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LIGHTING MODERNIZATION: SCIENTIFIC EVIDENCE, PATENTS, AND HISTORICAL DATA

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Abstract

Lighting modernization requires systems to be compared under equivalent lighting service rather than by energy use alone. This study integrates three evidence streams: a purposive corpus of 18 patent families or publications with priority dates from 1971 to 2022; 13 scientific and technical publications published between 2016 and 2025; and historical data from 13 university corridors and two industrial studies conducted in 2013-2014. The patent corpus was classified into sources and ballasts, LEDs and optics, drivers and Digital Addressable Lighting Interface (DALI), sensors and daylight, and tunable or integrative lighting. The literature was synthesized narratively, with emphasis on retrofit, efficiency, control, and comfort. Seven of the 13 corridors reached or exceeded the historical reference of 100 lx, while the minimum-to-average ratio (U_0) varied widely among environments, with particularly low values in several corridors, indicating spatial heterogeneity. The industrial cases confirmed that an underlit baseline may consume less energy while remaining technically inadequate. Campus studies reported a 45.5% reduction in installed power and estimated energy savings of 47.36% with LEDs, although economic feasibility depends on prices, operating hours and tariffs. Within the selected corpus, the documents illustrate a transition from ballasts and illuminance-responsive controls to white LEDs, DALI, distributed occupancy detection, spectral tuning and melanopic quantities. A phased modernization pathway is proposed: assessment and maintenance; photometric compliance; selection of suitable LED luminaires; zoning and controls with proper commissioning; and, finally, integrative features supported by CIE metrics and energy limits. The study is neither a patent census nor a systematic review; it provides a decision framework for service-equivalent lighting retrofits.

Keywords: energy efficiency; integrative lighting; lighting engineering; patents; retrofit.

1. Introduction

Lighting in workplaces and educational environments should provide suitable conditions for visual tasks, limit discomfort, and operate with energy use and maintenance requirements consistent with the building's function. In recent decades, the technical scope of the problem has broadened. In addition to horizontal illuminance, uniformity, glare, color rendering, correlated color temperature, spatial distribution, user response, daylight integration, and, more recently, quantities associated with the non-visual effects of light have become increasingly relevant.

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This broader scope has developed in parallel with technological changes in light sources and control systems. Recent literature and, illustratively, the documents in the selected patent corpus describe technologies ranging from conventional lamps and their control gear to solid-state devices, electronic drivers, addressable control networks, occupancy and illuminance sensors, connected platforms, and spectrally tunable luminaires. However, adding new features does not, by itself, guarantee performance. Retrofit projects may reduce installed power while still producing inadequate light distribution; poorly commissioned controls may cause underlighting or user rejection; and non-visual targets may increase energy demand when they are met solely through electric lighting.

The historical files analyzed in this study document a transition period experienced in Brazil in the early 2010s. One industrial study compared mercury-vapor lamps, T5 fluorescent lamps, and LED tubes using illuminance, payback, internal rate of return, and net present value. Another study assessed a furniture manufacturing facility with lighting levels far below the recommended values and designed a system suited to the visual tasks. A third dataset recorded measurements in university corridors, lamp inventories, and proposals to replace fluorescent lamps with LEDs. These data are valuable because they show how costs, product efficiency, and standards and technical criteria shaped past decisions.

Recent literature often examines LED retrofits, automation, visual comfort, and integrative lighting separately. Likewise, patent surveys may quantify filings without relating the claimed solutions to real field problems. A gap therefore remains in linking technological trajectories, contemporary scientific evidence, and historical data from lighting systems measured under real-world conditions.

The research question is: how can a documentary patent corpus and recent literature help reinterpret historical lighting data, and which criteria can prevent apparent energy savings from being conflated with underlighting? The contribution of this article is neither to estimate worldwide patenting intensity nor to update the financial feasibility of the historical cases. Rather, it integrates heterogeneous sources to propose a decision framework based on equivalence of lighting service. The overall objective was to analyze technological documents, recent scientific

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evidence, and historical data in order to identify functional trends, limitations, and criteria for technically appropriate, energy-efficient, and user-centered modernization.

2. Methodology

2.1 Study design and data sources

An integrative documentary analysis was conducted comprising: (i) a purposive patent corpus; (ii) a targeted narrative synthesis of the literature; and (iii) a descriptive reanalysis of historical data. The study is not an exhaustive patent landscape, a bibliometric analysis, or a systematic review. Consequently, corpus frequencies do not estimate the universe of inventions, and the selected literature does not support claims of comprehensive coverage.

External searches were conducted on July 29, 2026. SciSpace was used for semantic literature retrieval; official journal pages, DOI records, and institutional repositories were used for bibliographic verification; Google Patents and, when accessible, Espacenet or WIPO were used to verify patent documents; official ISO, CIE, Fundacentro, and Brazilian Ministry of Labor and Employment documents were consulted; and historical datasets were provided by the authors. The retained literature was published between 2016 and 2025; no 2026 publication was included in the final synthesis. The patent unit was the simple patent family or, when the database interface did not allow unequivocal identification, a representative publication from the same inventive core.

Table 1 - Design and criteria for the documentary datasets

Component	Period	Main sources	Retention criterion
Patents	1971-2022 (priority years of retained documents)	Google Patents; Espacenet/WIPO when accessible	Direct relationship to general indoor lighting, efficiency, control, LED, sensors, or integrative lighting; verifiable publication.
Literature	2016-2025 (search updated through July 2026)	SciSpace; publishers; DOI; repositories	Articles, reviews, or reports with methods and results applicable to retrofit, control, comfort, or energy.
Historical datasets	2013-2014	Undergraduate theses, preliminary manuscript, and attached spreadsheets	Measurements, inventories, and indicators whose origin and context could be identified.
Standards	Applicability checked in 2026	ISO/CIE, CIE, Fundacentro, NR-17	Official documents applicable to measurement, design, or non-visual effects.

Source: prepared by the authors.

Table 1 makes explicit the non-exhaustive nature of both the patent corpus and the literature synthesis, as well as the use of historical data as a documentary baseline.

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2.2 Documentary analysis of the patent corpus

The documentary search considered terms related to lighting control, ambient light, fluorescent ballast, LED, DALI, occupancy detection, daylight harvesting, tunable white, circadian lighting, melanopic illuminance, and human-centric lighting. Classes F21 and H05B were used as conceptual starting points and were complemented by the classifications reported in the documents consulted. Applications exclusively related to automotive lighting, displays, horticulture, phototherapy, ultraviolet disinfection, entertainment, and signaling without a direct relationship to general indoor lighting were excluded.

The documents were classified into five functional groups: G1, conventional sources and ballasts; G2, LEDs, phosphors, and optical systems; G3, drivers, dimming, and DALI communication; G4, sensors, automatic control, and daylight harvesting; and G5, tunable-white, circadian, and integrative lighting. For each record, the priority year, main publication, assignee when confirmed, status displayed by the consulted database, and predominant technical function were recorded. The status displayed by each database was treated solely as descriptive metadata as of the consultation date, without assessing validity, claim scope, or freedom to operate.

To improve corpus traceability, the selection pathway of the 18 retained records was audited against the study evidence database and documented in Supplementary Material S1. For each representative publication, the supplementary table identifies the functional group, retrieval descriptor associated with the recorded search terms, verification database, consultation date (July 29, 2026), specific inclusion criterion, and its role as a representative unit of the patent family or inventive concept. Because the search was purposive and iterative, literal query strings and raw hit counts that were not reliably preserved were not reconstructed retrospectively.

2.3 Targeted narrative synthesis of the literature

The scientific search was organized into four semantic blocks: (a) technical, energy, and economic performance of retrofits from fluorescent or discharge lamps to LEDs; (b) occupancy control, daylight, dimming, Internet of Things (IoT), and automation; (c) visual comfort and human-centric lighting (HCL); and (d) reviews of intelligent systems, implementation barriers, and research gaps. Screening considered title, abstract, DOI, environment type, method, and the presence of quantitative results or conclusions directly applicable to the problem.

Peer-reviewed articles, field studies, simulations under real-world or realistic conditions, systematic reviews, and recognized technical documents were prioritized. A 'directly applicable result' was defined as evidence or a conclusion applicable to at least one dimension of the decision framework: photometric performance, power or energy reduction, occupancy or daylight control, user acceptance, integrative lighting, or implementation barriers. Duplicates were resolved by DOI or, when necessary, by title, authorship, and year; published versions were preferred over preprints. A Lawrence Berkeley National Laboratory

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technical report was retained as gray literature because it directly compares simple LED retrofit with integrated packages involving shading, daylight-responsive dimming, task lighting, and occupancy control. Exclusively residential studies outside the scope, medical or agricultural applications, promotional texts, and records without a verifiable directly applicable result were excluded. Supplementary Material S2 documents the final corpus of 13 publications, including thematic axis, evidence type, retention criterion, and verification source. Initial screening and exclusion counts were not reconstructed because they were not reliably preserved; accordingly, the evidence is presented as a targeted narrative synthesis rather than a systematic review.

2.4 Treatment of historical data

The undergraduate theses, preliminary manuscript, and spreadsheets were treated as historical documents. Prices, tariffs, products, and requirements used in the original studies were preserved and were not retrospectively updated. For the corridors, the primary source for the reanalysis was the consolidated spreadsheet from the 2014 campaign containing 1,730 illuminance readings from 13 environments identified as I1, I2, I3, I4, J2, J3, J4, I5, J1, H3, L2, L1, and L3. In the currently preserved documentary set, the unequivocal original filename could not be recovered; therefore, no retrospective filename is assigned without documentary support. The remaining corridor files were used only to cross-check structure and content when they represented partial versions or reproductions of the same environments and were not added as independent observations.

The fields used in the reanalysis were corridor identification and the individual illuminance readings in lux. Consistency of the total was verified by summing the number of observations per corridor (168 + 168 + 168 + 168 + 105 + 112 + 126 + 105 + 126 + 105 + 126 + 127 + 126 = 1,730). Historical files containing data for the same corridor were not concatenated; incomplete versions or copies were not treated as new campaigns. The available documentation does not preserve a contemporaneous record-by-record deduplication log, and no retrospective reconstruction is claimed beyond what can be audited from the remaining files. For each corridor, the number of points, mean, minimum, maximum, and standard deviation were calculated from the retained readings. Descriptive uniformity was expressed as U_0 = E_min/E_m solely as an exploratory indicator because normative interpretation requires identification of the reference surface, measurement procedure, uncertainty, maintenance condition, and measurement conditions. The 100 lx reference was retained exclusively to reproduce the historical criterion used in the files. No inferential tests were applied because the data represent a historical set of specific environments rather than a probabilistic sample. No categorical cutoff was adopted for U_0; values were interpreted continuously, and lower values were used only as an indication of greater spatial heterogeneity and to support prioritization for renewed inspection.

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In the industrial cases, the originally reported diagnosis, power, energy use, investment, and economic indicators were compared. The present analysis focused on consistency between energy use and the lighting service delivered. No new NPV was calculated because the appendices do not provide complete information on current prices, tariffs, operating hours, maintenance, and the minimum acceptable rate of return. Historical NPV and IRR values were transcribed but not revalidated.

2.5 Economic analysis and decision framework

For future updates, annual energy use should be calculated from total power and annual operating hours. Net annual savings should incorporate differences in energy use, tariffs, maintenance, replacements, and control-system costs. Simple payback is the incremental investment divided by net annual savings. NPV should consider a time horizon compatible with service life and sensitivity scenarios.

$$E = P \times h$$

$$\textit{Simple payback} = \textit{incremental investment} / \textit{net annual savings}$$

$$NPV = -I_0 + \Sigma\, CF_t/(1 + i)^t$$

Decisions should not be based solely on minimizing kWh. Five integrated criteria were adopted: photometric compliance and quality; energy relative to the lighting service delivered; life-cycle cost; user acceptance and ability to intervene; and interoperability, commissioning, and maintenance. In this article, the expression 'energy relative to the lighting service delivered' is used as an operational principle for multivariable comparison rather than as a single index or universally validated mathematical ratio. Its interpretation requires joint consideration of energy use and attributes of the delivered service, including illuminance, uniformity, glare control, color rendering, operating period, and conditions of use.

3. Results

3.1 Functional timeline in the patent corpus

The final corpus comprised 18 representative patent families or publications with priority dates between 1971 and 2022. The temporal distribution reflects only the composition of the selected set and should not be interpreted as worldwide patenting intensity. Within the selected corpus, documents with priority dates in the 1970s and 1980s include ambient-light-responsive controls and fluorescent ballast circuits. Among the documents with priority dates in the 1990s are solutions for automatic daylight harvesting and a representative white-LED document based on a nitride semiconductor and phosphor.

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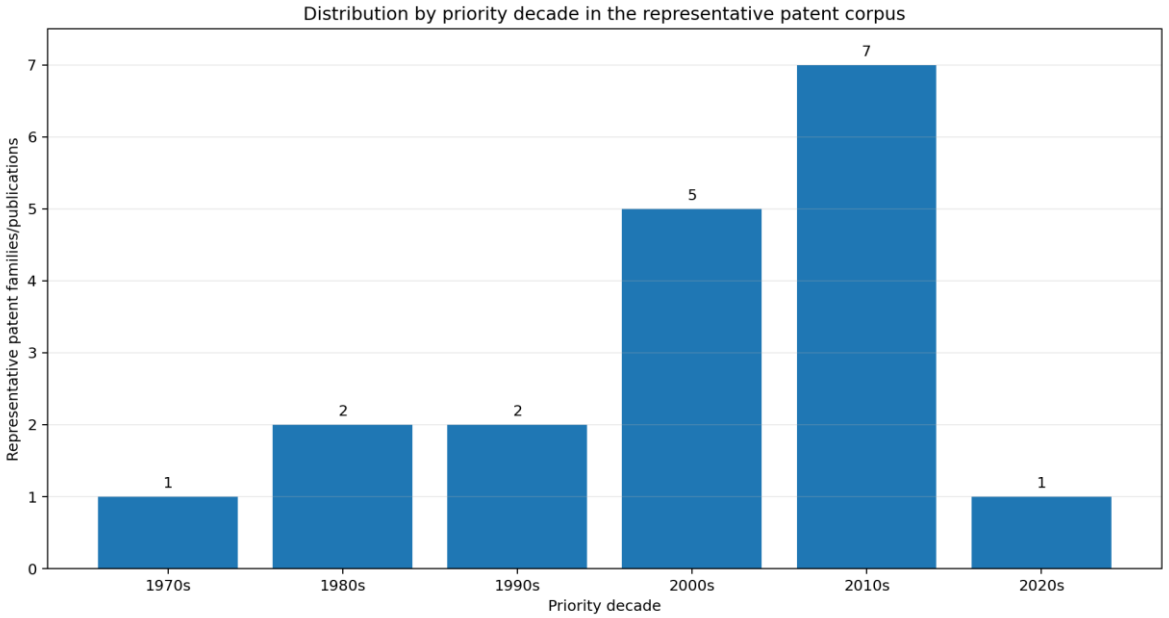
Figure 1 - Distribution by decade in the selected patent corpus



Source: prepared by the authors from the verified families.

Among selected documents with priority dates from the 2000s onward, there is a greater presence of solutions in which lighting is treated as a networked system: DALI, reduced standby consumption, addressable configuration, and occupancy detection shift the innovative function from the isolated component toward system coordination. Documents with priority dates in the following decade include spectral adjustability, tunable-white lighting, and control of quantities related to melanopic stimulus. More recent documents in the selected corpus combine distributed occupancy tracking, melanopic quantities, and HCL devices.

Table 2 - Representative documents in the patent corpus

Group	Year	Publication	Short title	Assignee	Status displayed by the consulted database*
G1	1971	US3735141A	Electronic lighting control responsive to ambient light	Sigma Instruments	Expired
G1	1985	US4689524A	Fluorescent lamp ballast	—	Expired
G1	1987	US4717863A	Frequency modulation ballast circuit	—	Expired
G4	1994	US5648656A	System to optimize artificial lighting levels with increasing daylight level	—	Expired
G2	1996	US5998925A	Light emitting device with nitride semiconductor and phosphor	Nichia	Granted
G3	2001	US6762570B1	Minimizing standby power in a DALI system	Microchip	Expired for non-payment of fees
G3	2001	WO2003017733A1	Multiple-master control system for DALI	Microchip	Lapsed
G4	2004	US7511613B2	Lighting control with occupancy detection	Philips/Signify	Expired

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Group	Year	Publication	Short title	Assignee	Status displayed by the consulted database*
G5	2005	US7893631B2	White luminaire with adjustable correlated color temperature	—	Granted
G4	2006	US9357620B2	Occupancy sensor dimmer and night light	—	Active
G5	2011	US8760074B2	Tunable white luminaire	—	Granted
G3	2015	US10575388B2	Mobile configuration of DALI lighting systems	—	Expired for non-payment of fees
G5	2016	US11369013B2	Two-channel tunable lighting with controllable melanopic output	—	Granted
G5	2017	US20170348506A1	Tunable circadian lighting at substantially constant perceived brightness	—	Published application
G5	2017	EP3626030B1	Maintaining melanopic illuminance at the eye	—	Active
G5	2017	US10850061B2	Circadian lighting control and enhanced performance	—	Granted
G4	2019	US10728987B1	Distributed occupancy-tracking lighting control	—	Active
G5	2022	US20240055565A1	LED human-centric lighting device	—	Published application

Source: prepared by the authors; status displayed by the databases consulted on July 29, 2026. *Descriptive metadata only; no opinion on validity or freedom to operate. The status displayed by the consulted database does not constitute a legal opinion on validity, enforceability, claim scope, or freedom to operate.

Table 2 should be read as a functional timeline: the presence of a document in a given decade does not represent filing volume, technological impact, or assignee dominance.

At the functional-group level, the selected documents illustrate progressively different technical problems and control variables. G1 addresses operation and regulation of conventional lighting sources and ballasts; G2 illustrates the transition toward solid-state white-light generation and optical conversion; G3 shifts the problem toward digital addressability, standby consumption, dimming, and network configuration; G4 links lighting operation to contextual information such as occupancy and available daylight; and G5 introduces spectral composition, correlated color temperature, and melanopic quantities as controllable design variables. This group-level interpretation is intended to identify the technical function represented by each document in the corpus rather than to perform legal claim construction.

Within the selected corpus, the selected documents illustrate a broadening of energy-saving strategies beyond source efficacy to include information and control, such as detecting occupancy, estimating available light, identifying position, adjusting spectral channels, and maintaining a target quantity at the work plane or the eye. This shift broadens the range of performance strategies but increases dependence on sensors, software, protocols, cybersecurity, commissioning, and maintenance.

3.2 Recent scientific evidence

Retrofit studies in educational buildings report substantial, although not universal, reductions in installed power and energy use. Ghisi et al. (2019) found in classrooms

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at the Federal University of Santa Catarina that 65% of the environments met the illuminance criterion during daytime and none did so at night; the proposed LED system reduced installed power by 45.5% and yielded a payback of 8.6 years. Pérez-Gosende (2019) proposed a phased replacement strategy on an Ecuadorian campus, validated in DIALux, with an estimated energy saving of 47.36%. These indicators are not directly comparable because one study reports installed-power reduction while the other reports energy savings under different prices, schedules, and contexts.

Replacing the light source alone does not complete the modernization process. Regnier et al. (2018) compared a fluorescent-to-LED retrofit with integrated packages combining shading, daylight-responsive dimming, task lighting, and occupancy control. In the tested scenarios, integration increased savings while preserving visual comfort. Conversely, Tan et al. (2018) showed that systems driven only by sensors may impose unsuitable lighting levels; incorporating human feedback and the possibility of user intervention is critical to acceptance.

The selected synthesis studies highlight recurring barriers: interoperability with legacy infrastructure, security and data management, and lack of continuous commissioning. Zocchi, Hosseini, and Triantafyllidis (2024) identified insufficient coordination between daylight and electric lighting and proposed integrating Building Information Modeling (BIM) and IoT throughout the design process. In a broader review of smart buildings, Poyyamozhi et al. (2024) identified initial cost, integration, and security as major obstacles.

The evidence base is more uncertain for integrative lighting. Through simulation, Papatsimpa and Linnartz (2020) showed that optimal profiles depend on chronotype, habits, and energy constraints. Hu and Davis (2021) found in offices that daylight made a greater circadian contribution than conventional downward electric lighting. Ngarambe, Kim, and Yun (2021) observed trade-offs among non-visual effects, comfort, and perceived performance. The Brazilian review by Moraes and Martau (2024) retained only seven studies and found no consensus on a single metric. Taghizadeh et al. (2025) showed that integrative targets met using electric lighting alone can substantially increase energy use, whereas daylight, spatial distribution, and spectrum can reduce the energy penalty.

Table 3 - Narrative synthesis of the selected scientific evidence

Study	Environment	Technology/topic	Applicable result	Limitation
Edirisinghe et al. (2016)	Commercial	LED versus fluorescent	Improved illuminance and user ratings	Specific products and site
Tan et al. (2018)	Office	Sensors + human feedback	Control preserves preferences and avoids underlighting	Testbed and user conflicts
Regnier et al. (2018)	Laboratory/office	Integrated retrofit	Controls increase savings beyond LED-only retrofit	Report and test conditions
Ghisi et al. (2019)	Classrooms	LED retrofit	Installed power −45.5%; payback 8.6 years	Single institution
Pérez-Gosende (2019)	Campus	Progressive implementation	Estimated energy saving of 47.36%	Simulation and local market

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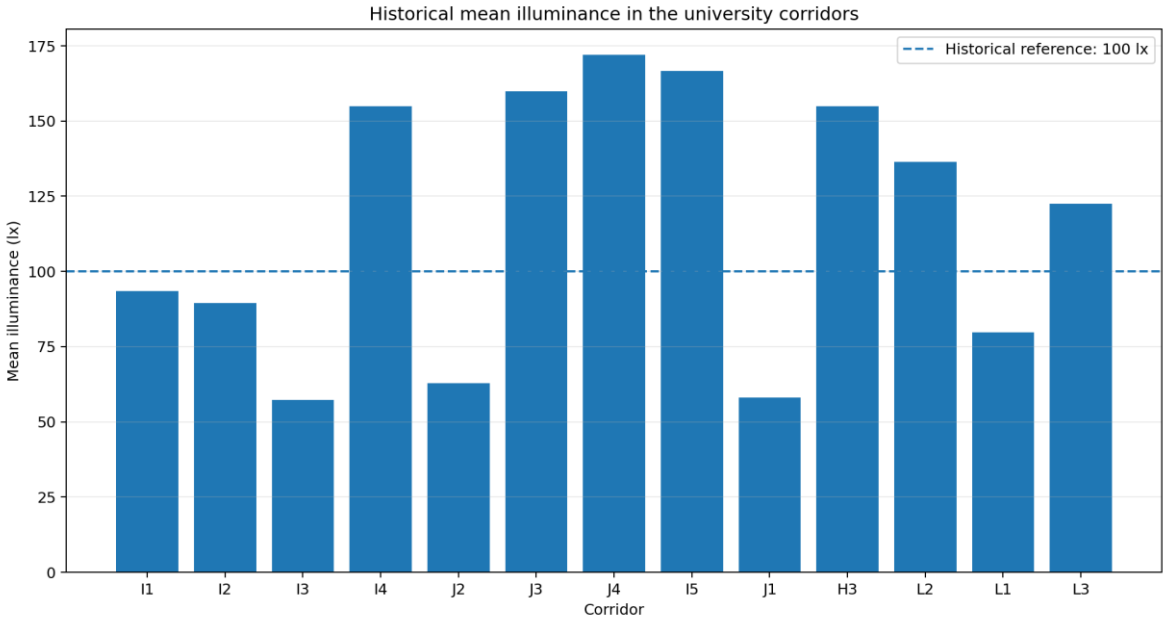
Study	Environment	Technology/topic	Applicable result	Limitation
Papatsimpa and Linnartz (2020)	Office	Bio-adaptive lighting	Profiles depend on the individual, habits, and energy constraints	Simulation
Hu and Davis (2021)	Offices	Visual and circadian light sources	Daylight provided the greatest circadian contribution	Specific conditions
Ngarambe et al. (2021)	Laboratory	spectral power distribution (SPD) of LED/OLED	Trade-offs among comfort, non-visual effects, and performance	26 participants
Zocchi et al. (2024)	Buildings	BIM + IoT + controls	Integration and commissioning remain gaps	Heterogeneity
Aliparast; Onaygil (2024)	Open-plan office	Individual HCL	Assesses 60 users and circadian metrics	Part 1 of the study
Poyyamozhi et al. (2024)	Review / smart buildings	IoT + energy management	Initial cost, integration, and security are barriers	Broad smart-building scope
Moraes and Martau (2024)	Review	Integrative metrics	No consensus; few studies	Seven studies retained
Taghizadeh et al. (2025)	Review	Energy impact of HCL	Daylight and spatial distribution reduce the energy penalty	Evidence base remains heterogeneous

Source: prepared by the authors.

3.3 Reanalysis of university corridors

The main dataset contains 1,730 readings distributed across 13 corridors. The weighted mean was 113.54 lx, a descriptive value that masks differences among environments. Seven corridors had mean illuminance equal to or above 100 lx, whereas six were below this reference. I3, J1, and J2 had means below 63 lx, while J4, I5, and J3 exceeded 159 lx. The distribution of observations by environment is shown in Table 4, allowing the total number of records used in the reanalysis to be audited.

Figure 2 - Historical mean illuminance in the corridors



Source: prepared by the authors based on the 2014 spreadsheets.

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Analysis of the minimum values revealed additional heterogeneity. U_0 varied widely among corridors, from 0.000 to 0.563, indicating different degrees of spatial heterogeneity. I3 had a minimum reading of zero; L3 had a minimum of 2 lx despite a mean of 122.60 lx; and J4 had a minimum of 20 lx despite a mean of 171.94 lx. J3 had the highest U_0 value (0.563). Because the ratio uses the lowest observed value, it is highly sensitive to localized minima and extreme observations. The zero reading recorded for I3 is retained as part of the historical dataset, but the available documentation does not allow its physical cause to be reconstructed—for example, whether it reflected a localized luminaire failure, obstruction, measurement condition, or recording issue. Accordingly, $U_0 = 0$ is treated as a screening flag for localized investigation rather than as evidence of a quantified uniformity failure or normative non-compliance.

Table 4 - Descriptive statistics of the historical measurements

Corridor	n	Mean (lx)	Min.	Max.	SD	U_0 (min./mean)	≥100 lx
I1	168	93.52	27	202	44.05	0.289	No
I2	168	89.48	8	223	45.59	0.089	No
I3	168	57.27	0	178	48.85	0.000	No
I4	168	155.00	53	278	62.42	0.342	Yes
J2	105	62.77	23	132	25.27	0.366	No
J3	112	159.86	90	295	48.23	0.563	Yes
J4	126	171.94	20	327	80.85	0.116	Yes
I5	105	166.67	47	285	55.16	0.282	Yes
J1	126	58.10	3	254	60.22	0.052	No
H3	105	154.99	34	235	48.10	0.219	Yes
L2	126	136.44	24	205	50.58	0.176	Yes
L1	127	79.71	13	188	48.28	0.163	No
L3	126	122.60	2	202	71.33	0.016	Yes

Source: prepared by the authors.

Measurements were performed at night using a stabilized Instrutherm LD-100 lux meter, with measurement points distributed on a grid. This choice reduces interference from daylight and is consistent with evaluating electric lighting, but it does not replace documentation of calibration, uncertainty, measurement-plane height, grid spacing, surface reflectances, maintenance condition, and environmental conditions. Thus, the values constitute a historical assessment and a baseline for a new measurement campaign rather than a contemporary compliance certification.

3.4 Reanalysis of the industrial studies

In the metalworking facility, measured illuminance was 51.7 lx, compared with the historical reference of 200 lx. In the 2014 scenario, the T5 fluorescent alternative required an investment of BRL 1,921.50, consumed 369.6 kWh/month, and had a 16-month payback; the LED system had the same installed power and monthly energy use, required an investment of BRL 9,765.00, and had an 81-month payback. The recommendation in favor of fluorescent lamps reflected the relative price of LEDs in that market at the time. IRR and NPV values are retained solely as historical results

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reported in the original studies. These indicators were neither recalculated nor revalidated in this article and therefore are not used for contemporary economic inference.

In the furniture manufacturing facility, all evaluated areas were underlit according to the historical references: restrooms measured 43 and 53 lx against 200 lx; the kitchen 63 lx against 200 lx; the office 71 lx against 500 lx; and general industrial lighting 31 lx against 300 lx. The proposed system increased installed power from 1,164.2 W to 5,464.66 W because it delivered a higher level of lighting service. The original study reported an increase in its historical indicator from 372 to 1,105.3 lm/BRL; this value is retained as a historical record and is not treated as a current life-cycle cost metric.

Table 5 - Historical economic indicators transcribed from the original studies and not revalidated in this article

Case	Diagnosis	Alternative	Power/energy use	Historical investment	Original indicators (not revalidated)
Metalworking facility	51.7 lx; historical ref. 200 lx	T5 fluorescent	1,680 W; 369.6 kWh/month	BRL 1,921.50	Payback 16 months; IRR 6.23%/month; reported NPV BRL 8,426.00*
Metalworking facility	Same diagnosis	LED tube	1,680 W; 369.6 kWh/month	BRL 9,765.00	Payback 81 months; IRR 1.04%/month; reported NPV BRL 21,777.87*
Furniture manufacturing facility	All areas below the reference	Task-based design	5,464.66 W; 961.78 kWh/month	BRL 9,783.18	1,105.3 lm/BRL versus 372 lm/BRL (historical indicator)

Source: Antunes (2013) and Moura (2013). *NPV and IRR are historical transcriptions from the original studies; the underlying calculation records and conventions were not revalidated in this article.

Table 5 is retained as documentary context for the 2013-2014 decisions; present-day feasibility is not inferred from these historical indicators.

The cases demonstrate the need to evaluate efficiency relative to the lighting service delivered. Comparing only the energy bill of the existing system with that of a compliant design may penalize the technically appropriate solution, because the existing system may consume less precisely because it does not provide sufficient illuminance. An appropriate baseline is an alternative capable of meeting the same tasks, quality requirements, and operating period.

3.5 Integrated synthesis of contemporary evidence and historical cases

Integrating the three evidence streams reveals a consistent modernization hierarchy. The historical datasets identify basic service deficiencies—underlighting, localized minima, legacy sources, and incomplete operational records—while the contemporary literature indicates where LED retrofits, controls, daylight harvesting, interoperable digital systems, and integrative-lighting approaches can add value. Table 7 summarizes this cross-evidence synthesis and links each contemporary technology to a need documented in the historical cases and to the corresponding recommended application.

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Table 7 - Matrix linking technology, evidence, and case-study needs

Technology	Recent evidence	Need observed in the historical files	Recommended application
Ballast/LED	Efficacy and service life	Aged systems, failures, and low illuminance	Retrofit with photometric equivalence
Sensors/occupancy	Additional but variable savings	Corridors with unoccupied periods	Vacancy-based zoning with time delay
Daylight harvesting	Reduces electric lighting when daylight is available	Historical nighttime measurements do not assess daytime potential	New daytime and nighttime campaign
DALI/IoT	Configuration, monitoring, and maintenance	Fragmented spreadsheets and no operational history	Open system with a documented data protocol
Tunable lighting/HCL	Spectral and temporal tuning	No melanopic metrics in the historical files	Pilot project with CIE S 026 and user evaluation

Source: prepared by the authors.

4. Discussion

4.1 From the isolated source to the information-driven system

The patent corpus and selected literature indicate a shift in the unit of analysis and design. In the conventional model, the primary object was the lamp, ballast, or luminaire. In the connected model, performance depends on the interaction among the light source, optics, driver, sensors, protocol, algorithm, occupancy, daylight, and human interface. Luminous efficacy in lm/W therefore remains necessary but is no longer sufficient.

This shift helps explain why component-by-component retrofit strategies can reach a limit. An efficient LED luminaire that remains continuously on ignores vacancy, diurnal variation, and differences among tasks. Conversely, adding sensors without zoning, calibration, or user override may reduce satisfaction and encourage informal disabling of the system. The relevant innovation is not the accumulation of features but their coordination with low operational complexity.

4.2 Energy relative to lighting service and the baseline problem

The historical cases reveal a common flaw in efficiency studies: using an inadequate environment as the reference baseline. The furniture facility consumed little energy because it provided illuminance far below the required level. Modernization increased absolute installed power but reduced the relative cost of the luminous flux produced and enabled task-appropriate lighting. In this context, interpreting the increase in energy use as inefficiency would be incorrect.

The recommended comparison should preserve, as far as possible, equivalence in area, operating hours, illuminance, uniformity, glare control, color rendering, and service life. When such equivalence cannot be ensured, absolute energy use should be reported together with an explicit description of the quality and conditions of the lighting service. Thus, 'energy relative to lighting service' functions in this study as an integrated decision principle rather than as a single index capable of collapsing all these dimensions into a universal ratio. This approach is also relevant to public policy because it avoids rewarding underlit buildings.

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The historical cases also establish a hierarchy of modernization needs. Advanced controls, IoT integration, tunable-white systems, and melanopic targets should not be treated as substitutes for basic photometric adequacy. In environments characterized by underlighting, localized minima, maintenance deficiencies, or uncertain baselines, the first priority is to restore an adequate, measurable, and maintainable lighting service. Connected and integrative technologies become technically meaningful only after photometric compliance, maintenance, and a reliable baseline have been established; they should therefore be viewed as subsequent layers of modernization rather than as corrective measures for fundamental lighting deficiencies.

4.3 Controls, commissioning, and user participation

The savings attributable to controls vary widely because they depend on occupancy, daylight availability, zoning granularity, and commissioning quality. Private offices, corridors, and restrooms may benefit from vacancy-based switch-off. Classrooms and shared spaces require time delays, scenes, and user override capable of accommodating different activities.

Human-in-the-loop literature adds an important principle: the user should not be treated merely as a disturbance. Feedback, local control, and information about system operation can help prevent rejection. In connected systems, the commissioning plan should include sensor-coverage testing, dimming limits, response time, standby consumption, communication failures, data governance, and post-occupancy verification.

Beyond initial performance, connected systems should be evaluated for long-term maintainability. The physical life of a luminaire may exceed the availability of an associated platform, gateway, application, or digital service. Specifications should therefore consider technical documentation, protocol openness and continuity, component replaceability, the possibility of local maintenance, and the risk of dependence on proprietary ecosystems, thereby reducing vulnerability to technological obsolescence.

4.4 Integrative lighting: potential without excessive claims

Integrative lighting seeks to account for both visual and non-visual responses, but current evidence does not support generic claims of health or productivity benefits. The CIE recommends the CIE S 026 metrology system to characterize stimuli related to intrinsically photosensitive retinal ganglion cells. However, observer position, time of day, exposure duration and history, age, spectrum, daylight, and behavior all modulate the response.

Taghizadeh et al. (2025) warn that meeting non-visual targets using electric lighting alone can substantially increase energy use. Integrative-lighting design should therefore begin with architecture, daylight, light distribution, and surface reflectances rather than simply increasing illuminance or color temperature. Spectral control should be accompanied by power limits, vertical measurements at the eye when relevant, and comfort assessment.

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4.5 Standards update and implications for the historical data

The original studies used ABNT NBR ISO/CIE 8995-1:2013. Internationally, ISO/CIE 8995-1:2025 replaced ISO 8995-1:2002 and specifies quantitative and qualitative lighting requirements for indoor workplaces, considering daylight, electric light, or their combination. This international publication should not automatically be equated with national adoption. In Brazil, occupational assessment should comply with NR-17 and Fundacentro NHO 11, which establish requirements and procedures for illuminance in indoor workplaces. For integrative applications, the CIE recommends characterizing stimuli using the CIE S 026:2018 metrology system.

This does not invalidate the 2014 measurements, but it changes how they should be used. They should not be mechanically compared with current standard values without reassessing the task, area, method, maintenance condition, and applicable standard. Because the historical corridor campaign was conducted at night, the results essentially characterize the contribution of electric lighting under the measured conditions rather than the overall luminous performance of the spaces throughout the day, when daylight can alter both lighting levels and the energy-saving potential of controls.

A new audit should, at minimum, identify visual tasks and reference surfaces; document maintenance conditions; measure electric lighting and, when appropriate, conduct both daytime and nighttime campaigns; record installed power and occupancy profiles; characterize daylight availability and control parameters; and incorporate user assessment when warranted by the use of the environment. Such a protocol would allow the historical baseline to be converted into a contemporary, comparable, decision-oriented measurement campaign.

4.6 Modernization pathway and innovation opportunities

Table 6 - Proposed pathway for lighting-system modernization

Stage	Main actions	Expected outcome
1. Diagnosis	Inventory, faults, reflectances, tasks and surfaces, measurement grid, illuminance, uniformity, glare, power, schedules, occupancy, and daylight availability.	Reliable dataset; urgent maintenance.
2. Photometric compliance	Define tasks and reference surfaces; simulate and measure equivalent solutions.	Fair comparison of alternatives.
3. Source and luminaire	LED with appropriate photometry, driver, color rendering index (CRI), correlated color temperature (CCT), flicker performance, service life, and protection.	Reduced power and maintenance.
4. Zoning and control	Occupancy, vacancy, daylight harvesting, scenes, and user override.	Additional savings without loss of comfort.
5. Commissioning and data	Calibration, testing, monitoring, security, interoperability, documentation, protocol openness, component replaceability, and verification.	Persistent savings, long-term maintainability, and lower risk of technological lock-in.
6. Integrative lighting	CIE S 026, daylight, vertical/spectral metrics, and an energy limit.	Applied research without unsupported benefit claims.

Source: prepared by the authors.

Innovation opportunities are concentrated in four areas. The first is data-driven retrofitting, supported by asset inventory and automated fault verification. The second is interoperable control with low standby consumption, suitable for existing buildings.

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The third is the fusion of occupancy and daylight sensing with explainability and user override. The fourth is energy-constrained integrative lighting, capable of adjusting distribution and spectrum without pursuing biological targets through indiscriminate increases in power.

5. Conclusion

Within the selected corpus, the functional trajectory of lighting is illustrated by five broad functional shifts: improvements in sources and ballasts; consolidation of white LEDs; digitalization through drivers and DALI; occupancy and daylight control; and spectral or melanopic adjustment. The literature shows that, in current systems, commissioning, data, interoperability, and human interaction are performance components rather than accessories.

The corridor reanalysis showed that the mean alone is insufficient: seven of the 13 corridors exceeded the historical 100 lx reference, while continuous U_0 values ranged from 0.000 to 0.563, revealing spatial heterogeneity and localized minima that justify renewed inspection. The industrial cases showed that energy use must be compared under equivalent service conditions; an underlit system may have a lower energy bill without being technically efficient or adequate.

The selected campus studies reported a 45.5% reduction in installed power and an estimated 47.36% energy saving with LEDs, but these indicators are not directly transferable across projects. Controls can increase savings when designed by zone, with user intervention and verification. Integrative lighting should be introduced cautiously and supported by CIE S 026, daylight, appropriate metrics, and energy constraints. In connected systems, decisions should also consider protocol openness, component replaceability, and technological obsolescence so that system life is not limited by the availability of proprietary platforms.

In response to the research question, integrating the evidence changes how retrofit options should be evaluated: decisions should compare alternatives that deliver equivalent lighting service. The recommended sequence is to measure and maintain; ensure compliance and uniformity; select LED luminaires based on photometry and quality; implement controls with commissioning; and only then evaluate connected or integrative features. The main outcome is a decision framework applicable to historical systems rather than a universal estimate of savings or patenting trends.

5.1 Limitations

The patent corpus is purposive and non-exhaustive. Databases use different definitions of patent family, legal coverage, and indexing; the displayed status corresponds to the consultation date and does not constitute a legal opinion. Citations, jurisdictions represented within the patent families, normalized assignees, independent claims, and all members of each family were not collected uniformly.

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Therefore, the analysis describes technological functions in selected documents and does not measure leadership, innovation intensity, or freedom to operate.

The scientific search used ranked semantic retrieval and did not include an exhaustive protocol in Scopus, Web of Science, or other databases. No PRISMA flow diagram or formal risk-of-bias assessment was performed for individual studies. The selection was documented in the evidence database and references were verified through DOI records or official pages, but the conclusions should be understood as a targeted narrative synthesis.

The historical datasets were produced approximately twelve years before this analysis and contain incomplete documentary elements, including measurement metadata, raw files, operating schedules, and economic calculation records. They are therefore used for retrospective technical interpretation and prioritization of new audits, not for current compliance certification, budgeting, or definitive financial reassessment.

The integrative-lighting literature includes simulations, small samples, and heterogeneous metrics. Health, sleep, or productivity benefits should not be inferred for the environments studied without a specific protocol, ethical review when participants are involved, and control of confounding factors.

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