascha Hammes

The integration of daylight and electric lighting, in connection with Internet of Things (IoT) technologies, has become one of the most significant trends in intelligent building design. Rather than treating lighting, shading and building automation as independent systems, modern solutions coordinate these functions through sensors, communication networks and advanced control algorithms. Such systems continuously monitor environmental conditions, occupancy and user preferences to optimize visual comfort, energy efficiency and occupant well-being. The approach is closely associated with Human Centric Lighting (HCL), smart building platforms and digital facility management, while also contributing to sustainability efforts.

In this chapter we present the findings from a comprehensive scientific literature review, show examples of current trends in industry, and conclude with comparison of market demands and the current state in the scientific literature.

5.1 Findings from a review of the current scientific literature

In a comprehensive review of 160 scientific articles [Hammes et al., 2024] the authors evaluated the potential of user-centred control concepts for daylighting and electric lighting systems and identified necessary technical system components for greater applicability. Here we present a summary of the main results of the work.

The literature review highlights that user behaviour in office environments is highly dynamic and influenced by a wide range of contextual factors, including work processes, social structures, demographic aspects, and individual preferences. This variability is reflected in fluctuating occupancy patterns and differing expectations regarding lighting conditions. Rather than being problematic, this heterogeneity should be considered an inherent characteristic of office environments that lighting systems must accommodate. Achieving this requires sufficiently detailed occupancy and preference data, which can be obtained through advanced sensing approaches such as sensor fusion or imaging systems. The analysed literature revealed different levels of information depending on the technology (see Figure 5.1).

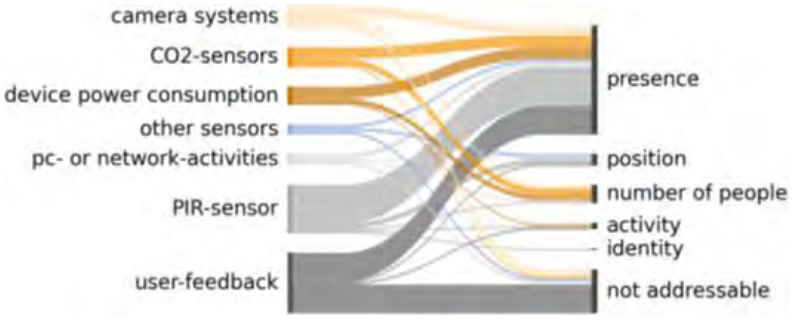


Figure 5.1: Sankey diagram of the relationships between occupancy-related sensors and level of occupancy information, based on the manual paper evaluation. Source: [Hammes et al., 2024]

Open-plan offices exemplify the challenges of user diversity. While they improve space efficiency and communication, they complicate lighting control because multiple users with different preferences share the same environment. In practice, control is often dominated by individuals who are most sensitive or have easiest access to controls, which can reduce overall satisfaction. Zoned lighting concepts offer a promising solution by enabling localized adaptation to user needs while maintaining energy efficiency. However, their effectiveness depends on careful design, including appropriate zone sizes, smooth transitions between zones, and sufficient ambient lighting to avoid discomfort from visual contrasts.

Design limitations, such as rigid luminaire grids, often restrict fine-grained zoning. To address this, approaches like consensus-based control for groups of luminaires and adaptive façade and shading systems have been proposed. These solutions must also reconcile conflicting user preferences and integrate with other building systems to ensure overall performance. Separating task and ambient lighting further enhances flexibility and user satisfaction.

Implementing zoned lighting with high-resolution occupancy detection requires sophisticated sensing infrastructure. Luminaire-integrated sensors, combined with wireless and implicit data sources (e.g., device activity), can provide detailed insights into occupancy and behaviour. Edge computing can reduce system complexity by enabling decentralized processing within lighting zones. However, the benefits of increased sensing must outweigh the associated energy and resource costs. Optimal placement and number of sensors remain key challenges, particularly in environments with high occupancy dynamics.

While these technological solutions can ensure energy efficiency and baseline comfort, they are limited in capturing the full variability and temporal evolution of user preferences. This underscores the importance of integrating users directly into the control loop.

A “human-in-the-loop” approach is therefore essential for user-centred lighting. Objective measurements alone are insufficient; subjective perception and feedback must also be considered. Preference learning can occur through passive observation of user interactions or active feedback via interfaces. Active methods provide richer contextual information but may suffer from declining user engagement over time, making passive methods and continuous monitoring equally important.

Providing users with feedback on the consequences of their actions – such as energy use or health impacts—can improve awareness and encourage more sustainable behaviour. Such learning effects may even extend beyond the office environment. To support this, control interfaces must be intuitive, transparent, and minimally intrusive to maintain user acceptance.

Post-occupancy evaluations (POEs) play a crucial role in capturing deeper insights into user behaviour, including physiological, psychological, and social factors. When conducted over extended periods and combined with sensor data, POEs enable the identification of recurring patterns and long-term trends. Integrating social science methods into these evaluations can further enhance understanding beyond what short-term feedback can provide.

The growing availability of large datasets opens opportunities for advanced analytical methods, including statistical modelling and machine learning. In particular, reinforcement learning (RL) offers a powerful framework for adaptive lighting control. RL systems can learn optimal control strategies over time by linking environmental conditions and user feedback to performance outcomes. Unlike rule-based systems, they can respond dynamically to changing conditions and optimize multiple performance indicators simultaneously. To ensure reliability, RL approaches should initially operate alongside conventional control strategies before gradually taking over.

Combining RL with multi-agent systems can further improve scalability and robustness by enabling knowledge transfer between different zones. Overall, integrating users into adaptive control systems through feedback, learning algorithms, and continuous evaluation can address many of the limitations of static or purely sensor-driven approaches.

From this review, several key elements of user-centred lighting concepts emerge. Their implementation depends on both technical requirements and the building lifecycle phase, ranging from design-stage decisions to post-commissioning adaptations. Successful solutions must balance system complexity, data availability, user acceptance, and performance objectives. The following table lists the user-centred lighting concepts as identified in the literature review (table adapted from [Hammes et al., 2024]).

Phase	Concept	Advantages (+) and disadvantages (-)	Relevant user-related metrics	Requirements identified via literature	References
Building design phase	Zoned lighting (artificial and shading) primarily for open-plan offices	Ensuring individual lighting preferences, with reduced energy consumption (+); conceptually solvable (+); sensor costs (-)	Visual preference, presence in zone	PIR and illuminance sensors (also luminaire-integrated); ensuring a general ambient lighting to avoid disturbing contrasts	[Chraibi et al., 2016; Tabadkani et al., 2023; Hammes et al., 2020; Koo, Yeo and Kim, 2010]
	Sensor fusion (use of several different data	Use of existing infrastructure (low costs) (+); recording of	High level of occupancy information	Interoperability between systems	[Labeodan et al., 2015; Shen,

	collection methods; including implicit methods, IoT, feedback-apps	physiological aspects (+); complex data analysis (-); low reliability in the network (-)	(identity & activity); physiological parameters; satisfaction		Newsham and Gunay, 2017]
	Camera-based methods	High information via a single sensor, including some physiological aspects (+); complex data analysis (-); critical in terms of data protection and low acceptance (-)	High level of occupancy information (identity & activity)	Clear view of the target area; direct image processing to ensure data protection and privacy (for example via edge computing)	[Salimi and Hammad, 2019; Labeodan et al., 2015; Choi et al., 2021; Seghezzi et al., 2021]
	User-related control logic (e.g., reinforcement learning)	Automated ongoing consideration of user needs and multi-objective optimisation (+); reward function can be complex and take a long time to maximise (-)	User preferences and behaviour	Simulation environment for the development of machine learning methods, suitable reward function (often with multi-criteria objective)	[Han et al., 2019; Park et al., 2019]

Operational phase	Data monitoring-based POE	Problem identification and feedback of knowledge gained into building design phase/simulation (+); sensor costs and need for evaluation skills (-)	Satisfaction of users with the control system	Data collection method including data logging and evaluation routines	[Preiser, 1995; Menezes et al., 2012]
	Survey-based POE	Collection of user data that cannot be collected via sensors (+); cost-effective (+); risks of low response rates because of high effort and duration (-)	Psychological and physiological aspects; perception of IEQ conditions	Implementation as a recurring event to absorb fluctuations over time	[Preiser, 1995; Choi and Lee, 2018; Bavaresco et al., 2020]
	Adaptation of the switch-off time to individual occupancy patterns (as a result of a POE)	Easy-to-collect data (presence at work/zone and artificial light operating times), use of statistical methods (+); critical in terms of data protection and privacy (-)	Occupancy profile at the workplace/ lighting zone	Presence-based artificial lighting control that includes technology-related switch-off times (e.g., PIR sensors)	[Hammes et al., 2021]
	Derivation of optimized user distributions in the room (as a result of a POE)	High energetic relevance with high user dynamics, simple data collection (Occupancy, illuminance & energy data) (+); critical in terms of data protection and privacy (-)	Individual occupancy profile at the workplace	Zoned lighting and recording of energetically weighted occupancy patterns, or coupled with available illuminance levels	[Hammes et al., 2022]

In conclusion, achieving desired lighting performance indicators depends strongly on how well user behaviour and preferences are represented within the system. Zoned lighting concepts aligned with the principle of delivering energy only where needed are particularly effective. However, their success relies on high-resolution user data, which remains challenging to obtain in practice. Combining direct sensing (e.g., integrated sensors) with indirect methods (e.g., digital activity data) or using high-resolution imaging systems offers viable pathways, provided data protection and privacy requirements are met.

POEs complement these approaches by capturing deeper behavioural insights and supporting continuous system improvement. To address the temporal variability of user preferences without repeated resource-intensive evaluations, reinforcement learning provides a promising solution for automating adaptation processes.

An interdisciplinary approach that integrates engineering and social sciences is essential to fully understand user behaviour and translate it into effective control strategies. Such approaches enable simultaneous optimization of multiple performance indicators, including energy efficiency, comfort, and health-related lighting effects.

Given the significant share of global energy consumption attributed to buildings, and lighting as a major contributor, user-centred lighting systems hold substantial potential for reducing energy demand while improving occupant well-being. By aligning technological innovation with human factors, these systems can contribute meaningfully to climate and sustainability goals. In this context, Figure 5.2 illustrates which objectives are most frequently achieved in the selected literature using specific sensor data and control concepts.

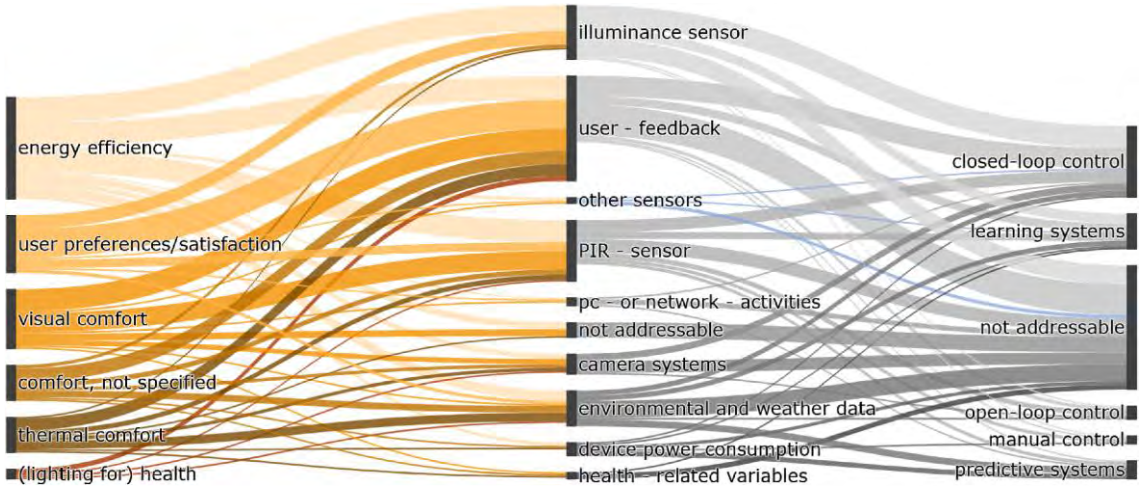


Figure 5.2: Sankey diagram for KPIs, sensors and control logic, based on the manual paper evaluation. Visual comfort also includes the KPIs previously listed separately: glare avoidance, view of the outside, daylight availability and lighting conditions for good visual performance. Source: [Hammes et al., 2024]

Finally, the authors emphasize the importance of continued research and systematic post-occupancy evaluation. Improved understanding of user behaviour will help reduce uncertainties in planning, minimize performance gaps between design and operation, and support the development of more effective and adaptable lighting systems in the future.

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5.2 Industry Trends

Here we describe two representative examples of the emerging trend of integrating daylight and electric lighting, in connection with IoT technologies: *Wellumic*, developed jointly by WAREMA and TRILUX, combines daylighting with human centric electric lighting solutions; and *Keyture*, developed by the Zumtobel Group, extends traditional lighting controls into a cloud-native IoT platform.

5.2.1 Wellumic

Wellumic[2] is an integrated daylight management system jointly developed by WAREMA[3], a specialist in automated solar shading, and TRILUX[4], a manufacturer of professional lighting systems. The collaboration was initiated to overcome the traditional separation between façade shading and electric lighting controls by creating a single platform that continuously coordinates both systems. Instead of simply dimming luminaires according to available daylight, *Wellumic* dynamically manages daylight admission through automated external venetian blinds while simultaneously controlling HCL luminaires. The primary objective is to maximize the use of natural daylight without causing glare, overheating or visual discomfort, thereby improving occupant well-being while minimizing building energy consumption.

Technically, the system combines multiple sensing technologies, including indoor illuminance sensors, occupancy sensors and an outdoor weather station with an integrated GPS module measuring solar radiation, temperature, wind and sun position. These inputs are processed by a central control algorithm implemented through WAREMA's *BAline* automation platform. External blinds equipped with SMI motors adjust slat angles continuously and precisely, directing diffuse daylight deep into the room while blocking direct sunlight. Simultaneously, TRILUX HCL luminaires adapt both illuminance level and colour temperature to complement the available daylight, maintaining stable visual conditions throughout the day. Users may select predefined lighting scenes (such as Presentation, Active, Relax or Focus) or create customized settings through room controllers or PC-based software.

Wellumic promotes that daylight is the primary lighting source, while artificial lighting acts only as a dynamic supplement. The integrated control algorithm continuously balances daylight harvesting, glare protection, thermal comfort and circadian-supportive lighting, producing a holistic indoor lighting environment rather than optimizing each subsystem independently. The coordinated operation also reduces cooling demand by limiting excessive solar heat gains while maintaining high daylight availability. Because of its integrated approach, *Wellumic* supports compliance with energy-efficiency standards and sustainable building certifications, including LEED, BREEAM, DGNB and WELL, and has been implemented in flagship projects such as the Zehnder Center of Climate in Germany.

5.2.2 Keyture

Keyture[5] represents the latest evolution of intelligent lighting from the Zumtobel Group[6], extending traditional lighting control into a cloud-native IoT platform for smart buildings. Whereas previous generations of lighting management systems primarily focused on local control of luminaires, *Keyture* positions lighting infrastructure as a distributed sensor network capable of delivering operational intelligence across entire facilities. The platform combines wireless connectivity, cloud computing and IOT technologies to transform lighting installations into data sources that support facility management, sustainability reporting and predictive maintenance. Lighting therefore becomes not only an energy-consuming building service but also an information platform supporting digital building operation.

The architecture integrates connected luminaires, sensors, gateways and cloud-based software into a unified ecosystem. Occupancy sensors, daylight sensors and energy monitoring continuously collect operational data, while cloud analytics convert these measurements into actionable insights. Key functions include automated scheduling, occupancy-based lighting control, energy dashboards, alarm management, predictive maintenance and detailed reporting of electricity consumption and greenhouse gas reductions. Facility managers obtain centralized visualization of lighting assets across multiple buildings, enabling remote monitoring, performance

[2] https://www.wellumic.com/
[3] https://www.warema.com/en/
[4] https://www.trilux.com/en/
[5] https://www.keyture.com/
[6] https://z.lighting/en/group/company/

analysis and lifecycle management. Because the platform is cloud-native, scalability across large building portfolios is considerably simplified compared with traditional building management systems.

Keyture places great emphasis on digital building services and operational intelligence. Although it also supports daylight-responsive lighting control and automation, its distinguishing capability lies in integrating lighting with enterprise-level analytics, sustainability management and IoT-enabled facility operation. The platform provides real-time data for energy optimization, maintenance planning and environmental reporting while supporting decarbonization strategies through continuous monitoring of energy performance. Consequently, *Keyture* illustrates the broader industry transition from intelligent lighting systems toward comprehensive smart-building ecosystems in which lighting infrastructure serves as both a control system and a digital information platform.

5.2.3 Further industry approaches

Several other manufacturers are pursuing comparable concepts that integrate daylight harvesting, connected lighting and IoT-based building management. Examples include Signify[7] with *Interact*[8], which combines connected lighting, occupancy sensing and cloud analytics; Fagerhult Group[9] with *Organic Response*[10], a sensor-based distributed lighting control platform; Helvar[11] with its intelligent lighting and building integration solutions; and Schneider Electric[12], which integrates lighting with broader building management and energy optimization platforms. Together with *Wellumic* and *Keyture*, these solutions demonstrate the industry's movement toward unified ecosystems where daylight control, electric lighting, sensing, analytics and building automation operate as a coordinated digital infrastructure.

5.3 Market demands

In 2024, Hammes et al. [Hammes et al., 2024a] performed a survey in the construction industry to obtain a representative picture of the market regarding current challenges and expectations of lighting controls, especially in the context of BIM, user-centeredness and integrated systems. The results of the market survey were compared with the findings from the literature research [Hammes et al., 2024b] presented in Section 0 and from a second literature research in the context of BIM and lighting control [Hauer et al., 2024]. Here we present a summary of the main results of the work.

Need for digital twins and improved control transparency

The market survey highlights that planners exert a strong influence over control design and sensor selection, yet their involvement often diminishes after the tendering phase. This creates a disconnect between design intentions and implementation by executing companies. While systems typically meet functional requirements, limited transparency between stakeholders can lead to errors and reduce both energy efficiency and user comfort, ultimately contributing to performance gaps between planning and operation. Moreover, planners are rarely involved after commissioning, meaning that systematic performance evaluation is uncommon. This lack of feedback prevents learning from past projects and hinders continuous improvement in planning practices.

Another key issue is the uncertainty surrounding actual building use, which complicates accurate system parameterization during design. As a result, user-related factors – critical for system performance – are often insufficiently considered until after commissioning. This makes post-occupancy system adjustments essential. Although facility management (FM) expresses a clear need to adapt systems during operation, they often lack the technical means or access to do so (cf. Figure 5.3). At the same time, planners tend to underestimate the importance of post-commissioning adjustments, increasing the risk that necessary interfaces for later modifications are not implemented.

[7] https://www.signify.com/global
[8] https://www.signify.com/global/specifier/interact-pro
[9] https://www.fagerhult.com/
[10] https://www.fagerhult.com/smart-lighting/organic-response/
[11] https://helvar.com/
[12] https://www.se.com/ww/en/

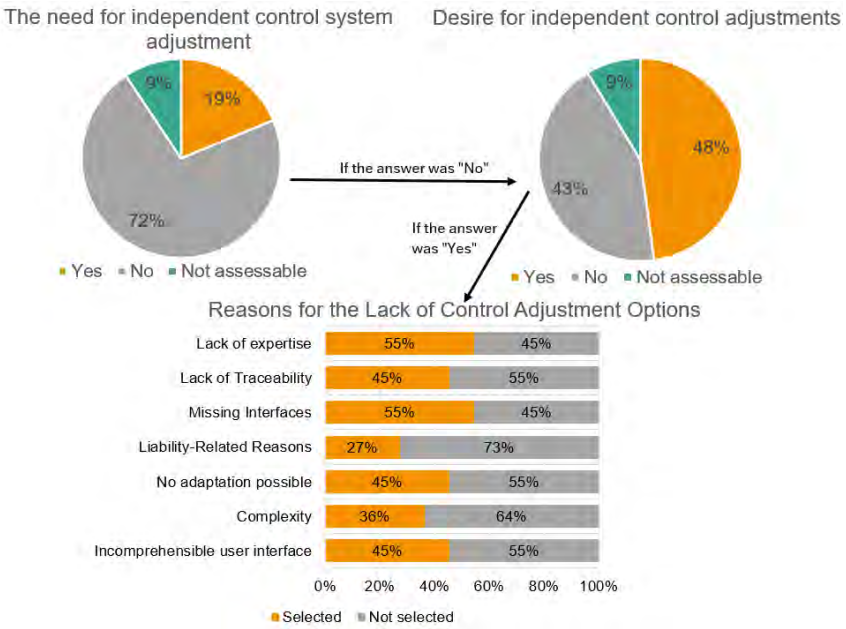


Figure 5.3: From the necessity of control system adaptation through FM to its possibilities and limitations. Based on the results of [Hammes et al., 2024a].

FM, as the primary interface with occupants, is well positioned to evaluate system performance in terms of comfort, efficiency, and reliability. However, limited transparency into design decisions and control logic makes this difficult (cf. Figure 5.3). Understanding and modifying system behaviour often requires extensive coordination with contractors, leading to high time and cost burdens. This lack of traceability and unclear allocation of responsibilities is widely recognized as a major challenge. Establishing clear governance for role-based access, change management, and documentation of control logic (including versioning) can reduce these barriers and accelerate safe modifications.

To address these issues, survey participants emphasize the potential of Building Information Modelling (BIM) as a central platform for improving transparency and information flow across all project phases.

Solutions for planning and implementation

BIM, particularly when combined with Building Energy Modelling (BEM), enables the simulation, evaluation, and optimization of control strategies during the design phase. This allows planners to assess different concepts in terms of energy efficiency and user comfort before implementation. However, achieving this requires more detailed representations of control systems and improved user models. BEM predictions should be calibrated with measured operational data where possible to reduce model-reality gaps and improve the robustness of design decisions. Performance evaluation methodologies and monitoring-based/continuous commissioning should be specified in contracts to ensure traceable over time.

Energy management is already considered important during planning and research, but its full potential is often only realized during operation. Therefore, contractual frameworks that ensure performance evaluation and continuous commissioning throughout the building lifecycle are essential. Insights gained from operational data, especially when integrated into a digital twin, can be fed back into planning, reducing future performance gaps.

Early involvement of FM in the design process is also crucial. Integrating operational expertise aligns with the principles of BIM-based integral planning and helps ensure that control systems meet real-world requirements.

Solutions for operation

Digitalization also offers significant benefits for building operation. BIM can serve as a central information hub for Computer-Aided Facility Management (CAFM), improving data accessibility, operational efficiency, and cost control. The integration of IoT technologies and big data systems further enhances FM capabilities by enabling continuous monitoring and data-driven decision-making.

To fully realize these benefits, interoperability and seamless communication between systems and stakeholders are essential. Semantic web technologies can support the integration and management of heterogeneous data sources, facilitating the development of digital twins.

Buildings must also remain adaptable to changing usage patterns and occupant behaviour. If control systems fail to reflect these changes, occupants may override automated settings, often at the expense of energy efficiency. Continuous commissioning, supported by real-time data integration into BIM, enables ongoing system optimization [Zech et al., 2025]. By linking operational data with control logic, digital twins allow for post-occupancy evaluation (POE) and targeted improvements. They also support maintenance and fault detection by enabling real-time performance monitoring.

However, the survey identifies time constraints and lack of expertise as major barriers for both planners and FM. Automated solutions such as auto-commissioning and auto-deployment can help address these challenges by reducing manual effort and enabling more efficient system adaptation. Interoperability between commissioning tools and information management systems is a key requirement for their successful implementation. Automated methods should enforce comfort and safety constraints, provide explainable recommendations, and include rollback strategies to known-good states to mitigate operational risk.

User-centred approach

While energy performance is well represented in current monitoring tools, user-related data is significantly underutilized. The survey shows that parameters such as occupancy and individual preferences are rarely collected or integrated into control systems. Consequently, personalization strategies are seldom implemented in practice.

Although IoT technologies could enable the collection of more comprehensive user data – including non-physical parameters – their adoption remains limited. Importantly, the survey indicates that technical barriers and data protection and privacy concerns are less significant than often assumed. Instead, the main obstacles appear to be related to implementation effort and lack of prioritization. A pragmatic minimum dataset for user-centric controls can include zone-level occupancy, schedule patterns, simple preference profiles, and feedback events, collected with low-intrusion methods.

Integrating daylight and artificial lighting control offers clear benefits for both energy efficiency and user comfort. However, these domains are still frequently planned separately, despite strong interest among planners in more integrated approaches. Procurement structures often limit such collaboration. BIM can address this by providing a shared platform for interdisciplinary planning and improving transparency between stakeholders.

Conclusions from the survey

In summary, the study of Hammes et al. (2024a) demonstrates that performance gaps in building operation are largely driven by insufficient consideration of user-related variables and limited opportunities for post-occupancy system adaptation. While facility management is well positioned to optimize system performance, it often lacks both the technical tools and access to relevant data. At the same time, user-centred data remains underutilized, and operational workloads in FM are high.

To address these challenges, the integration of operational data into digital building models – using BIM as a central platform – is essential. The development of digital twins enables continuous performance evaluation, supports post-occupancy optimization, and facilitates feedback into the planning process. Automated methods such as auto-commissioning and fault detection can further reduce workload and improve system performance (cf. [Zech et al., 2025]).

Successful implementation requires clear contractual frameworks for performance evaluation and commissioning, as well as interoperability between tools and systems across disciplines. Monitoring and post-occupancy evaluation could also serve as quality assurance mechanisms and potentially as certification criteria.

Although current user-centred approaches are often limited to simple zoning strategies, there are few fundamental technical or regulatory barriers to more advanced solutions. Given the strong influence of planners on system design, expanding user-centred control concepts is primarily a question of effort and prioritization. In this context, automated support tools and improved integration of control parameters into BIM are key enablers for enhancing transparency, adaptability, and overall building performance across the lifecycle.

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6 Conclusions and Recommendations

If we examine our objective of achieving stated energy and environmental goals at speed and scale for all areas of application, one could argue that further technological improvements in solid state lighting (SSL) source luminous efficacy from 204 to 228 lm/W (2020) to 250 to 325 lm/W by 2050, increased source lifetime, increased luminaire optical efficiency, and sustainable design to lower life-cycle embodied energy (e.g., replaceable lamps, ease of disassembly, material recycling) are the most assured means of achieving these goals. When combined with advanced sensors, controls, and digitalization to tune, dim, or turn off spatially resolved zoned lighting when not needed, further reductions in energy use, demand, and operational cost are achievable in both new and retrofit markets.

With advancements in fundamental chronobiology and neuroscience research, however, we know that human-centric *design* is essential for meeting diverse visual and non-visual health and well-being requirements in buildings. Business-as-usual design solutions can fall well short of meeting these demands. Case study evidence indicates significant increases in lighting energy use and decreased demand flexibility[13], which could counter the tremendous efficiency gains achieved by the global adoption (greater than 80%) of SSLs over the past two decades. Satisfaction of spectrally tuneable, user-adaptive flux requirements at individuals' eyes (i.e., vertical illuminance) requires not only engineering improvements to the optical efficiency and distribution of luminaires, flexible controls, and continuity of design intent through to the occupancy phase (i.e., via BIM, IoT systems, digitalization), but also rethinking space design and use, and potentially increased reliance on daylight.

Daylight is fundamentally understood by clients, end users, and the lighting industry to be an essential ingredient of a high-performance building, despite its inherent challenges of control. Windows and skylights offer views to the outdoors, natural light variability, superior spectral composition and colour rendering (assuming relatively clear glass), amongst other benefits. Further developments in chronobiology and neuroscience research could reveal additional arguments in favour of "natural" daylight (e.g., myopia crises in dense urban environments). As a technology, advancements in optics, mechanical and material dynamism, and automated / user-adaptive controls have striven to provide a more optimal balance between competing daylighting objectives (daylight provision and view vs. glare, solar gains vs. lighting, exposure to sunlight vs. overheating). Metrics for technological evaluations have historically focused on return on investment from the displacement of lighting energy use using redirected sun- or skylight in e.g., deep, open plan, shared, side-lit zones within glare discomfort and solar heat gain or HVAC limits. Some projects rely on economically driven criteria to justify the use of *any* windows in buildings (e.g., controversy over a new windowless student dormitory at the University of California at Santa Barbara[14]). Countering trends have shifted to better accommodate qualitative aspects of daylight through industry recognition programs (LEED or WELL points for indoor environmental quality) and standards (e.g., European EN17037, Daylight in Buildings). Workplace health and productivity trends increasingly focus on maximizing daylight benefits for all, not just the few near windows: enabling view out, providing zoning and workplace flexibility to enable users to adjust their task/ position, use of local (i.e., at your desk) shading to accommodate end users' broad range in glare sensitivity, and encouraging natural variability of daylight instead of suppressing it. New technologies are being engineered using advanced multi-objective optimisation methods to create context-specific solutions. AI-driven, kinetic solutions are at the leading edge, exploratory stage but show promise in delivering integrative and integrated whole building solutions.

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