

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

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25 **ABSTRACT**

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

42 **KEYWORDS**

43 Daylighting; Electric lighting; Shading; Lighting control; Case studies; Energy saving; View out; Non-
44 visual effects; Integrative lighting; Monitoring and verification.

45

46 **Abbreviations**

47 CIE : International Commission of Illumination

48 DLC : Daylight-Linked Control

49 EBC : Energy in Buildings and Communities programme

50 EC : Electrochromic

51 EFTE : Ethylene tetrafluoroethylene

52 HDR: High Dynamic Range

53 IEA : International Energy Agency

54 LCS : Lighting Control System

55 LENI : Lighting Energy Numerical Indicator

56 M&V : Monitoring and Verification

57 POE : Post-Occupancy Evaluation

58 PMMA : Poly methyl methacrylate, also known as plexiglass

59 SHC : Solar Heating Cooling programme

60 UI : User Interface

61 $T_{v,n-h}$: Visible light transmittance, i.e., hemispherical (h) transmittance at normal (n) incidence

62 **Terms**

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

65 **Integrative lighting:** CIE defines integrative lighting as: "*lighting integrating both visual and non-visual*
66 *effects, and producing physiological and/or psychological benefits upon humans*" (in CIE S 017/E:2020

67 ILV: International Lighting Vocabulary, 2nd Edition). Integrative lighting is also commercially known as
68 human-centric lighting, biocentric lighting, etc.

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

70 **1. INTRODUCTION**

71 Buildings are responsible nowadays for 28% of global energy-related CO₂ emissions, and most of these
72 emissions can be attributed to cooling and heating, lighting, and appliance end uses [1]. Lighting in
73 buildings required 430 Mtoe in 2017, which represents 14% of total building energy use (3000 Mtoe in
74 2017). Even with improvements in lighting energy efficiency over recent years – for example, due to the
75 deployment of light emitting diodes (LED) – global energy use for lighting has increased by an average
76 of 2.2% per year since the year 2000. This is due to the increase in demand, rise in purchasing power
77 of emerging economies, and increased floor area associated with population growth [1].

78 Within the building sector, lighting technology has recently witnessed significant advancement, with new
79 policies and recommendations having been introduced towards climate mitigation and decarbonization
80 targets. Conversely, much improvement is still needed in other domains of the building industry, as for
81 example in the design and operation of envelopes [1]. The design of the envelope, in fact, can have a
82 significant impact on the thermal behavior of a building, and improving its performance could increase
83 energy saving by 40%. However, thermally efficient envelopes need to also account for occupants’
84 needs for views and access to daylight [2], which are crucial for physiological and psychological well-
85 being. Hence, careful consideration is needed for integrating daylighting with electric lighting towards
86 more energy efficient solutions, while also fostering the health and well-being of users [3].

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

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

111 Previous international efforts for the integrated evaluation of daylighting and electric lighting solutions
112 have included, among others: the "Daylight Europe" programme (1994-1997), which monitored 60 case
113 studies of daylighting design in European buildings [19]; the International Energy Agency Solar Heating
114 and Cooling (IEA SHC) Programme Task 21 "Daylighting in buildings", which evaluated innovative
115 technologies for daylighting with performance monitoring in case studies [20]; and the IEA SHC Task
116 51, which monitored advanced lighting solutions for 24 retrofitted commercial buildings [17, 21].

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

124 The case studies focus on non-residential buildings featuring a wide range of state-of-the-art and
125 innovative daylighting and lighting strategies. Reduction of energy demand for lighting was usually a

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

137 **2. METHODS**

138 **2.1. Selection of the case studies**

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

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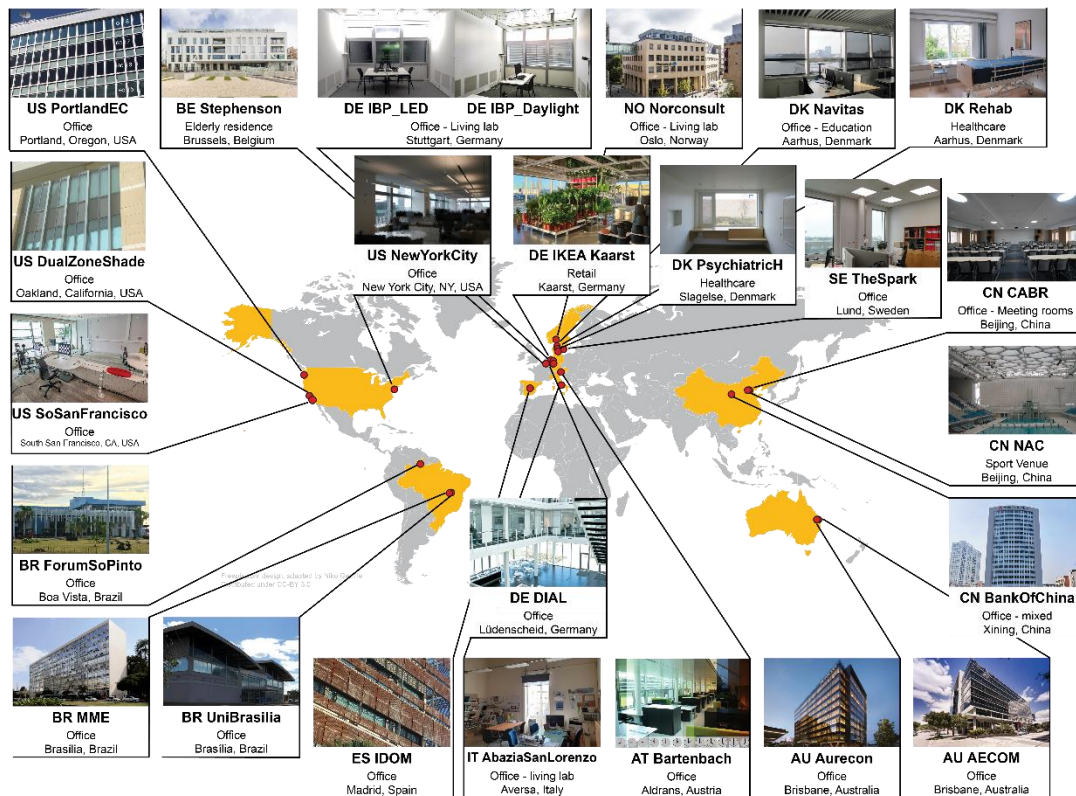


Figure 1. Geographical distribution of the case studies.

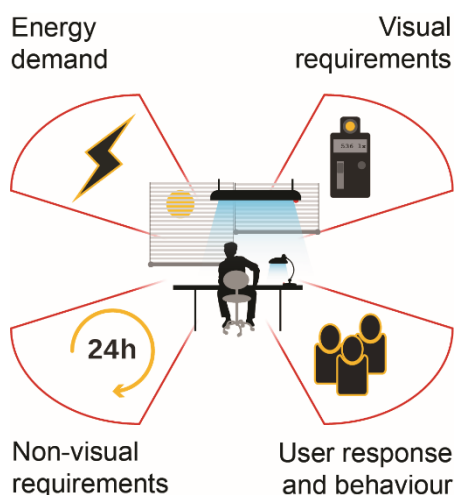
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152 The buildings included a variety of integrated solutions (Table A.1). Considering that most of the cases
 153 studied were newly built or recently retrofitted, several of the solutions included innovative technologies,
 154 such as spectrally-tunable LED lighting, automated shades or blinds, advanced controls and their
 155 integration with building management systems (BMS), integrative lighting, and the like. Control solutions
 156 were implemented using a wide variety of methods: integrative, integrated, or both (Table A.2). Case
 157 studies with more conventional solutions were also included. Most projects were designed to achieve
 158 specific goals (Table A.3 **Error! Reference source not found.**) with tailored solutions aimed at reaching
 159 the targeted objectives. Some cases had additional goals beyond improved energy efficiency and
 160 lighting quality, depending on their specific function (e.g., improving sleep quality in a rehabilitation
 161 facility). Clearly, local climate characteristics also affected the definition of objectives and of the
 162 solutions adopted, as was the case of cooling-dominated countries where the ingress of daylight had
 163 to be weighed against the risk of introducing unwanted solar gains. However, the monitoring focused
 164 on the lighting performance only. Summary details on each case study are provided in the form of freely
 165 available factsheets on the IEA SHC Task 61 / EBC Annex 77 website [22], were climatic information

166 of the site are also available. Details are also included in a project report [23]. Supplementary reference
167 sources for the case studies are given in Table A.1.

168 2.2. Monitoring process

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



177 **Figure 2. The four foci of the case studies monitoring.**

178
179 The monitoring primarily included field measurements, complemented, when necessary, by calculations
180 and computer-based performance simulations. This was particularly the case when spaces could not
181 be accessed during the periods of lockdown, or when specific metering for electric lighting alone was
182 not available. Table A.4 provides an overview of the data that were collected for each case study.

183 3. LESSONS LEARNED

184 3.1. Energy use

185 Technologically speaking, and without consideration of integrative lighting control, use of efficient LED
186 sources, granular lighting controls, advanced shading and daylighting control, and informed
187 commissioning and operations were shown to result in significant reductions of lighting energy use
188 compared to state-of-the-art practice. Annual energy use was, at least, three times lower compared to
189 current benchmarks (e.g., [25, 26]) when innovative technologies were used. This corresponds to
190 approximately 5-6 kWh/m²-y for most of the office case studies (Table 1). Switching to efficient light
191 sources corresponded to 41-59% of the total savings (the remainder were due to lighting controls) for
192 the US NewYorkCity case, which was in line with the expected savings from existing office buildings
193 retrofitted using efficient LEDs [27, 28].

194 When integrative LED lighting control was implemented with spectrally-tunable LED sources, without
195 including the contributions from daylight, annual lighting energy use was significantly greater than
196 benchmarks. As an example, the SE TheSpark annual energy use was 22.43 kWh/m²-y compared to
197 the 14.80 kWh/m²-y benchmark¹ provided in Table M.1 of EN15193-2:2017 [25].

198 When integrative lighting control included both LED and daylight contributions, annual lighting energy
199 use was significantly lower than benchmark levels, particularly for cases when daylighting and shading
200 strategies were well conceived and implemented conscientiously. With the AT Bartenbach case study,
201 owing to an integrated design planned from the early design stage and followed-up during the
202 operational phase, different daylight strategies were implemented to provide natural illumination to the
203 whole space. The design strategies included daylighting with windows, external static daylight
204 redirecting louvres on the south façade, and sloped linear skylights on the north façade, in combination
205 with fine-tuned integrative lighting controls that included daylight. With such strategies in place, the
206 resulting monitored lighting energy use was very low: 3.65 kWh/m²-y. In the CN CABR project,
207 monitoring of eight spaces, including offices and meeting rooms, resulted in an average lighting energy
208 use of 6.15 kWh/m²-y with monitored lighting power densities per space type that were considerably

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/m²; 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).

209 lower (between 11% and 39%) than benchmark levels². This figure can be attributed to a combination
 210 of efficient LEDs, a good daylight design featuring sidelight windows and tubular daylighting systems,
 211 and their controls.

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

215 The SE DE IKEAKaerst case study was an atypical project, where daylighting integration in a furniture
 216 store almost halved the annual lighting energy use in one of the monitored departments: 41.4 kWh/m²-
 217 y calculated on real usage patterns [29] compared to 78.1 kWh/m²-y as per the EN15193-2:2017
 218 benchmark [25]. This was achieved despite operational issues with the control system. In addition to
 219 energy benefits, this case study also showed the potential of integrated daylighting in enhancing the
 220 customers' shopping experience.

221 Key lessons learned

- 222 • Energy demand for lighting has been drastically reduced through a combination of daylight
 223 provision, more efficient light sources, and advances in control technology. With wide
 224 adoption of current dimmable LED systems, it is now possible to achieve annual lighting
 225 energy use as low as 3-4 kWh/m²-y in office spaces.
- 226 • If not properly designed and coordinated with daylighting, integrative lighting strategies
 227 may lead to significantly increased electric lighting energy demands (rebound effects),
 228 particularly due to high vertical illuminance requirements during the daytime.

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

Case study ID	Energy Use for Lighting (kWh/m ² y, 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 7.7 / 7.8	Bedroom before / after improvement (simulated value; for typical days) Dining room before / after improvement (simulated value; for typical days)
BR MME	17.23	Calculated LENI
BR ForumSoPinto	16.80 (13.70 / 20.10)	Average calculated LENI (min / max) calculated LENI
BR UniBrasilia	109.00	Simulated annual lighting energy use

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

Case study ID	Energy Use for Lighting (kWh/m ² y, unless specified)	Description of energy use / Further details on how the energy use / lighting power requirements were obtained
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 ² y)
DE IKEAkaarst	40.30 / 41.30 84.00 / 84.70	“living room” with DHS / without DHS “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 ² y (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 .

231

232

3.2. Lighting controls

233

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.

238

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).

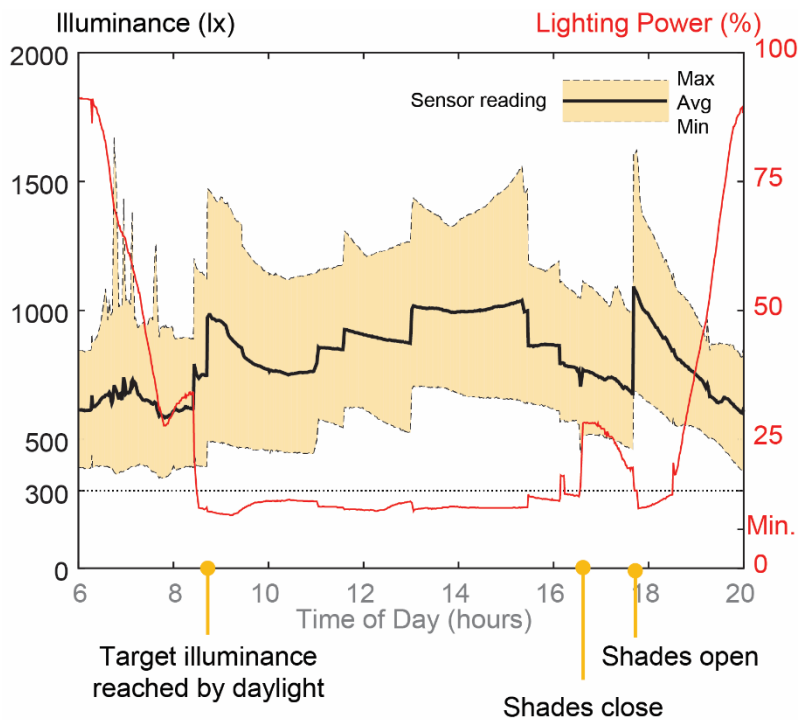
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Coupled with re-lamping from efficient T5 to very efficient LEDs, this strategy helped reduce lighting energy use by 25% in the AU Aurecon. Solutions included grouped control of fixtures associated with a daylit zone or highly granular control per 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/m²-y for a 15 m deep sidelit office in Madrid (ES IDOM) [34]. Daylighting controls are effective even in spaces different from offices.

246

247 DLCs were estimated to reduce annual lighting energy use by 59% and 54% compared to the existing
248 systems for the DK PsychiatricH and DK Rehab case studies, respectively.

249 Commissioning is key to achieving performance goals and user satisfaction with lighting and shading
250 controls. This is particularly important for DLC systems due to the dynamic nature of the source (i.e.,
251 variable solar position and changeable cloud cover). The analyzed case studies used closed- and open-
252 loop DLC [31, 33], with some systems adopting innovative algorithms to achieve reliable control. In the
253 US SoSanFrancisco study, monitored data in a full-scale testbed showed that the open-loop DLC
254 system maintained the target illuminance level for 70% of the operating time (Figure 3). Self-
255 commissioning routines determined source contributions at each photosensor, decreasing occurrences
256 of over-dimming. In contrast, the closed-loop DLC system maintained target levels for only 56% of the
257 time. Separately, the control of the automated shading system was finetuned to balance daylight, glare,
258 and view requirements. A 30-day burn-in period was reserved to commission all controls at the
259 completion of the 24,000 m² office building, during which the open-loop DLC and shading systems were
260 re-evaluated and fine-tuned, particularly in atypical areas such as open plan zones with sidelit windows
261 on three facades. The resulting DLC reduced daytime lighting power density (LPD) by 74% (5.52 W/m²
262 to 1.40 W/m²) in zones with a depth between 6.1 m and 9.1 m, coherent with the testbed outcomes [31,
263 33].



264

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

268

269 The DLCs did not always perform as desired. In the NO Norconsult, sunlight reflected from nearby
 270 venetian blinds onto the photosensor caused over-dimming, resulting in the system delivering 230 lx on
 271 the work plane instead of the target 500 lx. Similar issues have also been highlighted in the literature
 272 [35, 36]. In the atypical retail case (DE IKEAKaarst), the ceiling mounted photosensor was taped over
 273 by the employees due to unreliable control caused by changes in surface reflectances within view of
 274 the photosensor (Figure 4). The merchandise was changed and rearranged frequently while movement
 275 from a nearby sliding curtain caused annoying fluctuations in light output. It was observed at the DK
 276 PsychiatricH that abrupt stepped switching (due to changes in setpoint from day-mode to night-mode)
 277 or non-gradual dimming led to occupant annoyance, whereas gradual dimming up and down in the DE
 278 DIAL case study was appreciated by users. Whether the scope was to fine-tune the lighting control
 279 system, as it was the case with AT Bartenbach and US SoSanFrancisco, or to discover and fix issues,
 280 as with DE IKEAKaarst and NO Norconsult, monitoring and verification (M&V) was demonstrated to be
 281 of utmost importance to achieve target performance goals. This is discussed further in Section 3.7.



282

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

286

287 In some occasions, the literature has warned of increased energy use due to LCS standby power,
288 especially in cases with good daylight design, very efficient light sources, and low occupancy rate [37,
289 38]. For example, standby power due to the wireless communications connection accounted for 11 W
290 (24.7% of full power) out of the total 30-178 W for LED lighting (depending on the setting) in the large
291 26 m² private office of the IT AbaziaSanLorenzo case study (with LPD of 6.84 W/m² at 500 lx on
292 workspace). This standby power use accounted for at least a third of the total lighting energy use during
293 the observed period. For some lighting sources, manufacturers may advise against switching to standby
294 power due to concerns of shorter lamp life, in which case power use at minimum dimming levels
295 (approximately 20-35% of full power for fluorescent lighting) can significantly decrease potential energy
296 savings. With LEDs, both minimum and standby power are less of an issue compared to fluorescent
297 sources. Bench-scale measurements of LED fixtures in the US NewYorkCity building yielded a dimming
298 range of 10-100% of full power and a standby power of less than 1 Watt to power the radio
299 communications network. In addition, raising the standby question at the design phase can help
300 contextualize it. For example, at AT Bartenbach, the energy demand for the integral building control,
301 which included extensive LED lighting sensing and control, was measured to be 1.09 kWh/m²-y, which
302 was almost a third of the 3.65 kWh/m²-y used for the lighting itself. However, without the perfectly fine-

303 tuned LCS (DLC and occupancy) and the excellent daylight design, the projected energy use for lighting
304 would have been about 16.5 kWh/m²-y. In addition, as an example of good practice, the LCS installed
305 at US SoSanFrancisco contained a relay that switched off the power to the LED driver, thus reducing
306 standby [31].

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

316 Key lessons learned

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

325 **3.3. Control interface**

326 Providing an easy to understand and accessible user control interface for tailored adjustments and/or
327 manual override can increase occupant satisfaction and reduce energy use [39]. Individual
328 controllability of light sources is one of the most valued attributes of lighting projects [16, 40, 41].
329 Individual controls for lighting and/or shading were provided in the AT Bartenbach, AU Aurecon, AU
330 AECOM, DE DIAL, IT AbaziaSanLorenzo, SE TheSpark, and US PortlandEC buildings, and were highly
331 valued by users. There is a general concern that provision of manual override control will have a

332 negative impact on energy efficiency. In the IT AbaziaSanLorenzo case study, however, occupants
333 were trained prior to using a fully manual dimmable and tunable lighting and shading system (Figure
334 5). This resulted in very limited use of electric lighting, maximization of daylighting, and high occupant
335 satisfaction. Another strategy is to make control interfaces more user-friendly. Control interfaces need
336 to be designed in such a way that they are intuitive and easy to use [42]. Such design must not to be
337 taken for granted, considering the wide range of control possibilities at the user's end: switching,
338 dimming, tuning, etc. [43]. Well-designed interfaces can enhance the end-user experience and possibly
339 reduce energy demand [39, 44] (Figure 6). In the IT AbaziaSanLorenzo, manual switches for the lighting
340 and shading systems in individual offices were readily available on the desk. Side-by-side placement
341 of the lighting and shading control interfaces was highly appreciated by users, supporting interoperability
342 of the lighting and shading systems, as suggested by previous studies [45]. This, in turn, contributed to
343 reduce energy use. Even simple switch-off controls need careful design, particularly when CCT
344 adjustment is involved. Poorly designed and unlabeled switches at the DK PsychiatricH were reported
345 to be difficult to use by half of the staff, and possibly for many of the patients, to the extent that occupants
346 were unable to understand how to switch off the lights. The literature suggests that different designs of
347 simple switch on-off can lead to a threefold increase in lighting energy use [39, 46].

348 Forty-seven percent of occupants in the open plan office at the AU Aurecon believed that control over
349 lighting was important. This design included manually controlled blinds, and allowed manual override
350 over the automatic dimming and switching of luminaires. The former was achieved via a remote control
351 with text labels, whose meaning was likely unfamiliar to the general population (e.g., "300 lux"). A better
352 solution was adopted in the DE DIAL building, where a digital interface provided a wide array of control
353 settings via intuitive graphic icons (Figure 6). The BR MME case study monitored offices of different
354 sizes. For smaller offices hosting up to two employees, a manual-override switch and dimming interface
355 at the door was enough to provide 65% of satisfied employees. This percentage dropped to 39% when
356 larger offices with more than five occupants were monitored. Here, 43% of the employees complained
357 about having little to no control over the electric lighting, indicating that they were unaware or unable to
358 control the system as desired. The complex design of the control interface adopted in this building,
359 consisting of a long column of identical white colored buttons with codes as label, could help to explain
360 the difficulties experienced in operating the lighting. In addition, some settings could be adjusted only

361 after formal request to the building management, which also raises the issue of “ownership” over
362 automatic lighting control.

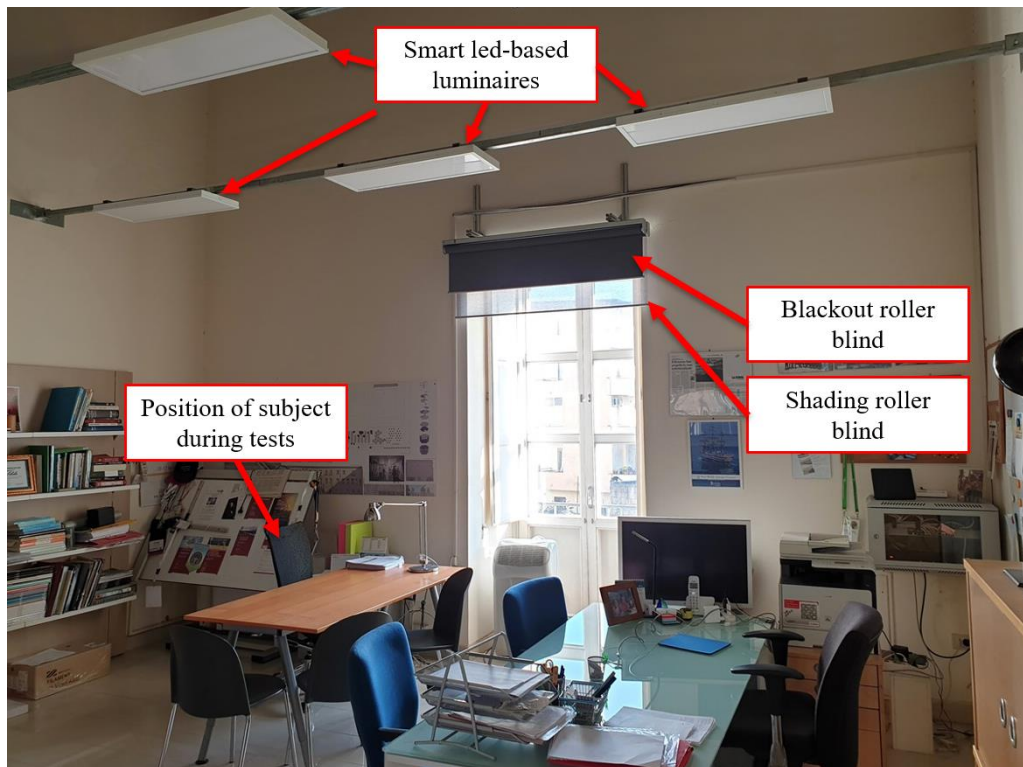






Figure 5. Given the choice, occupants in the IT AbaziaSanLorenzo case study rarely used the electric lights during the two-week test period, preferring to control the shading devices to manage the daylight. Both systems were controlled manually by the occupants using wireless switches placed on the desk,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

363

Intuitive	Non-intuitive
 <p data-bbox="475 510 732 539">IT AbaziaSanLorenzo</p> <p data-bbox="424 544 775 663">Two remotes for shadings, one for lighting, only two buttons, co-located on the desk. Labeled in the original setting</p>	 <p data-bbox="914 510 1059 539">AU Aurecon</p> <p data-bbox="810 544 1134 602">Remote with many buttons, information in "lux", no icons.</p>
 <p data-bbox="552 943 655 972">DE DIAL</p> <p data-bbox="424 976 767 1095">Icons with preview of effects; lighting, shading, and temperature on the same user interface.</p>	 <p data-bbox="887 943 1086 972">DK Psychiatrich</p> <p data-bbox="810 976 1166 1034">Switch with no standard design, unlabeled</p>

364
365 **Figure 6. Control interfaces that were considered easy to use and intuitive (left column) versus confusing**
366 **and non-intuitive (right column). The DK Psychiatrich interface, while simple, did not convey the day-**
367 **versus night-time spectrally-tuned control modes, which led to confusion for about half of the staff.**

368

369 **Key lessons learned**

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

375

376 **3.4. Integrative lighting**

377 Integrative lighting is defined as “*lighting integrating both visual and non-visual effects, and producing*

378 *physiological and/or psychological benefits upon humans*” [47]. Several metrics were used in the case

379 studies to measure the non-visual (or non-image forming, NIF) effects of light [48]; an overview of

380 metrics and recommended values is provided in Table 2. The metrics were derived from the photopic
 381 measurements (or simulations) taken vertically at eye level for all case studies.

382 **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) $0.7 \leq M/P \leq 0.9$ 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]

383

384 Ten out of the 25 case studies had effective implementation of integrative lighting strategies among
 385 their design objectives. This was often achieved with dynamic schedules of light intensity (dimming)
 386 and correlated color temperature (CCT) (tuning), as presented in Table 3³, with and without
 387 consideration of contributions from daylight (Table A.2).

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

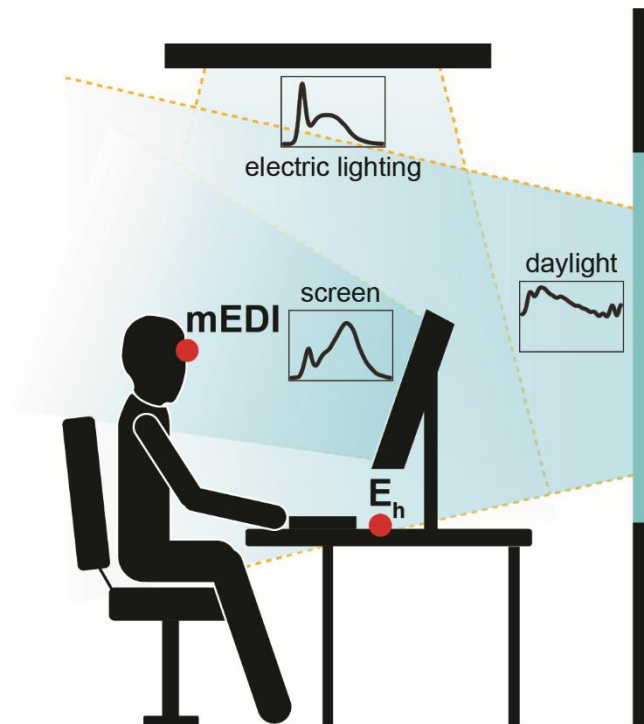
Case study	(Photopic) Illuminance		CCT	Notes
	Quantity	Values		
AT Bartenbach	E_h	450-1100 lx	2174 ~ 4095 K	Avg at max light output: $E_h=816$ lx, $E_v=310$ lx. When dimmed to avg $E_h=500$ lx, then $E_v=190$ lx.
CH CABR	E_h	na	3300 ~ 5300 K	
CH BankChina	E_h	127 ~ 615 lx	2939 ~ 5394 K 4225 ~ 6030 K 3616 ~ 5645 K 3497 ~ 5945 K	First row E_h and CCT refers to exemplary office, other CCT rows refer to other monitored spaces for which E_h is na
DK PsychiatricH	E_h	100 ~ 250 lx	1750 ~ 2700 K	

³ Table 3 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.

DK Rehab	E_h	47 ~ 430 lx	2700 ~ 5500 K	
DE DIAL	E_h	0 ~ 1200 lx 0 ~ 2000 lx 0 ~ 3000 lx	$na \sim 6500$ K	Each E_h range indicates target illuminance for 0-100% dimming. The occupant can select different dimming ranges, each providing the $na \sim 6500$ 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.

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



396

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

402

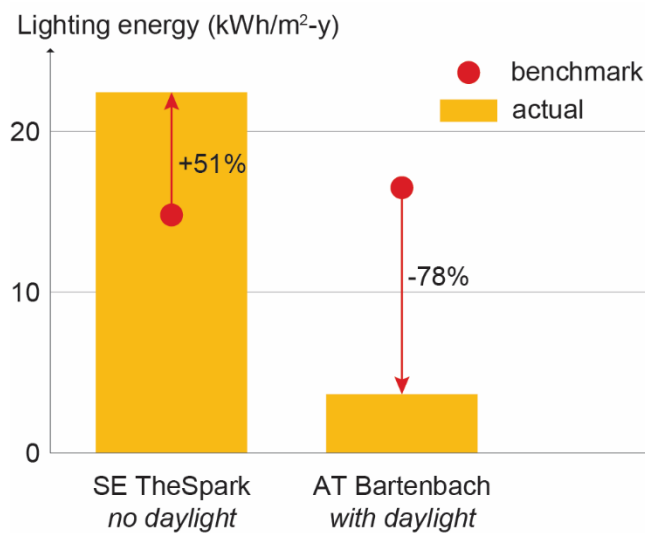
403 When the focus was on non-visual requirements, traditional lighting design based on electric lighting
 404 only resulted in high energy use (Figure 8). At SE TheSpark, the LED system was capable of catering
 405 to multiple settings of varying intensities, ranging from a maximum of ≈ 600 EML measured vertically at

406 eye for the “boost” scene (CCT of 6200 K; M/P = 0.97) to a minimum of less than 100 EML for the
407 “lounge” scene (2300 K; M/P = 0.51) [57]. With respect to visual requirements, these settings resulted
408 in E_h comprised between ≈ 1218 lx (or more in some rooms) and ≈ 640 lx for the two settings,
409 respectively. This resulted in a calculated LENI of 22.43 kWh/m²y, which was slightly above current
410 benchmarks and well above the energy performance levels of many of the other case studies. However,
411 including daylight in the design of the system would have largely lowered the energy use. Indeed,
412 measurements performed with daylight under clear sky conditions provided much stronger non-visual
413 stimulation, outdoing the effect of electric lighting (from over 2300 EML, M/P= 1.00 to about 250 EML,
414 M/P = 0.95 for the two scenes⁴). Even under overcast sky, the EML boost setting were raised from \approx
415 600 EML to ≈ 1000 EML due to daylight contribution [57].

416 When the focus was on visual needs, electric integrative lighting systems alone could not provide
417 sufficient non-visual stimulation, but these designs would have succeeded in supporting non-visual
418 requirements if the contributions of daylight had been considered when “sizing” the electric lighting
419 system. For example, the integrative electric lighting design at AT Bartenbach office provides $E_h = 500$
420 lx on the desk, but only $E_v = 190$ lx at the eye. This corresponds to 138 EML from the electric lighting
421 system, which is well below the requirements demanded by the WELL Building Standard v2.0 to achieve
422 up to 3 credits for integrative lighting [50]. This project, however, provided adequate daylight via
423 automated control of external louvers, skylights, and view windows (e.g., $E_v = 1898$ lx to 2576 lx with
424 and without shades on a partly cloudy day). With adequate daylight provision, daytime non-visual
425 requirements were met even in the absence of electric lighting, with values reaching 842 EML and 1647
426 EML during an overcast and sunny sky day, respectively. The integrative electric lighting system was
427 sized to deliver $E_h = 500$ lx on the task area even for the office at IT AbaziaSanLorenzo. In such
428 conditions, the electric lighting could only achieve 190 lx mEDI at the eye at its highest intensity levels
429 ($E_h = 500$ lx, CCT = 4000 K). However, the measured mEDI with daylight only varied between 89 and
430 346 lx throughout a partially overcast day, despite a relative low daylight penetration (this was a
431 historical building in Southern Europe with small windows, thick walls, and high ceiling). At DK Navitas
432 there was no integrative lighting installed, but only a carefully integrated daylight design. Calculated CS
433 and mEDI levels in the building for daylight only were close to the targets during mid-day hours on

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.

434 January 21st. CS and mEDI levels increased substantially when light from the computer displays was
 435 taken into account. This must be considered in future designs since office work, nowadays, is conducted
 436 almost exclusively in front of computer screens (Figure 7). At DE IKEAkaarst, M/P Ratios for mixed
 437 daylight and electric lighting, measured during a March afternoon, were found constantly higher than
 438 0.9 when daylight was in the field of view [29].



439

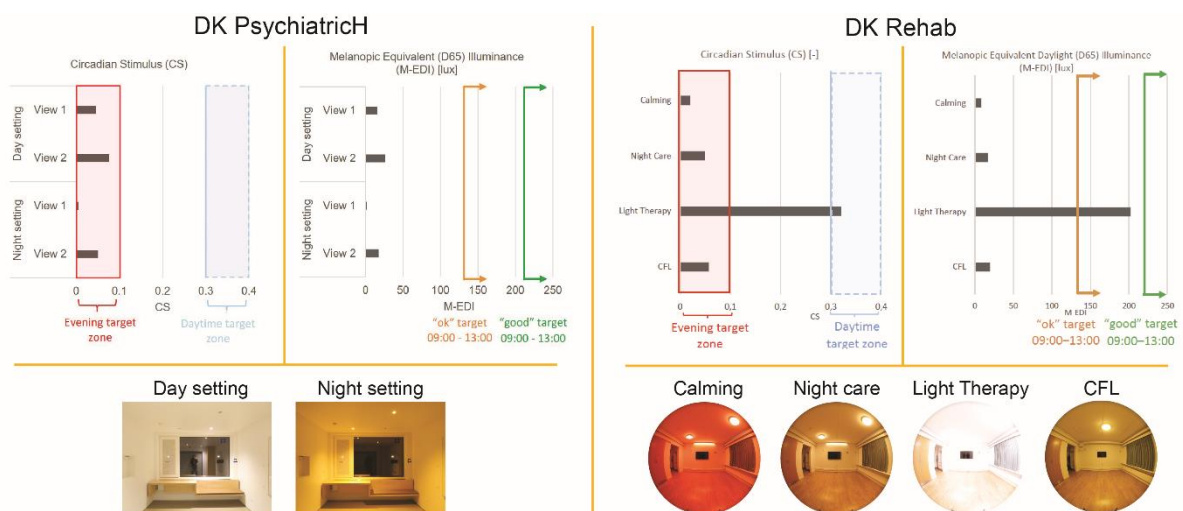
440 **Figure 8. Energy use for lighting for the SE TheSpark (focus on non-visual requirements, daylight excluded**
 441 **from the initial design) and the AT Bartenbach (focus on visual requirements, daylight included in the**
 442 **lighting design) case studies. Integrative lighting based on electric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

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

448 A well-balanced integrative lighting design should guarantee high values of mEDI, CS, EML, and M/P
 449 ratio during the daytime. These values should be lowered when evening approaches (Table 2). This is
 450 harder to achieve in residence-like spaces, as compared to offices with typical daytime (i.e., 09:00-
 451 17:00) occupancy. For example, in the BE Stephenson residential care home for the elderly, non-visual
 452 response targets were hardly reached during early morning and evening hours. Daylight provided
 453 insufficient non-visual stimulation in bedrooms during the morning (CS = 0.02, 12 EML), and excessive
 454 exposure in the dining room during summer evenings (CS = 0.23, 120 EML). The challenge of
 455 sufficiency and excess, which may arise from a scene's façade orientation, suggests that providing
 456 more daylight at any time is not always the correct solution for proper circadian entrainment. At BE

457 Stephenson, a change in the daily activity schedule and location of occupants was suggested, following
 458 the natural patterns of the sun-path, namely promoting activities in bright sunlit areas in the morning,
 459 and in more sheltered spaces during the late afternoons. This enabled elderly patients (whose threshold
 460 values differ from that of the general population due to ageing [4, 58]) to be exposed to appropriate
 461 levels of non-visual stimulation on all floors at all times of the day and year within the set targets for
 462 visual comfort. Such integrated and integrative design practices, which rely only on changes in daily
 463 schedules of activities rather than technology, can reduce the electric lighting capital costs of meeting
 464 non-visual lighting requirements.

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



476
 477 **Figure 9. Left: CS and mEDI for DK PsychiatricH, measured on 26 Feb 2020 at the eye of a hypothetical**
 478 **observer, 1.2 m above the floor from two viewpoints. Right: CS and mEDI at DK Rehab calculated for an**
 479 **estimated E_v simulated by DIALux at a height of 1.2 m above the floor for the four lighting scenarios. Target**
 480 **values for mEDI refers to WELL v2 [50], see Table 2.**

481

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

493 Key lessons learned

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

505 **3.5. Shading and daylighting systems**

506 The case studies covered a breadth of innovative technological solutions designed to improve daylight
507 admission (e.g., daylight redirecting systems, tubular skylights, and light pipes for core daylighting) and
508 control glare, solar heat gains, sunlight, and access to view (e.g., automated operable shades and
509 dynamic glazing). None of the fenestration solutions were designed explicitly to manage daylight for

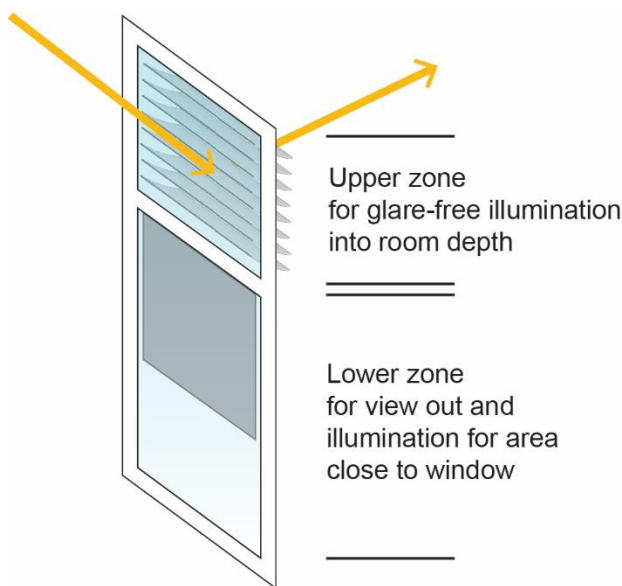
510 non-visual entrainment (as guidance from research is yet vague) nor were the case studies (except AT
511 Bartenbach) designed to monitor the effects of daylight from this perspective. Insights into timing of
512 luminous intensities over the day, distribution of flux within the room, and energy savings were,
513 therefore, generated from available data. Lessons learned pertain primarily to the advantages of
514 integrated shading and lighting design and control, some being relevant to integrative lighting.
515 Architectural design solutions are detailed in Section 3.6.

516 Integrated design was determined to be critical to achieving an adequate balance between competing
517 performance requirements. The AT Bartenbach case study provided monitored evidence of the
518 effectiveness of daylight in an open-plan, 36-m long by 5.5-m deep, office daylit with windows on the
519 south and sloped linear skylights on the north. Direct sunlight and glare were controlled on the south
520 with fixed exterior louvers and an automated exterior roller shade for the upper daylight aperture and a
521 top-down/bottom-up, manually operated, roller shade for the lower view aperture. Similarly, on the north,
522 the sloped skylight was fitted with fixed exterior shading and an automated indoor roller shade. The
523 LED electric lighting system was dimmed in proportion to available daylight according to scheduled
524 CCT and illuminance setpoints. As a result of this holistic design, monitored lighting energy savings
525 compared to the EN12464-1 benchmark (500 lx minimum) were 12.85 kWh/m²-y (78%). Monitored M/P
526 ratios and EML from daylight were 0.946 and 1558 EML respectively at noon on a sunny day, and 0.93
527 and 842 EML respectively on an overcast day.

528 Innovative daylight-redirecting technologies were shown to be more effective than conventional shading
529 solutions in admitting useful daylight. The NO Norconsult case study evaluated a horizontal light pipe
530 that transported sunlight 3.75 m from its 22 cm diameter aperture at the south-facing façade⁵ with
531 maximum output between 10:00 and 14:00 hours. Field measurements indicated that 70% of total
532 monitored workplane illuminance (500 lx setpoint) on sunny days was delivered by the light pipe, this
533 being less effective on overcast days, with only 14% of the total light contribution. Vertical tubular
534 skylights were used to bring daylight from the roof to the core areas of a 15 x 16 m conference room on
535 the top floor of an office building in the CN CABR case study. Monitored average daylight at the
536 horizontal work plane was 305 lx on a sunny day (365 lx if daylight from the windows was included),
537 while the average daylight factor was 0.61% (0.73% also considering windows). In the DE IBP_Daylight

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

538 case study, between-pane, static, large-scale micro-optical panels located in the upper clerestory
539 window were used to redirect sunlight to the ceiling plane far from the window. The advantage of such
540 systems is that, with light-coloured room surfaces, the added reflected and inter-reflected daylight on
541 the upper walls and ceiling is more likely to be effective at responding to non-visual lighting requirements
542 at the eye than conventional shading materials. On a clear summer day, monitored energy use (for non-
543 integrative lighting) in the 6 m deep test office was reduced by 64% compared to the reference room
544 with blinds in the upper window. Over the full period of the monitoring, lighting demand was reduced by
545 58% (May to September). In the US DualZoneShade case study, inverted white horizontal slats installed
546 in the upper clerestory zone of a south-facing window were adjusted automatically to redirect sunlight
547 to the ceiling plane (the blinds were raised under cloudy skies) while, in the lower part of the window,
548 a transparent film ($T_{v,n-h} = 0.02$) roller shade was manually adjusted. In the 4.6 m deep monitored testbed
549 office, average lighting energy savings were 51% compared to a partially-lowered fabric roller shade
550 during the summer period (Figure 10).



551

552 **Figure 10. Dividing the opening in two zones might be an effective solution to provide both glare-free**
553 **illumination in deep rooms and a view out. The DE IBP_Daylight, DE IBP_LED, and US DualZoneShade**
554 **case studies adopted different designs based on two zones openings, see Table A.1.**

555

556 The design and control of shading systems can significantly affect temporal availability of daylight. Use
557 of manual shading devices in the DK Navitas building affected daylight and energy use differently from
558 space to space, depending on the users. Active users frequently adjusted the shades in response to
559 daylight/sunlight conditions and the presence of glare, while less active users often left the shades

560 closed even when no direct sunlight or glare were present. A system that, at a minimum, automatically
561 retracts shades at the end of the day would allow for more daylight and energy-efficiency, as users
562 could start the day with shading devices retracted [39], as done at IT AbaziaSanLorenzo [62].
563 Automated integrated control systems can admit daylight and provide solar control when needed,
564 ensuring more reliable energy-efficient use of both HVAC and lighting. In the US NewYorkCity case
565 study, for example, daylight, glare, views, and sunlight across the 12.2 m deep open plan office zone
566 were managed with an automated motorized roller shade with the intent to minimize energy use and
567 discomfort. Such control, however, did not necessarily coincide with offering adequate circadian
568 stimulation to occupants. For the northeast zone, the roller shades were partially lowered in the morning
569 to reduce glare from direct sunlight and raised in the afternoon for daylight and views, contrary to non-
570 visual requirements. In the southwest zone, the opposite strategy was adopted.

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

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

586 Key lessons learned

- 587 • With careful design of windows, shading, and lighting systems and controls, several case
588 studies demonstrated that both integrated performance goals for energy efficiency and comfort
589 and integrative non-visual objectives could be satisfied.

- 590 • Innovative daylighting technologies, e.g. dual-zone shades, can be more effective in solving
591 difficult tradeoffs between daylight admission and solar/glare control compared to conventional
592 shades. The spectral and light-scattering properties of such glazing, daylight, and shading
593 systems and materials should be considered when conducting site-specific performance
594 evaluations.
- 595 • For shading device operation, a purely manual system may not lead to the desired utilization of
596 daylight and views out, since users might leave them in specific positions for extended periods
597 of time. One solution would be to (automatically) retract shading devices at the end of the day.
- 598 • Automated dynamic shading and glazing have the potential for optimal control but, given the
599 wide range in user requirements, it is important to provide manual override, training, and
600 education, so as to increase satisfaction among users.

601 **3.6. Daylight and view out**

602 As indicated in Section 3.5, architectural solutions (i.e., building shape, position of openings, shading
603 elements) tailored to the specific geographical location, climate, and urban context are more likely to
604 achieve integrated and integrative performance goals compared to conventional solutions [82, 84, 85].
605 The AT Bartenbach office was designed with both south-facing windows and north-facing skylights
606 (Figure 11), resulting in a minimum daylight factor of 3% across the depth of the office and a spatial
607 daylight autonomy of 500 lx for 82% of working hours. The BR UniBrasilia office building had north and
608 south facades with shallow offices distributed alongside them, achieving an average daylight factor of
609 over 3%. The thin, elongated floor plate of the BR MME building also made good use of daylight.

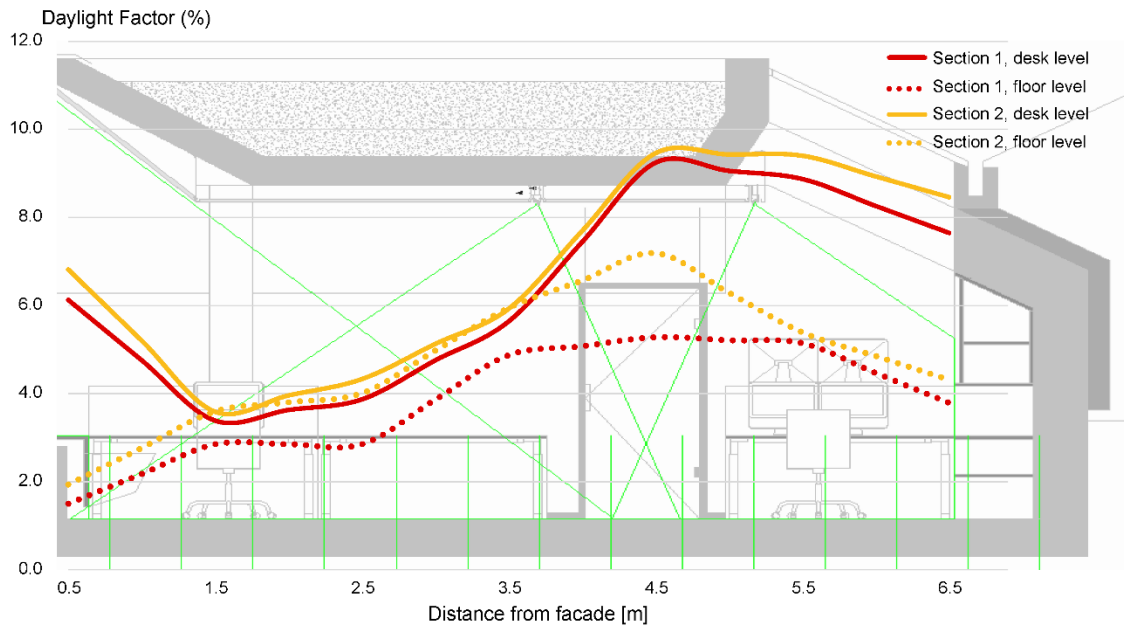


Figure 11. AT Bartenbach building section.

610
611

612

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



624
625 **Figure 12. DK Navitas floor plan, showing courtyards and atria.**

626

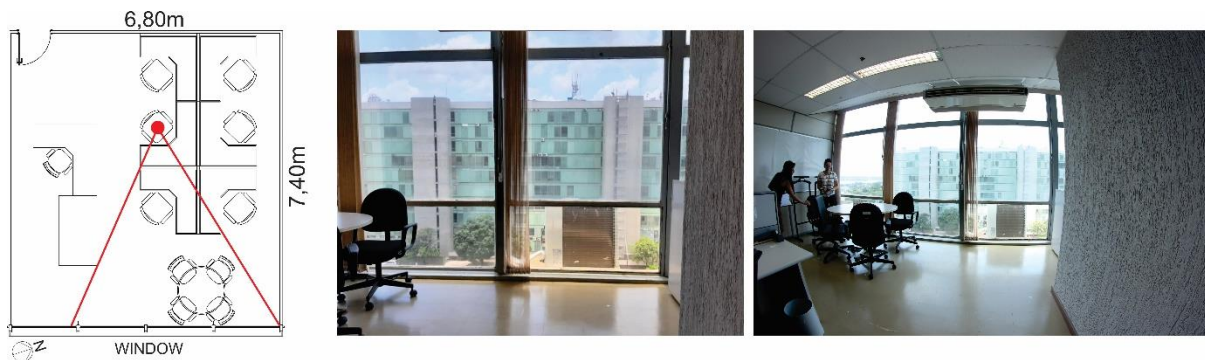
627 Space use and occupancy patterns should be factored into daylight design. At BR MME (low latitude,
628 sunny climate), most offices were located on the east façade to avoid glare and overheating during late
629 afternoon hours, whereas space uses requiring short term occupancy (e.g., conference rooms)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

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

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

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

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



655
656

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

657 Key lessons learned

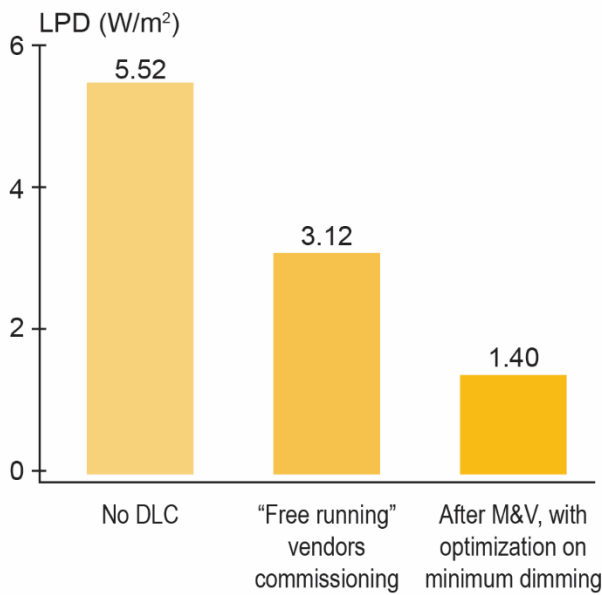
- 658 • Architectural solutions tailored to the site, surrounding context, building type, and occupancy
659 patterns were more likely to achieve high performance objectives associated with a well daylight
660 environment. More successful solutions increased the perimeter-to-core area ratio using
661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

3.7. Monitoring and verification

668

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

676 The US SoSanFrancisco case study focused heavily on the importance of M&V. The design team relied
677 on a rich set of sources to inform the design: they collected data from full-scale mock-ups, conducted
678 observations, had weekly collaborative meetings with all the stakeholders involved in the project, and
679 consulted with domain experts. A new control system for lighting was developed and optimized in a
680 mock-up testbed with a trial-and-error process, before proceeding to the final design. The design team
681 used a similar approach for the design of the shading system. In this way, the LPD was reduced from
682 5.52 W/m^2 to just 1.4 W/m^2 (Figure 14). The proof-of-concept was not just applied to the single building;
683 a new protocol was also planned for monitoring the built space so that actual performance data could
684 inform future decisions on other projects. For example, a traditional dimmable LED system was chosen
685 over an integrative system, as daylight provision was deemed sufficient to provide enough circadian
686 stimulation. Occupants were trained on the new system before occupancy and the facility management
687 invited feedback from occupants, which resulted in further fine-tuning of the lighting and shading
688 systems. As a whole, the design did not stop at procurement and construction, but was continuously
689 updated with feedback even after occupancy, resulting in a continuous circle of M&V and improvement,
690 and an exemplary integrated real project.



691

692 **Figure 14. Measured LPDs after introducing and optimizing DLCs at US SoSanFrancisco. The optimization**
 693 **followed an extensive M&V process and more than halved the LPD in comparison to a “free running”**
 694 **commissioning. Data source [33].**

695

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

705 The monitoring of case studies was, in itself, an occasion for verification and re-commissioning. The
 706 monitoring of the IKEA Kaarst, for example, identified a few malfunctions in both the daylight-linked
 707 (see Section 0) and integrative lighting systems – which were subsequently fixed. The POE (via
 708 occupants surveys and HDR measurements) of AU Aurecon identified glare issues with the existing
 709 roller shades ($T_{v,n-h} > 0.40$), and suggested the use of additional roller blinds with $T_{v,n-h} < 0.10$, which
 710 are now installed in the case study building. The M&V at the DK PsychiatricH and DK Rehab identified
 711 critical aspects – like the need for a smoother transition between lighting scenes and for more intuitive
 712 control interfaces (see Section 3.3) – which might have remained unnoticed without M&V. In the DK

713 Navitas, the target illuminance was increased from 300 to 900 lx for some unknown reason, resulting
714 in excessive energy use, as dimming no longer occurred. This was noticed only because of the
715 monitoring in the context of the IEA SHC Task 61 / EBC Annex 77.

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

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

726 Key lessons learned

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

733 4. Discussion

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

736 First and foremost, integration carries the potential for saving energy used for lighting. This opportunity
737 seems to be well exploited in actual buildings, as measured annual energy for lighting in office spaces
738 could easily reach 5 kWh/m²-y. This is in line with reported values in the literature, but comes with
739 stronger external validity, since it is derived from actual measurements in different contexts and for
740 occupied spaces in real buildings. Good energy performance calls for a combination of high quality,

741 comfortable daylight provision (not too much, not too little, well distributed, and not too much sun
742 penetration [75]), adoption of efficient electric lighting sources, and wise use of controls. Energy use
743 can be further lowered if integration is considered at early design stages of the building envelope, which,
744 for example, resulted in the outstandingly low annual lighting energy use of 3.65 kWh/m²-y, as
745 measured in the AT Bartenbach case study. It is worth noting that accounting for users' needs and
746 preferences supports the energy performance goals. The use of shading devices – automated or even
747 manual – is optimal when occupants are provided with daylighting strategies that can simultaneously
748 prevent glare as well as provide satisfactory view out (such as in AU Aurecon or IT AbaziaSanLorenzo).
749 Controls are best used when they provide individualized and granular control (such as in US
750 NewYorkCity), and/or manual override (such as in DE DIAL and AT Bartenbach).

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

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

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

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

780 **5. CONCLUSIONS**

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

786 Lighting energy use can be dramatically reduced with proper integration of daylighting, and annual
787 energy use below 5 kWh/m²-y is easily achievable in office spaces. Advanced control technologies
788 showed promise in providing reliable solutions (e.g., self-commissioning, self-learning, adaptable) but
789 training and education with manually operated systems were also shown to hold significant potential.
790 Informed specification, installation, commissioning, and monitoring and verification practices will also
791 be critical for success. For new construction, careful architectural design for daylight, solar control, and
792 view will be critical towards the achievement of targeted objectives.

793 Technological innovations are currently being driven by integrative lighting with wider adoption expected
794 to occur as knowledge increases in the field of non-visual lighting. Advancements in LED technology,
795 together with increased capabilities of control systems, could help to support non-visual requirements
796 through electric lighting when daylight alone is insufficient. The adoption of daylighting within integrative

797 lighting is currently very limited in practice, and tools and knowledge are still lacking for designers
798 towards proper implementation.

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

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

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

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

825

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843

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1119 **APPENDIX**

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1121 **Table A.1. 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 2200K – 5000K 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 28W T5	Occupancy	[79]
AU Aurecon	O-L	Sidelighting with manual double roller internal blind shading	Linear dimmable 20W 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 $T_{v,n-h}=0.50$ Internal venetian blinds	Recessed linear LED T8 2x18W 6500K	Manual	[80]
BR MME (2015)	O-M	Laminar shaped building Brise soleil Solar control films	Recessed T5 2x28W 4000K	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 soleil (North) Solar control films and internal curtains (South)	Recessed T5 2x32W 4000K	Manual switch on-off	[83-85]
CH BankChina* (2019)	O-M	Sidelighting with shading	Several luminaires type (depending on space) with white dimmable LED 2700K – 6000K	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 6500K (general lighting) LED spotlights 20W (<i>accent</i> 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]

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. 0.9m height	Linear T5-fluorescents (49W, 4000K)	Occupancy (automated) Daylight-dependent dimming with setting at 300lx Override function Manual roller shades	
DK PsychiatricH*	H-H	Sidelit windows across width of room Window sill at ca. 0.9m height	3 recessed LED downlights during daytime (2700K), 2 recessed LED downlight during night (2000K)	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 (2700K – 5500K)	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 22W	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 2300K – 6200K	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]

1122 "Space type": O-M = Office Mixed, O-L = Office Landscape, H-R = Healthcare Residence, S = Sport venue, R = Retail, H-H
1123 Healthcare hospital, O-I = Office Individual, O-2 = Office two occupants. LB = Living Lab setting.

1124 "Years" refers to construction year or year of latest refurbishment of daylighting and lighting

1125 "+" and "*" indicates integrative lighting projects. "+": Project with integrative control of electric lighting only. "*": Project with
1126 integrative control of electric lighting (includes source contributions from daylight).

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1133 **Table A.2. 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

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1135 **Table A.3. 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

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Table A.4. Data collected for each case study. M = Measured, C = Calculated, S = Simulated.

ID		ENERGY		VISUAL		NON-VISUAL		USER
AT Bartenbach	M	LENi	M S	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 Stephenso n	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	M S	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)	M S	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, U ₀ , 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, U ₀ , SPD, CCT, CRI, Stroboscopic ratio, UGR, spot luminance	-	-	M	Informal chats
DK Psychiatric H	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/m ² 100 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	M S	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 AbaziaSan Lorenzo	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	M S	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	M S	M/P ratios (calibrated ALFA simulations), Pattern of light intake with wearable sensors	M	KSS sleeping scale, interviews

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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