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Evaluation of integrated daylighting and electric lighting design projects: Lessons learned from international case studies

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ABSTRACT

This article presents and discusses the lessons learned from the monitoring of 25 integrated daylighting and electric lighting international case study projects. The case studies consist of real occupied buildings that have been monitored as part of the International Energy Agency (IEA) SHC Task 61/EBC Annex 77 Programme. The general goal of the case studies was to balance lighting energy use with occupants' visual and non-visual requirements. This was achieved using innovative solutions for daylighting and electric lighting with advanced controls, but also implementing simple and out-of-the-box strategies. The findings suggest that energy demands for lighting can significantly be reduced by combining sensible daylight provision, efficient lighting sources, and advances in controls. Yet, the effective achievement of project goals requires adequate monitoring, fine-tuning, and verification. The findings also suggest that the adoption of "integrative" lighting – that is, lighting systems that address both visual and non-visual responses – is getting increasingly popular. Catering to non-visual requirements will likely drive further innovation in lighting technology. Currently, there is limited investment available for developing daylighting systems for integrative lighting, and the current related electric strategies often come at the risk of energy rebound effects. Overall, providing daylighting and understanding user requirements are fundamental steps towards achieving quality projects, with potential benefits beyond saving energy.

1. Introduction

Buildings are responsible nowadays for 28% of global energy-related CO_2 emissions, and most of these emissions can be attributed to cooling and heating, lighting, and appliance end uses [1]. Lighting in buildings required 430 Mtoe in 2017, which represents 14% of total building energy use (3000 Mtoe in 2017). Even with improvements in lighting energy efficiency over recent years – for example, due to the deployment of light emitting diodes (LED) – global energy use for lighting has increased by an average of 2.2% per year since the year 2000. This is due to the increase in demand, rise in purchasing power of emerging economies, and increased floor area associated with population growth [1].

Within the building sector, lighting technology has recently witnessed significant advancement, with new policies and recommendations having been introduced towards climate mitigation and decarbonization targets. Conversely, much improvement is still needed in other domains of the building industry, as for example in the design and operation of envelopes [1]. The design of the envelope, in fact, can have a significant impact on the thermal

Abbreviations: CIE, International Commission of Illumination; DLC, Daylight-Linked Control; EBC, Energy in Buildings and Communities programme; EC, Electrochromic; EFTE, Ethylene tetrafluoroethylene; HDR, High Dynamic Range; IEA, International Energy Agency; LCS, Lighting Control System; LENI, Lighting Energy Numerical Indicator; M&V, Monitoring and Verification; POE, Post-Occupancy Evaluation; PMMA, Poly methyl methacrylate, also known as plexiglass; SHC, Solar Heating Cooling programme; UI, User Interface; Tv,n-h, Visible light transmittance, i.e., hemispherical (h) transmittance at normal (n) incidence.

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behavior of a building, and improving its performance could increase energy saving by 40%. However, thermally efficient envelopes need to also account for occupants' needs for views and access to daylight [2], which are crucial for physiological and psychological well-being. Hence, careful consideration is needed for integrating daylighting with electric lighting towards more energy efficient solutions, while also fostering the health and well-being of users [3].

To achieve this integration, an adequate compromise needs to be found between the contrasting needs of sunlight admission and protection, complementing daylight with adjustable levels of electric lighting while responding to the occupants' specific *visual* and *non-visual* needs, behaviors, and patterns of use. According to the CIE (International Commission of Illumination), non-visual (also called non-image forming, or NIF) effects of light encompass biological responses "*that powerfully regulate human health, performance and well-being*" [4]. Visual and non-visual stimuli can strongly influence the behavior of occupants and their interactions with environmental controls (e.g., blinds, electric lights, etc.), hence impacting potential energy savings. Buildings' energy performance can be improved with active controls and responsive facades [5]. On the other hand, digitalization and connected devices and sensors can entail a higher risk of increasing energy demands, if poorly designed, installed and operated [1].

Due to these multifactorial trade-offs, little is known about the actual performance of integrated solutions for daylighting and electric lighting in real buildings that encompass at once energy efficiency and visual and non-visual effects of lighting. In fact, although several case studies have shown to be effective and persuasive in bringing knowledge into action, the scientific literature has focused little on them. One reason may be a tendency to withhold results when the outcomes of a study did not meet expectations. This prevents designers, building managers, and the scientific community from learning from positive and negative experiences [6]. Another practical reason is that monitoring and evaluation of real-world case studies is often time consuming, costly and challenging due, for example, to the simultaneous presence of occupants [7]. This is a common concern for post-occupancy evaluations (POEs) in general, and POEs for lighting design in particular. In the scientific literature, lighting case studies have mostly focused on glare in office buildings [8,9], daylighting design [10,11], daylight and lighting integration [12], lighting controls and energy [13–16], and lighting retrofits [17], but seldom have reported on all aspects of lighting design including energy efficiency, occupants' health and well-being [18], and installation and running costs.

Previous international efforts for the integrated evaluation of daylighting and electric lighting solutions have included, among others: the "Daylight Europe" programme (1994–1997), which monitored 60 case studies of daylighting design in European buildings [19]; the International Energy Agency Solar Heating and Cooling (IEA SHC) Programme Task 21 "Daylighting in buildings", which evaluated innovative technologies for daylighting with performance monitoring in case studies [20]; and the IEA SHC Task 51, which monitored advanced lighting solutions for 24 retrofitted commercial buildings [17,21].

This article presents a comprehensive analysis of 25 integrated daylighting and electric lighting international case studies as part of the IEA SHC (Solar Heating and Cooling) Task 61/EBC (Energy in Buildings and Communities) Annex 77. The objective of this work was to gather a deeper understanding of how buildings can achieve energy-efficiency and human factor goals: i.e., what design strategies, façade and lighting technologies, controls, commissioning practices, end user education, operational practices, etc. are being used worldwide today and how do such strategies and practices perform in real buildings.

The case studies focus on non-residential buildings featuring a wide range of state-of-the-art and innovative daylighting and lighting strategies. Reduction of energy demand for lighting was usually a driver for the design, but many projects placed equal emphasis on improving overall lighting quality. A subset of projects (10 out of 25) was designed explicitly to satisfy non-visual requirements using spectrally tunable, dimmable LED lighting (i.e., "integrative" lighting), which represents a relatively new approach to lighting design. To the extent possible, all case studies were evaluated using a common, purposely-defined, evaluation framework. Data included lighting energy use, visual and non-visual requirements, and user perspectives. Section 2 of this article describes how the case studies were selected and evaluated. Section 3 presents the lessons learned from the case studies, highlighting opportunities from the integration of daylight and electric lighting in practice, while warning about potential pitfalls. Key insights and knowledge gained are provided at the end of each subsection. Section 4 discusses opportunities for daylighting and lighting integration that are yet to be exploited, and provides a perspective on the future advancements of daylighting and lighting integration.

2. Methods

2.1. Selection of the case studies

The selection of the cases to be monitored in this study was based on the following criteria: 1) daylighting and lighting are integrated in some form; 2) building or space(s) serve commercial functions; 3) building or space(s) are operational and occupied; and, 4) building or space(s) are accessible for data collection during the monitoring campaign (2019 to 2021). The fourth criterion could not be met in all the selected case studies due to the periods of lockdown that were imposed as a response to the Covid-19 pandemic. For this reason, in some cases, alternative solutions had to be found (see Appendix, Table A4). Ultimately, twenty-five (25) buildings were selected, spanning a wide range of latitudes and climates (Fig. 1). Among the cases chosen (see Appendix, Table A1), the majority were represented by office spaces (20), while the remaining featured healthcare facilities (2), an elderly residence (1), a retail building (1), and a sports arena (1).

The buildings included a variety of integrated solutions (Table A1). Considering that most of the cases studied were newly built or recently retrofitted, several of the solutions included innovative technologies, such as spectrally-tunable LED lighting, automated shades or blinds, advanced controls and their integration with building management systems (BMS), integrative lighting, and the like. Control solutions were implemented using a wide variety of methods: integrative, integrated, or both (Table A2). Case studies with more conventional solutions were also included. Most projects were designed to achieve specific goals (Table A3) with tailored solutions aimed at reaching the targeted objectives. Some cases had additional goals beyond improved energy efficiency and lighting quality, depending on their specific function (e.g., improving sleep quality in a rehabilitation facility). Clearly, local climate characteristics also affected the definition of objectives and of the solutions adopted, as was the case of cooling-dominated countries where the ingress of daylight had to be weighed against the risk of introducing unwanted solar gains. However, the monitoring focused on the lighting performance only. Summary details on each case study are provided in the form of freely available factsheets on the IEA SHC Task 61/EBC Annex 77 website [22], were climatic information of the site are also available. Details are also included in a project report [23]. Supplementary reference sources for the case studies are given in Table A1.

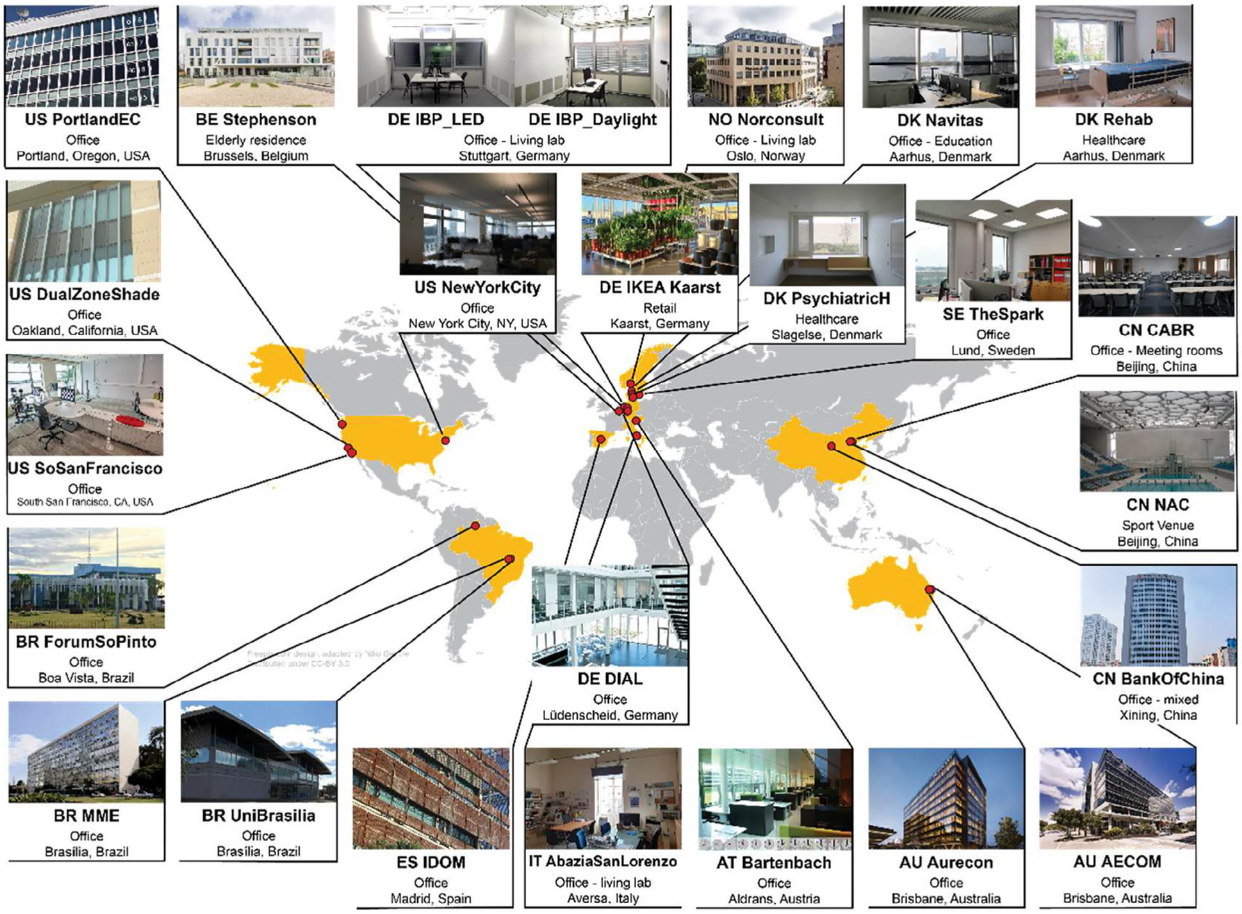

Fig. 1. Geographical distribution of the case studies.

2.2. Monitoring process

The monitoring of the case studies focused specifically on four aspects: 1) energy demand for lighting; 2) visual needs; 3) non-visual requirements; and, 4) user response and behavior (Fig. 2). The monitoring process was based on a framework developed within the IEA Task 61/Annex 77 [24], itself largely informed by previous monitoring experiences and protocols [7,17]. The monitoring was customized to the characteristics of each building studied. Therefore, the research teams, supported by building managers or supervisors, had to first identify the key aspects of each project (e.g., initial objectives, as presented in Table A3), before selecting appropriate monitoring protocols and tools.

The monitoring primarily included field measurements, complemented, when necessary, by calculations and computer-based performance simulations. This was particularly the case when spaces could not be accessed during the periods of lockdown, or when specific metering for electric lighting alone was not available. Table A4 provides an overview of the data that were collected for each case study.

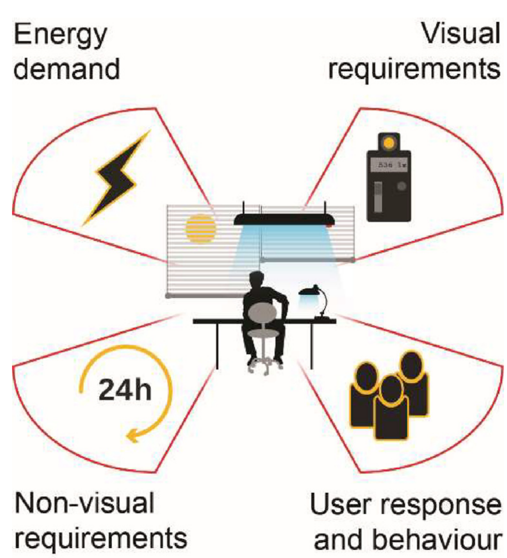

Fig. 2. The four foci of the case studies monitoring.

3. Lessons learned

3.1. Energy use

Technologically speaking, and without consideration of integrative lighting control, use of efficient LED sources, granular lighting controls, advanced shading and daylighting control, and informed commissioning and operations were shown to result in significant reductions of lighting energy use compared to state-of-the-art practice. Annual energy use was, at least, three times lower compared to current benchmarks (e.g., [25,26]) when innovative technologies were used. This corresponds to approximately 5–6 kWh/m^2-y for most of the office case studies (Table 1). Switching to efficient light sources corresponded to 41–59% of the total savings (the

Table 1
Lighting energy use in various case studies. Missing measurements were complemented, where possible, by qualitative evaluations of energy use.

Case study ID	Energy Use for Lighting (kWh/m^2y, unless specified)	Description of energy use/Further details on how the energy use/lighting power requirements were obtained
AT Bartenbach	3.65	Measured annual lighting energy use
BE Stephenson	5.8/3.8	Bedroom before/after improvement (simulated value; for typical days)
	7.7/7.8	Dining room before/after improvement (simulated value; for typical days)
BR MME	17.23	Calculated LENI
BR ForumSoPinto	16.80	Average calculated LENI
	(13.70/20.10)	(min/max) calculated LENI
BR UniBrasilia	109.00	Simulated annual lighting energy use
CN CABR	6.15	Measured LENI
CN NAC	174 W/m^2	LPD – Standard LPD for similar type of space is 290 W/m^2
CN BankChina	8.10	Measured annual lighting energy use
DK PsychiatricH	8.20/13.10/5.40	Standard (Danish standard)/Existing (calculated)/proposed change (calculated)
DK Rehab	13.70/15.20/6.90	Standard (Danish standard)/Existing (calculated)/proposed change (calculated)
DE IBP_LED	5.75 W/m^2	LPD at 100 lx for both lighting and LED structure
DE IBP_Daylight	< 1	Daily energy use for the entire office, in both clear and overcast sky conditions (estimated < 7 kWh/m^2y)
DE IKEAKaarst	40.30/41.30	"living room" with DHS/without DHS
	84.00/84.70	"home decoration" with DHS/without DHS.
IT AbaziaSanLorenzo	178.8 – 30.4 W	Measured power at different dimming settings. Electric lighting is almost never used after daylighting design
NO Norconsult	6.00	Measured LENI
ES IDOM	4.90	Simulated annual lighting energy used based on existing system and realistic occupancy schedules
SE TheSpark	22.43	LENI calculated based on real measured output of luminaires.
US PortlandEC	5.96	Measured annual lighting energy use
US DualZoneShade	20%	Measured energy saving for lighting and cooling of the automatic grey-grey shade vs reference roller shade (fluorescent DHS lighting)
US NewYorkCity	9.79	Measured lighting energy use. Reference value: 45.83 kWh/m^2y (reference case), 12.2 m deep perimeter zone
US SoSanFrancisco	1.40 W/m^2	Measured average daytime LPD of commissioned daylighting controls (DHS system). Reference (no dimming): 5.49 W/m^2.

remainder were due to lighting controls) for the US NewYorkCity case, which was in line with the expected savings from existing office buildings retrofitted using efficient LEDs [27,28].

When integrative LED lighting control was implemented with spectrally-tunable LED sources, without including the contributions from daylight, annual lighting energy use was significantly greater than benchmarks. As an example, the SE TheSpark annual energy use was 22.43 kWh/m^2-y compared to the 14.80 kWh/m^2-y benchmark[1] provided in Table M.1 of EN15193-2:2017 [25].

When integrative lighting control included both LED and daylight contributions, annual lighting energy use was significantly lower than benchmark levels, particularly for cases when daylighting and shading strategies were well conceived and implemented conscientiously. With the AT Bartenbach case study, owing to an integrated design planned from the early design stage and followed-up during the operational phase, different daylight strategies were implemented to provide natural illumination to the whole space. The design strategies included daylighting with windows, external static daylight redirecting louvres on the south façade, and sloped linear skylights on the north façade, in combination with fine-tuned integrative lighting controls that included daylight. With such strategies in place, the resulting monitored lighting energy use was very low: 3.65 kWh/m^2-y. In the CN CABR project, monitoring of eight spaces, including offices and meeting rooms, resulted in an average lighting energy use of 6.15 kWh/m^2-y with monitored lighting power densities per space type that were considerably lower (between 11% and 39%) than benchmark levels[2]. This figure can be attributed to a combination of efficient LEDs, a good daylight design featuring sidelight windows and tubular daylighting systems, and their controls.

When less efficient sources were used in existing buildings, such as the T5 lighting at BR ForumSoPinto or LED T8 replacements at BR MME, monitored lighting energy use was comparable to benchmark levels, indicating minimal energy savings, if any.

The SE DE IKEAKaarst case study was an atypical project, where daylighting integration in a furniture store almost halved the annual lighting energy use in one of the monitored departments: 41.4 kWh/m^2-y calculated on real usage patterns [29] compared to 78.1 kWh/m^2-y as per the EN15193-2:2017 benchmark [25]. This was achieved despite operational issues with the control system. In addition to energy benefits, this case study also showed the potential of integrated daylighting in enhancing the customers' shopping experience.

3.1.1. Key lessons learned

- Energy demand for lighting has been drastically reduced through a combination of daylight provision, more efficient light sources, and advances in control technology. With wide adoption of current dimmable LED systems, it is now possible to achieve annual lighting energy use as low as 3–4 kWh/m^2-y in office spaces.

[1] For those unfamiliar with this EU standard, the M.1 benchmarks are defined by a standard set of conditions. In this case: personal office (single office); standard, direct electric lighting system with installed power density of 16.43 W/m^2; 2250 daytime annual operating hours, manual illumination control; occupancy dependency factor = 0.8; daylight dependency factor = 0.49 (dependent on window orientation, degree of solar/ glare protection needed).

[2] The CABR team made a qualitative (non-metered) assessment of daylight levels and determined that they were adequate to meet integrative lighting requirements.

- If not properly designed and coordinated with daylighting, integrative lighting strategies may lead to significantly increased electric lighting energy demands (rebound effects), particularly due to high vertical illuminance requirements during the daytime.

3.2. Lighting controls

Lighting controls are crucial for achieving objectives of energy efficiency, and of visual and non-visual performance. The literature suggests that 30–60% of energy savings are attainable with lighting controls [28], and arguably similar figures were achieved in the case studies analysed. Even with significant improvements in source efficacy, daylight-linked controls (DLC) still contributed toward significant reductions in energy use, particularly in conjunction with integrative lighting as discussed in Section 3.1.

For non-integrative controls, DLC accounted for 9% of lighting energy savings (compared to no daylight-based dimming strategies) at the BR MME, despite dimming being limited to luminaires closest to the windows and applied to lighting sources already characterized by high luminous efficiency (103 lm/W). Coupled with re-lamping from efficient T5 to very efficient LEDs, this strategy helped reduce lighting energy use by 25% in the AU Aurecon. Solutions included grouped control of fixtures associated with a daylit zone or highly granular control per individual luminaires for more advanced systems, especially in large and deep spaces, such as open-plan offices [30–33]. An open-loop DLC with four daylit control zones, for example, reduced lighting energy use to a minimum of 4.90 kWh/m^2-y for a 15 m deep sidelit office in Madrid (ES IDOM) [34]. Daylighting controls are effective even in spaces different from offices. DLCs were estimated to reduce annual lighting energy use by 59% and 54% compared to the existing systems for the DK PsychiatricH and DK Rehab case studies, respectively.

Commissioning is key to achieving performance goals and user satisfaction with lighting and shading controls. This is particularly important for DLC systems due to the dynamic nature of the source (i.e., variable solar position and changeable cloud cover). The analyzed case studies used closed- and open-loop DLC [31,33], with some systems adopting innovative algorithms to achieve reliable control. In the US SoSanFrancisco study, monitored data in a full-scale testbed showed that the open-loop DLC system maintained the target illuminance level for 70% of the operating time (Fig. 3). Self-commissioning routines determined source contributions at each photosensor, decreasing occurrences of over-dimming. In contrast, the closed-loop DLC system maintained target levels for only 56% of the time. Separately, the control of the automated shading system was finetuned to balance daylight, glare, and view requirements. A 30-day burn-in period was reserved to commission all controls at the completion of the 24,000 m^2 office building, during which the open-loop DLC and shading systems were re-evaluated and fine-tuned, particularly in atypical areas such as open plan zones with sidelit windows on three facades. The resulting DLC reduced daytime lighting power density (LPD) by 74% (5.52–1.40 W/m^2) in zones with a depth between 6.1 m and 9.1 m, coherent with the testbed outcomes [31,33].

The DLCs did not always perform as desired. In the NO Norconsult, sunlight reflected from nearby venetian blinds onto the photosensor caused over-dimming, resulting in the system delivering 230 lx on the work plane instead of the target 500 lx. Similar issues have also been highlighted in the literature [35,36]. In the atypical retail case (DE IKEAKaarst), the ceiling mounted photosensor was taped over by the employees due to unreliable control caused by changes in surface reflectances within view of the photosensor (Fig. 4). The merchandise was changed and rearranged frequently while movement from a nearby sliding curtain caused annoying fluctuations in light output. It was observed at the DK PsychiatricH that abrupt stepped switching (due to changes in setpoint from day-mode to night-mode) or non-gradual dimming led to occupant annoyance, whereas gradual dimming up and down in the DE DIAL case study was appreciated by users. Whether the scope was to fine-tune the lighting control system, as it was the case with AT Bartenbach and US SoSanFrancisco, or to discover and fix issues, as with DE IKEAKaarst and NO Norconsult, monitoring and verification (M&V) was demonstrated to be of utmost importance to achieve target performance goals. This is discussed further in Section 3.7.

In some occasions, the literature has warned of increased energy use due to LCS standby power, especially in cases with good daylight design, very efficient light sources, and low occupancy rate [37,38]. For example, standby power due to the wireless communications connection accounted for 11 W (24.7% of full power) out of the total 30–178 W for LED lighting (depending on the

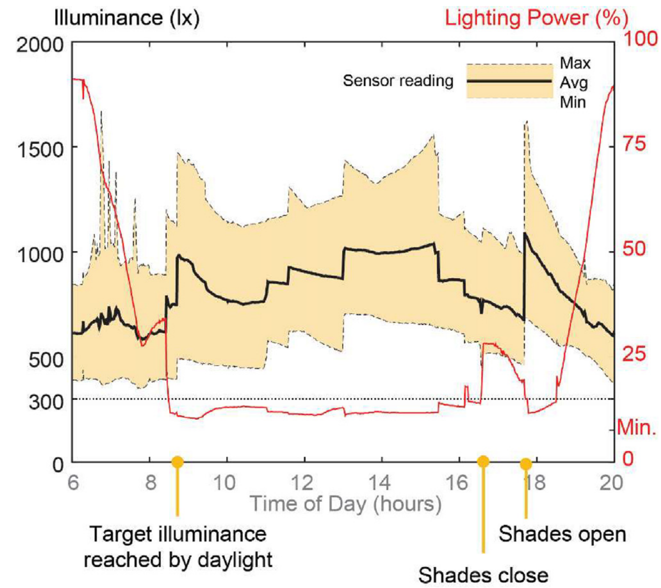

Fig. 3. Open-loop DLC tested at US SoSanFrancisco during a sunny day (April 30th). The electric lighting is effectively dimmed and it promptly responds to illuminance changes due to the operation of the shading devices to control glare. Figure adapted from [33].

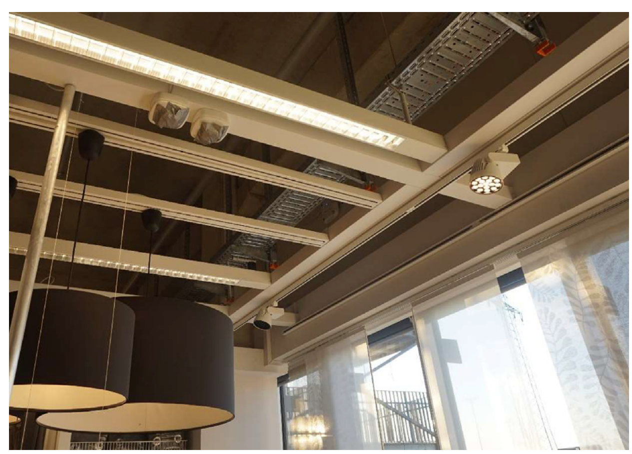

Fig. 4. Taped photosensors for DLCs were observed in some case studies. This was linked to unwanted fluctuations in light levels, due to either direct reflections from venetian blinds to the photosensor, or changes in surface reflectance within the room. Source: Lund University.

setting) in the large 26 m^2 private office of the IT AbaziaSanLorenzo case study (with LPD of 6.84 W/m^2 at 500 lx on workspace). This standby power use accounted for at least a third of the total lighting energy use during the observed period. For some lighting sources, manufacturers may advise against switching to standby power due to concerns of shorter lamp life, in which case power use at minimum dimming levels (approximately 20–35% of full power for fluorescent lighting) can significantly decrease potential energy savings. With LEDs, both minimum and standby power are less of an issue compared to fluorescent sources. Bench-scale measurements of LED fixtures in the US NewYorkCity building yielded a dimming range of 10–100% of full power and a standby power of less than 1 Watt to power the radio communications network. In addition, raising the standby question at the design phase can help contextualize it. For example, at AT Bartenbach, the energy demand for the integral building control, which included extensive LED lighting sensing and control, was measured to be 1.09 kWh/m^2-y, which was almost a third of the 3.65 kWh/m^2-y used for the lighting itself. However, without the perfectly fine-tuned LCS (DLC and occupancy) and the excellent daylight design, the projected energy use for lighting would have been about 16.5 kWh/m^2-y. In addition, as an example of good practice, the LCS installed at US SoSanFrancisco contained a relay that switched off the power to the LED driver, thus reducing standby [31].

Finally, innovative lighting and shading controls are being increasingly tailored to the requirements of individual users. The CN BankOfChina proposed an individualized lighting management system based on integrative lighting principles, which continuously updated the lighting set-point based on personal preferences. To do so, it collected and elaborated use data on a cloud platform. The DE DIAL design was made with user-centeredness as the key principle. The office lighting combined three different concepts regulating the direct and indirect (ceiling or wall reflected) lighting intensity and CCT levels with settings that were individually adjustable via a digital user interface (UI). Lighting was controllable at the individual level in the AT Bartenbach case study, while the US NewYorkCity building included high granularity of lighting control (per luminaire), enabling lighting adjustment at individual level.

3.2.1. Key lessons learned

- To meet or exceed energy-efficiency benchmarks, daylight contributions must be considered when implementing conventional and integrative lighting controls. Daylight controls, however, require careful design and proper commissioning to effectively achieve energy savings and occupant satisfaction.
- Case studies with auto-commissioning systems or user-centered systems showed improved reliability and performance.
- Standby power for lighting controls can significantly reduce energy savings in some applications and must be considered when designing and implementing dimming control systems.

3.3. Control interface

Providing an easy to understand and accessible user control interface for tailored adjustments and/or manual override can increase occupant satisfaction and reduce energy use [39]. Individual controllability of light sources is one of the most valued attributes of lighting projects [16,40,41]. Individual controls for lighting and/or shading were provided in the AT Bartenbach, AU Aurecon, AU AECOM, DE DIAL, IT AbaziaSanLorenzo, SE TheSpark, and US PortlandEC buildings, and were highly valued by users. There is a general concern that provision of manual override control will have a negative impact on energy efficiency. In the IT AbaziaSanLorenzo case study, however, occupants were trained prior to using a fully manual dimmable and tunable lighting and shading system (Fig. 5). This resulted in very limited use of electric lighting, maximization of daylighting, and high occupant satisfaction. Another strategy is to make control interfaces more user-friendly. Control interfaces need to be designed in such a way that they are intuitive and easy to use [42]. Such design must not to be taken for granted, considering the wide range of control possibilities at the user's end: switching, dimming, tuning, etc. [43]. Well-designed interfaces can enhance the end-user experience and possibly reduce energy demand [39,44] (Fig. 6). In the IT AbaziaSanLorenzo, manual switches for the lighting and shading systems in individual offices were readily available on the desk. Side-by-side placement of the lighting and shading control interfaces was highly appreciated by users, supporting interoperation of the lighting and shading systems, as suggested by previous studies [45]. This, in turn, contributed to reduce energy use. Even simple switch-off controls need careful design, particularly when CCT adjustment is involved. Poorly designed and unlabeled switches at the DK PsychiatricH were reported to be difficult to use by half of the staff, and possibly for many of the patients, to the extent that occupants were unable to understand how to switch off the lights. The literature suggests that different designs of simple switch on–off can lead to a threefold increase in lighting energy use [39,46].

Forty-seven percent of occupants in the open plan office at the AU Aurecon believed that control over lighting was important. This design included manually controlled blinds, and allowed manual override over the automatic dimming and switching of luminaires. The former was achieved via a remote control with text labels, whose meaning was likely unfamiliar to the general population (e.g., "300 lx"). A better solution was adopted in the DE DIAL building, where a digital interface provided a wide array of control settings via intuitive graphic icons (Fig. 6). The BR MME case study monitored offices of different sizes. For smaller offices hosting up to two employees, a manual-override switch and dimming interface at the door was enough to provide 65% of satisfied employees. This percentage dropped to 39% when larger offices with more than five occupants were monitored. Here, 43% of the employees complained about having little to no control over the electric lighting, indicating that they were unaware or unable to control the system as desired. The complex design of the control interface

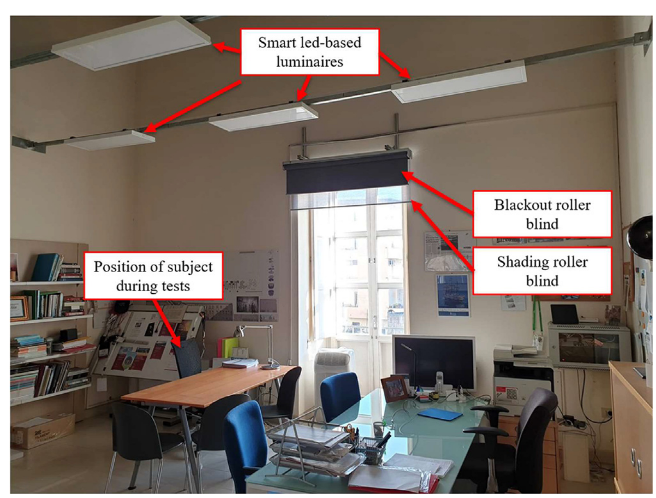

Fig. 5. Given the choice, occupants in the IT AbaziaSanLorenzo case study rarely used the electric lights during the two-week test period, preferring to control the shading devices to manage the daylight. Both systems were controlled manually by the occupants using wireless switches placed on the desk, see Fig. 6. Source: University of Campania, Italy.

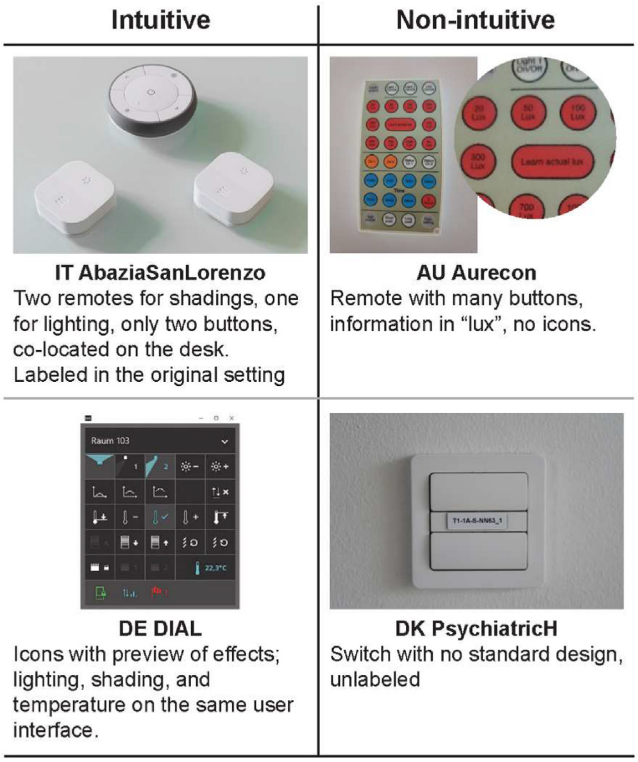

Fig. 6. Control interfaces that were considered easy to use and intuitive (left column) versus confusing and non-intuitive (right column). The DK PsychiatricH interface, while simple, did not convey the day- versus night-time spectrally-tuned control modes, which led to confusion for about half of the staff.

adopted in this building, consisting of a long column of identical white colored buttons with codes as label, could help to explain the difficulties experienced in operating the lighting. In addition, some settings could be adjusted only after formal request to the building management, which also raises the issue of "ownership" over automatic lighting control.

3.3.1. Key lessons learned

- Providing some degree of user autonomy over automated control of shading and lighting was shown to increase occupant acceptance and satisfaction with the system and, for some case studies, resulted in reduced lighting energy use compared to benchmark levels.
- An easy-to-use, intuitive, interface supported by education and training can help to increase occupants' understanding and acceptance of automatic controls over the life of the installation.

3.4. Integrative lighting

Integrative lighting is defined as "*lighting integrating both visual and non-visual effects, and producing physiological and/or psychological benefits upon humans*" [47]. Several metrics were used in the case studies to measure the non-visual (or non-image forming, NIF) effects of light [48]; an overview of metrics and recommended values is provided in Table 2. The metrics were derived from the photopic measurements (or simulations) taken vertically at eye level for all case studies.

Ten out of the 25 case studies had effective implementation of integrative lighting strategies among their design objectives. This was often achieved with dynamic schedules of light intensity (dimming) and correlated color temperature (CCT) (tuning), as presented in Table 3[3], with and without consideration of contributions from daylight (Table A2).

The energy performance of the systems (Table 1) varied depending on whether the lighting design had been guided by visual needs, which translates to providing adequate illuminance on the *horizontal* task plane (e.g., 500 lx for offices), or non-visual requirements, i.e. reaching the recommended values vertically at the eye (Fig. 7). It was found that designing integrative lighting with electric lighting only may not provide sufficient non-visual stimulation and may result in increased energy demands.

When the focus was on non-visual requirements, traditional lighting design based on electric lighting only resulted in high energy use (Fig. 8). At SE TheSpark, the LED system was capable of catering to multiple settings of varying intensities, ranging from a maximum of ≈ 600 EML measured vertically at eye for the "boost" scene (CCT of 6200 K; M/P = 0.97) to a minimum of less than 100 EML for the "lounge" scene (2300 K; M/P = 0.51) [57]. With respect to visual requirements, these settings resulted in E_h comprised between ≈ 1218 lx (or more in some rooms) and ≈ 640 lx for the two settings, respectively. This resulted in a calculated LENI of 22.43 kWh/m^{2}y, which was slightly above current benchmarks and well above the energy performance levels of many of the other case studies. However, including daylight in the design of the system would have largely lowered the energy use. Indeed, measurements performed with daylight under clear sky conditions provided much stronger non-visual stimulation, outdoing the effect of electric lighting (from over 2300 EML, M/P = 1.00 to about 250 EML, M/P = 0.95 for the two scenes[4]). Even under overcast sky, the EML boost setting were raised from ≈ 600 EML to ≈ 1000 EML due to daylight contribution [57].

When the focus was on visual needs, electric integrative lighting systems alone could not provide sufficient non-visual stimulation, but these designs would have succeeded in supporting non-visual requirements if the contributions of daylight had been considered when "sizing" the electric lighting system. For example, the integrative electric lighting design at AT Bartenbach office provides E_h = 500 lx on the desk, but only E_v = 190 lx at the eye. This corresponds to 138 EML from the electric lighting system, which is well below the requirements demanded by the WELL Building Standard v2.0 to achieve up to 3 credits for integrative lighting [50]. This project, however, provided adequate daylight via automated control of external louvers, skylights, and view windows (e.g., Ev = 1898 lx to 2576 lx with and without shades on a partly cloudy day). With adequate daylight provision, daytime non-visual requirements were met even in the absence of electric lighting, with values reaching 842 EML and 1647 EML during an overcast and sunny sky day, respectively. The integrative electric lighting system was sized to deliver E_h = 500 lx on the task area even for the office at IT AbaziaSanLorenzo. In such conditions, the electric lighting could only achieve 190 lx mEDI at the eye at its highest intensity levels (E_h = 500 lx, CCT = 4000 K). However, the measured mEDI with daylight only varied between 89 and 346 lx throughout a partially overcast day, despite a relative low daylight penetration (this was a historical building in Southern Europe with small windows, thick walls, and high ceiling). At DK Navitas there was no integrative lighting installed, but only a carefully integrated daylight design. Calculated CS and mEDI levels in the building for daylight only were close to the targets during mid-day hours on

[3] Table 33 does not include two of the integrative lighting projects. BE Stephenson is not included since integrative lighting is realized with daylighting only, namely proposing ideal routines and changing room layouts to reach non-visual requirements. DE IKEA Kaarst is not included in the table because the schedule was not available to the surveyors.

[4] These monitored data included EML contributions from both the LEDs and daylight during peak sunny periods, but integrative control of the LEDs did not include source contributions from daylight.

Table 2
Non-visual metrics used in the case studies and recommended values for day-active people.

	Full name	Ref	Recommended values for day-active people	Notes
EML	Equivalent Melanopic Lux	[49]	WELL v2 [50] ≥ 240 EML (from electric lighting only) ≥ 180 EML from electric lighting (if certain daylighting criteria are met) To be achieved for at least four hours between 09:00–13:00. Lower levels after 20:00	The definition of daylighting criteria is provided in [50]
M/P	Melanopic over photopic ratio		< 0.7 blue-depleted lighting (promoting relaxation) 0.7 ≤ M/P ≤ 0.9 neutral> 0.9 blue-enriched lighting (promoting alertness)	M/P describes the melanopically-weighted content of SPD compared to the photopically-weighted one.
CS	Circadian Stimulus	[51,52]	UL DG 24480 [53] ≥ 0.3 for at least two hours during 07:00–16:00 ≤ 0.2 during 17:00–19:00 ≤ 0.1 after 20:00	
mEDI	Melanopic Equivalent Daylight Illuminance	[54]	Brown et al [55] ≥ 250 lx daytime (06:00–19:00) ≤ 10 lx before bed (19:00–22:00) ≤ 1 lx during sleep (22:00–06:00) WELL v2 [50] ≥ 218 lx (from electric lighting only) ≥ 163 lx from electric lighting (if certain daylighting criteria are met) To be achieved for at least four hours between 09:00–13:00. Lower levels after 20:00	EML values can be transformed in mEDI via conversion factors [56]

January 21st. CS and mEDI levels increased substantially when light from the computer displays was taken into account. This must be considered in future designs since office work, nowadays, is conducted almost exclusively in front of computer screens (Fig. 7). At DE IKEAKaarst, M/P Ratios for mixed daylight and electric lighting, measured during a March afternoon, were found constantly higher than 0.9 when daylight was in the field of view [29].

It can be argued that proper integrated daylight in offices may suffice for non-visual requirements during the day. Integrative electric lighting alone can support circadian targets, possibly only under overcast winter skies at high latitudes. In addition, light from computer screens cannot be ignored, as it provides a further and effective luminous stimulation.

A well-balanced integrative lighting design should guarantee high values of mEDI, CS, EML, and M/P ratio during the daytime. These values should be lowered when evening approaches (Table 2). This is harder to achieve in residence-like spaces, as compared to offices with typical daytime (i.e., 09:00–17:00) occupancy. For example, in the BE Stephenson residential care home for the elderly, non-visual response targets were hardly reached during early morning and evening hours. Daylight provided insufficient non-visual stimulation in bedrooms during the morning (CS = 0.02, 12 EML), and excessive exposure in the dining room during summer evenings (CS = 0.23, 120 EML). The challenge of sufficiency and excess, which may arise from a scene's façade orientation, suggests that providing more daylight at any time is not always the correct solution for proper circadian entrainment. At BE Stephenson, a change in the daily activity schedule and location of occupants was suggested, following the natural patterns of the sun-path, namely promoting activities in bright sunlit areas in the morning, and in more sheltered spaces during the late afternoons. This enabled elderly patients (whose threshold values differ from that of the general population due to ageing [4,58]) to be exposed to appropriate levels of non-visual stimulation on all floors at all times of the day and year within the set targets for visual comfort. Such integrated and integrative design practices, which rely only on changes in daily schedules of activities rather than technology, can reduce the electric lighting capital costs of meeting non-visual lighting requirements.

For integrative lighting installations in residence-like spaces, namely spaces with a 24 h occupancy schedule, the evening target values of both CS and mEDI were achieved under both "day" and "night" electric lighting settings at DK PsychiatricH (Fig. 9). However, in the absence of sufficient daylight, the electric lighting could not provide sufficient non-visual stimulation throughout the day. In fact, CS was always lower than 0.1 and mEDI lower than 50 lx, for all the settings and view positions tested. Similar values were found for the integrative lighting system at DK Rehab. However, in this case, a "light therapy" setting delivering 5500 K and E_h = 430 lx could reach values of CS > 0.3 and mEDI > 200 lx even in the absence of daylight (Fig. 9). It should be noted that the target horizontal illuminance for visual requirements for this space typology would be E_h = 300 lx, meaning that the "light therapy" mode is delivering 43% more illuminance to reach an "ok" target for mEDI. This is in line with the above-mentioned findings for office spaces (Fig. 8).

In general, fulfilling non-visual requirements with electric lighting only may result in energy rebounds, potentially offsetting gains from the adoption of efficient LED light sources. This energy rebound is also arguably linked to the fact that non-visual lighting design is still an evolving discipline. Such risk could be minimized over the coming years, particularly due to the following: a) standards are shifting their design focus from horizontal workplane illuminance to both horizontal and vertical illumination, so as to balance visual and non-visual requirements in the most energy efficient way; b) designers are starting to become adequately trained to understand the potentially conflicting requirements for visual and non-visual lighting, for different spaces, use typologies, and age groups; and c) designers have access to tools, e.g. software, capable of handling non-visual lighting design for both daylighting and electric lighting, so that lighting systems can be sized with daylight harvesting even to respond to non-visual requirements [59–61].

3.4.1. Key lessons learned

- Fulfilling non-visual requirements with electric lighting only may result in energy rebounds.

Table 3
Range in light intensity (expressed as measured photopic horizontal or vertical illuminance (lx) at selected points) and CCT at maximum light output for the integrative electric lighting system of selected case studies.

Case study	(Photopic) Illuminance		CCT	Notes
	Quantity	Values		
AT Bartenbach	E_h	450–1100 lx	2174 ~ 4095 K	Avg at max light output: E_h = 816 lx, E_v = 310 lx.
				When dimmed to avg E_h = 500 lx, then E_v = 190 lx.
CH CABR	E_h	*na*	3300 ~ 5300 K	
CH BankChina	E_h	127 ~ 615 lx	2939 ~ 5394 K	First row E_h and CCT refers to exemplary office,
			4225 ~ 6030 K	other CCT rows refer to other monitored spaces for which E_h is *na*
			3616 ~ 5645 K	
			3497 ~ 5945 K	
DK PsychiatricH	E_h	100 ~ 250 lx	1750 ~ 2700 K	
DK Rehab	E_h	47 ~ 430 lx	2700 ~ 5500 K	
DE DIAL	E_h	0 ~ 1200 lx	*na* ~ 6500 K	Each E_h range indicates target illuminance for 0–100% dimming.
		0 ~ 2000 lx		The occupant can select different dimming ranges,
		0 ~ 3000 lx		each providing the *na* ~ 6500 K CCT options.
IT AbaziaSanLorenzo	E_v	15 ~ 351 lx	2200 ~ 4000 K	Manual dimming and tuning
SE TheSpark	E_v	640 ~ 1218 lx	2300 ~ 6200 K	

E_v = Vertical Illuminance at the eye; E_h = Horizontal illuminance at workspace.

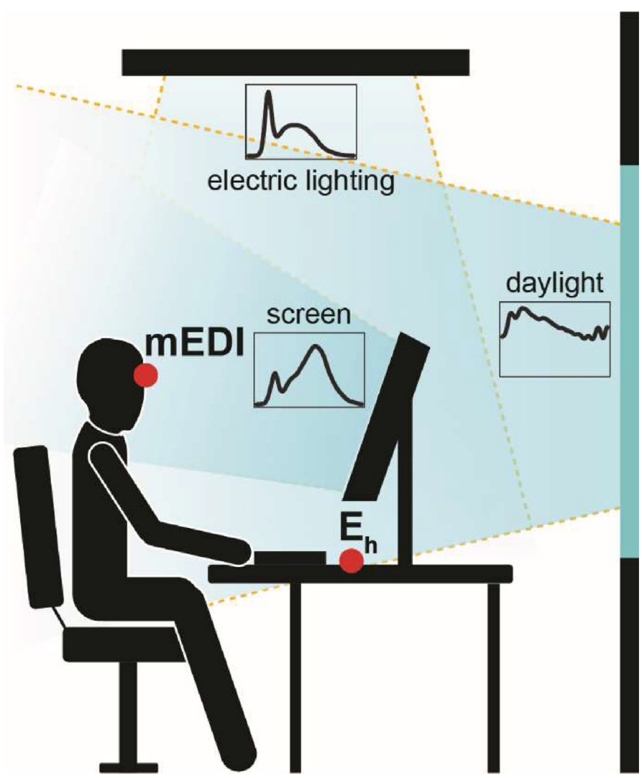

Fig. 7. Visual needs are typically verified horizontally on the task (operationalized in figure with a target E_h), while non-visual requirements are measured vertically at the eye level (operationalized in figure with a target mEDI). Generally, three light sources contribute to both: electric lighting, daylighting, and lighting from screens. Responding to visual needs with electric lighting only may result in over dimensioned lighting systems since light is typically distributed downwards.

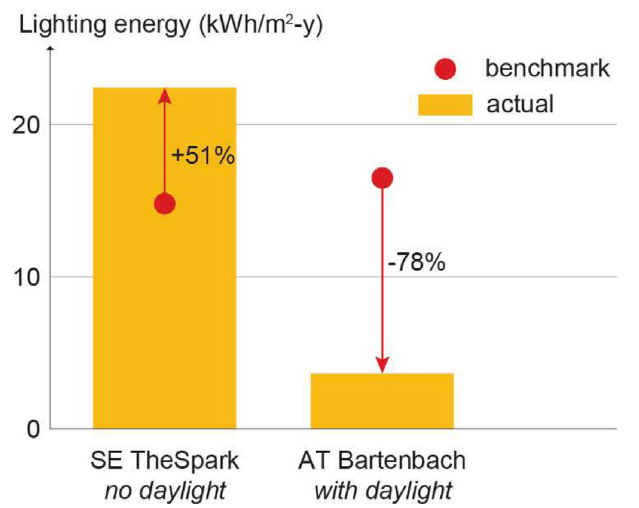

Fig. 8. Energy use for lighting for the SE TheSpark (focus on non-visual requirements, daylight excluded from the initial design) and the AT Bartenbach (focus on visual requirements, daylight included in the lighting design) case studies. Integrative lighting based on electric lighting only results in high energy use. Benchmarks from EN15193-2:2017.

- With appropriate design, daylight can significantly offset the energy rebound effects of integrative LED lighting.
- Daylight availability is highly dependent on sun and sky conditions, window orientation, light-scattering properties of shades (e.g., E_v versus E_h distribution), and shade controls, which may not be correlated to non-visual lighting requirements. Automatic control of shades could be designed to support non-visual lighting requirements but will also need to address energy efficiency, comfort, and other needs.
- Occupants can be encouraged through training (e.g., remote control of shades) or scheduling of activities (e.g., elderly home) to use daylight more proactively in order to satisfy their non-visual requirements.

3.5. Shading and daylighting systems

The case studies covered a breadth of innovative technological solutions designed to improve daylight admission (e.g., daylight redirecting systems, tubular skylights, and light pipes for core daylighting) and control glare, solar heat gains, sunlight, and access to view (e.g., automated operable shades and dynamic glazing). None of the fenestration solutions were designed explicitly to manage daylight for non-visual entrainment (as guidance from research is yet vague) nor were the case studies (except AT Bartenbach) designed to monitor the effects of daylight from this perspective. Insights into timing of luminous intensities over the day, distribution of flux within the room, and energy savings were, therefore, generated from available data. Lessons learned pertain primarily to the advantages of integrated shading and lighting design and control, some being relevant to integrative lighting. Architectural design solutions are detailed in Section 3.6.

Integrated design was determined to be critical to achieving an adequate balance between competing performance requirements. The AT Bartenbach case study provided monitored evidence of the effectiveness of daylight in an open-plan, 36-m long by 5.5-m deep, office daylit with windows on the south and sloped linear skylights on the north. Direct sunlight and glare were controlled on the south with fixed exterior louvers and an automated exterior roller shade for the upper daylight aperture and a top-down/bottom-up, manually operated, roller shade for the lower view aperture. Similarly, on the north, the sloped skylight was fitted with fixed exterior shading and an automated indoor roller shade. The LED electric lighting system was dimmed in proportion to available daylight according to scheduled CCT and illuminance setpoints. As a result of this holistic design, monitored lighting energy savings compared to the EN12464-1 benchmark (500 lx minimum) were 12.85 kWh/m^2-y (78%). Monitored M/P ratios and EML from daylight were 0.946 and 1558 EML respectively at noon on a sunny day, and 0.93 and 842 EML respectively on an overcast day.

Innovative daylight-redirecting technologies were shown to be more effective than conventional shading solutions in admitting useful daylight. The NO Norconsult case study evaluated a horizontal light pipe that transported sunlight 3.75 m from its 22 cm diameter aperture at the south-facing façade[5] with maximum output between 10:00 and 14:00 h. Field measurements indicated that 70% of total monitored workplane illuminance (500 lx setpoint) on sunny days was delivered by the light pipe, this being less effective on overcast days, with only 14% of the total light contribution. Vertical tubular skylights were used to bring daylight from the roof to the core areas of a 15 $\times$ 16 m conference room on the top floor of an office building in the CN CABR case study. Monitored average daylight at the horizontal work plane was 305 lx on a sunny day (365 lx if daylight from the windows was included), while the average daylight factor was 0.61% (0.73% also considering windows). In the DE IBP_Daylight case study, between-pane, static, large-scale micro-optical panels located in the upper clerestory window were used to redirect sunlight to the ceiling plane far from the window. The advantage of such systems is that, with light-coloured room surfaces, the added reflected and inter-reflected daylight on the upper walls and ceiling is more likely to be effective at responding to non-visual lighting requirements at the eye than conventional shading materials. On a clear summer day, monitored energy use (for non-integrative lighting) in the 6 m deep test office was reduced by 64% compared to the reference room with blinds in the upper window. Over the full period of the monitoring, lighting demand was reduced by 58% (May to September). In the US DualZoneShade case study, inverted white horizontal slats installed in the upper clerestory zone of a south-facing window were adjusted automatically to redirect sunlight to the ceiling plane (the blinds were raised under cloudy skies) while, in the lower part of the window, a transparent film ($T_{v,n-h}$ = 0.02) roller shade was manually adjusted. In the 4.6 m deep monitored testbed office, average lighting energy savings were 51% compared to a partially-lowered fabric roller shade during the summer period (Fig. 10).

The design and control of shading systems can significantly affect temporal availability of daylight. Use of manual shading devices in the DK Navitas building affected daylight and energy use differently from space to space, depending on the users. Active users frequently adjusted the shades in response to daylight/sunlight conditions and the presence of glare, while less active users often left the shades closed even when no direct sunlight or glare were present. A system that, at a minimum, automatically retracts shades at the end of the day would allow for more daylight and energy-efficiency, as users could start the day with shading devices retracted [39], as done at IT AbaziaSanLorenzo [62]. Automated integrated control systems can admit daylight and provide solar control when needed, ensuring more reliable energy-efficient use of both HVAC and lighting. In the US NewYorkCity case study, for example, daylight, glare, views, and sunlight across the 12.2 m deep open plan office zone were managed with an automated motorized roller shade with the intent to minimize energy use and discomfort. Such control, however, did not necessarily coincide with offering adequate circadian stimulation to occupants. For the northeast zone, the roller shades were partially lowered in the morning to reduce glare from direct sunlight and raised in the afternoon for daylight and views, contrary to non-visual requirements. In the southwest zone, the opposite strategy was adopted.

For both integrated and integrative lighting control, selection of proper shading materials is critically important. For the US NewYorkCity and US DualZoneShade case studies, use of densely woven roller shades or dark-tinted window film-controlled discomfort glare but at the cost of reduced mEDI when fully lowered. Similarly, the top-down blackout roller shades used in the AU AECOM, AU Aurecon, and IT AbaziaSanLorenzo case studies helped to control discomfort glare and direct sunlight, but admitted little daylight within the space as a whole through the lower unshaded portion of the window. Dark-colored shading devices with partial light transmission allow more view out, but can shift the spectral qualities of the light from the neutral appearance of clear untinted glass.

Electrochromic (EC) windows produce a significant shift from neutral clear to deep blue when tinted. With integrated control, such switchable windows can produce substantial HVAC and lighting energy savings but their strategies of operation should also take into account non-visual lighting requirements. For example, the south-facing EC windows at US PortlandEC were heavily tinted to mitigate glare during periods of low altitude sun. Here, the shift towards blue-rich short wavelengths resulted in high M/P ratios during midday hours (M/P of 1.3 from 10:30–16:00) despite the lower daylight intensities but maintained a high M/P ratio (M/P of 0.95) even in the late afternoon.

3.5.1. Key lessons learned

- With careful design of windows, shading, and lighting systems and controls, several case studies demonstrated that both integrated performance goals for energy efficiency and comfort and integrative non-visual objectives could be satisfied.
- Innovative daylighting technologies, e.g. dual-zone shades, can be more effective in solving difficult tradeoffs between daylight admission and solar/glare control compared to conventional shades. The spectral and light-scattering properties of such glazing, daylight, and shading systems and materials should be considered when conducting site-specific performance evaluations.
- For shading device operation, a purely manual system may not lead to the desired utilization of daylight and views out, since users might leave them in specific positions for extended periods of time. One solution would be to (automatically) retract shading devices at the end of the day.
- Automated dynamic shading and glazing have the potential for optimal control but, given the wide range in user requirements, it is important to provide manual override, training, and education, so as to increase satisfaction among users.

3.6. Daylight and view out

As indicated in Section 3.5, architectural solutions (i.e., building shape, position of openings, shading elements) tailored to the

[5] Some daylight transport systems (e.g., active-tracking heliodon systems) aim to provide near constant illumination levels throughout the day.

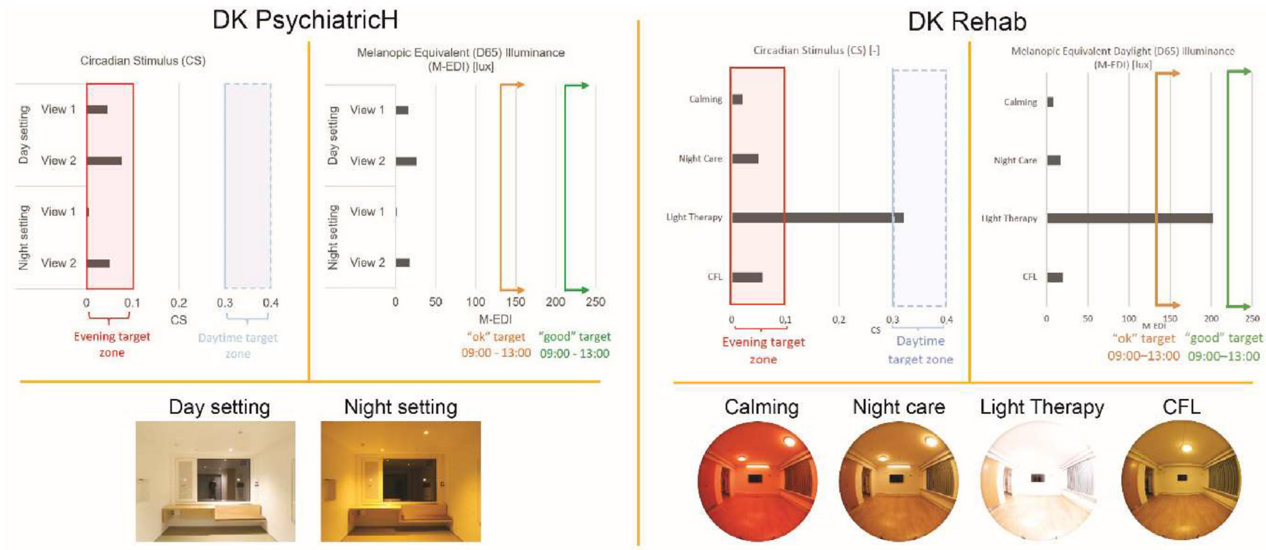

Fig. 9. Left: CS and mEDI for DK PsychiatricH, measured on 26 Feb 2020 at the eye of a hypothetical observer, 1.2 m above the floor from two viewpoints. Right: CS and mEDI at DK Rehab calculated for an estimated E_v simulated by DIALux at a height of 1.2 m above the floor for the four lighting scenarios. Target values for mEDI refers to WELL v2 [50], see Table 2.

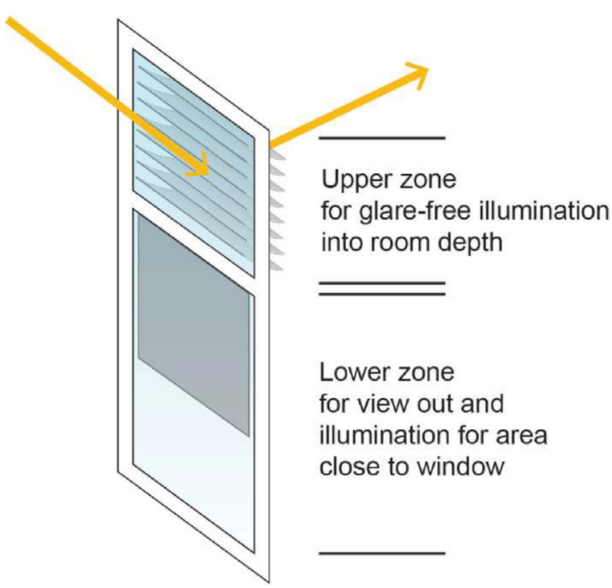

Fig. 10. Dividing the opening in two zones might be an effective solution to provide both glare-free illumination in deep rooms and a view out. The DE IBP_Daylight, DE IBP_LED, and US DualZoneShade case studies adopted different designs based on two zones openings, see Table A1.

specific geographical location, climate, and urban context are more likely to achieve integrated and integrative performance goals compared to conventional solutions [82,84,85]. The AT Bartenbach office was designed with both south-facing windows and north-facing skylights (Fig. 11), resulting in a minimum daylight factor of 3% across the depth of the office and a spatial daylight autonomy of 500 lx for 82% of working hours. The BR UniBrasilia office building had north and south facades with shallow offices distributed alongside them, achieving an average daylight factor of over 3%. The thin, elongated floor plate of the BR MME building also made good use of daylight.

Core daylighting strategies using atria, skylights, and courtyards or voids with different facades configurations per orientation can also be effective in sunny climates for self-shading or in overcast climates for increased daylight exposure [63]. The AU Aecom building was designed with large voids to deliver daylighting to open plan offices on multi-level floors. With the DK Navitas building, all spaces occupied for extended periods were daylit via windows facing outwards to the city or inwards to courtyards and atria (Fig. 12). This building provided a daylight factor of at least 2.1% or 300 lx for half of the daylight hours at 2.5 m from the south-facing façade. In the ES IDOM office building, the façade was fully glazed on the north and had a distinctive double skin with a microperforated sheet and landscape windows on the other orientations. In the SE TheSpark, highly-glazed facades and roof openings provided plenty of daylight, even in the core of the building. A similar strategy was adopted at DE DIAL.

Space use and occupancy patterns should be factored into daylight design. At BR MME (low latitude, sunny climate), most offices were located on the east façade to avoid glare and overheating during late afternoon hours, whereas space uses requiring short term occupancy (e.g., conference rooms) were located along the heavily-shaded west facade. In the ES IDOM, all common spaces were located facing south, while the landscape offices were located towards the north for greater access to daylight.

In addition to daylight, research has indicated that views to the outdoors or towards nature (i.e., greenery, flora and fauna) can have a positive effect on occupants' psychological and physiological health and wellbeing [64,65]. In this study, views were evaluated both quantitatively, using the methods described in EN 17037:2018 [66] and qualitatively, using occupant surveys.

As a general observation across case studies, occupants seemed to care both about *how much* and *what* they could see. The aesthetic quality of the view (i.e., rendered appearance through the window) must be factored in with its content and the context in which the building is located. In the DE IKEAKaarst, shop visitors spontaneously reported that having a view out contributed to improvements in the shop's atmosphere [29]. Yet, some visitors complained about its content, claiming that a view of the parking lot was a bad choice since other beautiful views were available around the building. At the BR ForumSoPinto, solar control films reduced $T_{v,n-h}$ from 0.89 to 0.50 and shifted the spectral transmission of daylight from clear neutral to smoky brown. In the occupant survey, two thirds of users reported a neutral vote or did not appreciate the view out, despite the generous size of the

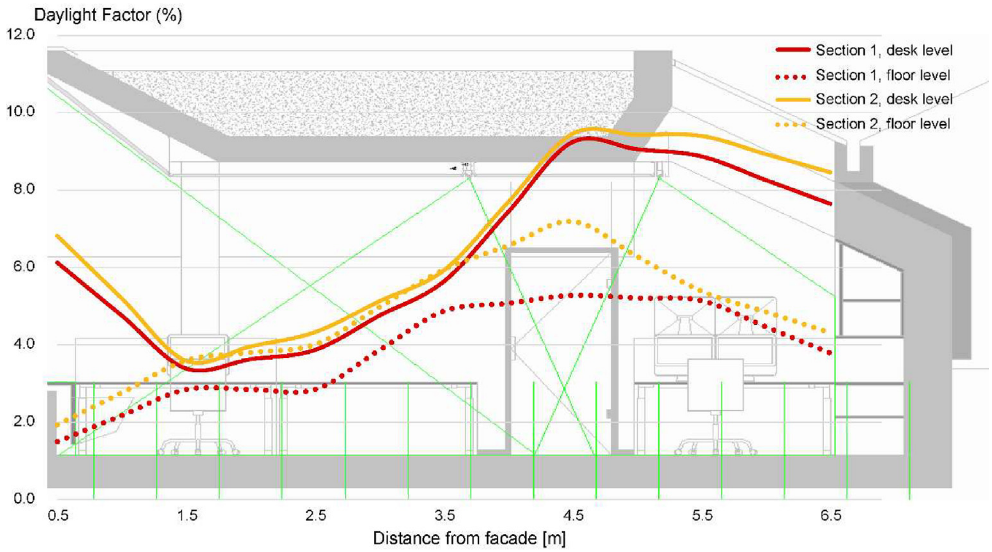

Fig. 11. AT Bartenbach building section.

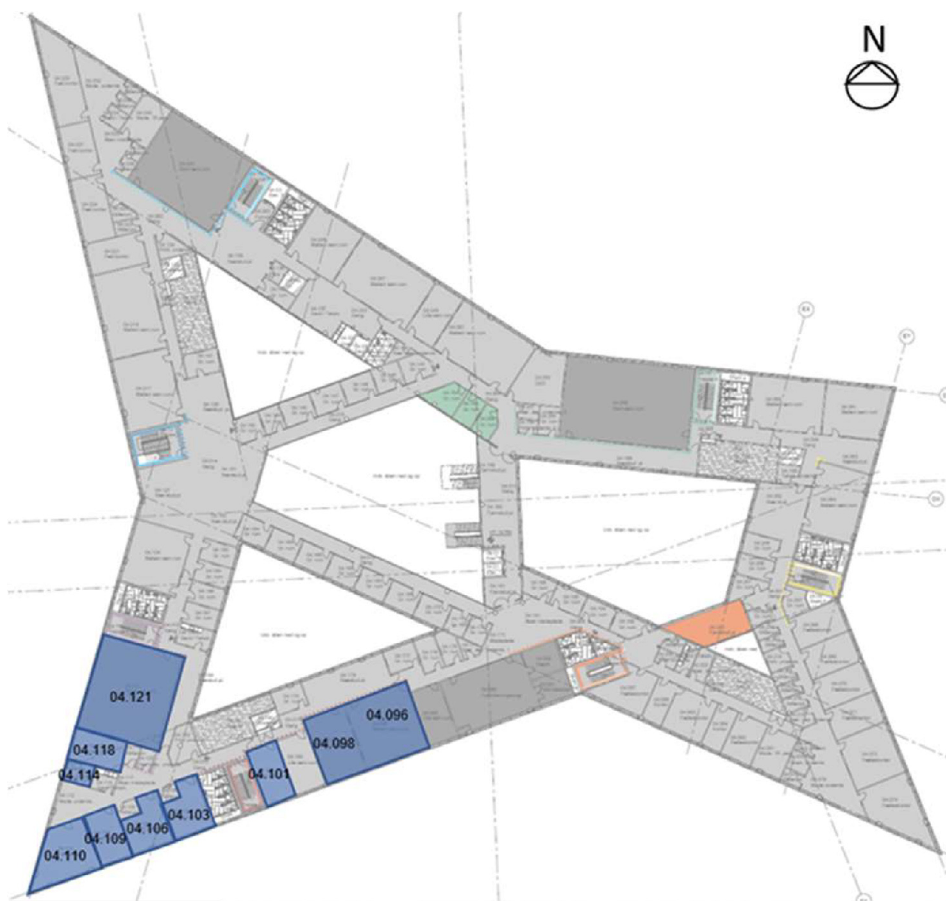

Fig. 12. DK Navitas floor plan, showing courtyards and atria.

window openings. In this case, the view out did not offer a variety of layers (as defined by EN17037:2018) and the solar control films altered the naturalness of the view out. According to data collected at US PortlandEC, occupants were unsatisfied with the reduction of daylight when the electrochromic (EC) windows were tinted to control glare, but they preferred the EC windows instead of venetian blinds. Interestingly, use of the darkest tint in automatic control was eliminated, since this tint level was the least appreciated by the occupants (occupants could select the darkest tint with manual override).

The quality of view seemed to affect occupants' perception of the visual environment. Views out were one of the determinants for occupants' satisfaction with daylight in the BR MME case study. In some cases, the presence of views out reduced complaints of glare [67,68], as in the BR MME (Fig. 13), BR UniBrasilia, US DualZoneShade, and US PortlandEC case studies.

3.6.1. Key lessons learned

- Architectural solutions tailored to the site, surrounding context, building type, and occupancy patterns were more likely to achieve high performance objectives associated with a well daylit environment. More successful solutions increased the perimeter-to-core area ratio using shallow floor plates, atria, courtyards, etc. with geographic- and climate-appropriate solar control measures.
- Views to the outdoors were not satisfactory if the scene was deemed unpleasant or unnatural. Occupants disliked solar control measures that permanently altered the naturalness of the view (e.g., window films), and preferred systems that temporarily changed the appearance of the scene (e.g. electrochromic windows) over those that provisionally blocked it (e.g., venetian blinds).

3.7. Monitoring and verification

Monitoring and verification (M&V) can play a key role in achieving energy savings [69,70] by guaranteeing that design measures are in place and operating as intended [71]. M&V, in practice, focuses on the technical performance of integrated systems, but rarely accounts for occupants' perspectives via post-occupancy evaluations (POEs) [72]. However, each project must address specific end user needs, and a mere M&V of technical performance may be too limiting [73,74]. The case studies demonstrated how M&V and POEs identified room for improvements, even in the best-conceived projects.

The US SoSanFrancisco case study focused heavily on the importance of M&V. The design team relied on a rich set of sources to inform the design: they collected data from full-scale mock-ups, conducted observations, had weekly collaborative meetings with all the stakeholders involved in the project, and consulted with domain experts. A new control system for lighting was developed and optimized in a mock-up testbed with a trial-and-error process, before proceeding to the final design. The design team used a similar approach for the design of the shading system. In this way, the LPD was reduced from 5.52 W/m^2 to just 1.4 W/m^2 (Fig. 14). The proof-of-concept was not just applied to the single building; a new protocol was also planned for monitoring the built space so that actual performance data could inform future decisions on other projects. For example, a traditional dimmable LED system was chosen over an integrative system, as daylight provision was deemed sufficient to provide enough circadian stimulation. Occupants were trained on the new system before occupancy and the facility management invited feedback from occupants, which resulted in further fine-tuning of the lighting and shading systems. As a whole, the design did not stop at procurement and construction, but was continuously updated with feedback even after occupancy, resulting in a continuous circle of M&V and improvement, and an exemplary integrated real project.

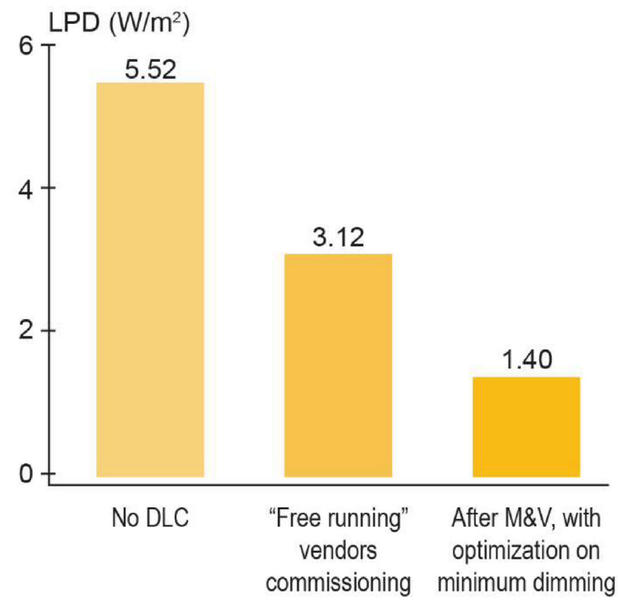

Fig. 14. Measured LPDs after introducing and optimizing DLCs at US SoSanFrancisco. The optimization followed an extensive M&V process and more than halved the LPD in comparison to a "free running" commissioning. Data Source [33].

In the other four case studies (BR MME, CN CABR, AT Bartenbach, and US NewYorkCity), M&V was carried out mainly in the post-occupancy phase. A potentially efficient integrated system at BR MME did not reach the design goal due to the lack of appropriate technical support and poor training of users. Conversely, similar systems at the CN CABR and AT Bartenbach delivered on design goals, since the technical staff was in-house and could change the system settings over time. The US NewYorkCity was a success in terms of both energy savings and occupants' satisfaction (with only 16 requests over the year to override automatic shades). An educational program with interactive sessions was thereafter developed to train design professionals, owners, installers, and facility managers on commissioning best practices.

The monitoring of case studies was, in itself, an occasion for verification and re-commissioning. The monitoring of the IKEA Kaarst, for example, identified a few malfunctions in both the daylight-linked (see Section 3.2) and integrative lighting systems – which were subsequently fixed. The POE (via occupants surveys and HDR measurements) of AU Aurecon identified glare issues with

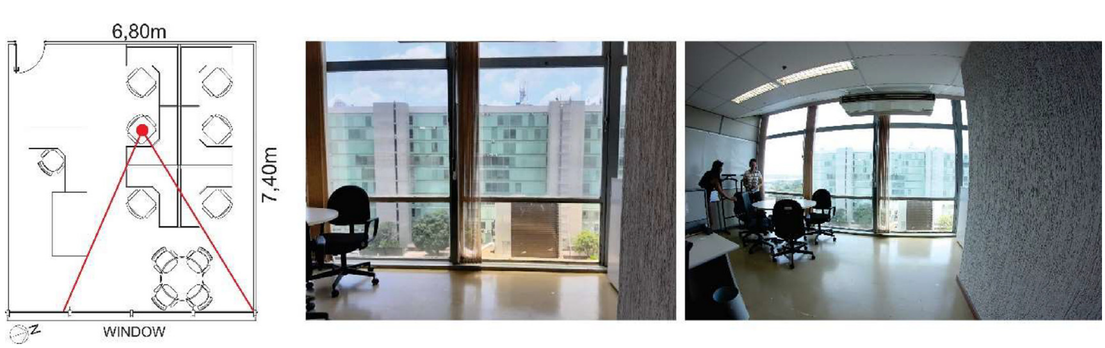

Fig. 13. Evaluation of the view out for BR MME.

the existing roller shades ($T_{v,n\text{-}h}$ > 0.40), and suggested the use of additional roller blinds with $T_{v,n\text{-}h}$ < 0.10, which are now installed in the case study building. The M&V at the DK PsychiatricH and DK Rehab identified critical aspects – like the need for a smoother transition between lighting scenes and for more intuitive control interfaces (see Section 3.3) – which might have remained unnoticed without M&V. In the DK Navitas, the target illuminance was increased from 300 to 900 lx for some unknown reason, resulting in excessive energy use, as dimming no longer occurred. This was noticed only because of the monitoring in the context of the IEA SHC Task 61/EBC Annex 77.

The US SoSanFrancisco case study showed that the best results can be reached using the M&V early in the building design stage. Mixing evaluation based on objective and subjective parameters, designers adjusted the light control strategy considering the building, users, and boundary conditions. In addition, using M&V during the building operation allowed further optimizations of the lighting control systems.

M&V also pointed out the complexity of ensuring the right lighting for different types of occupants, e.g., patients versus care staff in the DK Rehab. In fact, the same lighting condition was judged satisfactory by patients but was identified as too dark or too red-shifted for working by about 50% of DK Rehab staff members. These outcomes show that, even if M&V on objective parameters confirm compliance with standard requirements, light conditions may not be comfortable for all users. Also, M&V using subjective quantities (surveys) can be useful to evaluate the light conditions from the users' point of view.

3.7.1. Key lessons learned

- M&V and post-occupancy evaluations revealed various technical problems with lighting and shading controls (e.g., location of photosensors, zones, calibration settings, setpoints, etc.) and more nuanced problems associated with end user preferences. Conducting such evaluations are critical to ensuring that energy and quality goals are achieved over the life of the installation.
- Evaluating controls in the real world prior to specification and procurement can improve the likelihood of success in the final building.

4. Discussion

The themes covered in these "lessons learned" provide grounds for cross-analysis, encompassing the overarching opportunities offered by the integration of daylighting and electric lighting in real projects.

First and foremost, integration carries the potential for saving energy used for lighting. This opportunity seems to be well exploited in actual buildings, as measured annual energy for lighting in office spaces could easily reach 5 kWh/m^2-y. This is in line with reported values in the literature, but comes with stronger external validity, since it is derived from actual measurements in different contexts and for occupied spaces in real buildings. Good energy performance calls for a combination of high quality, comfortable daylight provision (not too much, not too little, well distributed, and not too much sun penetration [75]), adoption of efficient electric lighting sources, and wise use of controls. Energy use can be further lowered if integration is considered at early design stages of the building envelope, which, for example, resulted in the outstandingly low annual lighting energy use of 3.65 kWh/m^2-y, as measured in the AT Bartenbach case study. It is worth noting that accounting for users' needs and preferences supports the energy performance goals. The use of shading devices – automated or even manual – is optimal when occupants are provided with daylighting strategies that can simultaneously prevent glare as well as provide satisfactory view out (such as in AU Aurecon or IT AbaziaSanLorenzo). Controls are best used when they provide individualized and granular control (such as in US NewYorkCity), and/or manual override (such as in DE DIAL and AT Bartenbach).

Adequate performance can be supported by extensive M&V, including post-occupancy evaluations and possible re-commissioning. It is worth noting that all successful stories in the case study collection included re-commissioning to some extent. The monitoring itself served as "unofficial" M&V, leading to re-commissioning in some cases. This suggests that real integrated projects should always include follow-up plans for M&V. In a wider perspective, the adoption of follow-up plans for M&V is not strictly a technical issue, since it depends on the way in which projects are procured and contracted. The authors recognize a few practical concerns for the actuation of M&V for daylighting and electric lighting projects in traditional business, as for example when different contractors are responsible for different parts of the systems. As a matter of speculation, future business models shifting the ownership of systems to the contractors – e.g., via Light-as-a-Service (LaaS) models – can potentially support the adoption of M&V on a wider scale, since the ownership of the system as well as the know-how stays with the same stakeholders.

The integration of daylight and electric lighting offers the potential of sustaining healthier indoor environments. Access to daylight and view out was highly valued by all surveyed occupants in the case studies, suggesting a reduction in psychological stress and a perceived improvement in performance. In addition, daylight might successfully provide adequate circadian stimulation for a large part of the day. To the best of the authors' knowledge, there is a lack of research on strategies for daylight control with respect to non-visual requirements. Glazing and shading devices are still designed for visual needs only, whereas the market for integrative (electric) lighting is swiftly expanding.

Integrative electric lighting may be able to complement the lack of daylight during limited winter periods or during few heavily overcast days at high latitudes – for which electric lighting systems can deliver higher levels of illumination in respect to daylight. Demand from such integrative lighting systems is higher than what is normally required by traditional visual lighting design (e.g., 500 lx on the working plane). Such intensity requirements might, however, increase energy use for integrative lighting, especially when systems are designed at a late design stage, and independently from daylight.

In general, it seems that optimizing for either visual or non-visual requirements may lead to very different design choices. Arguably, the next big challenge in lighting design will concern the simultaneous tackling of both visual and non-visual human responses in a holistic and energy efficient way. The integration of daylight would be key for achieving positive results.

5. Conclusions

The building industry is facing significant challenges related to energy efficiency, greenhouse gas emissions, and visual aspects, with new ambitious goals related to health and well-being increasingly being included. Monitored data and subjective responses from 25 case studies from around the world quantified the degree in which a wide variety of design and technological solutions were able to satisfy these increasingly complex and often competing requirements.

Lighting energy use can be dramatically reduced with proper integration of daylighting, and annual energy use below 5 kWh/m^2-y is easily achievable in office spaces. Advanced control technologies showed promise in providing reliable solutions (e.g., self-commissioning, self-learning, adaptable) but training and education with manually operated systems were also shown to hold significant potential. Informed specification, installation, commissioning, and monitoring and verification practices will also be critical for success. For new construction, careful architectural design for daylight, solar control, and view will be critical towards the achievement of targeted objectives.

Technological innovations are currently being driven by integrative lighting with wider adoption expected to occur as knowledge increases in the field of non-visual lighting. Advancements in LED technology, together with increased capabilities of control systems, could help to support non-visual requirements through electric lighting when daylight alone is insufficient. The adoption of daylighting within integrative lighting is currently very limited in practice, and tools and knowledge are still lacking for designers towards proper implementation.

A final reflection concerns the reason for seeking integration of daylighting and electric lighting in real buildings. Until recently, the motivation for integration was only approached from an energy saving perspective; that is, reducing electric lighting to its minimum while maximizing daylight in the space. Design projects focusing exclusively on conventional 'photometric' perspectives – typically based on horizontal illuminance and rarely on luminance ratios and contrasts – did not achieve much beyond visual sufficiency. Such approach was rarely observed in the case studies, where the prevailing questions focused often on health and comfort related to lighting, including aspects of alertness, sleep quality, and views to the outside. These questions are – and will be – the drivers of innovation in future (day)lighting technology. Such drivers suggest that integration must go beyond vision, and must also address other aspects of human experience in built spaces. Extreme daylight exploitation needed for integration also brings up other potentially adverse issues, such as thermal comfort and risks of increased heating and cooling loads, which should also be comprehensively considered.

It can be claimed that integration of daylighting and electric lighting has moved from:

a) strictly a *photometric* definition (light quantity) to a wider consideration of *spectral* qualities;
b) merely *supporting visual sufficiency* to *fostering visibility, well-being, comfort and restoration* e.g., via quality views;
c) *space-centeredness* to a *user-centered* approach, that is, designing lighting for the individual via vertical measurements at the eye, rather than for the workspace using horizontal grid-based measurements, and providing high-degree of individual customization for daylighting and electric lighting;
d) *reducing lighting energy use* to *decreasing overall energy demands for lighting, heating, and cooling, while also ensuring visual and thermal comfort and views to the outside.*

Integration can, therefore, be defined as *the combined use of daylighting and electric lighting (and their controls) to increase vision, well-being, comfort, and restoration of individuals, while saving energy in buildings*. This wider definition implies that designers need to be equipped with new tools and methods to be able to address the more ambitious design goals of integrated projects.

6. Terms

Integrated lighting: The integration of daylighting with electric lighting for any purposes, such as for saving energy.

Integrative lighting: CIE defines integrative lighting as: "*lighting integrating both visual and non-visual effects, and producing physiological and/or psychological benefits upon humans*" (in CIE S 017/E:2020 ILV: International Lighting Vocabulary, 2nd Edition). Integrative lighting is also commercially known as human-centric lighting, biocentric lighting, etc.

Rebound effect: The increase in energy use despite increase in energy efficiency of technologies.

CRediT authorship contribution statement

Niko Gentile: Writing – original draft, Visualization, Supervision, Project administration. **Eleanor S. Lee:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Werner Osterhaus:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Sergio Altomonte:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Cláudia Naves David Amorim:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Giovanni Ciampi:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Veronica Garcia-Hansen:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Marshal Maskarenj:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Michelangelo Scorpio:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition. **Sergio Sibilio:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Case studies and main solutions adopted.

ID (YEAR of LAST (DAY)LIGHTING REFURBISHMENT)	SPACE TYPE	DAYLIGHTING	LIGHTING	CONTROL	REFs (in addition to [23])
AT Bartenbach* (2015)	O-M	Surface reflectors + automated exterior sun/glare protection in upper part of window Manual internal shading in lower part of window Skylight with exterior fixed shading and interior motorized diffusing screen	LED 2200 K – 5000 K with glare control and asymmetrical beam	Automated shadings Occupancy DLC, closed loop Integrative lighting schedule Manual override is provided	[76–78]
AU Aecom	O-L	Sidelighting with manual internal blind shading	Non-dimmable recessed 28 W T5	Occupancy	[79]
AU Aurecon	O-L	Sidelighting with manual double roller internal blind shading	Linear dimmable 20 W LED luminaires	Occupancy DLC closed-loop Central control for override	[79]
BE Stephenson*	H-R	Sidelighting with shading	LED lighting	Occupancy DLC open loop (simulated)	
BR ForumSoPinto (2005)	O-M	Fixed horizontal and vertical concrete elements Glazing film Tv,n-h = 0.50 Internal venetian blinds	Recessed linear LED T8 2x18W 6500 K	Manual	[80]
BR MME (2015)	O-M	Laminar shaped building Brise soleil Solar control films	Recessed T5 2x28W 4000 K	Manual on–off DLC closed loop Individual override close to windows Central control for central section Institutional dimming 50% and shut-off after working day	[81,82]
BR UniBrasilia (2017)	O-M	External horizontal brise solei (North) Solar control films and internal curtains (South)	Recessed T5 2x32W 4000 K	Manual switch on–off	[83–85]
CH BankChina+ (2019)	O-M	Sidelighting with shading	Several luminaires type (depending on space) with white dimmable LED 2700 K – 6000 K	Peer to peer distributed network Integrative lighting with 0–100% dimming in all spaces Offices with two settings: "health" with integrative lighting and human-in-the-loop "energy" with DLC and occupancy Meeting rooms with scene settings	
CH CABR* (2013)	O-M	Sidelight windows with venetian blinds Vertical daylight pipes	655 sets of highly-efficient luminaires, including dimmable and tunable LED	Automated blinds Occupancy DLC POE with mobile APP control	[77]
CH NAC (2019)	S	ETFE Inflatable pillows	High power dimmable LED	Scene settings and dimming at luminaire level via DMX512 system	
DE DIAL+ (2013)	O-M	Central atrium with skylight Perimeter offices with side window and automatic external blinds (adjustable slats) with manual override Glass partitions to harvest daylight from atrium	Indirect ceiling LED 2x80W 6500 K (general lighting) LED spotlights 20 W (*accent* lighting)	Fully integrated BMS Automated shadings DLC closed loop Individual adjustments of illuminance, blinds positions PC app, no traditional switches	[77,86]
DE IBP_Daylight (2019)	O-2-LB	Micro-optical PMMA sheets integrated in upper clerestory window; Automated venetian blind in lower view window	Direct-Indirect LED dimmable pendant Injected LED on one side of the micro-optical sheets	DLC closed loop Shade control for direct sun	[87–89]
DE IBP_LED (2019)	O-2-LB	Micro-optical PMMA sheets integrated in upper clerestory window; Automated venetian blind in lower view window	Direct-Indirect LED dimmable pendant Injected LED on one side of the micro-optical sheets	DLC closed loop Shade control for direct sun	
DE IKEAKaarst+ (2018)	R	Sidelit windows in living room department (dpt) Fully glazed facades with automatic venetian blinds in home decoration dpt	Linear LED and LED spotlight in living room dpt LED linear, LED spotlights, and LED integrative panels in home decoration dpt	Institutional shut-off DLC closed loop Integrative lighting in home decoration dpt	[29,83,90]

Table A1 (*continued*)

ID (YEAR of LAST (DAY)LIGHTING REFURBISHMENT)	SPACE TYPE	DAYLIGHTING	LIGHTING	CONTROL	REFs (in addition to [23])
DK Navitas	O-M	Sidelit windows nearly across whole width of classrooms and offices Window sill at ca. 0.9 m height	Linear T5-fluorescents (49 W, 4000 K)	Occupancy (automated) Daylight-dependent dimming with setting at 300 lx Override function Manual roller shades	
DK PsychiatricH+	H-H	Sidelit windows across width of room Window sill at ca. 0.9 m height	3 recessed LED downlights during daytime (2700 K), 2 recessed LED downlight during night (2000 K)	Central control operation for switching between day and night for integrative lighting purposes (2 settings only) Manual on/off control in room Manual curtains	
DK Rehab+	H-R	Sidelit window in each room	2 LED ceiling luminaires, 1 LED-Wallwasher (2700 K – 5500 K)	Central control for scheduled integrative lighting changes across day and night 4 manual settings via switches in room Emergency lighting switch Manual on/off in room	[83,91–93]
ES IDOM (2010)	O-L	Internal roller shade (North) Microperforated double-skin façade and internal roller shades (South) Skylight	T5 2x28W (104 lm/W) 4000 K pendants, dimmable Compact CFL 2x26W	Manual shading DLC	
IT		AbaziaSanLorenzo* (2020)	O-I-LB	Two internal motorized roller blinds (one shading and one blackout)	Six
dimmable (in 7 steps) and tunable (in 3 steps) LED luminaires		Manual remote controls for both lighting and shading, placed on the users' work plane	[94–97]		
NO Norconsult (2020)	O-I-LB	Horizontal light pipe Manually operated venetian blinds (in fixed position during monitoring)	Two dimmable LED pendant 22 W	Daylight on–off with DLC	[98–100]
SE TheSpark+ (2019)	O-M	Central atrium with skylight Glass partitions to harvest daylight from atrium Perimetral offices with side windows and automatic internal roller shades with manual override Different glazing and façade constructions depending on the façade	Recessed ceiling LED lighting 2300 K – 6200 K	Roller shades manual switch Integrative lighting schedule with manual override Scene setting	
US DualZoneShade (2018)	O-M	Manual or automated inverse venetian blind in upper clerestory; transparent film roller shade in lower view window	Dimmable fluorescent lighting in response to daylight	Automated upper blinds (slat angle and raise/lower)	[101]
US NewYorkCity (2017)	O-L	Automated indoor roller shades with manual override	Indirect/ direct, pendant LED fixtures with occupancy, daylight, and setpoint tuning closed-loop control per fixture	Shade control for direct sun, glare, solar load, daylight, and view	
US PortlandEC (2016)	O-M	Automated switchable electrochromic (EC) windows with manual override	Manual, on/off control of fluorescent lighting with occupancy sensing	EC windows switched to minimize glare, solar load and maximize daylight and views	[102]
US SoSanFrancisco (2015)	O-M	Automated indoor roller shades with manual override	Indirect/direct pendant LED fixtures with occupancy, daylight, and setpoint tuning closed loop control per fixture	Shade control for direct sun, glare, solar load, daylight, and view	[31,33]

"Space type": O-M = Office Mixed, O-L = Office Landscape, H-R = Healthcare Residence, S = Sport venue, R = Retail, H-H Healthcare hospital, O-I = Office Individual, O-2 = Office two occupants. LB = Living Lab setting.
"Years" refers to construction year or year of latest refurbishment of daylighting and lighting.
"+" and "*" indicates integrative lighting projects. "+": Project with integrative control of electric lighting only. "*": Project with integrative control of electric lighting (includes source contributions from daylight).

Table A2
Modes of shading and lighting control for integrated and integrative performance requirements.

Mode No.	Control mode	Case study ID
1	Integrative & Integrated: Automatic CCT and intensity (C&I) integrative control of LEDs to top up available daylight; automatic integrated control of lighting and shades for visual (daylight, glare) and other requirements (energy-efficiency, thermal comfort, indoor environmental quality, etc.)	AT Bartenbach, CN CABR, DE IKEAKaarst, IT AbaziaSanLorenzo (manual remote control with training)
2	Integrative: Automatic C&I integrative control with LEDs to top up available daylight	CN BankChina, DK PsychiatricH, DK Rehab
3	Integrative: Automatic C&I integrative control with LEDs, daylight contribution not included	SE TheSpark
4	Integrated: Automatic control of lighting & shades for visual and other requirements	DE DIAL (automatic shades; manual, intensity-controlled lighting), DE IBP_LED, DE IBP_Daylight, US DualZoneShade, US NewYorkCity, US PortlandEC, US SoSanFrancisco
5	State-of-the-art: Automatic control of electric lighting via daylight responsive and other modes (e.g., scheduling, occupancy, etc.)	AU Aurecon, BE Stephenson, BR MME, CN NAC, DK Navitas, ES IDOM, NO Norconsult
6	Other: fixed or manually controlled shades, manual control of electric lighting or automatic modes based on occupancy.	AU AECOM, BR ForumSoPinto, BR Unibrasilia

Table A3
Main design objectives.

ID	SPACE TYPE	DESIGN OBJECTIVES
AT Bartenbach	O-M	Balancing comfort and energy use by maximizing daylight provision, exploiting advanced lighting control, and offering individual control to occupants.
AU Aecom	O-L	Increasing visual comfort and satisfaction, while reducing energy use by maximizing daylight provision with individual control of blinds
AU Aurecon	O-L	Increasing visual comfort and satisfaction, while reducing energy use with lighting controls and by maximizing daylight provision with individual control of blinds
BE Stephenson	H-R	Covering visual and non-visual requirements throughout the day
BR ForumSoPinto	O-M	Balancing solar protection with lighting loads, while providing comfortable visual environments and view out
BR MME	O-M	Exploiting energy saving with lighting controls
BR UniBrasilia	O-M	Evaluating daylighting provision, its relative potential for energy saving, and its benefits beyond savings
CH BankChina	O-M	Retrofitting lighting with advanced solutions to reduce energy use and increase qualities of the space
CH CABR	O-M	Saving energy for lighting via different integrated solutions in different spaces
CH NAC	S	Saving energy for lighting and satisfy visual (and broadcasting) requirements for the particular case of a sports venue, by exploiting skylight and using advance electric lighting systems
DE DIAL	O-M	Complete BMS balancing comfort and energy use by maximizing daylight provision, exploiting advanced lighting control, and offering individual override to occupants.
DE IBP_Daylight	O-2-LB	Guaranteeing daylight penetration in room depth, while preserving visual comfort, access to view, and save energy for lighting.
DE IBP_LED	O-2-LB	Guaranteeing lighting penetration in room depth via LED illuminated microstructure, while preserving visual comfort, access to view, and save energy for lighting.
DE IKEAKaarst	R	Improving customer experience by introducing daylight in exhibition areas; increasing workers' wellbeing with daylight and integrative lighting. Saving energy for lighting.
DK Navitas	O-M	Providing energy-efficient lighting as part of sustainable design and certification.
DK PsychiatricH	H-H	Improving staff and patients' circadian rhythms with integrative lighting.
DK Rehab	H-R	Improving staff and patients' experience via different lighting scenes aimed at better circadian entrainment.
ES IDOM	O-L	Maximizing daylight provision and reduce energy use with out-of-the-box solutions.
IT AbaziaSanLorenzo	O-I-LB	Providing extensive individual control on light environment and reducing energy use for lighting via occupants training, available switch interfaces, and prompts.
NO Norconsult	O-I-LB	Maximize daylight penetration in deep room with HLP, while saving energy with DHS and guaranteeing comfort
SE TheSpark	O-M	Increase wellbeing and alertness of occupants via integrative lighting
US DualZoneShade	O-M	Increase solar control, daylight and view with a retrofit shading and daylighting technology
US NewYorkCity	O-L	Improve energy efficiency, comfort and indoor environmental quality in existing open plan perimeter office zones
US PortlandEC	O-M	Increase comfort, daylight and views, and balance peak cooling demand in an existing building
US SoSanFrancisco	O-M	Balancing comfort and energy use by maximizing daylight provision and exploiting advanced lighting control. Demonstrating the importance of M&V

Table A4
Data collected for each case study. M = Measured, C = Calculated, S = Simulated.

ID		ENERGY		VISUAL		NON-VISUAL		USER
AT Bartenbach	M	LENI	MS	Illuminance, presence, dimming level (longitudinal); DF, DA (simulated), HDR for DGP	M	CCT, Ev, EML, M/P (measured for daylight, electric lighting, mix)	M	Questionnaires to occupants (appreciation, perception)
AU Aurecon	C	LENI for different scenarios-	M	HDR at individual level via calibrated smartphone for DGP and DGI, cylindrical illuminance via low cost distributed sensors (longitudinal)	M	M/P via measured SPD	M	Questionnaire to occupants (preference, glare)
AU Aecom	C	–	M	HDR at individual level via calibrated smartphone for DGP and DGI, cylindrical illuminance via low cost distributed sensors (longitudinal)	M	M/P via measured SPD	M	Questionnaire to occupants (preference, satisfaction, glare)
BE Stephenson	S	LENI for different scenarios-	S	DF, sDA, Spatial Glare Distribution (calibrated Climate Studio simulations)	S	EML, M/P, CS (calibrated ALFA simulations) ; use of personas	M	Discussion with personnel
BR MME	C	LENI calculated (long term), measured baseline + intervention (short term for checking energy savings)	M	Horizontal illuminances, DF, view out, HDR for directionality, luminance for contrast	M	EML via illuminance meter method	M	Questionnaires to occupants
BR Forum SoPinto	C	LENI calculated	MS	Measured illuminances, Simulated sDA, ASE, UDI, view out	M	EML via illuminance meter method	M	Questionnaires to occupants
BR UniBrasilia	S	LENI and LPD simulated via Design Builder)	MS	Measured horizontal, vertical, cylindrical illuminance, view out, HDR for directionality; simulated DF, Annual DGP.	M	EML via illuminance meter method	M	Questionnaires to occupants
CH CABR	M	Measured LENI, LPD	M	Measured illuminances, ADF, U0, SPD, CCT, CRI	–	–	M	Questionnaires to staff
CH NAC	C	Calculated LPD and energy use	M	Measured horizontal and vertical illuminances, UGR, CCT, CRI	–	–	M	Informal chats
CH BankChina	C	Total energy use (kWh), LENI calculated	M	Measured illuminances, ADF, U0, SPD, CCT, CRI, Stroboscopic ratio, UGR, spot luminance	–	–	M	Informal chats
DK PsychiatricH	C	Calculated LENI based on field power data and schedule	M	Horizontal illuminance, HDR for DGP and UGR, SPD, CCT, CRI Ra	M	Measured M-EDI, CS	M	Interviews with staff
DK Navitas	M	Energy use for selected days	M	DF, illuminance (logged), HDR	M	Measured M-EDI, CS	M	Interviews with occupants
DK Rehab	C	LENI calculated, DIALux simulations based on monitored data	M	Measured illuminances	M	Measured M-EDI, CS, Pattern of light intake with wearable sensors	M	Semi-structured interviews
DE IBP_LED	M	Installed power (W/m2 100 lx)		Measured illuminances	–	–	M	Within-subjects surveys
DE IBP_Daylight	M	Energy use (kWh)		Measured illuminances	–	–	M	Within-subjects surveys
DE DIAL		–	C	Design values	–	–	M	Informal chats
DE IKEAKaarst	C	Calculated LENI based on measured usage pattern	MS	DF, DA, cylindrical illuminance, DGP, view out	M S	M/P ratios (calibrated ALFA simulations)	M	Questionnaires to visitors; interviews, and survey to employees
IT		AbaziaSanLorenzo	M	Measured power for different scenarios	M	Measured horizontal and vertical illuminances, occupancy (longitudinal); SPD, CCT, view out, shade properties	M	EML, M/P, M-EDI (measured for daylight, electric lighting, mix)
M		Interviews with occupants		NO Norconsult	M	Measured LENI	M	Measured and simulated illuminances (horizontal and vertical)
–	–	M		Questionnaires with occupants	ES	IDOM	S	Simulated LENI via Daysim
MS		Measured DF, reflectance, simulated sDA, UDI, DGP	S	M/P ratios (calibrated Lark simulations)	M	Questionnaires with occupants		
SE TheSpark	C	Calculated LENI based on measured usage pattern	M	DF,SPD, vertical illuminance	MS	M/P ratios(calibrated ALFA simulations) , Pattern of light intake with wearable sensors	M	KSS sleeping scale, interviews

(*continued on next page*)

Table A4 (*continued*)

ID		ENERGY		VISUAL		NON-VISUAL		USER
US PortlandEC	M	Measured LENI	M	Monitored EC tint status, blind position, HDR for DGP, vertical and horizontal illuminance	M	M/P daylight-driven for different times and EC tints, (measured via HDR)	M	Questionnaires to occupants
US DualZone Shade	M	Measured energy for lighting and cooling	M	Measured illuminances, lighting energy, HDR for DGP	–	–	M	Questionnaires to occupants
US NewYork City	M	Measured LENI	M	Measured illuminances, shade height, dimming level, lighting energy, HDR for DGP	–	–	M	Questionnaires to occupants, PPD/PMV for thermal comfort
US SoSan Francisco	M	LPD for different scenarios	M	Measured illuminances, shade height, dimming level, lighting energy, HDR for DGP	–	–	M	Interviews with the facility management

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