DAYLIGHTING AND ELECTRIC LIGHTING RETROFIT SOLUTIONS

A SOURCE BOOK OF IEA SHC TASK 50
'ADVANCED LIGHTING FOR RETROFITTING BUILDINGS'

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DAYLIGHTING AND ELECTRIC LIGHTING RETROFIT SOLUTIONS

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PREFACE

Lighting accounts for approximately 19 % (~3000 TWh) of the global electric energy consumption. Without essential changes in policies, markets and practical implementations it is expected to continuously grow despite significant and rapid technical improvements like solid-state lighting, new façade and light management techniques.

With a small volume of new buildings, major lighting energy savings can only be realized by retrofitting the existing building stock. Many countries face the same situation: The majority of the lighting installations are considered to be out of date (older than 25 years). Compared to existing installations, new solutions allow a significant increase in efficiency – easily by a factor of three or more – very often going along with highly interesting payback times. However, lighting refurbishments are still lagging behind compared to what is economically and technically possible and feasible.

IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings" therefore pursues the goal to accelerate retrofitting of daylighting and electric lighting solutions in the non-residential sector using cost-effective, best practice approaches.

This includes the following activities:

» Develop a sound overview of the lighting retrofit market
» Trigger discussion, initiate revision and enhancement of local and national regulations, certifications and loan programs
» Increase robustness of daylight and electric lighting retrofit approaches technically, ecologically and economically
» Increase understanding of lighting retrofit processes by providing adequate tools for different stakeholders
» Demonstrate state-of-the-art lighting retrofits
» Develop as a joint activity an electronic interactive source book ("Lighting Retrofit Adviser") including design inspirations, design advice, decision tools and design tools

To achieve this goal, the work plan of IEA-Task 50 is organized according to the following four main subtasks, which are interconnected by a joint working group:

Subtask A: Market and Policies
Subtask B: Daylighting and Electric Lighting Solutions
Subtask C: Methods and Tools
Subtask D: Case Studies
Joint Working Group (JWG): Lighting Retrofit Adviser

IEA SOLAR HEATING AND COOLING PROGRAMME

The Solar Heating and Cooling Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is "to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50 % of low temperature heating and cooling demand by 2050.

The member countries of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 52 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

» Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
» Solar Cooling (Tasks 25, 38, 48)
» Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
» Solar District Heating (Tasks 7, 45)
» Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
» Solar Thermal & PV (Tasks 16, 35)
» Daylighting/Lighting (Tasks 21, 31, 50)
» Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
» Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
» Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
» Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

» SHC International Conference on Solar Heating and Cooling for Buildings and Industry
» Solar Heat Worldwide – annual statistics publication
» Memorandum of Understanding with solar thermal trade organizations
» Workshops and conferences

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EXECUTIVE SUMMARY

Due to the world's growing population and the increasing electrical energy demand in emerging economies, an increase of electric energy use for lighting is expected. Energy efficient lighting is said to be one of the most cost-effective approaches to save energy and reduce $C0_2$ emissions. In order to stimulate the application of lighting retrofits of good quality, IEA Task 50, Subtask B "Daylighting and Electric Lighting solutions" has looked into the assessment of existing and new technical retrofit solutions in the field of façade and daylighting technology, electric lighting and lighting controls.

The document provides information for those involved in the development of retrofit products or involved in the decision making process of a retrofit project, such as buildings owners, authorities, designers and consultants, as well as the lighting and façade industry. In contrast to other retrofit guides, this source book addresses both electric lighting solutions and daylighting solutions, and offers a method to compare these retrofit solutions on a common basis, including a wide range of quality criteria of cost-related and lighting quality aspects.

Simple retrofits, such as replacing a lamp or adding interior blinds, are widely accepted, often applied because of their low initial costs or short payback periods. The work presented in this report aims at promoting state-of-the-art and new lighting retrofit approaches that might cost more but offer a further reduction of energy consumption while improving lighting quality to a greater extend. A higher lighting quality can increase health, self-assessed performance, and lead to a higher job satisfaction and thus productivity in work environment. In this, the use of daylight is specifically promoted, as an optimized daylighting design, or the use of innovative daylighting systems are rarely taken into consideration in the retrofit processes of buildings, and daylight utilization will both reduce energy consumption for electric lighting as well as increase user well-being.

In order to assess retrofit technologies on their ability to save electrical energy, to increase lighting quality and to affect operational costs, a Catalogue of Criteria was developed. It consists of a large number of quality measures that can be applied to evaluate the performance of lighting controls, electric lighting retrofits and daylighting retrofits. The selection of quality measures can be used to describe the performance of lighting retrofit solutions, qualitatively and to some degree quantitatively. The Catalogue of Criteria allows to make a sensible, first, decision for a (selection of) lighting retrofit solution(s). In this source book, the Catalogue of Criteria is used to evaluate the performance of a selection of retrofit solutions. Product families of lighting retrofit technologies are evaluated, and an overall performance assessment for each type of retrofit solution is given. The actual performance of a specific product in that retrofit family needs to be established within the context of a project.

The assessment of selected technologies showed that

» next to replacing a lamp or adding interior blinds, a task - ambient lighting concept, occupancy sensing, personal control in daylit spaces, daylight responsive lighting control through switching, time scheduling, wireless controls (occupancy and daylight responsive), and replacing an magnetic ballast with an electronic ballast, can be economical solutions that reduce energy consumption for electric lighting.

» most electric lighting retrofit solutions offer high energy savings but do not necessarily improve lighting quality.

» daylighting retrofit solutions generally have higher investment costs. The energy savings potential offered by these retrofits can be (partially) harvested when applying a daylight responsive lighting control system or offering the user personal control over the electric lighting.

» non-economic benefits, or indirect economic benefits, such as the increase of lighting quality, can be achieved with daylighting retrofit solutions that enhance daylight provision in a room, and electric lighting and control solutions that might require a redesign of the lighting installation.

While the choice for a lighting retrofits solution nowadays is mainly based on cost and energy reduction, a retrofit solution can affect lighting quality and thermal loads as well, which has an indirect economical or environmental impact. This should be considered in the selection of the appropriate lighting retrofit solution. The greater part of electric lighting retrofit solutions focuses on reduced price and increased efficacy to achieve short payback periods; high end electric lighting solutions, as well as the majority of lighting controls and daylighting solutions are developed and applied to increase user comfort and lighting quality.

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Lighting accounts for approximately 19% of the global electric energy consumption (IEA 2006). Depending on the application, an installed Lighting Power Density (LPD) of 10 to 30 W/m², on average a yearly energy consumption of 20 – 25 kWh/m²y , can typically be found in commercial buildings. Modern lighting solutions can reduce the LPD to 5 – 15 W/m², with even larger savings on the annual energy consumption when appropriate controls are being used (5 - 9 kWh/m²yr, Dubois and Blomsterberg 2011). Nonetheless, due to the world's growing population and the increasing electrical energy demand in emerging economies, a further increase of 40% of electric energy use for lighting is expected in 2030 (Dubios et al. 2014, based on IEA 2006). The global 'Carbon abatement opportunities map' of McKinsey and Vattenfall Institute of Economic Research (McKinsey 2008) indicates that the use of energy - efficient lighting is one of the most cost-effective approaches to reduce $C0_2$ emissions, especially for a simple retrofit, the switch from incandescent to LED light sources (McKinsey 2010).

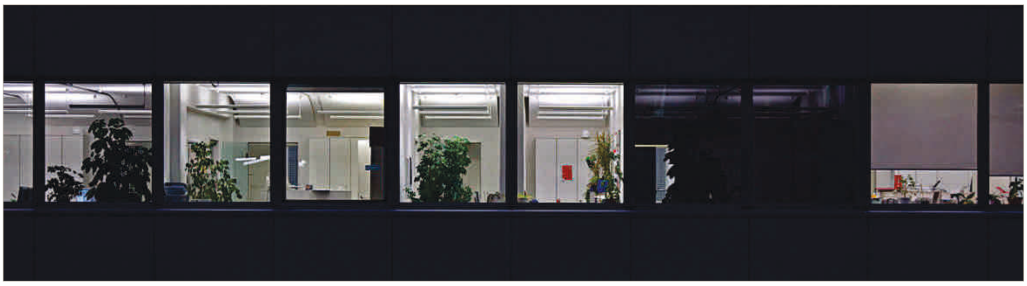
Simple retrofits, such as replacing a lamp or adding interior blinds, are widely accepted, often applied because of their low initial costs or short payback periods. In practice, an optimized daylighting design, or the use of innovative daylighting systems or lighting control systems are rarely taken into consideration in the retrofit processes of buildings. The work presented in this report aims at promoting state-of-the-art and new lighting retrofit approaches that might cost more but offer a (further) reduction of energy consumption while improving lighting quality to a greater extend.

This source book summarizes the work done within Subtask B "Daylighting and Electric Lighting Solutions" of IEA Task 50 "Advanced Lighting Solutions for Retrofitting Buildings". Other projects, such as IEA Task 21 "Daylight in Buildings", IEA Task 31 "Daylighting Buildings in the 21st Century", IEA ECBCS Annex 45 "Energy-Efficient Future Electric Lighting for Buildings" and Task 47 "Solar Renovation of Non-Residential Buildings" have dealt with related topics. From these projects it was possible to summarize the key steps for energy efficient lighting solutions:

1. Use natural lighting indoors as much as possible, and consider both lighting and thermal impact in the overall energy consumption.
2. For times with insufficient daylighting, use efficient electric (lighting) components: lamps, ballasts and luminaires, in an appropriate lighting design. The design should address that light is applied where it is needed.
3. Use lighting controls, especially those that take advantage of available daylight. Lighting controls should be applied to offer light when it is needed.
4. Develop an appropriate maintenance regime; keep luminaires and lamps clean.

The main reasons for a lighting retrofit are to achieve energy savings or a green building certification, to reduce cost or maintenance, or to increase lighting quality or user satisfaction.

1



The majority of refurbishment, retrofitting and renovation activities is nonetheless typically related to reduction of energy use (Gohardani and Björk 2012). This document looks into a lighting retrofits that can be applied for further reduction of energy consumption while improving lighting quality to a greater extend. Even though no precise definition of lighting quality exists (CIE 1998), it is typically related to the degree of which the lighting meets the needs of the occupants of the space. Research showed that lighting with a higher quality can positively affect job satisfaction, organizational commitment, health and self-assessed performance (Veitch et al. 2010).

The use of daylight should be promoted. From an environmental point of view (in contradiction to a pure economical one), daylight utilization is of importance. Any electric lighting solution needs electricity often generated by non-renewable source, such as fossil or nuclear fuels. Even though the LPD will be reduced significantly by the implementation of LED lighting solutions, and the absolute energy savings to be reached by using controls is diminishing, from an environmental point of view, any reduction of energy consumption is sensible. Although payback periods for daylight responsive controls might increase at first when LED systems are widely applied as retrofit solutions, it is expected that new technology will result in a reduction of costs for sensors and controls in the near future, which might affect the payback period. Additionally to that, besides offering a reduction of energy consumption for the electric lighting installation, daylight utilization also likely increases user well-being. It is generally acknowledged that occupants prefer daylight to electric lighting. Daylight can positively affect stress and mood, and support visual and non-visual responses (e.g. Boyce et al. 2003, Veitch and Galasiu 2012, Strong 2012 and section 3.2).

1.1 OBJECTIVE AND SCOPE OF THIS SOURCE BOOK

This document aims at promoting state-of-the-art and new retrofit approaches, considering both electric lighting and daylighting solutions.

- » In Chapter 2 a Catalogue of Criteria is presented, that can be used to rate and compare various retrofit technologies on a holistic basis. It includes the description of a baseline as well as 30 quality criteria.
- » Chapter 3 includes general descriptions of retrofit technologies. These technologies are assessed by means of the Catalogue of Criteria in Chapter 4, giving an indication of the performance of each technology in a quantitative manner.
- » Conclusions and an outlook can be found in Chapter 5

HOW TO USE THIS BOOK 1.2

Readers seeking information on how to compare retrofit technologies, especially those not included in this source book, should read Chapter 2.

For those interested in the variety of lighting retrofit technologies, a presentation of selected types of retrofit solutions can be found in Chapter 3, including a description, the advantages and disadvantages of the technology, pictures and references to literature of interest. The description is representative for the majority of products within this technology family, but does not represent the performance of each product available for this technology

An overview of the performance of these selected technologies can be found in Chapter 4. Note that this chapter looks into daylighting and electric lighting retrofit solutions on a product level only. It gives an overview of the potential of products when installed, calibrated and commissioned properly. It allows to make a sensible, first, decision for a (selection of) lighting retrofit solution(s). The ultimate decision for a solution, based on the costs, the estimated energy savings and the lighting quality in an application, should be determined with knowledge about that specific application. For this, please refer to

» the tools as proposed by IEA Task 50 Subtask C "Methods and Tools",
» the case studies evaluated within IEA Task 50 Subtask D, or
» the "Lighting Retrofit Adviser" of the Joint Working Group of IEA Task 50.

Application relevant information can also be found in public guidelines, such as the Advanced Energy Retrofit Guides of the US Office of Energy Efficiency & Renewable Energy (EERE 2011, 2013, www.energy.gov). Barriers for renovation and retrofit activities are specifically addressed in the material provided by Subtask A of IEA Task 50.

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2. RATING AND COMPARISON OF RETROFIT TECHNOLOGIES

One hurdle to overcome when considering alternative solutions in a retrofit project is the lack of an appropriate approach to compare solutions on a common basis. Previous projects that have considered both cost-related and lighting quality aspects, focused either on the evaluation of daylighting solutions or on the assessment of electric lighting solutions. The quality of (parts) of an electric lighting solution is often described with features such as light output or lifetime. However, the quality criteria used for electric lighting are usually not applicable or not sufficient to describe the quality of daylighting solution or the effect on people. Resulting, to properly evaluate the impact of lighting retrofit decisions, a wide range of quality criteria should be considered, preferably applicable to both electric lighting and daylighting solutions. This chapter offers a list of quality measures to evaluate the effectiveness of lighting retrofit solutions to reduce energy consumption and running costs as well as improve lighting quality. This selection of quality measures, the so called Catalogue of Criteria, can be used to describe the performance of lighting retrofit solutions, qualitatively and to some degree quantitatively.

2.1 CATALOGUE OF CRITERIA

In order to evaluate a large variety of daylighting and electric lighting retrofit solutions, on an equal and holistic basis, a Catalogue of Criteria was defined, to allow for a quantitative comparison of retrofit possibilities. The quality measures included in the Catalogue of Criteria were taken from literature, standards, and experience (e.g. Ruck et al. 2000, CEN 2005, CEN 2007, CEN 2011) and consider:

» aspects from an ecological and economic point of view, such as those related to acquisition of the system, energy consumption, and maintenance
» user requirements, such as psychological and physiological, visual and non-visual, human needs
» impact of the lighting retrofit on the overall retrofit process
» thermal benefits of daylighting systems
» geographical and climatological applicability.

Focusing on product related aspects only and rejecting all application relevant quality criteria from the approximately 100 established measures, the Catalogue of Criteria contains over 30 quality measures that primarily focus on the following reasons to retrofit:

» reduce energy consumption
» increase the lighting quality
» reduce the operational costs.

The Catalogue of Criteria also includes aspects related to possible drawbacks of the retrofit solution, such as the impact of the retrofit process, the duration and costs of the lighting retrofit, as well as thermal characteristics that do not affect the potential savings for electrical lighting, but could affect the overall building energy consumption.

By allowing an evaluation of both daylighting and electric lighting solutions on the main features, potential energy savings for electric lighting, lighting quality, thermal aspects and costs, a comparison of distinct different retrofit approaches on a common basis is feasible, see chapter 4.

In order to describe the performance of the lighting retrofit solutions with respect to energy efficiency and lighting quality, and to allow for a comparison between different retrofit solutions, a baseline for product performance was defined. The baseline refers to a widely accepted, often applied, general lighting solution (common practice). The baseline does not represent the generally preferred lighting installations.

From a daylighting point of view, lighting retrofit solutions are compared to the following specified reference situation: a clear double pane window (τv = 0.8, g = 0.6), providing

- a clear view out (classification according to EN 14501[1]: Class 4),
- no night view protection (classification according to EN 14501: class 0), as well as
- no glare control (classification according to EN 14501: Class 0).

Windows on sun-facing façades (East, South or West orientated façades on the northern hemisphere, East, North and West orientated façades on the southern hemisphere) are provided with simple venetian blinds on the inner side of the façade. When global irradiance levels reach 120 W/m² on the façade during occupancy hours, these blinds will be completely closed, providing

- no view out (classification according to EN 14501: Class 0), and
- glare control (classification according to EN 14501: Class 4).

The reference situation does not have skylights or other daylighting devices in the roof. The roof construction has standard thermal characteristics, and no light transmission.

The reference electric lighting solution depends on the application in which the retrofit solutions is typically applied in. A literature review conducted within Subtask D "Case Studies" of IEA Task 50 (Dubois et al. 2014) indicated that T8 solutions, compact fluorescent lamps, incandescent and halogen, as well as metal halide lamps cover the majority of lamp types applied in indoor lighting solutions. Resulting, reference characteristics for these four lamp types are defined:

- 60 lm/W system efficacy for luminaires with T8 fluorescent with a conventional ballast solution (with a Light Output Ratio (LOR) of approximately 0.70), a Colour Rendering Index (R_a[2]) = 80, CCT 3000 K, no dimming possible, lamp life 15 000 h, a Lamp Lumen Maintenance Factor (LLMF) at 12 000 h of 0.89,
- 15 lm/W system efficacy for luminaires with tungsten halogen lamps, R_a = 100, CCT = 3000 K, dimming is possible, lamp life 3 000 h,
- 40 lm/W system efficacy for CFL downlights, R_a = 80, CCT 3000 K, no dimming possible, lamp life 8 000 h,
- 55 lm/W system efficacy for luminaires with metal halide lamps, R_a = 80, CCT = 4000K, dimming is typically not possible, lamp life 8 000 h.

In the evaluation of performance, it is assumed that the baseline situation does not include occupancy sensing or daylight responsive lighting controls. The lighting is switched on and off manually.

1 CEN (2005)
2 R_a (CIE 2011, eILV: http://eilv.cie.co.at/) or CRI (Colour Rendering Index)

Even though the Catalogue of Criteria is drawn up to compare lighting retrofit approaches on a product level, simulations for a more detailed analysis of the product's potential might be required. A reference room was defined for such purpose:

» size of the room: 9.00 x 3.00 x 6.00 m (width, height, depth),
» the window occupies the 2/3 of the upper part of the façade,
» occupancy rates for office buildings (70 % - 100 %), educational buildings (75 % - 90 %), industry buildings (100 %), hospitals / healthcare facilities (80 - 100 %), wholesale and retail premises (100 %), hotel rooms (70 - 75 %),
» reflectances for ceiling, wall, and floor respectively 0.70, 0.50 and 0.20.

The characteristics for window size, surface reflectance and occupancy rates are widely accepted and often applied. The depth of the room of 6.00 m allows a proper evaluation of the functioning of daylighting systems, developed to bring daylight deeper into the room. The size of the reference room does not reflect a specific application. As a result, the reference room will give an indication of the performance of a system; the actual performance needs to be established within the context of a project.

2

2.1.2 QUALITY MEASURES: ENERGY EFFICIENCY

In the Catalogue of Criteria, a number of aspects reflect the efficiency of lighting solutions. The energy savings potential is the major aspect. To determine the savings potential of electric lighting retrofits, simulations comparing the baseline with the retrofit solution are necessary. A comparison on **system efficacy** (# 1, in lm/W) can give some insight into the savings potential, but these measures do not indicate the impact of the retrofit solution on the lighting conditions in the application. A one-to-one replacement based on the efficacy of components (e.g. lm/W), does not guarantee that lighting requirements for standards are met. **Luminous flux** (# 2, in lm), **luminous intensity distribution** (# 3) or **emitting angle** (# 4) are characteristics that give complementary information, when a comparison on product efficacy alone is necessary.

Two additional aspects are relevant for the energy savings potential of an electric lighting retrofit, but not directly included in savings percentage. **Dimmable** (# 5) lighting systems offer a larger savings potential when included in a lighting solution with controls; light sources with a low **power factor** (# 6) are inefficient, even though this is not reflected in the metered use of power.

The energy savings potential of lighting control systems is typically derived from the manufacturer, preferably based on simulations of a larger number of applications. Table 1 includes information on energy savings of lighting control systems realized in a large number of field studies. A meta-analysis of these studies was made by Williams et al. (2011). If the design of the control solution allows for **zoning** (# 7) in larger areas, the controls offer larger savings potential.

Table 1: Lighting energy savings, derived from analysis of field studies (Williams et al. 2011)[3]

	Office	Warehouse	Lodging	Education	Retail, other than mall	Healthcare, outpatient	Public assembly
Personal control	35 %			6 %			
Daylight responsive lighting control	27 %	28 %		29 %	29 %		36 %
Occupancy sensing	22 %	31 %	45 %	18 %		23%	36 %
Tuning	36 %				60%		

The energy savings potential of retrofit daylighting solutions needs to be determined by means of simulations, comparing the baseline and retrofit solution. Some daylighting systems are specifically developed to **perform best** under **diffuse sky** conditions (# 8); others are optimized to function with **direct sunlight** (# 9). The first category of systems is preferably applied in regions with prevailing overcast sky conditions, the second one in sunny climates. Translucent or retractable systems that are developed to redirect or block sunlight perform well under both daylighting conditions. The prevalent climate conditions, as well as the orientation, need to be considered carefully in the choice of appropriate daylighting systems.

Note that the savings potential of daylighting solutions can only be seized if an appropriate lighting control system is applied, tuning the electric lighting to the daylight availability (section 3.3.5).

In all cases, it is of importance to reflect the likeliness that the energy savings potentials are achieved. If maintenance of the system is elaborate, or a system requires specific climate conditions, the savings might not be realized in practice.

[3] Tuning: Over specified lighting installations are dimmed down to reduce energy consumption while still provide required lighting levels with reduced energy consumption.

2.1.3 QUALITY MEASURES: THERMAL CONSIDERATIONS

This report focusses on the energy consumption by electric lighting and daylighting solutions. Nonetheless, it needs to be pointed out, that any lighting solutions has an impact on the energy consumption for cooling and heating of the building as well.

The energy consumed by the electric lighting can be considered as an internal load to the building. An improvement of the electric lighting solutions, such as more efficient technology or more efficient control of the luminaire's use, may lead to a significant reduction of the energy consumption of the electric lighting. This will impact the internal gains and related heating and cooling needs. In general, internal loads due to the lighting installation lead to a reduction of the heating needs or increase of cooling needs. In cold climates and/or in winter, internal loads may be beneficial, but too high internal loads may be a disadvantage in hot climates and/or in summer. Cooling energy savings can be a significant factor in the cost-effectiveness of retrofit solutions. For every additional W put into the system, not needed for heating up the building, approximately 2.7 W of cool air needs to be produced. The cost-effectiveness is affected by the energy source as well, heating typically relies on the use of gas, whereas cooling and lighting use electrical energy.

Daylight usage can affect the thermal requirements in building as well and change the energy used for cooling or heating. Solar radiation entering the room will increase the internal load, which may increase the need for cooling or reduced the need for heating. On the other hand, due to a lower thermal insulation of window panes, in comparison to the opaque part of the façade, additional thermal losses can occur. The interaction between lighting and HVAC, and its effect on the annual heating and cooling requirements should be considered in the overall assessment of product quality. Appropriate assessment of the overall energy consumption needs to be made building and context specific, considering aspects such as, climate, orientation, actual window size and obstruction.

The Catalogue of Criteria looks at the performance on a product level only, and therefore includes a few of parameters that give an informative indication of the thermal performance only.

For daylighting solutions:

» the measure for solar energy transmittance, the **g value** (# 10) of the system. The g value is equal to the center-of-glass Solar Heat Gain Coefficient (SHGC), and ranges from 0 to 1, with a lower value representing less solar gain (classification according to EN 14501),

» the **maximum g value variation** (# 11), for façade solutions that can change light and heat transmission properties according to changing needs, such as (re)moveable shading systems, electrochromics, thermochromics, and liquid crystals. The variation indicates the systems' flexibility to respond to different sky conditions

» the **light to thermal ratio** (# 12, the light-to-solar-gain, LSG) , being a measure that indicates the ability of a daylighting solution to allow for an relatively higher daylight contribution compared to the solar heat gain ("selectivity"),

» the secondary internal heat transfer, the **q_i value** (# 13), describes the heat dissipation due to convection and radiation of long-wave radiation from the system (classification according to EN 14501).

Thermal impact of electric lighting solutions can be evaluated by means of **system efficacy** (# 1, in lm/W). More efficient solutions will require lower installed power and thus reducing the internal gain, which can be both beneficial and disadvantageous.

In the Catalogue of Criteria, the quality aspects glare, colorimetric qualities, room appearance and personal control, as well as a small number of technology specific aspects are considered to assess lighting quality of retrofit solutions.

Personal control (# 14) or individual control allows for adjustment of the daylighting or electric lighting of the user. Research indicates that the occupants value the ability to choose lighting conditions (Tregenza et al. 1974, Bordass et al. 1994). Individual control can be offered through switches or push buttons, pull cords or handset controls that are easily accessible by the user. Personal control increases satisfaction, comfort and performance of users (Moore et al. 2002, Boyce et al 2000, Galasiu et al. 2007, Newsham et al. 2008, Moore et al. 2004) and reduces energy consumption for electric lighting with 35 % on average as a result of the individually adjusted light levels (Williams et al. 2011). Other lighting control solutions, such as occupancy sensing or daylight harvesting, should preferably offer some personal control possibility to overrule the controls, to guarantee user acceptance as well. These can, in combination, result in additional savings of up to 30 % (Galasiu et al. 2007, Jennings et al. 2000, Maniccia et al. 1999).

Additionally, the lighting quality of an electric lighting retrofit solution is evaluated based on the following quality measures.

» In order to assure visual comfort, and prevent from direct or reflected glare, bright electric light sources need to be properly shielded. As a reference value, the Unified Glare Rating Reference, **UGR_R** (for 4H/8H, and reflectances of 0.7/0.5/0.2 for respectively ceiling, wall, and floor - # 15) can be used for to quantify visual comfort of retrofit luminaires or retrofit lamps in existing luminaires.

» The colorimetric qualities of a retrofit solution are reflected in the change of **colour rendering index** (R_a, # 16) and **correlated colour temperature** (CCT, # 17) in comparison to the baseline. Dynamic changes in colour temperature are positively rated, when the bandwidth of colour temperature is chosen specifically to realize architectural or non-visual lighting effects (CEN 2011). Additional information on individual colour rendering indices (R_i), for example R_9 for red tones, can be included to give a better representation of colour rendering qualities, when required for an application.

» Room appearance is greatly determined by the wall and ceiling luminances (Loe et al. 1994, Newsham et al. 2005, Kirsch 2015). The **directionality** or **beam angle** (# 18) of lighting solutions effects wall and ceiling luminance, and should therefore be considered in the choice of a retrofit solution. Energy efficient solutions that reduce vertical luminances might lead to lower user satisfaction.

» For electric lighting, **flicker** (# 19) needs to be considered as a lighting quality aspect. The Flicker Index and Flicker Percentage are proposed for evaluation of flicker, but are currently under discussion (Lehman et al. 2011, Bullough et al. 2012, CIE 2013). Therefore, product samples are preferably tested by means of a mobile phone, digital pocket camera or a white plastic rod, according to the Subtask D Monitoring Protocol (Dubois et al., to be published).

The lighting quality of a daylighting retrofit solution is evaluated by means of the following quality measures.

» Glare from direct sunlight, reflected sunlight, and bright sky patches should be avoided. Therefore, daylighting retrofit solutions should be evaluated on their ability to **provide glare protection** (# 20) which can be classified according to EN 14501.

» Colour distortion, fidelity, and selectivity of the daylight should be considered, especially when looking into spectral selective materials, heat insulated or solar control glass. The

colour rendering index (# 16) of the resulting light can give insight into this effect.

» Room appearance is affected by the distribution of daylight as well. Retrofit solutions that bring light deeper into a room, realize a higher horizontal uniformity or further increase wall and ceiling luminances, are perceived to **provide a better light distribution** (# 21).

» Specifically for daylighting retrofit solutions, the light transmittance (τ_v, # 22) of the solution, the **provision of a view out** (# 23) without distortion or blockage of the view, and the **provision of privacy at night** (# 24) are important lighting quality measures. The performance of a retrofit solution with respect to view and privacy can be classified according to EN 14501.

The quality aspects light transmittance, view out, colour distortion, and glare protection are evaluated under overcast sky conditions as well as conditions with direct sunlight, accounting for daylighting solutions with different shading properties.

2.1.5 QUALITY MEASURES: MAINTENANCE

Proper maintenance of lighting installations is required to ensure that the lighting solution performs as it was designed. Typical maintenance activities are cleaning of lamps and luminaires, and replacement of broken and aged lamps. Especially in situations where maintenance is problematic (e.g. swimming pools or high industry halls with 24 hour operation) retrofit of a lighting installation can be considered to reduce the costs of maintenance. In general, two product related characteristics can positively affect maintenance requirements:

1) **Lamp life** (# 25), defined as the time after which 50 % of the lamps in a group, tested in the laboratory under controlled operating conditions, have failed. A high lifetime reduces maintenance efforts and activities.
2) **Lumen depreciation over lifetime** (# 26). Due to aging of the lamp, the lumen output of lamps depreciate over lamp lifetime and lighting installations need re-lamping as soon as the lighting conditions drop below the required lighting levels. With a low depreciation over lifetime, re-lamping is delayed and with this, the required maintenance reduced.

For LEDs the representation of lamp life and lumen depreciation over lifetime is different. Lumen maintenance, Lx, specifies the percentage of remaining luminous flux compared to the new product, where x is the level of acceptable lumen depreciation depending on the kind of application (for example L90B10 or L70B10 at 50000 hours). In this, “By” denotes the LEDs rate that is expected to fail for given boundary conditions (e.g. reach the admissible lumen output (x) for a given lifetime). The notation L70B50 means that the 50 % of tested LEDs are not meeting the 70% of the initial luminous flux for a given operating time. The remaining 50% satisfies this condition. In the assessment with the Catalogue of Criteria, the lumen depreciation (Lx) for the light source lifetime category as set under ‘lamp life’ (criterion # 25) needs to be stated. For example, the lumen depreciation for a LED retrofit lamp is determined for a lifetime of 19 500 h for fluorescent replacements, and 15 000 h for CFL replacements.

In case of the use of lighting controls, the retrofit solution might require **re-commissioning** (# 27) as part of the maintenance procedure. Re-commissioning can for example include the recalibration of set points to achieve the required lighting levels, or adjustment of the detection area or delay time of occupancy sensors.

Most daylighting systems must also be maintained through regular servicing and cleaning. Cleaning glazing on the inner and outer side avoids reduction of light transmission. Maintenance of louvers and blinds can be difficult, especially when they have reflective slats. Interior slats collect dust and exterior slats accumulate dirt and snow. Daylighting systems that use moveable elements might need re-commissioning and regular maintenance.
In general, regular painting of indoor walls and ceiling (in light colours or white) will help maintaining the interior lighting levels. Recovery painting of indoor walls and ceiling in the specified period.

The required maintenance has a direct impact on the running costs of a lighting installation, to be discussed in the following paragraphs.

QUALITY MEASURES: COSTS 2.1.6

Typically, running costs are a reason to renovate a lighting installation, in addition to products reaching the end of life. These **operational costs** (# 28) consist of energy costs as well as costs for maintenance, covering costs for cleaning, re-lamping, and re-commissioning. Systems that require appropriate tracking or clean surfaces, such as heliostats or sunlight collectors, need special consideration, as they might require maintenance that is more (labour and frequency) intensive.

Although running costs are often significantly higher than the initial costs, the latter are often decisive in the decision making process. The **initial costs** (# 29) consist of the cost for all components of the lighting solution (lamp, luminaire including ballast, wiring, sensors, controls …) as well as the installation and commissioning of it. In some cases, initial costs cover de-installation and disposal as well. A rough classification of impact of the type of lighting retrofit on the installation costs can be read from the solution matrix (Figure 4), where a redesign will be more time intensive than the upgrade of an existing situation, resulting in higher labour costs (**ease of retrofit**, # 30).

Payback periods are not included in the Catalogue of Criteria. Practical experience indicates that daylighting solutions often have higher initial costs and longer periods to reach the break-even point. The lifetime of most daylighting solutions is longer than the lifetime of electric lighting solutions, which should be considered in the comparison of payback periods of retrofit solutions.

USE OF THE CATALOGUE OF CRITERIA 2.1.7

The Catalogue of Criteria allows for a description of the quality aspects of electric light and daylight retrofit approaches in detail, on a common basis. Comparison of a retrofit solution with the baseline situation using the quality criteria included in the Catalogue of systematically reflects the advantages and disadvantages of the retrofit solution quantitatively and qualitatively. The assessment can be made with the main features (e.g. "energy efficiency") or on a detailed level, addressing specific topics (e.g. "the system does not provide glare protection during wintertime"). A list with the main features and detailed quality measures can be found in Appendix A.

2.1.8 DRAWBACKS OF THE CATALOGUE OF CRITERIA

The Catalogue of Criteria includes relevant, broadly applicable quality criteria. In the use of the Catalogue of Criteria, it needs to be assumed that the systems are properly installed, calibrated and commissioned, as well as optimally operated, in line with the intended operation as defined by the manufacturer of the given system and/or the lighting designer.

Dependencies for appropriate system operation, e.g. linked to maintenance or control, must be evident and reflected in the product description. As indicated in section 2.1.2 "Quality measures: Energy efficiency", potential savings are harder to achieve when maintenance of a system is labour-intensive, or a daylighting system is applied under climate conditions the system is not developed for. The Catalogue of Criteria does not prompt this system specific information as a clear disadvantage. In order to put emphasis on this system specific information, the Catalogue of Criteria results need to be extended with a short description of the retrofit solution. This description should include:

- climate specific information. Climate related restrictions need to be indicated, when the daylighting solution is specifically suitable for clear sky sunny conditions, primarily using direct sunlight, or better suitable for overcast sky conditions, primarily using diffuse skylight.
- orientation. In line with the climate specific information, the description should indicate the preferred orientation for best performance, if applicable.
- the preferred position of the retrofit solution, when applicable, indicating its required position in a horizontal (roof or ceiling), vertical (façade or wall) or tilted plane for optimal performance.
- its applicability in specific building types: offices, educational buildings, wholesale and retail trade, industrial buildings, hospitals and other healthcare facilities, or hotels and restaurants.
- the (day)lighting related benefits. For some lighting solutions, studies were performed that indicated increased productivity, academic results, sales or user comfort due to the applied (day)lighting solution (see section 1. and 3.3).
- other restrictions and considerations in use (e.g. noise of moveable parts, maintenance of moveable parts, frequent required re-commissioning, seasonal adjustment)

Performance assessment by using the Catalogue of Criteria is an assessment on product level only, giving an indication of the quality of a retrofit solution in comparison to the baseline situation or other retrofit solutions. The actual performance of a retrofit solution can be determined only when building and context specific conditions, in which the retrofit solution will be applied, are taken into consideration.

2.2 COMPARISON OF RETROFIT SOLUTIONS

Comparison of retrofit technologies is feasible when it is based on a quantitative assessment. In order to allow for a purely quantitative assessment, a smaller number of criteria of the Catalogue of Criteria are selected to assess the system's performance on designated topics, which represent the main reasons to retrofit a lighting installation: 'Reduce energy consumption', 'Reduce operational costs' and 'Increase lighting quality', as well as the thermal benefits of daylighting retrofit solutions. The thermal benefits of electric lighting and control solutions are assumed to be marginal in comparison to the benefits of daylighting solutions that affect solar gains, and are therefore not included in the assessment.

At present, energy efficiency is represented by the energy savings potential of a lighting retrofit solution. Lighting quality is addressed by visual comfort, colorimetric qualities, room appearance, and personal control possibilities. For daylighting solutions, this list of lighting quality aspects is extended with view out, privacy and light transmittance, as these aspects are also of utmost importance in the overall lighting quality assessment. To assess costs of retrofit solutions, both initial costs and operational costs are considered in the product comparison. In the assessment of daylighting systems, thermal considerations are included as additional information, relevant for the overall energy savings potential, even though the thermal considerations are not included in the savings potential.

The relevance of each item within the main categories should be defined in a project and be reflected in weighting factors per item. Examples for weighting factors, as used within IEA Task 50, are given in Chapter 4.

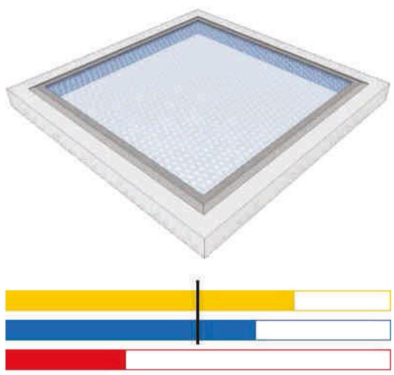
Baseline conditions are, again, used to reflect the performance of a retrofit solution, allowing for product comparison. An evaluation and a comparison of innovative retrofit techniques as well as state-of-the art solutions, of electric lighting and daylighting retrofit solutions is possible.

REPRESENTATION OF TECHNOLOGY PERFORMANCE 2.3

The quality assessment including the weighting factors allows for a representation by means of a performance icon as shown in Figure 3. The representation will support the decision making process of suitable lighting retrofit solutions. In order to promote state-of-the-art solutions as well as innovative techniques, the main criteria presented in this document are energy efficiency and lighting quality. Costs are not highlighted in the performance representation, having a prominent role in the decision making process already, and therefore not reflected in the performance icon of the retrofit solution.

3

- Upper bar - Yellow - Energy efficiency
  Reflects savings potential of retrofits depending, for example, the technology's efficacy and luminous intensity distribution, savings found in field studies, or its performance under diffuse and direct sky conditions.
- Middle bar - Blue - Lighting quality
  Reflects the retrofit's impact on lighting quality aspects such as visual comfort, personal control and colour rendering.
- Lower bar - Red - Thermal benefits
  Reflects the thermal benefit of façade and daylight technology retrofit. Thermal benefits of electric lighting and control solutions are assumed to be marginal in comparison to the benefits of daylighting solutions that affect solar gains, and are therefore not included in the assessment.
- Baseline performance
  positioned in the middle (marked by black line)



3. OVERVIEW OF SOLUTIONS

As indicated in the introduction, retrofit by means of simple lamp or luminaire replacements are widely accepted, due to its effectiveness from an economic point of view, focusing on energy savings for electric lighting and payback periods. The remaining retrofit solutions, taking into account the usage of other components or a new design of the lighting installation are often neglected in the retrofit process. The unsatisfactory implementation of unconventional retrofit solutions is partly due to the abundance of approaches, and the great diversity amongst them. To structure the variety of solutions, a matrix was developed (see Figure 4) to present these.

A. in the following categories:

» daylighting solutions (façade & daylighting technology + blinds & shading technology),
» electric lighting solutions (electric lighting solutions + electric lighting controls),
» changes to the building interior that affect the lighting conditions.

B. according to the retrofit process:

» Upgrade of the existing situation,
realized by, for example, replacing the lamps in an electric lighting installation with lamps with a higher efficiency, adding a simple daylighting system to improve user comfort or painting the walls to increase room surface reflectance.
» Use of new components in an existing situation,
such as the replacement of a window with one that has glazing with improved thermal qualities, the replacement of a luminaire with one that has a more suitable luminous distribution, and replacement of partitions in an open plan office with partitions with reduced height.
» Redesign, the so called deep retrofit,
for example, of a roof by adding sky lights, of an electric lighting installation by changing from general lighting to a task / ambient lighting solution, or of the building interior by removing walls.

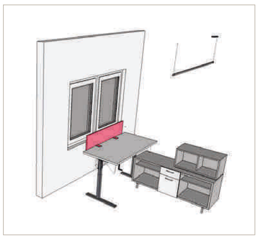
It needs to be pointed out that these retrofit options are addressed in different design stages, for both daylighting and electric lighting. According to the Advanced Energy Retrofit Guides (EREE 2011, 2013), standard retrofit solutions (upgrade and use of a new component) offer approximately 25 – 45% savings for electric energy, a deep retrofit offers more than 45% energy savings, but typically has higher investments and longer payback periods.

In the following chapters, product families of lighting retrofit technologies are evaluated, and an overall performance assessment for each type / family of retrofit solution is given. As an example, LED solutions for T8 replacement are available in a large variety. The products considered in the performance assessment are replacement lamps offered by larger, well-known, manufacturers. Resulting, the performance icon (see Figure 3) and the representation of the main features in technology descriptions (as can be found in chapter 4) will not reflect the performance of all LED solutions for T8 replacement available on the market. The technology descriptions can include relevant information about outliners in performance, pointing out possible quality restrictions, whenever this information is available. It remains of importance to assess the actual performance of a specific product before implementation in a retrofit project, for example by means of the Catalogue of Criteria.

Evaluations are based on state-of-the-art technology (to date – February 2016). With respect to daylighting retrofit solutions, no relevant changes in technology are expected in the coming 5 years. With respect to electric lighting solutions, especially LED, significant changes are expected. In 2015, the LED efficacy on luminaire level is approximately 100 lm/W, and expected to be 200 lm/W in 2020. The costs of LED packages is currently at 1.0 – 1.2 $/klm, which will drop approximately by 65% in 2020 (U.S. Department of Energy 2015). Consequently, LED solutions will become (even) more efficient and cheaper. This will affect the rating of systems in this source book for these specific solutions, as well as their weight in the retrofit process, already being a, so-called, simple electric lighting retrofit solution. The evolving of LEDs has also its drawbacks; light sources, or modules, are not standardized (except those by the Zhaga consortium), and thus it might be difficult to get spare parts for future retrofits.

4

	Upgrade of existing situation	Use new components in existing situation	Redesign
Façade & daylighting technology	'Add on' to the window plane: add simple daylighting system (e.g. light redirection blinds)	Add construction to the façade or window replacement (e.g. daylighting system fitting in existing window frame)	Redesign of façade or façade elements (e.g. increase window size, add skylight)
Blinds & shading technology	'Add on' to the window plane: add shading devices (static or dynamic)	Add construction to the façade or window replacement (e.g. electrochromic glazing, double glazing with blinds, louvres)	Redesign of façade or façade elements (e.g. add architectural shading elements, light shelves)
Electric lighting solutions	Lamp replacement: improvement in lamp or ballast technology, improvement of spectral quality of light source, increase of luminous flux, …	Luminaire replacement: improvement in luminaire technology, lamp or ballast technology that requires a new luminaire, …	Redesign of lighting installation: more efficient luminaires, use of task / ambient lighting, reduction of maintained illuminance levels, …
Electric lighting controls	Stand-alone controls: use time switch to reduce total switch-on time, use of sensors for presence detection (switching), …	Luminaire based controls: use of sensors for presence detection (dimming), daylight dimming, manual dimming, …	Install advanced lighting control system, building management system to link electric lighting to heating and cooling, networked lighting, …
Changes to the interior	e.g. increase of surface reflectance, rearrange position of work places	e.g. reduce partition height, redesign of work place position	e.g. increase ceiling height, remove walls



>> Highlights & Lowlights:

Cost effective and easy retrofits: change of surface reflectances

Easy retrofit: change of partition height

Effective but labour intensive retrofit: removing and replacing of interior walls

The building interior is a relevant parameter in the efficiency of lighting solutions. The so called utilisation factor reflects how well the lighting can be used to illuminate specified surfaces, it is the ratio of the luminous flux received by this surface to the overall luminous flux of the light sources of an installation. It is affected by a number of characteristics in the room, such as room size and shape, surface reflectances and partitions, as well as luminaire characteristics, such as lumen output ratio, luminous intensity distribution and position of the luminaire. If the building interior, and the related utilisation factor, is not properly considered, the efficiency of daylighting and electric lighting is reduced and the energy saving potential of retrofit solutions might not be reached. Additionally to that, the building interior affects the daylight distribution, which can influence both energy saving potential and room appearance. A better daylight distribution also results in the reuction of contrast between the areas near the window and areas away from the window. This can improve visual comfort in larger space.

Therefore, a number of retrofit activities related to the building interior influence the lighting conditions in a room. These ranges from cheap to expensive changes, such as painting the walls, changing the carpet colour, adding partitions in large open space, or removing and replacing interior walls. These activities can be additional to, or an alternative solution when lighting retrofits are not suitable or possible, to enhance lighting efficiency.

A brief overview of economical room related changes are those looking into:

» room surface reflectance
Light in space with high surface reflectances is better distributed than in spaces with low surface reflectances. Higher surface reflectances will enhance the reflection of daylight and electric lighting in a room and increase the energy savings potential, especially in daylit spaces. Average wall reflectances should preferably be higher than 50%. Average floor reflectances should preferably be higher than 25%. Ceiling reflectance has an effect when luminaires with an indirect component or redirecting daylighting systems are applied and is preferably high (70 – 80%).

» partition heigth
The height of partitions between workstations significantly influences the utilization of daylight and electric lighting that enters the rooms. This affects the energy savings potential, especially for daylight solutions in deep spaces and for electric lighting solutions using luminaires with an indirect component. A balance between appropriate lighting contribution and acoustical separation is required. Lower partition heights can offer a better view outside, increase energy saving for electric lighting, but also reduce the acoustical separation between workspaces.

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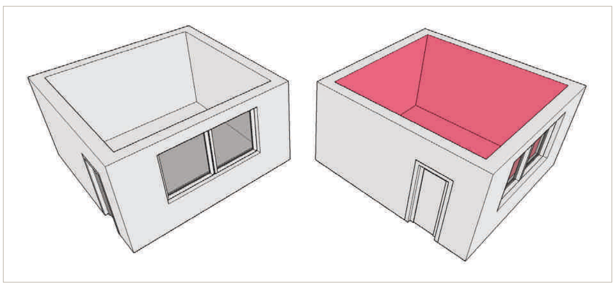

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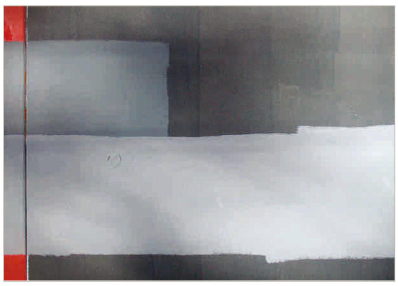
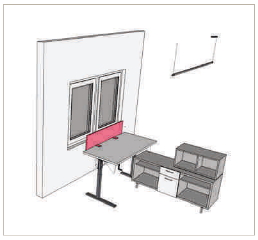


» reflection of partitions and furniture
The impact of reflectances of vertical surfaces of a workstation on energy savings potentials is higher for indirect luminaires, as they rely on these surfaces to illuminate the desk. Lower reflection of partitions also reduces the daylight levels deeper into a room. Transparent partitions could be considered, as they provide acoustical privacy as well as improved dalyight performance in the interior space.



Building retrofits that consider removing interior walls or replacing interior walls with glass walls will typically increase lighting efficiency. This retrofit approach is more expensive and can be considered in a deep retrofit only.

It should be noted that aesthetic and interior design considerations can overpower the consideration of improved lighting distribution.

>> References

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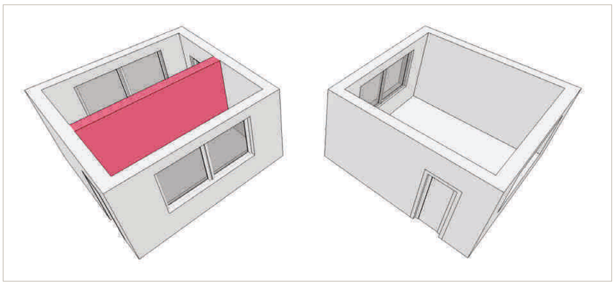

3.2 FAÇADE AND DAYLIGHT TECHNOLOGY

In view of the finite reserve of fossil fuels, daylight should be the primary source of lighting in buildings. Appropriate daylighting design is required, to ensure that the overall use of energy is minimized. This includes the energy use for electric lighting, cooling and heating as a result of the daylight design. Increased cooling or reduced heating might be the result of the thermal load of sunlight entering the room. Supplementary heating might be required because increased window size leads to additional thermal losses. Summarized, increased daylight utilization could increase energy consumption if energy to compensate for the additional thermal load (cooling load) and / or thermal losses (heating load) exceeds the energy saved by reducing the use of electric lighting.

In the overall energy consumption, geographical position plays a role. For example, a study of five daylight regions in North American showed that energy savings fall with rising latitude and total annual solar radiation, with the biggest differences in the winter months due to the shorter day lengths with increasing latitude (Reinhart 2002). However, an analysis of the applicability of a large number of retrofit options as such (EERE 2011 and 2013) indicates that the climate as such does not play a significant role in the effectiveness of the studied options (daylight harvesting, replacing windows, add exterior window film, window shading or light shelves, as well as the retrofit of interior fixtures and occupancy sensors).

Orientation plays a role when considering daylight utilization as well. On the northern hemisphere, the use of daylight from north facing façades is more effective to save energy in sunny climates, whereas the overall energy consumption in cold climates is lower for south facing façades when daylight is used to illuminate the building. For the southern hemisphere for respectively the south and north facing façades.

Even though the actual performance is depending on climate and orientation, it will not be included in the energy efficiency assessment of the retrofit products presented in this report. If geographical location or orientation is an important factor, it will be mentioned in the description of the product.

!

Daylight utilization affects the switch-on probability for electric lighting, which in result influences energy consumption for electrical lighting. Switching tends to be correlated to minimum indoor illuminance levels at the work plane upon arrival (Hunt, 1979; Love, 1998; Reinhart 2004). Likely as a result of this, higher levels of energy savings are achieved with manual control of electric lighting in daylit spaces compared to spaces without daylight.

As indicated in the introduction, daylight utilization offers benefits beyond the reduction of energy for electric lighting. It is generally acknowledged that occupants prefer daylight to electric lighting. Daylight can positively affect stress, well-being and mood. Additionally to

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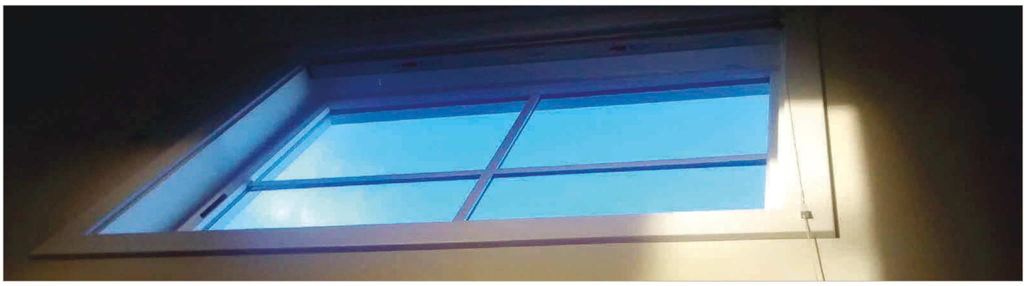


that, it is effective in causing visual and non-visual responses, due to its availability in large amounts during the day, the strong blue component in its spectrum, and its excellent colour rendering qualities. Studies have indicated that daylight can increase productivity, academic results as well as user comfort (e.g. reviews of Boyce et al. 2003, Veitch and Galasiu (2012) and Strong (2012), studies conducted by the Heschong Mahone Group (California Energy Commission (2003a, 2003b) and http://h-m-g.com/Projects/daylighting/projects-PIER.htm) and ongoing work of the CIE Joint Technical Committee on "Visual, Health, and Environmental Benefits of Windows in Buildings during Daylight"). Studies also indicate that daylight utilization can increase sales (Heschong et al. 2002).

Up until today, these benefits cannot be quantified in an economical value or be represented in the lighting quality. Nonetheless, research indicates that the most important attributes of windows are the admission of daylight and the view out. In order to get an impression of the daylight provision for human related aspects, specific consideration of a small number of quality criteria, such as light distribution in the room (criterion # 21) and view out (# 23), could be considered in the decision for a daylighting retrofit solution. Increasing the glazing area in the building envelope, by adding skylights or enlarging the window size, will positively affect the daylight contribution.

Resulting, daylighting retrofit solutions should be applied to modulate and enhance daylight admittance, especially under sunny conditions, to reduce energy consumption for electric lighting, while increasing user comfort. These systems focus on the appropriate use of daylight under sunny sky conditions:

» blocking the sunlight, to prevent glare and overheating, but letting in diffuse sky light, or
» redirecting sunlight into the room to increase lighting levels while reducing direct glare from sunlight.

In both cases, a better use of daylight is realized in comparison to the situation with a closed sunshading system which prevents daylight utilization under sunny conditions completely (see baseline, section 2.1.1)

This source book includes a number of efficient daylighting retrofit solutions. Additional information on daylighting solutions can be found in the IEA Task 21 source book (Ruck et al. 2000) or at the Database of Light Interacting Technologies for Envelopes (D-LITE, http://d-lite.org/).

On the following pages, the performance of selected retrofit solutions is described in detail, and structured according to Figure 4.

>> Redesign

Adding an opening to or increasing the size of an opening in the building envelop will result in a redesign of the façade or the roof. Even when the product costs as such might not be very high, this retrofit solution will have high labour and constructional costs. The window opening can increase solar gains and thermal losses as well, which might affect the overall energy balance of the building. The resulting long payback period for these retrofit solutions might be balanced out by the financial, human-performance and psychological benefits of the higher daylight contribution in the building.

Retrofit technologies: skylights, acrylic skylights, light tubes, lamellae heliostats, translucent skylight systems, micro sunshading louvres, light shelves and enlargement of window area (Section 3.2.1 - 3.2.8)

>> Use of new components
Adding a construction to the façade. Replacing a window with one that has different characteristics increasing either energy efficiency, such as glazing with improved thermal qualities, or lighting quality, such as solutions that provide glare protection and a view under sunny sky conditions.

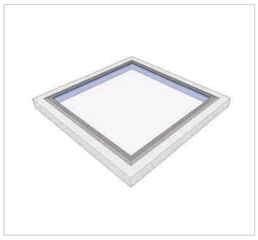
Retrofit technologies: Louvres, shutters, electrochromic glazing, micro lamellae, microstructured glazing, prismatic elements, laser cut panels (Section 3.2.9 - 3.2.16) and (redirecting) blinds integrated in an insulating glass unit (Section 3.2.18 and 3.2.19).

>> Upgrade of existing situation
A system can be retrofitted by means of adding a daylighting technology to the existing situation. These solutions are typically added on the outside of the façade. In this, the devices can reduce the cooling load of buildings (23% - 89%, with the highest savings obtained for solutions with a low shading coefficient (Dubois 2001). External systems nonetheless need to be robust, not to be affected by outdoor weather conditions. These systems might need more maintenance, which can be more difficult when not directly accessible from the building. Internal systems are sheltered from wind, rain, temperature changes and snow, and are typically less expensive than external systems, but do not provide thermal benefits. Both solutions can offer personal and glare control.

Retrofit technologies: sun protection films, blinds, exterior redirecting blinds, stainless steel roller shutters, sunscreens (Section 3.2.17 - 3.2.22)

SKYLIGHTS 3.2.1

Skylights as a retrofit solution affect the building envelope. They are used to increase daylight contribution in a room, in order to enhance user comfort and reduce energy consumption. Skylights are typically prefabricated and installed in an existing roof construction. Skylights are preferably applied in areas in which fluctuation of lighting level is not a serious problem.



>> **Description**:

Depending on the size of skylights, considerable daylight contribution is possible. Energy savings potential offered by the use of daylight can be realized only with a daylight harvesting controls (dimmable or switchable). Skylights perform best in situations with diffuse skylight. In order to block out the sunlight, to prevent from glare and heat, skylights need to be properly orientated or provided with sunscreens. Translucent skylights offer some sun protection, but will have a lower light transmission. From a retrofit point of view, the roof structure must allow penetration, which often leads to the choice for smaller skylights. These have other advantages as well: a better light distribution and higher uniformity, when properly spaced.
Skylights are effective as a retrofit solution for areas in which fluctuation of lighting is not a serious problem, such as retail, warehouses, restaurants, public areas, transportation areas and residential areas. The costs for the system and its installation are relatively high and payback periods are typically several years or longer. Maintenance cost increase, as skylights need to be cleaned from time to time, to ensure optimum daylight contribution.

Skylights can introduce considerable heat gain and losses that may offset the benefits of electric light savings and cause an increase in yearly net energy use. On the northern hemisphere, south facing skylights provide the greatest solar heat gain, north facing skylights provide illumination without large thermal loads. Horizontal skylights require the smallest glazing area to achieve set indoor lighting conditions and provide the lowest heat losses. It should be noted that for permanent work places, such as offices, skylights do not provide the necessary view out which is highly appreciated by building occupants.

>> **References**

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Heschong (2003): Daylight and retail sales: Technical report
Lawrence and Roth (2008): Commercial building toplighting: energy saving potential and potential paths forward
EREE (2011): Advanced energy retrofit guide - Retail buildings

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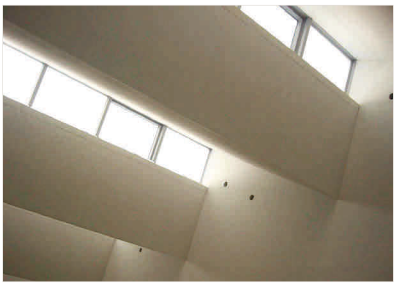

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>> Highlights & Lowlights:

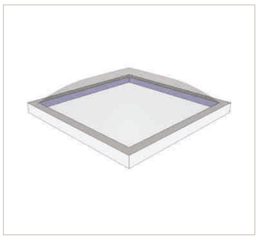
Increased daylight contribution, with resulting physiological, psychological as well as monetary benefits

Moderate energy savings potential

Poor thermal insulation

Retrofit to the building envelope, long payback periods

3.2.2	ACRYLIC SKYLIGHTS



Acrylic skylights are comparable to traditional skylights, but instead of using glass as a transparent material, they use a single or multiple acrylic sheets. Acrylic skylights are often shaped by blowing and have streamlined shapes.

>> Highlights & Lowlights:

Increased daylight contribution, with resulting physiological, psychological as well as monetary benefits

Moderate energy savings potential

Poor thermal insulation, small size of skylight

Retrofit to the building envelope, long payback periods

>> **Description**:

Acrylic skylights have similar properties as traditional glazed skylights; they significantly increase daylight contribution in the room and have daylight-related physiological and psychological benefits. Energy saving potential can be realized with a daylight harvesting controls. They function best in locations with predominating diffuse skylight.

In comparison to skylights, acrylic skylights can have a somewhat lower initial cost and easier installation, due to their weight.

They have simple, effective design and limited size, but while the price of materials is consistently low, installation costs may be high and will vary depending on the size and type of skylight as well as the type of roof construction. The view out might be slightly distorted due to the use of the material. Acrylic skylights as such have a higher total transmittance of light than traditional glazed skylights as they do not have any metal profiles for support of heavy glazing but their limited size makes that the number of skylights have to be larger and the impact of the reflectance of the light-well surfaces (between ceiling and skylight) have a stronger impact.

The most serious drawback of acrylic skylights is that they are (typically) not equipped with sunscreens or other devices for control of solar energy transmittance and glare. The light level fluctuation in interiors with acrylic skylights may be very large. Additionally to that, like in case of a traditional skylight, they offer little thermal protection, which can drastically increase HVAC use. In comparison to a single layer acrylic sky light, the thermal performance of a multilayer solution is better, but has a lower light transmittance. The longevity of acrylic skylights is shorter compared to traditional skylights.

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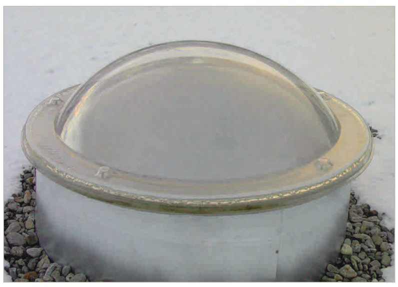
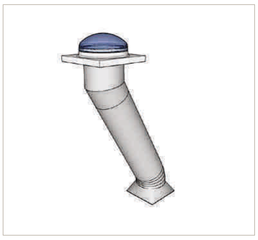


Tubular daylighting systems, or light tubes, are linear devices that channel daylight into the core of a building. They consists of a linear light transport unit, a tube, with some device for collecting natural light at the outer end and a means of distribution of light within the interior at the inner end. Tubular daylighting systems are especially suitable for windowless and underground places, in which daylight contribution is desired and a view out not required.



>> Description:

Tubular daylighting systems, light pipes or light tubes have been developed to increase daylight contribution in windowless places and thus improve lighting conditions and reduce energy consumption at the same time. Light tubes are suitable for a variety of different types of buildings such as industry plants, underground car parks, supermarkets or homes and are most often used for roof applications.

A typical light transmittance of the system is 0.60-0.70 and the effective g-value is 0.20-0.35. Under overcast sky conditions the light transmittance is low due to multiple reflections. Light tubes can be applied in all climates, but might be preferred in sunny climates while giving a rather dull lighting under overcast skies. Light tubes deliver glare free light, but typically cannot adjust for the dynamic changes of exterior illuminance, resulting in light level fluctuation. The biggest flaw of the tubular daylighting system is the lack of view out. Some products offer an adaptor to adjust the daylight contribution in the room, or include LED technology to provide additional light from the same fixture when available daylight is insufficient. The installation cost for light tubes are high, as the building envelope has to be perforated. The running costs are moderate, as light tubes need cleaning from time to time. In comparison to electric lighting installations, the total cost of ownership (€/Mlm.hr, per year) for useful light on the work plane is better for light tubes and skylights (section 3.2.3 and 3.2.1) then for electric lighting installations (Fontoynont 2008).

>> Highlights & Lowlights:

Increased daylight contribution, with the subsequent benefits.

Glare free light

High installation costs, as a result of the redesign of the building envelope

No view out

>> References

Fontoynont (2008): Long term assessment of costs associated with lighting and daylighting techniques
Kim and Kim (2010): Overview and new developments in optical daylighting systems for building a healthy indoor environment
CIE (2012): CIE 173:2012 Tubular daylight guidance system
Aizenberg (2013): Hollow light guides: 50 years of research, development, manufacture and application - A retrospective and looking to the future

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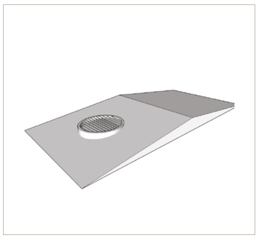
3.2.4 LAMELLAE HELIOSTATS



Lamellae heliostats are light guiding devices for the introduction of sunlight into the interior of a building. Independent of the position of the sun the light is always reflected vertically down and can thus be guided far into deep courtyards or light wells. This retrofit solution is specifically developed to enhance daylighting of buildings by effective use of direct sunlight.

>> Highlights & Lowlights:

Increased daylight availability in deep spaces

Energy savings through reduced demand for electric lighting

Need for precise tracking of the sun

High initial costs

>> Description:

Lamella heliostats are applied in skylights or roofs to redirect sunlight deep into light wells or inner courtyards. The system with multiple, serially arranged highly specular deflecting blades is designed to reflect sunlight from any sun position vertically down into the adjacent room or light duct. Thus, sunlight can be directed very deep into buildings and used there for illumination.

The specular lamellae are swivelled around horizontal axes to ensure the incident direct light is always redirected vertically downwards depending on the elevation of the sun. In addition to the single blades, also the overall circular system is controlled and rotated to match the respective sun azimuth angle.

Usually clear or diffusing covers are used at the top of light tubes to allow sunlight and skylight to enter the duct. However, light from low sun angles and diffuse light are strongly attenuated due to multiple reflections in the pipe. As light exiting a lamella heliostat is always parallel, this issue is overcome with this system. Lamellae heliostats are more effective than light tubes, but need more maintenance and have higher initial costs.

The development of the lamella heliostat system is currently in the stage of a functional model where the proof of concept and the functionality were verified. The system can provide substantial daylighting benefits for deep and dark atria or wells in climates with a high sunshine probability.

>> References

Light Guiding Device (2012), Patent US020120126098A1 / DE102009039136A1

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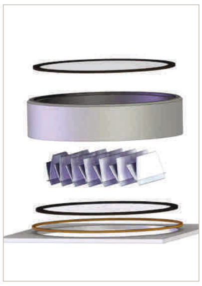

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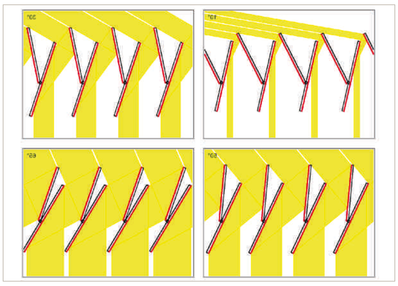

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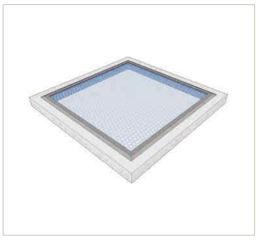
The translucent skylight system can be used to increase usage of both sunlight and light form the sky for illumination of interiors, including task lighting. Comparing to a clear glass skylight, it will contribute to enhancement of user comfort and reduction of energy consumption. The translucent skylight system, similarly to skylight, as a retrofit solution affects the building envelope.



>> **Description**:

The translucent skylight system consist of three elements: a skylight, a vertical well covered by a specular reflective material and an especially designed light transmitive-scattering (T-S) perforated acrylic plate situated horizontally beneath the well in the ceiling plane. The height of the well depends on the thickness of the roof. The design of T-S plates has to be optimized to the latitude of the building site.

The translucent skylight system, dissimilarly to a simple skylight, performs very good in any daylight condition as the light transmittance of the T-S plates for the diffuse light from the sky is very high (over 90%) and the perforation design of the T-S plates is optimized for scattering of sunlight down and around the skylight (avoiding reflection upwards to the sky). The scattering of sunlight assures rather even light distribution and good visual comfort; it is not necessary to use sunscreens.

Depending on the size of the skylight system, considerable daylight contribution is possible. Energy savings potential offered by the use of daylight can be realized only with a daylight harvesting controls (dimmable or switchable).

The translucent skylight system, contrary to a simple skylight, is effective as a retrofit solution for all possible areas and functions, excluding only areas where a low light level is needed. The costs of the system and its installation are rather high and the payback time is typically several years or longer. Maintenance cost increase, as skylight system needs to be cleaned from time to time, to ensure high light transmittance.

The technology is currently under research and development.

>> Highlights & Lowlights:

Increased daylight contribution, with resulting physiological, psychological as well as monetary benefits

Moderate to high energy savings potential, to be realized with daylighting harvesting control

Slightly distorted view

Retrofit to the building envelope, long payback time

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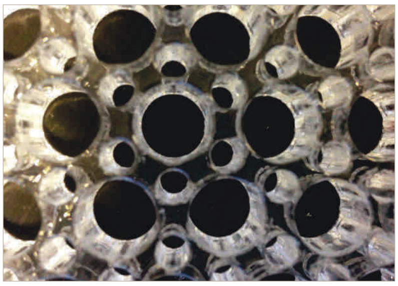

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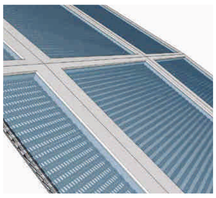
3.2.6

MICRO SUNSHADING LOUVRES



Micro sunshading louvers are highly specular systems that are installed in horizontal or slightly inclined glazings (glazed roofs or skylights). They are efficient sun shading solutions with SHGCs around 10-15% while providing daylighting from diffuse skylight and visual contact to the outside.

>> Highlights & Lowlights:

Highly efficient sun shading and low SHGC.

Homogeneous interior daylight distribution through sun shading

No variation in SHGC possible

Retrofit to the building envelope, the system being integrated in an insulating glass unit

>> Description:

Micro sunshading louvers are applied in horizontal or lightly inclined roof areas. The retrofit approach is comparable to adding a skylight, as the micro sunshading louvres are integrated in an insulating glass unit (IGU). Redesign of the building envelope is required (see "skylights", section 3.2.1). High energy savings can be achieved, due to high daylight utilization, as a result of efficient sun shading and a homogeneous diffuse daylight distribution in the adjacent room. Micro sunshading louvres are designed to block sunlight while transmitting diffuse skylight. The specially formed geometry is aligned with its opening to the north allowing the northern skylight to pass into the room. On the northern hemisphere, skylight from northern and zenithal areas that is not directly transmitted is reflected into the room via highly reflective coating without substantial losses. The specular surface facing the sun (south facing) reflects all direct light from possible sun positions back out. The intelligent geometry of the system allows highly effective sun protection with SHGCs of lower than 15% in typical installations inside double or triple insulating glazing units. At the same time, view to the outside is offered to the north and the transmitted diffuse skylight provides adequate and sufficient daylighting of the interior space. Variations of the geometry even allow to combine the solar shading properties of the system with reliable glare protection. Similar to specular louvers of luminaires the light entering the interior of the room is only emitted at restricted angles. Accepting a decrease in the transmission of diffuse skylight and a distortion of the view outside thus allows for application in scenes with high visual requirements such as offices and control rooms. Installation costs are significantly lower when an existing skylight is replaced by an IGU with micro sunshading louvres to improve thermal characteristics and glare protection while maintaining a view to the outside.

>> References

Reithmaier and Pohl (2002): Ein feststehendes Sonnenschutz- und Ausblendraster zwischen Isolierglas für Oberlichten

Buntkiel-Kuck (2014): Daylight Systems – Required components of integrated light solution

Ruck et al. (2000): Daylight in buildings. Source book on daylighting systems and components

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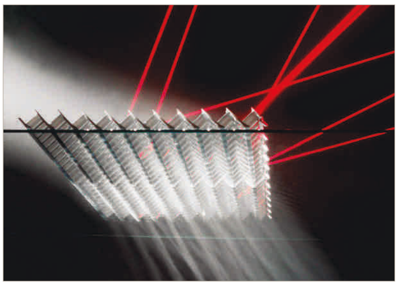

ENLARGEMENT OF WINDOW AREA 3.2.7

To enhance lighting quality and energy efficiency, the enlargement of windows in the façade can be considered as a possible retrofit solution. To maximize energy efficiency, both thermal and lighting considerations need to be respected.

>> Description:

Increasing the window size can improve the daylight contribution in a building, which will positively affect energy consumption for electric lighting as well as user well-being. Nonetheless, studies looking into the impact window to wall ratio (WWR) indicate that the additional window area needs to be designed with consideration in order to achieve these energy savings. Daylight provision does not increase much when the glazed part is added in the bottom part of the façade. Additionally to that, visual comfort can decrease at high WWR, which can lead to a more frequent usage of shading systems, which subsequently reduces the daylight contribution in a building. The appropriate size of the glazed area is linked to the choice of glazing type and the system's ability to control solar radiation and daylight. Typically, for rooms with 2-layer glazing units (one pane Low-E coating, $\tau_v = 0.79$), the working area provided with daylight is generally limited to two times the distance between the upper edge of the glazing and the height of the working plane. For extended daylight provision redirecting devices, skylights or other daylighting systems are required. Defining the ideal window area to obtain the best balance between lighting, visual comfort, heating and cooling loads requires location specific considerations. Software, such as Diva for Rhino, can provide simulations and various annual performance metrics to identify the optimal window size.

When refurbishing a façade from a thermal point of view, effective window area is often reduced, as a result of thicker walls due to increased façade insulation. Results of SHC Task 47 show that thermal renovation strategies of the building envelope can lead to a significant reduction of daylight provision. Changing the window pane from double to triple glazing reduces the secondary heat transfer as well as the light transmittance. Both façade retrofits will reduce daylight provision and thus increase lighting energy consumption.

>> References

Poirazis., Blomsterberg, Wall (2008): Energy simulations for glazed office buildings in Sweden

Kalz et al. (2015): SHC TASK 47: Renovation of nonresidential buildings towards sustainable standards

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>> Highlights & Lowlights:

Increased daylight contribution, with subsequent benefits.

Moderate energy savings potential

Poorer thermal insulation of the building envelope

Redesign of the façade

3.2.8 LIGHT SHELVES

Light shelves are horizontal or nearly horizontal baffles in the façade to simultaneously shade and reflect daylight. They enhance user comfort by providing more uniformly distributed daylight in rooms. Light shelves affect a buildings architecture and need high rooms to function effectively.

>> Highlights & Lowlights:

Increased uniformity of daylighting

Slight increase in daylight provision for external light shelves

Applicability depends on architectural/constructional factors as well as location and orientation

Increased maintenance requirements

>> Description:

A light shelf is generally a horizontal or nearly horizontal baffle in the façade, in the upper part of the window aperture. The light shelf can be an integral part of the façade, in retrofit applications it is typically mounted in front of or on the inside of the building envelope. External light shelves affect the architectural appearance of the building. Simple, diffuse light shelves have their main function in shading, more advanced versions employ specular coatings or complex – even sun-tracked – optical systems to redirect light into the depth of the adjacent rooms. They are usually mounted above eye level and divide the glazed area into a view area and a clerestory. While an internal light shelf reduces the amount of daylight in the interior when compared to a window without a light shelf, an external light shelf might be able to increase it. Both applications provide a more uniform daylight distribution.

Light shelves are not standard products and need to be customized according to orientations, room configurations and latitude. Generally, they can be applied in climates with significant direct sunlight on South oriented façades on the northern hemisphere (and vice versa). They do not perform well on east and west façades due to low sun angles and in climates dominated by overcast sky conditions. The costs for light shelves and their installation are relatively high and payback periods are typically several years or longer. Maintenance costs increase, as such systems, in particular external light shelves, need to be cleaned from time to time to ensure optimum functionality. Movable light shelves need to be controlled and maintained to tap their full potential. Though external systems may slightly increase the interior daylight levels, most light shelves do not provide high illuminances in deep spaces. Thus, the expected energy savings are modest.

>> References

Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components

Littlefair (1995): Light shelves: computer assessment of daylighting performance

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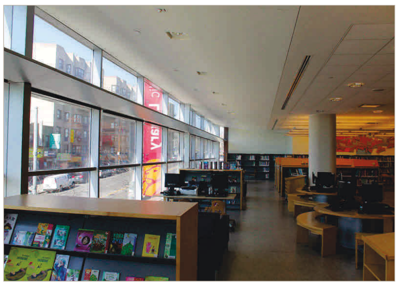

Louvres are applied to shade the heat of the sun and its glare in order to enhance user visual and thermal comfort and reduce energy consumption. They are situating mainly in the exterior in front of the façade with a wide variety in their designs. Louvres affect the architectural appearance of a building. They can be used in any locality on sun facing façades. The maintenance of louver slats should be frequent in polluted locales.

>> Description:

Louvres are developed to increase daylighting in deeper parts of the room while protecting areas near windows from direct sunlight and allow view to the exterior. Louvers can be effectively used for façade orientations towards the sun and in all latitudes. They are made from a wide variety of materials and structural design and can be added to a vertical, slope or horizontal window systems. Louvers are situated mainly on the exterior side of the façade thus affecting the architectural and structural design of buildings. They can be composed from horizontal, vertical or sloping slats with flat or curved shape and various kinds of surface treatments. The impact of louvers depends on the sun position, façade orientation, angle of slats and their surface light reflectance characteristics. The optical and thermal properties of the windows with louvers are various. Fixed systems are designed for stable solar shading while operable systems (manually or automatically) can be used to control thermal gains, protect against glare and redirect daylight in the interior. Operable louvers during overcast situations shade the interior only partially and promote even distribution of daylight.

Louvers can reduce up to 60 - 90 % of direct incident light, depending on their tilt. Costs and saved energy are products of the more efficient utilization of daylight without cooling loads (circa 20% reduction in warm seasons) while added solar heat gains (circa 80% reduction in colder periods). During wintertime louvers can offer the potential for the benefits of the thermal resistance in their closed position. Maintenance of louvers can be difficult, especially when they are automatic, or have reflective surface of slats especially in high buildings.

Wooden and timber louvres are frequently used for making external shading systems for light control and privacy mainly in family and residential houses. Their horizontal or vertical slats act to regulate the light and air allowed into a room. At the same time, they can limit noise from outside. They provide an environmentally friendly and sustainable option to aluminium or plastic louvre systems. They are produced from various kinds of the wood. Resulting, wood louvers provides sustainable sun and energy control for the building while providing a highly attractive aesthetic which combines functionality, modernity and elegance. In dependence

>> Highlights & Lowlights:

Better daylighting distribution, increase of visual and thermal comfort

Moderate energy savings potential

Maintenance of an adjustable, exterior system

Retrofit to the building envelope with possible longer payback periods

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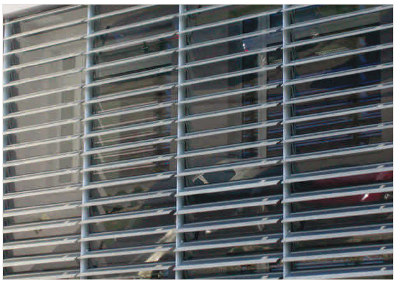

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on the thickness of lamellas and their rotation the light transmittance through window can be reduced up to 10%.

Timber louvers which have thicker lamellas. Light transmission 30-40 %, total solar energy transmittance 12-50 % und Ug-value 1,2 - 2,0 W/(m^2K) can be achieved by installation of timber louvers. The maintenance of slats should be frequent in wet environment. Extreme temperature changes also cause wooden louvers to warp or splint and thus need a high maintenance because they need regular painting or varnish to preserve them in good shape.

Plastic louvres can be used in many localities. Their horizontal or vertical slats regulate the light and air penetrated into a room. These are commonly applied residential and tertiary buildings due to their low weight, durability, aesthetic look and clean finish. Resulting, plastic louvres are an appropriate retrofit solution for older buildings. Plastic louvres require lower maintenance, have a lower initial cost, are 100 % recyclable, high resistance to moisture and UV-stabilized. They are outdoor weathering resistant when UV-stabilized, suitable for an operating temperature range from -30°C to +70°C. PVC louvers are suitable for application also in chemical zones where use of metal materials is restricted for corrosion reasons. The light transmittance of whole window system with plastic louvers can decrease by around 10 %.

Aluminium louvres are manufactured from corrosion-resistant extruded aluminium alloy with stainless steel fixings. They can be solid or perforated for improved visibility, with wide range of various shape profiles, fully manual or automatic operable or fixed. This retrofit solution can be used in any geographical localities. The major advantage of aluminium louvers is low cost of aluminium and easy maintenance. Aluminium louvers in most cases are light, durable and they will still offer sufficient alternatives for many applications and aluminium louvers are lighter then wooden or glass louvers. Additionally they will not rust having a glossy surface for a long time. While aluminium louvers are sufficient for many applications in all types of buildings, it has to be considered that under high temperatures, aluminium expands twice as much as steel, which should be a factor in deciding dimension design for the shading system. Anodising treatment can provide excellent corrosion resistance and thus such finishes can be widely used for exterior applications in arbitrary climatic zones. In dependence on the position of slats sunlight can be redirected into deeper parts of the room.

The impact of the louvers on daylight illuminance in a room depends on the solar altitude and slope of slat , e.g. for a slat slope of 30° and

» solar altitude 30° the light transmission is 60% - 80%,
» solar altitude 45° it is in the range 50% - 75%,
» solar altitude 60° it can be 45% - 60%.

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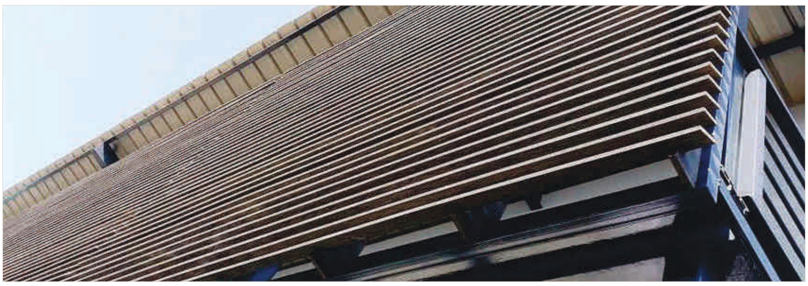

For a slat slope of 45° and
» solar altitude 45° the light transmission is roughly 30% - 50%,
» solar altitude 60° it can be 20% - 40%,
and for 60° slat slope and 60°solar altitude it can decrease to 10% - 25%.

Other merits of aluminium louvers are: good plasticity, easy fix and install, used recyclable material and environmentally friendly, flexible size and shape, simple assembly and retrofit.

Glass louvers can be used for a fixed or controllable solar shading system that can be installed either vertically or horizontally in front of the façade or in the interior. Glass louvers are available in various colours, surface finishes and coatings. These louvres offer better light transmittance. Depending on the chosen type of glass or film, light and radiation transmission can be accurately predetermined for many specific applications. The role of glass louvers to enhance the solar protection and the protection against glare can be achieved using diffuse or laminated glass with a printed film. The high energy absorption property of glass louvers reduces the solar gain in interiors. The variations of transparency achieved with the patterned laminated glass also emphasize the overall aesthetic of the diamond image. At the same time the movement the louvers (pivoting and stacking) adds overall animated effect to the active skin of buildings. Controllable or fixed glass louver shading system can reduce solar heat gain and costs for air conditioning as well as protect against glare whilst maximising the use of natural daylight. Light transmittance of glass louvers depends on the colour and material of the glass but generally it is relatively high, for clear glass in the range 70% - 80%. Glass louvres offer potential to integrate photovoltaic systems.

>> **References** for wooden and timber louvres:
Ching, Jarzombek and Prakash (2011): A global history of architecture
Guzowski (2000): Daylighting for sustainable design
Fortmeyer and Linn (2014): Kinetic architecture: Design for active envelopes
Vassigh and Chandler (2011): Building systems integration for enhanced environmental performance.
>> **References** for plastic louvres:
Egan (1983): Concepts in architectural lighting
>> **References** for aluminium louvres:
Mumovic and Santamouris (2009): Handbook of sustainable building design and engineering – An integrated approach to energy, health and operational performance of buildings
Yu (2013): Skins, envelopes and enclosures: concepts for designing building exteriors
Bovill (1991): Architectural design: integration of structural and environmental systems
>> **References** for glass louvres:
Chen and Kennedy (2007): Contemporary design in detail: Sustainable environments

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3.2.10 SHUTTERS

Shutters are elements which dynamically solve fundamental functions of the façade: solar shading, daylight control, dynamic façade U-value, natural ventilation, and noise reduction. The shutters can be moved horizontally or vertically in front of the window. Shutters cannot be used on fully glazed façades.

>> Highlights & Lowlights:

Increased daylight utilization

High energy saving potentials for heating, cooling and lighting

Need regular service and maintenance

Applicability depends on façade design

>> Description:

In their most sophisticated versions shutters can increase the façade insulation and control utilization of solar heat gain and daylight, thus reducing the energy needs for heating, electric lighting, cooling and ventilation. An aluminium framework-based façade system is mounted directly on the outside of the window frames using an integrated, exterior placed drive system.

To illustrate the effectiveness of shutters, the following example compares 2-layer low-E glazing with a shutter (heat resistance of 1.0 m^2K/W) with a 3-layer low-E glazing solution. When the shutter is closed, the transmission heat loss is reduced by 30 % compared to the 3-layer glazing. When the shutter is withdrawn, the system allows for 85 % more solar gain and 34 % more daylight than a 3-layer solar protective glazing. At the same time the 2-layer glazing gives a better visual environment, due to the increased daylight level and a brighter and clearer view to the exterior, especially compared to a 3-layer solar protective glazing solution.

Shutters should be operated automatically (with manual override) to realize the potential energy savings and improvement of thermal and visual indoor climate. Shutters are suitable for plane façades and can be used for both new and existing buildings and for all façade orientations. However, since the shutters need 'parking spaces' when they are open, the energy saving potentials can normally only by realized on façades with maximum 50 % glazing. The costs for shutters and their installation are relatively high but they offer many of the same benefits as double skin façades, which are much more expensive. Maintenance costs increase, since shutters need regular service and maintenance (typically once every year) to ensure optimum functioning.

>> References

Johnsen and Winther (2015): Dynamic facades, the smart way of meeting the energy requirements.
Winther (2012): Intelligent glazed facades, an experimental study

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In an electrochromic (EC) window, a coating on the inside surface of the outer pane allows the glass to change transmittance in response to a small applied voltage (±3-5V). Electrochromic coatings are switchable thin-film coatings applied to glass or plastic that can change appearance reversibly from a clear to a dark Prussian Blue tint. Electrochromic glazing is to be applied when solar heat gains need to be reduced, while allowing a view out and daylight contribution.

>> Description:

An electrochromic coating is a nanometer-thick (1x10-9, 4x10-8 inch), multi-layer film or stack deposited on a glass or plastic. Transparent conductors form the outer layers of the stack, an active electrochromic and passive counter-electrode layer form the middle layers, and an ion-conducting electrolyte layer forms the center portion of the stack. The system works like a battery. A bipolar potential is applied to the outer transparent conductors, which causes lithium ions to migrate across the ion-conducting layer from the counter-electrode layer to the electrochromic layer. A reversible electrochemical reaction takes place causing a tinted Prussian Blue appearance. Reversing the potential causes the ions to migrate back, causing a bleached clear appearance. The relative transparency and color tint of electrochromic windows can be electrically controlled. The visible transmittance of the glass varies from about 60%-70% in the fully bleached state to about 0.5%-2% in the fully tinted state, depending on the chosen material and quality.

Low-voltage power is required to switch electrochromic (EC) windows, for some types a small applied voltage is needed to keep the EC in a constant state, irrespective of the level of tint. The EC window can be operated automatically or manually to control light penetration, without compromising the view out. By providing unobtrusive dynamic shading, EC glazing has significant potential to improve daylighting and energy use in new and existing buildings. A shift in spectral power distribution, which might result in colouration of space, might take place if all windows are equipped with EC glazing. Design guidelines should be followed to maintain neutral daylight (Saint Gobain 2014). The light transmittance (τ_v) and solar heat gain coefficient (SHGC) range of EC coatings vary depending on the material composition. Speed of the change in tint varies in the ranges of millisecond to seconds. U-factor is not affected by the change in tint.

Significant lighting energy savings potential is achievable when the window is zoned and controlled properly. Average daily lighting energy savings in a private south facing office in Berkeley, California were 10 – 23% given non-optimized glare / daylight control, compared

>> Highlights & Lowlights:

Preserve outward view while reducing transmitted light, glare and solar heat gains

Energy savings due to reduced demand for electric lighting, heating and cooling

No glare protection for direct sunlight

High initial costs (installation and investment)

to a conventional high-transmittance window (τ_v = 0.60) with a fully – lowered, slightly open venetian blind (comparable level of glare control to EC window) with the same daylighting control system.

Typically limited sizes and shapes are available, to keep costs down. EC glass cannot be installed in existing window frames. EC glass must be part of a sealed insulating glass unit assembly. Latest development in research proposes a separate control of light and solar energy transmittance and increase the range of possible SHGC.

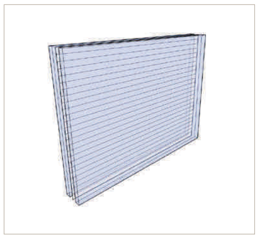
>> References

Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components
Kelly et al. (2013): Retrofit electrochromic glazing in an open plan office: a case study
Lawrence Berkeley National Laboratory (2006): Advancement of electrochromic windows
Azens and Granqvist (2003): Electrochromic smart windows: energy efficiency and device aspects
Saint Gobain (2014): How to maintain neutral daylight Illumination with SageGlass® electrochromic
Mardaljevic, Waskett and Painter (2015): Electrochromic glazing in buildings: A case study

MICRO LAMELLAE

3.2.12

Micro lamellae are stainless steel strips with a large number of small perforations mounted in the cavity of low-E glazing. Sunlight from low angles passes relatively unimpeded, sunlight from higher angles is blocked. This daylighting system enhances visual and thermal comfort and reduces energy consumption. Micro lamellae should be used for façade and roof application where strong solar shading and no maintenance is required, such as high rise buildings, roofs and large glass façades.



>> Description:

Micro lamellae have been developed to effectively shade direct sunlight and provide good daylight provision at the same time. The micro lamellae system reduces or blocks direct sunlight progressively with the height of the sun. Resulting, energy consumption for ventilation and cooling is reduced during summertime, while still allowing passive heating during wintertime. A typical effective g-value for summer is 0.10-0.15 and measurements show that the indoor temperature is lowered by 4-5 °C. The micro lamellae are perforated and allow a view to the outside. The average light transmittance is around 40%. Micro lamellae are installed and have proven its effect in a number of landmark buildings in northern Europe.

>> References

Rasmussen (2013): MicroShade® provides daylight and view out in the new Confederation of Danish Industry' building in Copenhagen

Fernandes et al. (2015): Angular selective window systems: Assessment of technical potential for energy savings

>> Highlights & Lowlights:

Protection against high angle sun with remaining view out.

Good light transmission and diffuse light distribution of light inside.

No glare protection, an addition glare control is needed

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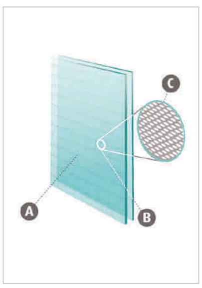

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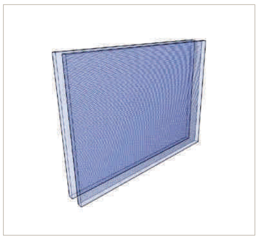
3.2.13 MICROSTRUCTURED GLAZING



Microstructured glazing uses microscopic structures as a film to the surface of a window or inside the insulated glass unit to enhance the daylight provision and/or to reduce glare caused by direct sunlight. The seasonal thermal gains can potentially be optimized. Microstructured glazing is to be used when a simple retrofit of façade is required and parameters as low maintenance and daylight usage are important.

>> Highlights & Lowlights:

Better daylight distribution

Moderate energy savings

Not a wide-spread solution, complex behaviour

Location specific choice, can require to be combined with blinds for full glare and solar gains control.

>> Description:

By using a film consisting of microscopic structures (20-500 micrometers) in the window area, sunlight can be redirected and guided deeper into the building. The redirection of sunlight can be achieved by refraction with various prismatic or curved shapes. It can also be achieved by reflection on metallic coated surfaces. Applying the film to the existing window pane is somewhat cheaper than including the film in an insulating glass unit, but the overall performance is slightly worse.

Numerous approaches for microstructured glazing are explored in research and some are commercially available. They offer various unique bidirectional scattering distributions functions (BSDF). Some microstructured glazing versions aim to block the direct component of light only. This is useful to strongly reduce glare and thermal gains while keeping sound daylight provision. This has an impact on energy savings while positively affecting visual comfort and well-being of occupants.

The main advantages of microstructured solutions over other light redirecting devices are the reduced thickness of the resulting devices and potentially the reduced cost. For the special case of embedded micro mirrors (research status), vertical micro mirrors are invisible to the eye and transparency at normal incidence is hereby increased when compared to reflecting blinds.

With the use of microstructured glazing, the daylit area is extended by a deeper penetration of daylight (see figure 51) in comparison to a standard insulated glazing unit (figure 52) , and the reduction of direct sunlight generally decrease the glare risk. Care has to be taken to avoid glare from the redirected light beam. Therefore and because they mostly are not completely transparent, such devices are generally placed in the top part of a window. Their efficiency depends on their transmittance and strongly on the climate, the type of sky (clear, overcast, intermediate), the orientation, window size and the lighting requirements.

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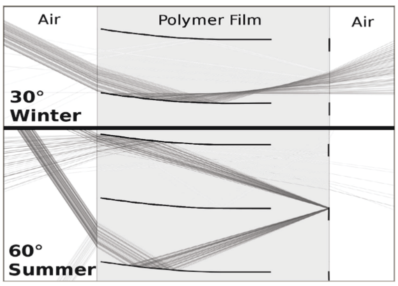

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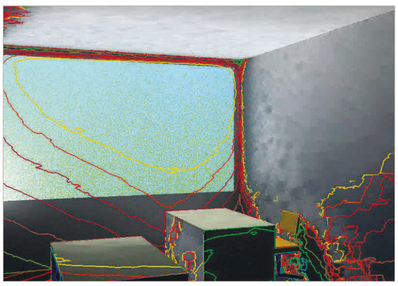

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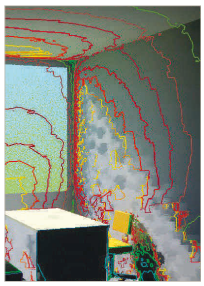
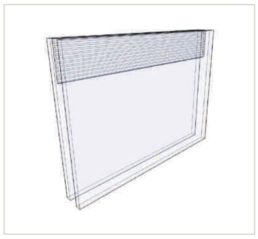


Prismatic elements are thin, planar saw tooth devices made of clear acrylic that are used to redirect or reflect sunlight. Depending on the optical properties they are either used in fixed or sun-tracking arrangements and can be applied in façades and skylights. Prismatic elements are used for sun shading on all façade orientations and in glazed roof areas. Energy efficiency is mainly due to improved thermal behaviour and lighting distribution.



>> Description:

Prismatic systems for sun shading have been developed to avoid direct sunlight entering rooms while concurrently utilizing diffuse skylight for illuminating these rooms. Combining the basic principle of total internal reflection with appropriate geometry allows the definition of an effective range for retroreflection.

To avoid the transmission of direct sunlight into the room the prismatic structure has to be aligned similar to a heliostat to ensure retroreflection of the sun during the course of the day. Only light that hits the panel perpendicularly is mirrored back, light outside the range of retroreflection is deflected from its initial direction and transmitted through the system. Thus, such systems might be critical if an optimal visual contact to the outside is desired.
If no sun tracking is desired, prisms with reflective coatings can be applied. This application is usually found in glazed roof areas (see figure 55). The prismatic structure is designed according to the movement of the sun and the panels are integrated into an insulating glass unit (IGU) for protection.

Moveable and static prisms allow a highly efficient sun shading with SHGCs as low as 10-15% including the IGU, while at the same time offering high transmission of diffuse daylight.

Daylight harvesting prismatic systems are normally used in the vertical plane of the façade to redirect skylight into the upper half of the interior room. They can also be used to direct sunlight into a room. In this case the correct profile and seasonal tilting are essential to prevent glare and colour dispersion.

>> Highlights & Lowlights:

Highly efficient sun shading and low SHGC

Improved interior daylight distribution through sun shading and redirection

Sun tracking possibly needed

High initial costs

>> References

Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components
Pohl et al. (2012): Principles of daylight guiding design

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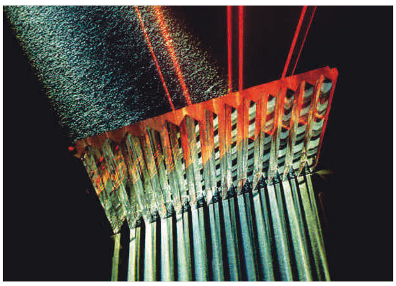

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3.2.15 LASER CUT PANELS

Laser cut panels are daylighting systems produced by making laser cuts in a thin panel of clear acrylic material. These cuts function as small internal mirrors, redirecting sunlight into the room, to increase daylight contribution in the depth of the room. Laser cut panels perform best under sunny conditions, while also allowing diffuse daylight penetration. They are preferably positioned in the upper part of the window frame.

>> Highlights & Lowlights:

Performance well under overcast and sunny sky conditions

Moderate savings, to be realised with daylighting harvesting controls

Relative high initial costs

No reducing effect on solar heat gain, no glare protection

>> Description:

A laser cut panel placed in the façade redirects light incident from higher elevations (>30°). Light from other incident angles will pass through the system and might cause glare. The energy savings potential of laser cut panels depends on the location in window. Laser cut panels fixed in the upper part of a window will redirect light towards the ceiling, increasing the daylight levels by 10% to 30% in the depth of the room, and with this improve the light distribution and uniformity.

These panels perform best with direct sunlight. Daylighting performance can be significantly improved if the position of the panels is adjusted depending on time of day and year, which would in return require mechanical adjustment and with this higher maintenance of the system. As the laser cut panels have a high transparency, they allow for high daylight contribution under overcast skies as well. Laser cut panels cause limited distortion of the view out. Nonetheless, it is desirable that laser cut panels be installed above eye level in windows to avoid glare caused by redirected sunlight.

Laser cut panels are placed between two panes of glass, and thus easy to install in a normal window frame. They can be used as new components in an existing situation and require no re-design. Therefore, laser cut panels are effective as a retrofit solution for areas where the horizontal extent of the rooms is large, such as schools, hospitals, warehouses or office buildings. The cost of the panels is approximately 130 euros per square meter for small areas (< 20 m^2). For larger areas, the cost approaches 100 euros per square meter. Maintenance costs are low, normal window cleaning is required for appropriate functioning.

>> References

Edmonds (1993): Performance of laser cut deflecting panels in daylighting applications
Edmonds (2005): Daylighting high-density residential buildings with light redirecting panels
Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components

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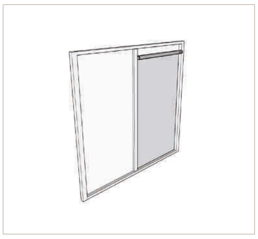
Sun protection film for windows can be applied to windows to reduce solar gains or thermal losses. They generally have a higher transmittance in the visible range than in the infrared. Daylight provision is maintained and glare can potentially be reduced. These films are to be used when overheating or high thermal losses are a problem and replacement of windows is not possible or too expensive.



>> **Description**:

Sun protective films can be applied simply to existing windows as they are self-adhesive. They offer solar protection in cases where overheating is a problem. This protection is provided by a strong reduction of the transmitted infrared radiation (0 to 10%). The application of this film may slightly change the thermal properties of the window and reduce the thermal losses during the cold season, as reflectivity is high only in the low infrared, not in the higher infrared. The protection film needs to be applied on the outside of the windowpane to be effective. High temperature stress may occur, when the film is put to the inside of the windowpane, which might lead to breakage of the pane.

Daylight provision is slightly reduced by the sun protective film. With a lower transmittance in the visible range, glare can be reduced from daylight. Nonetheless, glare from direct sunlight cannot be avoided and additional (interior) glare protection is required. In some situations, with moderate glare and moderate overheating, the use of blinds can be avoided, allowing better daylight utilization and saving energy for electric lighting. The right choice of films provides a good aesthetic integration as some are spectrally neutral and appear transparent (not coloured).

>> Highlights & Lowlights:

Quick retrofit possible

Limited costs

Can reduce daylight provision

Does not prevent glare from direct sunlight

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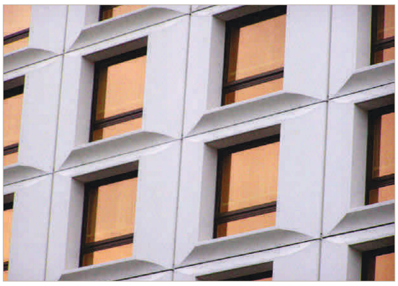

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3.2.17 BLINDS

Blinds are solar shadings used to control the solar incident radiation and protect against glare. Blinds are build-up of lamellas blocking and/or redirecting the direct sunshine, in function of their slope. The dimensions, colour and gloss of the lamellas determine the properties of blinds. Blinds perform best when they are placed on the exterior of the façade. Due to their limited resistance to wind, blinds are best applied on low height buildings.

>> Highlights & Lowlights:

Retractable when no sun is on the façade, optimal daylight utilization and high energy savings potential

Increase thermal comfort and reduced thermal loads if placed on the exterior of the façade

Slat positions are a trade-off between daylighting and glare protection

Medium resistance to high wind pressure and risk of dirty

>> Description:

Blinds consist of multiple horizontal or vertical slats that can be fixed or movable. Static systems are usually designed for solar shading while operable systems are used to protect from glare and to control thermal gains and daylight illumination. Because slats partially obstruct the user's view to the outside, most systems are designed to be retractable. Vertical slats are mainly used in east- or west-oriented façades, while horizontal systems are installed on all orientations. They can be applied at all locations and orientations and are available on the market in a large variety.

Exterior blinds placed in front of windows can reduce the solar gains significantly (direct and secondary heat transfer) providing a limitation to the risk of overheating of the building (lower g value of the complex fenestration system: window + blinds). Placed at the interior of the building, they can achieve good daylight control but they do not contribute significantly to the reduction of the heat gains.

Blinds can be also used to increase visual comfort. They can be used in a dynamic way to control daylight and provide a protection against glare. The view out and the night privacy are mainly properties function of the slope of the lamellas.

Materials and surface properties used for blinds are manifold, varying from fabrics, diffusely painted materials or highly specular finishes to translucent objects and prismatic structures. The colour and the specularity (gloss) of the lamellas combined with the geometrical dimensions determine the thermal performances. The form of the lamellas does not have a big impact on the thermal properties but it has a big impact on the daylighting performances (redirecting the direct and diffuse daylight into the building). Unless using specular finishes (see "redirecting blinds", section 3.2.18), blind systems do not enhance interior daylighting levels, but provide shading and a somewhat more uniform daylight distribution inside the room. Energy savings are to be expected for heating and cooling, but not for electric lighting. The installation of blinds on existing buildings can be achieved with moderate effort by

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adding an additional element to the façade. It is especially recommended for high glazed buildings. The impact of exterior systems to the architectural design of the building has to be considered.

The costs for blinds range from cheap for simple, interior systems to medium or high for movable exterior systems with advanced controls. If the blinds do not have optical treated surfaces, the maintenance requirements are low for fixed or medium for movable systems.

Automatic control of blinds is recommended but, to ensure the user's acceptance, manual overruling has to be possible. When manually controlled, blinds are typically lowered when solar radiation levels at the façade reach 120 W/m² (sun at the façade) to 250 W/m² or at sky luminances around 2000 – 2500 cd/m², automatically controlled blinds are often lowered at levels between 120 and 150 W /m² on the façade. If the blinds are permanently retracted, a northern façade has the lowest energy savings due to the absence of direct sunlight. On the other hand, as an automated system excludes direct sunlight, it yields very similar savings for all façade orientations. As hardly any direct sunlight is ever incident on a northern façade, automated and manual are nearly identical for this orientation. Manual blind control predicts considerably higher energy savings for a northern and western than for a southern or eastern façade (Reinhart 2002).

>> References

ES-SO (2012): ES-SO Manual Solar Shading for Low Energy Buildings
Andersen (2002): Light distribution through advanced fenestration systems
Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components
Reinhart (2002): Effects of interior design on the daylight availability in open plan offices

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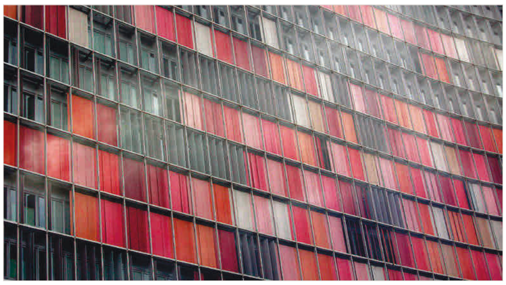

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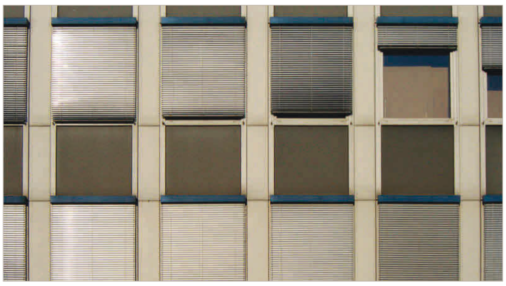

3.2.18 REDIRECTING BLINDS

Redirecting blinds reflect daylight from sun and sky to the ceiling to provide improved daylight illumination even in the depth of the adjacent rooms. For optimal functionality, the upper surfaces are highly specular leading to somewhat increased maintenance costs. A retrofit solution for enhanced daylighting and improved visual comfort, especially suitable for deep rooms.

>> Highlights & Lowlights:

Increased visual comfort and lighting quality

Energy savings through possible reduced demand for electric lighting, heating and cooling

Increased maintenance requirements, especially for exterior systems

Higher initial costs compared to classical blinds

>> Description:

Compared to classical blinds (see "Blinds", section 3.2.17), redirecting blinds generally consist of an upper surface of highly specular material and concave curvature. They are designed to reflect the maximum possible amount of daylight to the ceiling and thus to interior areas far from the façade. At the same time, the luminances below the horizontal plane are minimized to avoid glare.

Based on their optical design, redirecting louvers work for all façade orientations if designed for using skylight, or for East / South / West oriented façades (on the northern hemisphere) if the primarily used daylight is sunlight. Some redirecting blinds consist of a reflector for elimination of summer sun radiation during high solar angles avoiding interior overheating and a light-shelf element improving sunlight reflection into the interior while providing glare protection in wintertime.

Movable redirecting systems allow a good control of daylight illumination and solar gains leading to increased possible energy savings for heating and cooling as well as electric lighting. Most moveable redirecting blinds are operated automatically, with a possibility to overrule manually. Fixed redirecting louvers do not need to be controlled, but the full potential in terms of variable SHGCs and daylight transmittances cannot be tapped with such systems. Some redirecting blinds are developed for exterior use, which need more cleaning to function properly. The majority of redirecting blinds are designed to be installed between two panes of glass or in double skin façades to reduce exposure to dust (interior) or dirt and snow (exterior). In a retrofit process this equals a trade-off between lower installation costs but higher maintenance needs for interior/exterior systems and vice versa for systems embedded between glass panes.

The view out can, depending on the design, be more or less restricted under sunny sky conditions.

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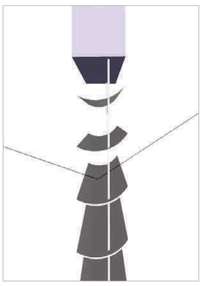

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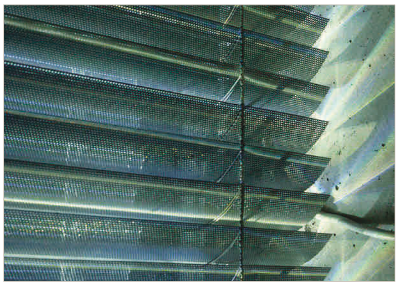

The costs for redirecting systems are usually higher than for classical blinds. However, the benefits appear in significantly improved visual comfort (glare protection) and lighting quality (more homogeneous daylight distribution). While the system is more expensive than classical blinds, costs and efforts for installation are comparable.

>> References

Ruck et al. (2000): Daylight in buildings. A source book on daylighting systems and components
Pohl (2012): Principles of daylight guiding design
Geisler-Moroder (2013): Complex daylighting systems
Köster (2004): Dynamic Daylighting architecture: Basics, systems, projects

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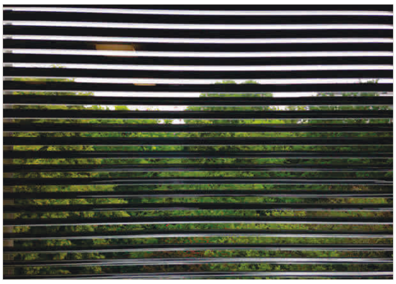

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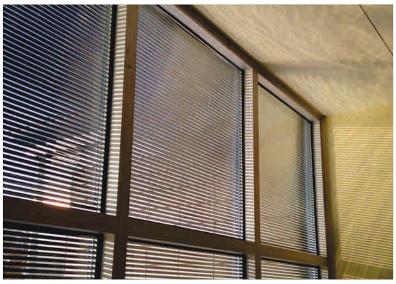

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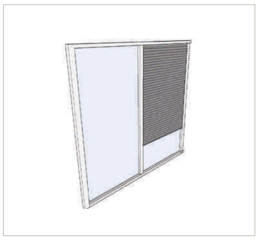
3.2.19 STAINLESS STEEL ROLLER SHUTTERS



Stainless steel roller shutters are made of thin sturdy profiles that can be rolled up. The special form of the profiles blocks most of the direct sunlight and glare, while allowing view contact with the outside. These specific roller shutters should be used as a solar control device, installed in sunlit façades, when a significant reduction of the g-value is desired.

>> Highlights & Lowlights:

More wind-resistant than blind slats or fabrics due to the compact profile with several folded edges.

Moveable, the blinds can be rolled up.

The system allows for view contact in close position, although this is significantly reduced.

>> Description:

The profile selectively blocks out certain angular segments of the sky. This results in very good solar control (effective g-value of 5 - 8 %) and a transparent appearance. Except when the sun is extremely low in the sky, no glare occurs and the daylight is directed into the room. Due to the compact profile with folded edges, the solution is more wind-resistant than blind slats or fabrics. In contrast to micro lamellae, this solution is retractable, and covers the window only in situations with direct sunlight, thus utilizing the available daylight appropriately under overcast sky conditions. Stainless steel roller shutters are installed and have proven its effect in buildings around the world, for example in Switzerland, Malaysia and California.

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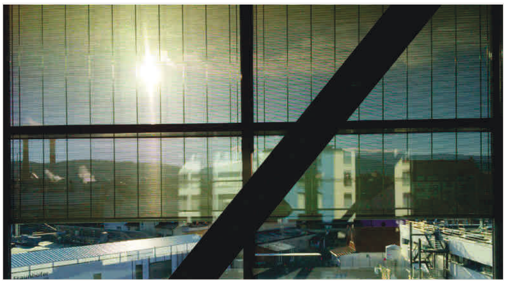
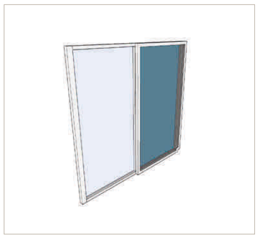


Sunscreens are textile solar shadings used to control the solar incident radiation. The threads of the fabrics are mainly made of glass fibre, polyester or acrylic weft. The fabric and the colour of the determine the properties of the sunscreen. Sunscreens perform best when they are placed on the exterior of the façade. Due to their limited resistance to wind, sunscreens are best applied on low height buildings.



>> Description:

Exterior sunscreens placed in front of windows can reduce the solar gains significantly (direct and secondary heat transfer) providing a limitation to the risk of overheating of the building (lower g value of the complex fenestration system: window + sunscreen). Placed at the interior of the building, they can achieve good daylight control but they do not contribute significantly to the reduction of the heat gains.

Sunscreens can be also used to increase visual comfort. They can be used on a dynamic way to control daylight and provide a protection against glare. The view out and the night privacy are properties function of the colour of the weft and the fabric. Black sunscreens with openness factor of higher than 10 allow a high quality view out. White sunscreens with openness factor of lower than 3 do not allow any view out. The opacity of sunscreens is important for specific applications as in projection rooms where there is a need to achieve the black out. Night privacy has to be encountered for specific cases as bedrooms.

The installation of sunscreens on existing buildings can be achieved with moderate effort by adding an additional element to the façade. It is especially recommended for high glazed buildings.

Automatic control of sunscreens is recommended but, to ensure the user's acceptance, manual control has to be possible. Initial costs and running costs are limited.

>> Highlights & Lowlights:

Increased visual comfort

Increased thermal comfort if placed on the on the exterior of the façade.

Risk of user's non-satisfaction if the control system is not efficient

Low resistance to high wind pressure and risk of dirty

>> References

ES-SO (2012): ES-SO Manual Solar Shading for Low Energy Buildings
Andersen (2002): Light distribution through advanced fenestration systems

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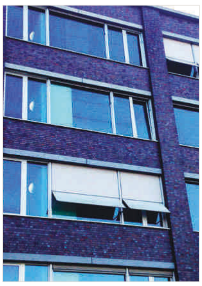

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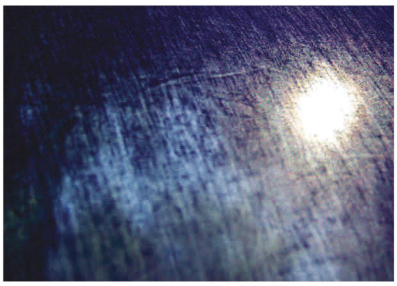

3.3 ELECTRIC LIGHTING AND CONTROLS SOLUTIONS

Within this chapter, electric lighting retrofit solutions are considered. The energy efficiency of electric lighting installations can be improved by a number of measures, such as the choice of lamp and ballast, the use of lighting controls and the lighting design. A specific, indirect, advantages of new lighting components can be a longer lifetime, which results in less maintenance as well as less material to be disposed in time.

In the evaluation of solutions, it is assumed that lighting levels as stated in current standards and recommendations are applied. A reduction of light levels to save energy is not promoted. Over-installation without specific reasoning should be avoided, even though it might be tempting do so, just because it is more efficient. An over-installed lighting solution can / should be corrected by means of controls (tuning) or luminaire replacement.

Using controls will typically increase initial costs, requiring dimming ballast, sensors and controls as well as additional installation and commissioning costs. Energy savings potential offered by daylight can be released by using daylight harvesting controls only, even though an increased daylight contribution also might lead to other user behaviour, resulting in a later switch on of the electric lighting. The switch-on probability for electric lighting tends to be correlated to minimum indoor illuminance levels at the work plane upon arrival (Hunt, 1979; Love, 1998).

Typically, climates with high cooling energy rate benefit from electric lighting retrofits that have a higher luminous efficacy. A reduction of the energy consumption of the lighting installation, will lead to a reduction of the internal load linked to the modified luminaire. Nonetheless, a low lighting power density, as a result from a higher luminous efficacy, might require a higher heating energy rate in cold climates. This could reduce the overall energy reduction or even lever out the lighting energy savings. As an example, Ahn et al (2014) evaluated the impact of climate for a retrofit scenario replacing T12 lamps with LED lamps. Even though the energy savings for lighting are the same, the overall energy saving in the hot and humid region was higher than in the cold climate. For the specific situation, 20% savings were reached in the hot climate (40% for lighting, 8,4% for cooling), 12% in the cold climate, due to an increase of heating load of 10%.

On the following pages, the performance of selected retrofit solutions is described in detail, and structured according to Figure 4.

>> Redesign
Redesign of the electric lighting installation, resulting in the use of new components in a new layout or with new wiring. The product costs as such can be higher, as this retrofit solution will have higher labour and sometimes constructional costs. The resulting longer payback period

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for these retrofit solutions might be balanced out by the financial, human-performance and psychological benefits of a lighting condition with a higher quality.

Retrofit technologies: task-ambient lighting, algorithmic lighting, virtual windows, demand driven lighting controls, daylight responsive lighting controls (Section 3.3.1 - 3.3.5)

>> Use of new components
Replacing a luminaire with one that has different characteristics, typically increasing energy efficiency, due to an improvement of light source or ballast technology that requires a new luminaire, or due to an improvement in luminaire technology. Adding luminaires with luminaire based controls, such as sensors for presence sensing, daylight dimming or personal control.

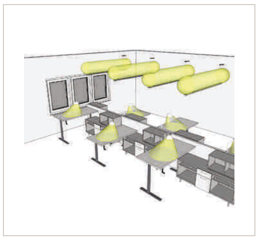
Retrofit technologies: daylight responsive lighting controls - luminaire based, occupancy sensing - luminaire based, personal control, LED retrofits for CFL downlights, LED luminaire replacements (Section 3.3.5 - 3.3.10)

>> Upgrade of existing situation
Replacing a component within the electric lighting installation, such as a lamp by a light source with improved efficiency, spectral quality or increased luminous flux, or a magnatic ballast by an electronic ballast. Adding stand-alone controls, such as a time switch to reduce total switch-on time, wireless sensors, or sensors for presence sensing that allow switching of luminaires only.

Retrofit technologies: occupancy sensing - room based, personal control through switches, time scheduling, wireless controls, electronic ballasts, fluorescent lamp replacements, LED replacements for halogen and incandescent lamps, LED T8 replacement lamps (Section 3.3.9 - 3.3.16)

3.3.1

TASK - AMBIENT LIGHTING



Task - ambient lighting is an alternative lighting solution, which is applied to replace a general lighting solution, making a distinction between the illumination of (a) task area(s) with a higher lighting level and the illumination of the remaining ambient area with a lower lighting level. Task – ambient lighting is to be used to reduce energy consumption while increasing personal control, in an existing lighting situation, a new lighting design or a lighting condition that does not reach the required lighting levels throughout the room.

>> Highlights & Lowlights:

Personal control over task lighting possible

Moderate energy savings

Higher initial costs (new lighting installation, or components for a lighting installation)

Reduced flexibility in some task – ambient lighting solutions

>> Description:

A task – ambient lighting concept as retrofit solution is either based on a new lighting design or supplementing the existing general lighting solution, which either does not fulfil the requirements or is dimmed down, with floorstanding or desk luminaires. Task – ambient lighting solutions are typically used in office settings, as for example commonly applied in Denmark, with light levels between 50 and 200 lux in the ambient area. In the EN 12464-1, when task illuminance is 500 lx, Illuminance in immediate surrounding areas should be 300 lx and in the background area 1/3 of the illuminance on surrounding areas. The energy savings achieved with this task – ambient lighting concept depend significantly on the proportion of the task area to the overall lit area, the required lighting levels and the chosen lighting equipment. Savings up to 20% can be achieved in comparison to a general lighting solution with a comparable light source. Higher savings can be achieved, if the general lighting is realized by daylighting and the task lighting is used to provide higher lighting levels wherever required. A light source change to a more efficient one can increase the energy savings even more.

The task - ambient lighting concept is typically realized with floorstanding luminaires or individual desk luminaires. Floor standing luminaires can often realise the ambient and task lighting conditions by itself, desk luminaires need additional (ceiling) luminaires to achieve the required ambient lighting level. Those lighting solutions offer high flexibility. When ceiling luminaires are used to realise the task lighting, areas for task lighting are typically set or pre-programmed and reduce the flexibility of work place position or need commissioning of the lighting solution when other task areas are required. Floor standing luminaires and individual desk luminaires are in reach of the user, offering the possibility for personal control and with this increase user comfort. It also offers an easy access for maintenance activities.

>> References

Dubois and Blomsterberg (2011): Energy saving potential and strategies for electric lighting in future North European, low energy office buildings

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ALGORITHMIC LIGHTING 3.3.2

Algorithmic lighting is a lighting solutions that offers automatically controlled varying lighting conditions over time for a specific application and a purpose. The lighting typically varies in light level, luminance distribution and / or colour temperature, to promote human comfort and well-being. Algorithmic lighting is especially effective in areas with low daylight availability or for users with limited access to daylight.

>> Description:

Algorithmic lighting offers lighting conditions varying in luminance distribution, light level and / or colour temperature over time. Studies have indicated that algorithmic lighting can have a positive impact on human well-being and health, especially in locations with low daylight availability or for users with limited access to daylight. Algorithmic lighting solutions are typically used to induce physiological responses, for example to increase alertness or concentration of pupils in schools or employees in office buildings through higher light levels or cooler colour temperatures, or to support phase shifts for people coping with jet lags or those working in a night shift with appropriate timed light doses. Algorithmic lighting is especially effective in windowless workplaces or workplaces with low daylight availability or for users with limited access to daylight, such as patients in a hospital and immobile elderly in a nursing home.

Algorithmic lighting can be realized by using scene-setting program varying lighting conditions over time. Algorithmic lighting may produce a financial payback in terms of increased productivity or enhanced well-being but will likely also result in an increase in energy use, offering light levels above required lighting conditions. Solutions equipped with presence or daylight harvesting sensors reduce energy consumption. The appropriate lighting conditions should be chosen according to individual needs and to the type of application, daylight availability and its location.

>> References

CIE: Technical Report of TC 3-46: Research roadmap for healthful interior lighting applications
Lighting Europe (2013): Human Centric Lighting: Going beyond energy efficiency

>> Highlights & Lowlights:

Increase of human comfort and / or well-being

[Possibly a financial payback in terms of increased productivity

Installation needs calibration

Higher initial costs and energy consumption

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3.3.3

VIRTUAL WINDOWS

Virtual windows are electric lighting solutions that have the appearance of a window or sky light and offer lighting conditions that intend to mimic the daylight in for example dynamic changes of light level and / or spectral characteristics. Virtual windows are typically applied in areas without daylight, such as underground spaces, to increase lighting quality and enhance room appearance, at the cost of energy consumption.

>> Highlights & Lowlights:

Impression of a real daylight atmosphere in windowless spaces

Latest LED technology

High product and installation costs

>> Description:

In order to address the benefits of daylight, virtual windows or artificial skylights have been developed that intend to replicate windows and / or daylight. New technologies, such as LED light sources and advanced controls, offer the possibility to imitate the dynamics of daylight in light level and colour temperature with electric lighting. A large variety of virtual windows is available, prototypes and products. Virtual windows are realised with or without a projected or simulated view. Very few solutions offer the combination of simulated sunlight and skylight.

A recently developed solution uses the physical reproduction of the phenomena that occur in the atmosphere to mimic daylight conditions (www.coelux.com). From a technological point of view, this system is composed of an artificial light source, very similar to the visible part of sunlight (CCT 5770 K), and of a nanostructured material which recreates the Rayleigh scattering process that occurs in the atmosphere. Blue light is almost completely diffused, mimicking a clear sky. The artificial light source produces a strong and almost parallel beam. This combination gives an impression of real skylight, strengthened even more by the construction of the luminaire and the light levels produced.

Virtual windows are supplementary lighting solutions to enhance lighting quality, installed additionally to the general lighting in a room, thus having a negative effect on the energy consumption for electric lighting.

>> References

Canazei et al. (2015): Room-and illumination-related effects of an artificial skylight
Mangkuto et al. (2014): Analysis of various opening configurations of a second-generation virtual natural lighting solutions prototype
Meerbeek and Seuntiens (2014): Evaluating the experience of daylight through a virtual skylight

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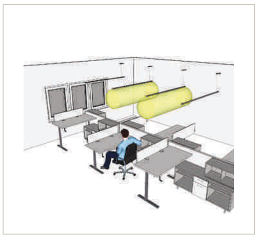
Demand driven lighting control is a system consisting of an electric lighting solution and a control strategy to achieve a very high level of lighting quality and reducing the energy consumption at the same time. A control strategy and electric lighting solution to be used when lighting quality and personalization is very important.



>> Description:

Demand driven control solutions can optimize the energy consumption of the lighting system while maintaining high visual comfort for the occupants. The idea is to provide the room only with the necessary amount of light. In areas out of vision the level of illuminance can be reduced. The necessary amount of light is depending on the number of people, their position and their current task. Technically demand driven lighting systems generally consist of several luminaires that can be controlled separately. In addition a precise detection of the occupant's position with presence detection systems (PIR or camera based) is necessary. When the occupant is entering one zone of the room, the lighting for this part of the room is provided. Depending on the algorithm the adjacent zones can be dimmed to respectively lower illuminance level. Recently developed lighting systems use distributed intelligence to create a demand driven lighting system. Every luminaire is equipped with a presence sensor. If an occupant is detected, the luminaire will raise the light level and send a signal to the adjacent luminaires. The activated luminaires build an illuminated area that moves with the occupants when they change their position. In the case of several occupants in the room several light areas will be formed. When the room is completely crowded the whole area is illuminated.

Currently the demand driven control is developed further. With a set of deep image infrared sensors the position and viewing direction can be captured by the system. This information can be processed to determine the activity of the user and to dim the light to his needs. To provide the optimal lighting conditions the luminaires are extremely flexible regarding level, distribution and colour of the lighting. This way the system can change the whole lighting situation dynamically depending on the user, his task and the time of the day. User acceptance studies for single offices have been carried out and hints could be found that savings up to 40% are possible without reducing the user-acceptance of the lighting situation.

>> References

Woodward (2014): Distributed intelligence for energy saving smart-lighting

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>> Highlights & Lowlights:

Increase in lighting quality and high amount of personalization

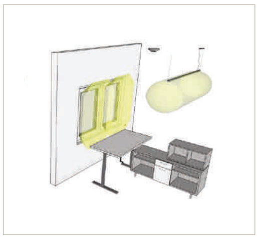
High reduction of energy consumption possible

Installation needs calibration

Very high investment costs

3.3.5

DAYLIGHT RESPONSIVE LIGHTING CONTROLS



Daylight responsive lighting controls, or so-called daylight harvesting controls, switch off the electric lighting when daylight reaches a set value or dims the electric lighting to combine daylight and electric light to a constant light level. The lighting is switched on by the user or the system. Daylight harvesting systems are to be used in areas with good daylight contribution.

>> Highlights & Lowlights:

Moderate to high energy savings

Higher savings through combination with personal control possible

Relative high initial costs

Redesign of the lighting installation required

>> Description:

Daylight harvesting is used to maintain a required illuminance level on a reference plane (typically workplace area) in response to daylight availability to reduce electrical energy use for lighting. Studies show a large bandwidth of 20 – 70% for savings potential of daylighting harvesting systems. Geographical location plays an important role as well as building related aspects, such as window size and orientation, as well as visual task requirements and application related working time.

The layout of controlled luminaires influences the savings potential. Luminaires in side-lit spaces are preferably divided into groups running parallel to the windows, and each group is, if possible, controlled according to the available daylight. A distinction between daylit and non-daylit zones should be considered in the planning of daylight harvesting systems. There are different approaches available to determine the daylit area:

» a daylit area will typically lie within 6 m of a façade if the window area with normal glazing (τ_v > 70%) is at least 20% of the window wall area. For roof-lit spaces, this area should be larger than 10% of the floor area (Littlefair 2014).
» DIN V18599 (DIN 2007) defines daylit areas with medium to high savings potentials as those with a Daylight Factor > 2%.
» The 'Tips for daylighting with windows' guide advices to the use of daylight harvesting at a Feasibility Factor larger than 0.25. The Feasibility Factor is the sum of the light transmittance, the window to wall ratio and an obstruction factor (Robinson and Selkowitz 2013).

Windows that offer lower daylight factors, feasibility factors or window to wall ratios might not offer high energy savings for electric lighting, but likely will provide a view and with this positively affect user comfort, and should therefore still be considered in the redesign process.

The available daylight can be measured for each group of luminaires or each individual luminaire by means of a sensor. Sensors can be mounted in the lamp or at the ceiling of the

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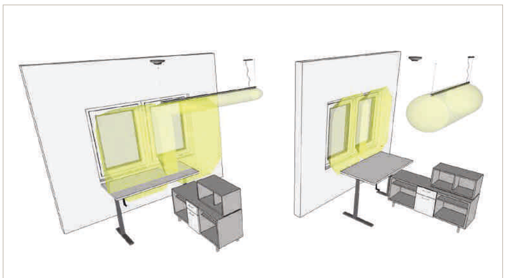
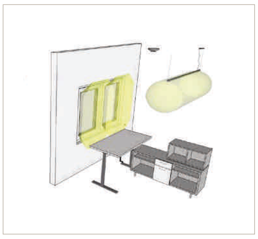


room or placed outdoors, on the roof or at the façade, using different control strategies to dim the electric lighting. For indoor sensors, the detection range of the sensor is of important to ensure appropriate functioning of the system. The light entering the sensor (sensor signal) is considered to represent the lighting conditions on the illuminated surfaces of interest. Therefore, changes in the interior, like a new carpet, painted room surfaces, moved furniture or the use of a daylight redirecting system, or (seasonal) changes in the outdoor environment, such as loss of leaves in autumn or snow in the winter, may have an impact on the functioning of a daylight harvesting solution. Re-commissioning of the system is required, when changes take place and a new correlation between sensor signal and required lighting conditions needs to be established.



The energy savings potential of daylight harvesting is related to the savings that can be reached with normal window openings (baseline, section 2.1.1). The implementation of daylighting retrofit solutions as presented in section 3.2 will affect this potential. Energy consumption for electric lighting can be further reduced for example by a more advanced use of direct sunlight, if compared to the baseline, in which sunlight is completely blocked by blinds, or through the use of redirecting systems increasing the light levels in 'non-daylit' areas.

>> References

Littlefair (2014): BRE Digest DG 498 Selecting lighting controls
Williams et al. (2011) A meta-analysis of energy savings from lighting controls in commercial buildings
CIE: Technical Report of TC 3-49: Decision scheme for lighting controls for tertiary, non-residential lighting in buildings

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3.3.6 LED LUMINAIRE REPLACEMENTS

Luminaire exchange with LED Luminaires are applied, if the luminaire has to be exchanged, to reduce energy consumption and to reduce maintenance costs by increasing the lifetime of the light source. LED luminaires are available in many sizes ad lumen packages with very high efficacies. Luminaire exchange should be applied when an efficient retrofit is required and low maintenance and life time are important. Lighting quality can be enhanced as well.

>> Highlights & Lowlights:

Easy replacement possible, long lifetime, high reduction of energy consumption

Less products with very high lumen output

Not for very high temperature areas

Higher invest costs

>> Description:

LED Luminaires can have a very high system efficacy of 130 lm/W and more. They are available with different correlated colour temperature and lumen packages like fluorescent lighting solutions. The lifetime of LEDs is typically longer (50 000h), which will reduce maintenance costs. The light distribution depends of the placement of the LEDs and possible external optics and can be designed especially for desired purposes to avoid glare and to focus light in preferred directions. LEDs are generally dimmable and can be used for colour changing luminaires. But dimmability and multi-colour raises the cost of a luminaire by around 20% to 50% for the additional electronics. Dimming reduces the junction temperature of LEDs and thus increases their life time. Their efficacy also remains on higher level when dimmed unlike with fluorescent lamps. In retrofitting an old lighting system the installation time and costs increase if additional wiring is needed for the control.

Most products on the market have a colour rendering index (CRI) above 80 up to 95. Prices are going down significantly and a portion of products have almost reached the price level of fluorescent luminaires.

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LED RETROFITS FOR CFL DOWNLIGHTS 3.3.7

A LED retrofit solution for CFL downlights is an LED based module or luminaire that can replace a CFL in a downlight or replace the CFL downlight completely, typically in order to reduce maintenance effort and costs or to save energy. These LED retrofit solutions are to be used when operational costs are to be reduced (higher energy savings, a longer lifetime and reduced maintenance), and lighting quality needs to be maintained.

>> Description:

In 2012, 14 LED retrofit downlights were tested within a CALiPER project of DOE (U.S. Department of Energy 2012). These downlights were equivalents for typical CFL downlights (32 W) (and incandescent downlights 65 W), which are often applied for ambient lighting in normal ceiling heights. The LED downlights had a lumen output between 500 and 1000 lm, with a comparable light distribution and a system efficacy of 39 to 69 lm/W (in situ testing), which was equal or better than system efficacy of the conventional technology equivalents. Colour rendering of the majority was above 80, the power factor above 0.90. Today, lumen output of LED downlights has increased further, with system efficiencies above 80 lm/W. Lighting quality is at par with the conventional CFL solutions. LED downlights might give a narrower beam than the equivalent CFL, which could result in lower luminances on the walls. Non-dimmable and dimmable versions are available. Life time of the retrofit solution is longer, resulting in lower maintenance and replacement costs. The 2012 CALiPER study showed that downlight retrofits in the US typically use a type of spring-loaded clip to mount the retrofit module with trim and reflector in the existing recessed downlight housing. They mostly have a screw base or GU 24 base, some offer the possibility to be hard wired or use an adapter to contact to a CFL pin base socket. In Europe, LED retrofits for CFL downlights typically supply a complete housing to fit through an existing hole in the ceiling.

In 2012, the extra mass of the luminaire necessary for thermal management needed to be considered. Today, solutions with higher efficiency and resulting lower installed power have comparable weight to a CFL solution.

>> References

U.S. Department of Energy (2012): DOE Solid-State Lighting CALiPER Program

>> Highlights & Lowlights:

Reduced operational costs due to large energy savings and low maintenance

Lighting quality at par with the conventional solution (CFL)

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3.3.8 PERSONAL CONTROL

Personal control allows for adjustment of the daylighting or electric lighting by the user, and can be offered switches or push buttons, pull cords, computer or handset controls that are easily accessible by the user.

>> Highlights & Lowlights:

Increased user satisfaction, comfort and performance

High energy savings

Possibily higher energy consumption, when wide range of lighting conditions can be chosen

When not combined with other controls, light can be left on after leaving or dimmed up to higher levels than required from the standards

>> Description:

Personal control for lighting allows the user to switch or dimm the electric lighting or control the daylight provision in a room or area by the use of switches, pull cords, a computer or handheld remote controls. As indicated in section 2.1.4, research indicates that personal control increases satisfaction, comfort and performance of users. Offering personal control to the lighting can save energy; some studies show that users chose lighting levels that are above the level required by the standards, but the majority of studies indicate that users work under dimmer lighting conditions. The use of personal control cannot be predicted; some occupants set an initial preferred illuminance level and rarely changed it afterwards, others use the individual, manual control more frequently. On average, 35% savings can be achieved through personal control, which can be increased by another 10 to 30% when combined with occupancy sensing or daylight responsive lighting controls. Studies indicate that daylit spaces offer a higher savings potential for personal control than spaces without daylight, and is said to be dependent on time of day and minimum daylight factor (Littlefair 2014). In order to maximize energy savings and prevent annoyance amongst the users of the controls, interfaces for personal control should be close to the user, easy to understand and to use.

>> References

Littlefair (2014): BRE Digest DG 498 Selecting lighting controls
CIE: Technical Report of TC 3-49: Decision scheme for lighting controls for tertiary, non-residential lighting in buildings
Newsham et al. (2008): Individual control of electric lighting in a daylit space
Boyce, Eklund and Simpson (2000): Individual lighting control: task performance, mood, and illuminance

OCCUPANCY SENSING

3.3.9

A lighting solution equipped with occupancy sensing switches or dims the lighting in response to the absence or presence of people in a defined area. In case of absence control, the lighting is switched on by the user through personal control. Presence controlled solutions switch on the light when persons enter the detection area. Occupancy sensing is preferably applied in areas that have low occupancy rates, are occasionally visited or in which the lighting is not controlled by the user.

>> Description:

Energy savings between 18 and 45% are found in a number of field studies in commercial buildings using occupancy sensors to control the electrical lighting installation. Large savings can be achieved in spaces that are occasionally visited, such as restrooms and storage rooms, in areas in which the lighting is not controlled by the users, such as corridors and stair cases and in spaces with low occupancy rates (< 50 %).

An occupancy sensor detects motion; in case there is no movement the signal can be used to dim or switch off the lights. In case of an old installation with magnetic ballasts, the signal can control a contactor switch that is able to switch off the lights, the lighting is not dimmable. Wired and wireless versions are available on the market. Occupancy sensors are typically positioned near the door or in the ceiling.

User acceptance of the system depends largely on the delay time, the time period between detecting vacancy and switching off the system. Although larger savings can be achieved with short delay times (a few minutes), the system might switch off because people are not moving around. Proper delay times depend on the application; corridors might allow for shorter delay times, office areas require longer delay times. Some systems dim down first when no motion is detected, which might increase user acceptance, but will reduce energy savings. Next to the delay time, the shape of the detection area as well as the position of the sensor is of importance to ensure user acceptance. Personal control through manual switching of the system will increase user acceptance and can increase energy savings as well, when spaces are well daylit and occupants feel responsible towards the use of light.

>> Highlights & Lowlights:

Inexpensive, typically easy, upgrade of an existing situation, low maintenance

Higher savings through combination with personal control possible

User acceptance of the system depends on parameters set

>> References

Littlefair (2014): BRE Digest DG 498 Selecting lighting controls

Williams et al. (2011): A meta-analysis of energy savings from lighting controls in commercial buildings

Maniccia et al. (1999): Occupant use of manual lighting controls in private offices

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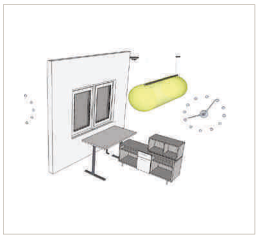
3.3.10 TIME SCHEDULING



With time scheduling the lighting is switched off, switched to a lower lighting level or dimmed down and predefined times during the day and the year. This type of lighting control is an straightforward and low cost solution to save energy for electric lighting. Time scheduling is to be applied in buildings with regular hours.

>> Highlights & Lowlights:

Cost effective lighting control, no redesign of the lighting installation required

High savings possible

Personal control required for safety and comfort reasons

Lower savings when people rely on the time scheduling to switch the lights off automatically

>> **Description**:

Time scheduling controls the lighting on the basis of time of day. The lighting in the building or in predefined areas of the building is switched off, switched to a lower lighting level or dimmed down and set times during the day and the year. Therefore, time scheduling is most effective in buildings with regular using hours. Time scheduling needs information about the use of the building, to define time slots in which the building is not used, or used for a different purpose. It can be used for example to reduce the lighting in a shop after opening hours when only staff and cleaners are in the building or to switch off lighting in daylit areas at midday and allowing users to switch them back on if required. Energy savings are typically low during regular office hours but very high in the evening and in weekends. Time switching usually needs a centrally controlled lighting installation. Additionally, the lighting installation needs to be equipped with some personal control, such as wall switches, to ensure user comfort and to guarantee safety.

>> **References**

Littlefair (2014): BRE Digest DG 498 Selecting lighting controls

Jennings, Colak and Rubinstein (2001): Occupancy and time-based lighting controls in open offices

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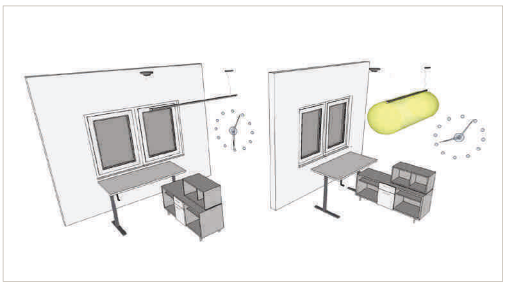

Wireless lighting control solutions for daylight responsive lighting control and occupancy sensing are easy to install and easy to use luminaire based control approaches. It is used when additional control wires are expensive or not desired. Wireless lighting control can be used in different retrofit strategies; using new components in an existing situation, as well as in the redesign of the lighting installation. Energy savings depend on daylight and usage context. New zoning concepts and personal controls improve user comfort.

>> Description:

Wireless lighting controls offer a control approach without the need for rewiring the lighting installation. It is used when additional control wires are expensive or not desired, as for example in a design environment. The solution offers the characteristic functionality of daylight responsive lighting controls (section 3.3.5) and occupancy sensing (section 3.3.9), and can switch the electric lights automatically on and off based on occupancy and dims the luminaires when enough daylight enters the room.

The solution typically consists of a sensor and a luminaire-based control unit with a dimmable driver (DALI or 1-10V). The sensor contains two main functions - a light sensor for daylight dependent light level regulation and a movement detector for occupancy sensing. The luminaire can still be controlled manually by a wired switch, but often wireless user interface (UI) devices can be easily added. These are typically battery powered today, but standardization is paving the way for energy harvesting devices that operate without any battery (ZigBee Green Power).

With commissioning procedures several luminaires can be linked together so they will act as one system, and further customization like scenes or specific light levels can be set.
Because of the wireless connection between luminaires, sensors and UI, retrofit control solutions can be easily and cost-efficiently designed into existing buildings. The extension of sensor coverage with wireless devices linked to a particular lighting control group allows for flexible adaptation to application needs.

>> References

Halonen et al. (2010): IEA ECBCS Annex 45 Guidebook on energy efficient electric lighting for buildings
Daintree: The value of wireless lighting controls (white paper)

>> Highlights & Lowlights:

Quick and easy retrofit, allowing energy savings, zoning and personal control

Highly adaptable to changing building layouts or occupancy patterns

When dimming is required, the existing luminaires need to be fitted with dimmable ballasts

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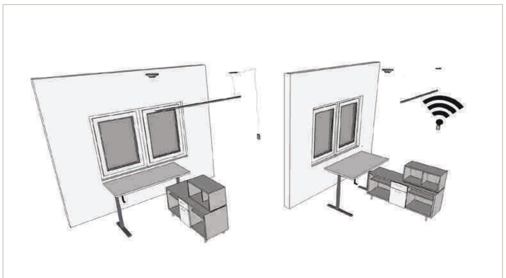

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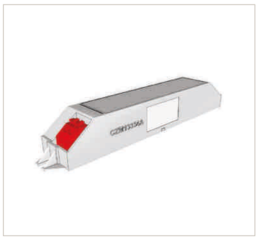
3.3.12

ELECTRONIC BALLASTS (HF+)



Replacement of a magnetic ballast by an electronic ballast is a solution that increase the visual comfort in a room and reduce the energy consumption in a room. Replacement of magnetic ballast by electronic ballast performs good when ballast is easily accessible and when the lighting quality is already correct.

>> Highlights & Lowlights:

Moderate energy savings

Increased visual comfort by avoiding flickering and stroboscopic effect.

Not for all discharge lamps

Impact on the electric mark labelling of the luminaire

>> Description:

The replacement of a magnetic ballast by an electronic ballasts is a solution mainly used for discharge lamps (typically for T8-lamps). This solution provides energy savings through a reduction of the ballast losses also, the discharge itself is more effective (typically 20 % reduction of the energy consumption 'lamp + ballast').

The stroboscopic and flicker effects of discharge lamps with magnetic ballast (50 Hz) are avoided through the high frequency mode (> 20 kHz), resulting in an improvement of the visual comfort. The colour rendering of the light is not affected by this operation.

Additional functionalities as (daylight)dimming and constant illuminance control, linked to the electronic ballast functionalities, may even be added to the lighting installation.
The time spent for the retrofitting operation is limited. Initial costs and running costs are limited but may be not negligible due to the electric adaptation (CE mark).

The depreciation of the luminous flux emitted by the lamp is lower and the lamp survival factor is higher. The average lamp life is 15.000 to 25.000 hours versus 12.000 hours with magnetic ballast.

Particular attention has to be paid to the mark or the labelling of the luminaires as the operation may be assimilated to an electric modification the luminaires. Note that not all discharge lamps are compatible with this operation.

>> References

NLPIP (2000): Electronic ballasts
LBNL: A guide for energy – efficient research laboratories

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FLUORESCENT LAMPS (T5, CFL) 3.3.13

Retrofit with fluorescent lamps (T5, CFL): In retrofitting T8 in luminaires, these can be replaced with T5 fluorescent lamps. Compact fluorescent lamps (CFL) can be used to replace incandescent and halogen lamps. Fluorescent lamps are cheap, they have a long lamp life and colour temperature can be chosen according to application. Luminous efficacy is good.

>> Description:

A fluorescent lamp is a low-pressure gas discharge light source, in which light is produced predominantly by fluorescent powders activated by ultraviolet radiation generated by a mercury arc. The final spectral distribution of emitted light can be varied by different combinations of phosphors and thus colour properties can vary (colour rendering and correlated colour temperature). Tubular fluorescent lamps have luminous efficacy between 50 and 100 lm/W, they are cheap and lamp life is 12 000 to 20 000 hours. Efficacy of compact fluorescent lamps (CFL) is 40 - 65 lm/W, and lamp life is 6 000 to 12 000 hours. Typically, the T5 lamps contain smaller amounts of mercury than older lamps. Fluorescent lamps need auxiliaries for starting and operation, either magnetic ballast and a starter or electronic ballast.

T5 fluorescent lamps operate always with electronic ballast. With electronic ballasts the losses are reduced, the discharge itself is more effective and light is flicker-free and there is the opportunity of using dimming devices.

T5s are shorter than counterparting T8s and thus the whole luminaire has to be changed or special retrofit kit used. T5s have a very good luminous efficacy (up to 100 lm/W without ballast losses). Dedicated luminaries for T5 lamps may reach a better light output ratio (LOR), as the lamp diameter is smaller thus allowing the light to be redirected in a more effective way. The performance of a fluorescent lamp is sensitive to ambient temperature. The maximum performance of T5 is at 35°C, while for T8 lamps it is at 25°C. The inner luminaire temperature of 35°C is a more realistic situation for indoor installations. Dimming of fluorescent lamps is possible down to 1 %. CFLs with E27-base are usually not dimmable.

>> Highlights & Lowlights:

T5 > T8 Reduced maintenance due to long life time

T5 >T8 Moderate energy savings

T5s operate with electronic ballasts.

Retrofitting from T5 to T8 might need a luminaire change

>> References

Halonen et al. (2010): IEA ECBCS Annex 45 Guidebook on energy efficient electric lighting for buildings

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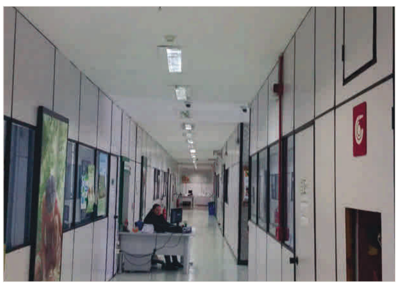

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3.3.14 LED REPLACEMENT FOR HALOGEN AND INCANDESCENT LAMPS

LED replacements for halogen and incandescent lamps are applied to replace halogen and incandescent lamps, to reduce energy consumption and to increase lifetime of the lighting solution. The LED retrofit lamps have the form factor and size of the conventional light source and include a ballast in the base. These retrofit lamps are to be used when energy savings, maintenance and life time play a role, and optimal colour representation is not very important.

>> Highlights & Lowlights:

High energy savings

Long life time, reduced maintenance cost

Possible to have a lower colour rendering

Dimming not always possible

>> Description:

A review of LED lamps and LED spot lights in 2014 showed a range for luminous efficacy of LED lamps from 60 to 110 lm/W, the average of 30 different lamp types was 79 lm/W. The luminous efficacy of the LED spots were between 43 and 94 lm/W, average of nineteen lamp types was 66 lm/W. Most of the LED spots lamps had a lamp base GU10 or GU3.5. Colour rendering index was close to 80, few lamp types had CRI over 90. Products with a higher colour rendering typically had a lower efficacy. The beam angle of retrofit lamps is determined by the arrangement of LEDs and the optics used in the retrofit lamps. Quality increased rapidly, as a study looking into 17 different LED lamp types published on March 2015 showed that the luminous efficacy of these lamps ranged from 63 to 121 lm/W, average being 98 lm/W. CCT values were around 2700K to 2900K. The colour rendering index for most exceeded 80.

Not all LED replacement lamps are dimmable, and phase cut dimming can be problematic. For dimmable LED replacement lamps, the compatibility with existing phase cut dimmers need to be checked. Five of the LED lamps in the 2015 study were marketed as 'dimmable' and they were tested both with leading edge and trailing edge dimmers (these two dimmer types are most common on European market). Three lamps failed with one of the dimmers. Typically, the colour temperature of the light remains the same while dimming the lamp, some products offer the dimming appearance of incandescent lamps, having a stronger red component in dimmed stages. A CALiPER report (2008) pointed out that the low wattage lamps might not provide enough load to the existing transformer, dimmers or related controls. In that case, the retrofits may not work or cause flicker or stroboscopic effects.

>> References

Bennich et al. (2015): Test report – clear, non-directional LED lamps

U.S. Department of Energy (2008): CALPER report. Performance of halogen incandescent MR16 lamps and LED replacement

Poplawski and Miller (2013): Flicker in solid-state lighting: Measurement techniques, and proposed reporting and application criteria

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LED retrofits for T8 lamps are applied to replace fluorescent lighting solutions with a G3 base, to reduce energy consumption and to increase lifetime of the lighting solution. The LED retrofit lamp is installed in an old luminaire by replacing the old lamp and the starter. LED retrofit lamps have the size of the conventional light source and typically include a LED driver. LED Retrofit for T8 lamps are to be used when a simple retrofit is required and low maintenance and life time are important. Lighting quality could be slightly reduced.

>> Description:

The performance is often optimized for energy savings. Energy savings are typically 50…60% depending on the power. At the same time the luminous flux is about 60...70% of the luminous flux of the equivalent fluorescent lamp. In the LED tube LEDs are only on one side emitting light to a specific opening angle, resulting in higher luminaire light output ratio with a LED tube than with fluorescent lamp. Therefore they are a good option in places where luminaire's reflectors are worn out or get dirty quickly. On the other hand, the original luminous intensity distribution is no longer valid for the luminaire. With a lower luminous flux, the illuminance level can be lower with LED tubes than in the original installation. Although the lighting solution is more efficient in illuminating horizontal planes under the luminaire, positively affecting the energy consumption, the light contribution to the vertical planes can be lower, which might affect lighting quality (darker walls and ceiling). If, for instance, the luminous distribution of the original luminaire is wide, the opening angle of the LED tube should be wider than 120°.

LED retrofit lamps have developed fast with the development of LED chip technology. The majority of retrofit lamps has a luminous efficacy between 110 - 120 lm/W, good colour rendering (R_a > 80) and a power factor above 0.90. The lifetime of the retrofit lamps is typically longer (> 50 000 h), which will reduce the maintenance costs. Lamps with a clearly visible line of single LEDs seem to induce more glare than the conventional fluorescent lamps.

Retrofit can be done by a quick replacement of the lamp. In most cases, the LED retrofit lamp includes a LED driver (internal converter). Most products are suitable only to luminaires with magnetic ballast. The ballast of the fluorescent lighting solution needs to be disconnected and the retrofit lamp can be placed directly in the lamp holder (follow the mounting instructions and pay attention that the old starter is bypassed). If there is a compensation capacitor in the luminaire, one should confirm from the installation instructions, whether or not it should be removed. LED tubes are not normally compatible with electronic ballasts.

>> Highlights & Lowlights:

Reduced maintenance due to long life time

Moderate energy savings

Possibly weak on lumen output

Smaller beam angle can lead to darker walls and ceiling, affecting room appearance negatively

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>> References

U.S. Department of Energy (2009): CALiPER Benchmark Report - Performance of T12 and T8 fluorescent lamps and troffers and LED linear replacement lamps
Ryckaert et al. (2012): Performance of LED linear replacement lamps
Ryckaert et al. (2012): Linear LED tubes versus fluorescent lamps: An evaluation
Richman, Kinzey and Miller (2011): U.S. DOE Solid-State Lighting Technology Demonstration GATEWAY Program. Laboratory Evaluation of Light-Emitting Diode (LED) T8 Replacement Lamp Products

In this chapter, the performance of the retrofit solutions presented in Chapter 3 is included. As stated in Chapter 2, comparison of retrofit technologies is feasible when it is based on a quantitative assessment of reduction of energy consumption and operational costs, and increase of lighting qualtiy and thermal benefits. Within IEA Task 50, weighting factors for the selected number of quality measures were defined (Table 2). Additionally to that, the performance in for each quality measure was catagorized (Table 3 and Table 4). The resulting representation of performance as presented in Section 2.3 is included in both the Technology Viewer of the Lighting Retrofit Advisor, as well as in this chapter to give a quick overview of the performance of each single retrofit solution.

Table 2: Predefined weighting factors for quality criteria used withing IEA Task 50

	Daylight retrofit solutions		**Electric light retrofit solutions**	
Energy efficiency	Energy savings potential	100 %	Energy savings potential	100 %
Lighting quality	Provides glare protection	20 %	Unified Glare Rating for specified room size	30 %
	View out	20 %		
	Personal control possibilities	20 %	Personal control possibilities	25 %
	Colour distortion due spectral selectivity	10 %	Colour rendering index of light sources	25 %
			Correlated colour temperature	20 %
	Light transmittance	15 %		
	Providing a good light distribution	10 %		
	Privacy at night	5 %		
Costs	Ease of retrofit (acc. Figure 4)	25 %	Ease of retrofit (acc. Figure 4)	25 %
	Initial costs	25 %	Initial costs	25 %
	Operational costs	50 %	Operational costs	50 %
Thermal considerations	Minimum g value	25 %		
	Variable thermal consideration	25 %		
	Visible to thermal ratio (LSG)	25 %		
	Secondary heat transfer	25 %		

Table 3: Catalogue of Criteria for Daylighting Retrofit Solutions

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
			Energy efficiency		
Energy savings potential	energy savings potential < -30 %	-30 % ≤ energy savings potential < -10 %	-10 % ≤ energy savings potential ≤ 10 %	10 % < energy savings potential ≤ 30 %	energy savings potential > 30 %
Performs well under diffuse skylight	no		yes		performs well under both diffuse skylight as well as direct sunlight
Performs well under direct sunlight	no		yes		performs well under both diffuse skylight as well as direct sunlight
			Visual comfort		
Provides glare protection (overcast sky)	no protection (or EN 14501 - Class 0)		depends (or EN 14501 - Class 1 & 2)		yes (or EN 14501 - Class 3 & 4)
Provides glare protection (direct sunlight)	no protection (or EN 14501 - Class 0)		depends (or EN 14501 - Class 1 & 2)		yes (or EN 14501 - Class 3 & 4)
			Visual amenity		
View out (overcast sky)	serious distortion / blockage (or EN 14501 Class 0 & 1)		minor distortion / blockage (or EN 14501 Class 2 & 3)		no blockage / distortion (or Class 4)
View out (direct sunlight)	serious distortion / blockage (baseline) (or EN 14501 Class 0 & 1)		minor distortion / blockage (or EN 14501 Class 2 & 3)		no blockage / distortion (or Class 4)
Light transmittance (overcast sky)	less than -30 % ($\tau v < 0.55$)	less than -10 % ($\tau v < 0.75$)	small change $\tau v = 0.75 - 0.80$		more than 10 % ($\tau v > 0.80$)
Light transmittance (direct sunlight)	less than -30 % ($\tau v < 0.07$)		small change $\tau v = 0.07 - 0.13$		more than 30 % ($\tau v > 0.13$)
Colour distortion / fidelity (overcast sky)	affects R_a considerably ($R_a < 80$)		affects R_a slightly ($80 < R_a < 90$)		maintains R_a ($90 < Ra < 100$)
Colour distortion / fidelity (direct sunlight)	affects R_a considerably ($R_a < 80$)		affects R_a slightly ($80 < R_a < 90$)		maintains R_a ($90 < R_a < 100$)
Privacy at night	minimal (or EN 14501 - Class 0)		medium (or EN 14501 - Class 1 & 2)		high (or EN 14501 - Class 3 & 4)
Providing a good light distribution	worse distribution	no	depends on sky condition		yes

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
			Ease of use		
Personal control possibilities	no, having a negative impact on user comfort	no, having little impact on user comfort	no, but without consequences	depends (yes, but not to full required impact)	yes
			Thermal considerations		
Thermal consideration (MINIMUM g value)	$g \geq 0.50$ (EN14501 Class 0) / highly increased solar heat gain (larger window plane)	$0.35 \leq g < 0.50$ (EN14501 Class 1) / increased solar heat gain (slightly larger window plane)	$0.15 \leq g < 0.35$ (EN14501 Class 2) / similar to baseline	$0.10 \leq g < 0.15$ (EN14501 Class 3) / reduced solar heat gain (slightly smaller window plane)	$g < 0.10$ (EN14501 Class 4) / highly reduced solar heat gain (smaller window plane)
Variable thermal consideration (MAXIMUM g value variation)	no		variation of g more than 0.15		variation of g more than 0.30
Light to thermal ratio (LSG)	τv /g reduces by > 30 %	τv /g reduces by > 10 %	similar to baseline (+/- 10 %)	τv/g increases by > 10 %	τv/g increases by > 30 %
Surface temperatures / secondary heat transfer ($qi = ge - te$; EN14501)	very high difference between room and surface temperature $qi \geq 0.30$ (EN 14501 Class 0)	high difference between room and surface temperature $0.20 \leq qi < 0.30$ (EN 14501 Class 1)	similar to baseline $0.10 \leq qi < 0.20$ (EN 14501 Class 2)	small difference between room and surface temperature $0.03 \leq qi < 0.1$ (EN 14501 Class 3)	very small difference between room and surface temperature $qi \leq 0.03$ (EN 14501 Class 4)
			Costs		
Ease of retrofit according to Figure 4	redesign		use new components in existing situation		upgrade of existing situation
Initial costs	€€€		€€		€
Operational costs	€€€	€€	€		no costs
Need for tracking , automatic control, sensors	yes		depends (functions with rough tracking as well)		no
Need for cleaning	yes, frequently	yes, from time to time (more than normal)	comparable to baseline	less then baseline	no

Table 4: Catalogue of Criteria for Electric Lighting Retrofit Solutions

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
			Energy efficiency		
Energy savings potential	energy savings potential < -30 %	-30 % ≤ energy savings potential < -10 %	-10 % ≤ energy savings potential ≤ 10 %	10 % < energy savings potential ≤ 30 %	energy savings potential > 30 %
Efficacy of component	component efficacy for luminaire replacement: » < 42 lm/W for fluorescent » < 10.5 lm/W for tungsten halogen » < 28 lm/W for CFL downlights » < 38.5 lm/W for metal halogen	component efficacy for luminaire replacement: » 42 - 54 lm/W for fluorescent » 10.5 - 13.5 lm/W for tungsten halogen » 28 - 36 lm/W for CFL downlights » 38.5 and 49.5 lm/W for metal halogen	component efficacy for luminaire replacement: » 54 - 66 lm/W for fluorescent » 13.5 - 16.5 lm/W for tungsten halogen » 36 - 44 lm/W for CFL downlights » 49.5 - 60.5 lm/W lm/W for metal halogen	component efficacy for luminaire replacement: » 66 - 78 lm/W for fluorescent » 16.5 - 19.5 lm/W for tungsten halogen » 44 - 52 lm/W for CFL downlights » 60.5 - 71.5 lm/W lm/W for metal halogen	component efficacy for luminaire replacement: » < 78 lm/W for fluorescent » > 19.5 lm/W for tungsten halogen » > 52 lm/W for CFL downlights » > 71.5 lm/W for metal halogen
Emitting angle	emitting angle ≥ 180°		120 ≤ emitting angle < 180°		emitting angle < 120°
Power factor	power factor ≤ 0.6	0.6 < power factor ≤ 0.75	0.75 < power factor ≤ 0.9	0.90 < power factor ≤ 0.98	0.98 < power factor ≤ 1.0
Dimmable	no				yes
			Lighting quality: Visual comfort		
UGR_R for 4H/8H	UGR_R ≥ baseline UGR + 6	baseline UGR + 3 ≤ UGR_R < baseline UGR + 6	baseline UGR- 3 ≤ UGR_R < baseline UGR + 3	baseline UGR - 6 ≤ UGR_R < baseline UGR- 3	UGR_R < baseline UGR - 6
Flicker	yes, perceptible	yes, imperceptible			none
			Lighting quality: Visual amenity		
Directionality - beam angle / increased luminance on the wall & ceiling	beam angle direct solution ≤ 45°	45° < beam angle direct solution ≤ 60°	60° < beam angle direct solution ≤ 90°	beam angle direct solution > 90° beam angle direct / indirect solution downward and upward beam ≤ 60°	beam angle direct solution > 120° beam angle direct / indirect solution downward or upward beam > 60°
Colour rendering index (Ra)	$R_a \leq 65$	$65 < R_a \leq 75$	$75 < R_a \leq 85$	$85 < R_a \leq 95$	$95 < R_a \leq 100$
CCT	negative deviation of standard		standard		dynamic

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
	Lighting quality: Ease of use				
Personal control	no, having a negative impact on user comfort	no, having little impact on user comfort	no, but without consequences	depends (yes, but not to full required impact)	yes
	Thermal considerations				
Efficacy of component	component efficacy for luminaire replacement: » < 42 lm/W for fluorescent » < 10.5 lm/W for tungsten halogen » < 28 lm/W for CFL down-lights » < 38.5 lm/W for metal halogen	component efficacy for luminaire replacement: » 42 - 54 lm/W for fluorescent » 10.5 - 13.5 lm/W for tungsten halogen » 28 - 36 lm/W for CFL down-lights » 38.5 and 49.5 lm/W for metal halogen	component efficacy for luminaire replacement: » 54 - 66 lm/W for fluorescent » 13.5 - 16.5 lm/W for tung-sten halogen » 36 - 44 lm/W for CFL down-lights » 49.5 - 60.5 lm/W lm/W for metal halogen	component efficacy for luminaire replacement: » 66 - 78 lm/W for fluorescent » 16.5 - 19.5 lm/W for tungsten halogen » 44 - 52 lm/W for CFL down-lights » 60.5 - 71.5 lm/W lm/W for metal halogen	component efficacy for luminaire replacement: » > 78 lm/W for fluorescent » > 19.5 lm/W for tungsten halogen » > 52 lm/W for CFL down-lights » > 71.5 lm/W for metal halogen
	Costs				
Ease of retrofit according to Figure 4	redesign		use new com-ponents in exist-ing situation		upgrade of ex-isting situation
Initial costs	€€€		€€		€
Operational costs	€€€	€€	€		no costs
Lamp life	lamp life of re-placement for » fluorescent luminaires < 10500 h » tungsten halo-gen luminaires < 2100 h » CFL down-lights < 5000 h » luminaires with metal halogen < 5600 h	lamp life of re-placement for » fluorescent luminaires: 10500 - 13500 h » tungsten halogen luminaires: 2100 - 2700 h » CFL down-lights: 5000 - 8000 h » luminaires with metal halogen: 5600 - 7200 h	lamp life of re-placement for » fluorescent luminaires: 13500 - 16500 h » tungsten halo-gen luminaires: 2700 - 3300 h » CFL down-lights: 8000 - 10000 h » luminaires with metal halogen: 7200 - 8800 h	lamp life of re-placement for » fluorescent luminaires: 16500 - 19500 h » tungsten halogen luminaires: 3300 - 3900 h » CFL down-lights: 10000 - 15000 h » luminaires with metal halogen: 8800 - 10400 h	lamp life of re-placement for » fluorescent luminaires > 19500 h » tungsten halo-gen luminaires > 3900 h » CFL down-lights > 15000 h » luminaires with metal halogen > 10400 h
Lumen depre-ciation over lifetime	lumen depreci-ation > 30 %	20 % < lumen depreciation ≤ 30 %	10 % < lumen depreciation ≤ 20 %	5 % < lumen depreciation ≤ 10 %	0 % ≤ lumen depreciation ≤ 5 %

As most technology families consist of a large number of different products, with varying characteristics, a number of assumptions had to be made in the performance assessment:

» Clear glazing solutions that do not have the purpose to redirect sunlight (e.g. low iron glass, double to triple glazing) are equipped with simple venetian blinds on the inner side of the façade, as is the baseline.
» Redirecting systems, such as laser cut panels, prismatic elements and microstructured glazing do not use blinds under sunny sky conditions, and have a resulting high light transmittance under sunny sky conditions.
» Louvres are manually rotatable, not retractable
» Blinds are positioned at the exterior, and are adjustable and retractable
» Redirecting blinds are automatically controlled, to perform optimally. These systems are not equipped with personal control and do not provide glare protection under overcast sky conditions, nor privacy at night.
» Moveable systems with personal control, such as blinds, shutters and stainless steel roller shutters can be used to increase privacy at night. Standard venetian blinds as applied in the baseline are not used for this purpose.
» Automatically controlled sun shading devices need sensors to properly function.
» Retractable systems, such as redirecting blinds, moveable blinds, shutters and stainless steel roller shutters, perform well under both overcast sky conditions (not in front of the window pane), and sunny sky conditions (providing sun protection).
» Increased light transmittance under overcast sky conditions is possible when the window area is increased, for example due to adding a skylight or a light tube.
» Micro sunshading louvres and translucent skylight systems need to be applied in a skylight. The baseline does not include a skylight, thus this retrofit solution is comparable labour intensive as the other skylight types. Both solutions can be applied in existing skylights by exchange of the insulating glass unit.
» The majority of electric lighting retrofit solutions does not improve lighting quality, as it is presupposed that both the old installation and electric lighting retrofits need to fulfil the requirements of the standards. Consequently these solutions already offer a minimum level of quality. Products with a lower quality are not considered in the evaluation.

With the set weighting factors and the considerations as described above, the evaluation of the retrofit solutions is presented on the following pages and integrated in the Lighting Retrofit Advisor of IEA Task 50.

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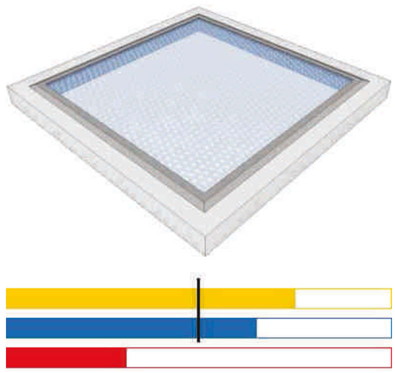
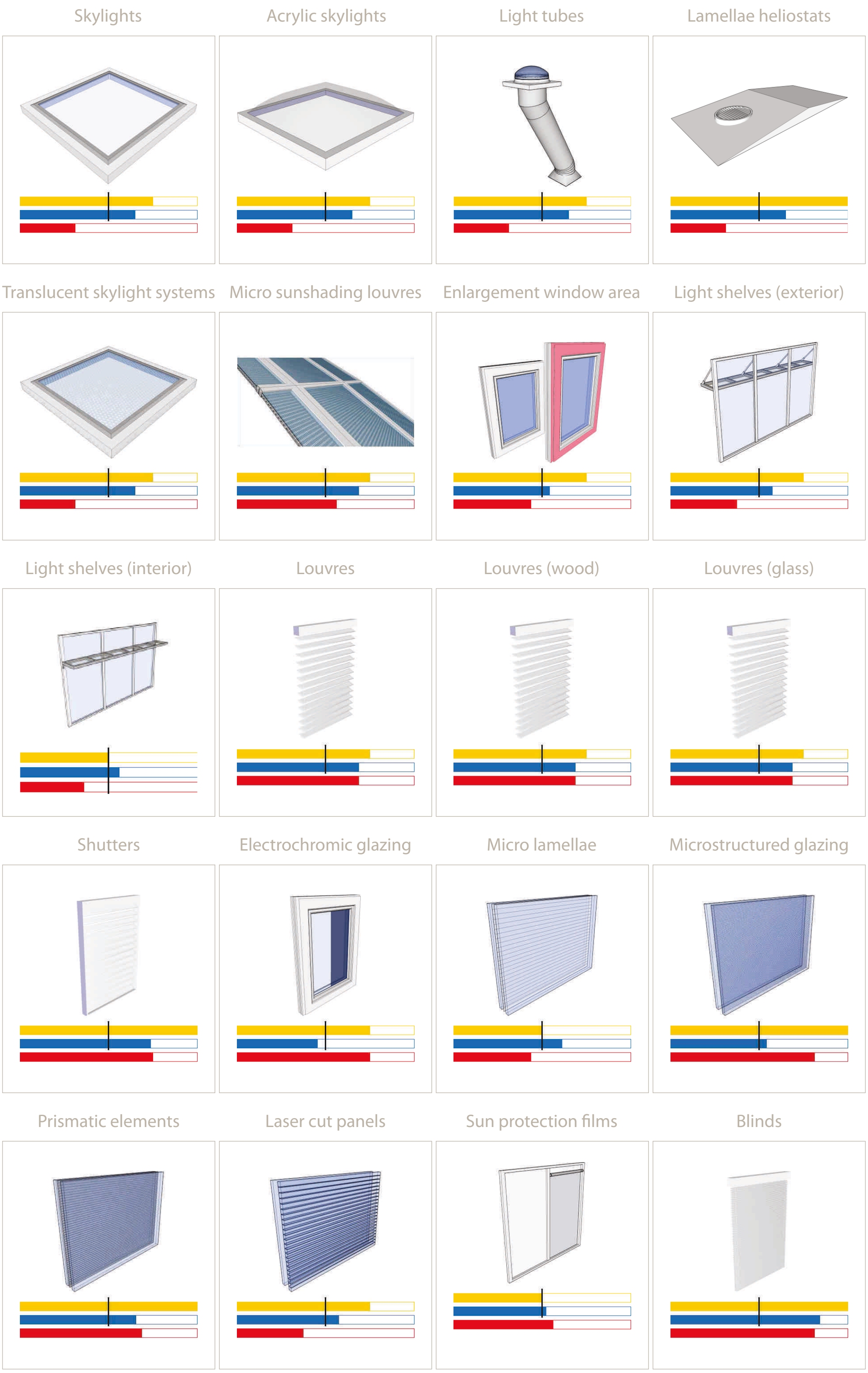
» Upper bar - Yellow - Energy efficiency
Reflects savings potential of retrofits
» Middle bar - Blue - Lighting quality
Reflects the retrofit's impact on lighting quality aspects
» Lower bar - Red - Thermal benefits
Reflects the thermal benefit of façade and daylight technology retrofit
» Baseline performance
positioned in the middle (marked by black line)

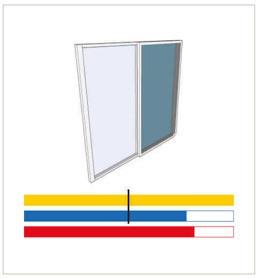



Skylights
Acrylic skylights
Light tubes
Lamellae heliostats
Translucent skylight systems
Micro sunshading louvres
Enlargement window area
Light shelves (exterior)
Light shelves (interior)
Louvres
Louvres (wood)
Louvres (glass)
Shutters
Electrochromic glazing
Micro lamellae
Microstructured glazing
Prismatic elements
Laser cut panels
Sun protection films
Blinds

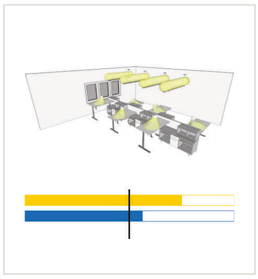
Redirecting blinds

Stainless steel shutters

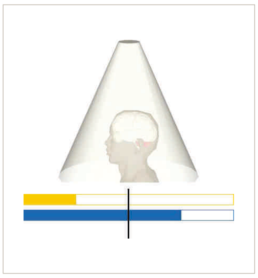
Sunscreens



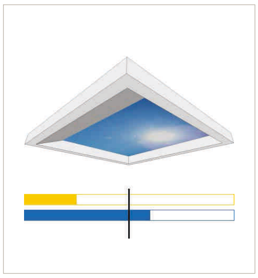
Task - ambient lighting



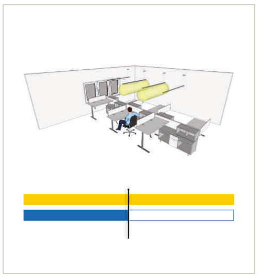
Algorithmic lighting



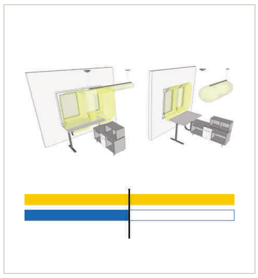
Virtual windows



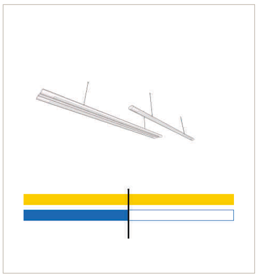
Demand driven controls



Daylight harvesting

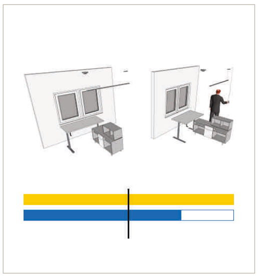


LED luminaire replacements

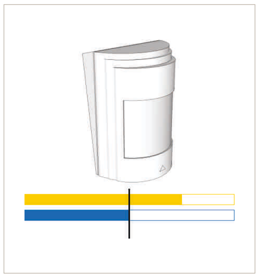


LED for CFL downlights

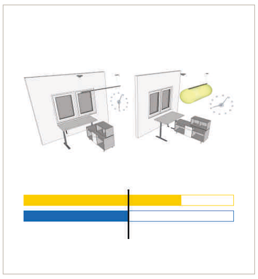
Personal control



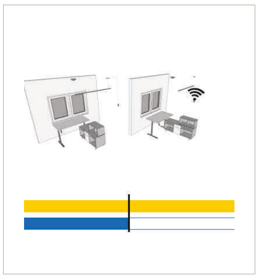
Occupancy sensing



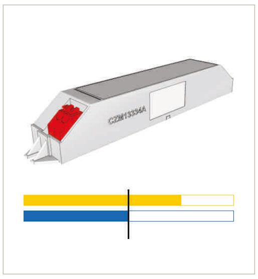
Time scheduling



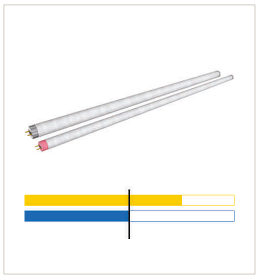
Wireless lighting controls



Electronic ballast (HF+)

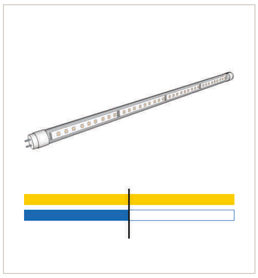


Fluorescent lamps



LED for incandescent lamps

LED T8 replacement lamps



CONCLUSIONS AND OUTLOOK

The work presented in this source book looked into the assessment of a selection of existing and a number of new technical solutions in the field of façade and daylighting technology, electric lighting and lighting controls.

The appropriateness of a lighting retrofit solution largely depends on the reason to retrofit, which can be to increase lighting quality, to save energy for electric lighting, to reduce costs or to affect thermal loads. Therefore, lighting retrofit solutions need to be evaluated on each of these quality aspects, which is possible with the proposed Catalogue of Criteria. Chapter 3 offers background information on a large bandwidth of possible retrofit solutions, which are assessed in Chapter 4.

The review showed that non-economic benefits, or indirect economic benefits, such as the increase of lighting quality, can be achieved with daylighting retrofit solutions that enhance daylight provision in a room, and with electric lighting and control solutions that might require a redesign of the lighting installation. The remaining electric lighting retrofit solutions looked into did not improve lighting quality, as it was presupposed that both the old installation and electric lighting retrofits need to fulfil the lighting quality requirements of the standards.

Whereas replacing a lamp or adding interior blinds are seen as simple retrofits, which are widely accepted, this review showed that additionally to that
» a task - ambient lighting concept,
» occupancy sensing,
» personal control in daylit spaces,
» daylight responsive lighting control through switching,
» time scheduling,
» wireless controls (occupancy and daylight responsive), and
» replacing an magnetic ballast with an electronic ballast
can be economical solutions that reduce energy consumption for electric lighting.

Daylighting retrofit solutions generally have higher investment costs. The full energy savings potential of a retrofit that offers a higher daylight provision can be harvested only when a daylight responsive lighting control solution is installed. The savings potential can be achieved to some extend when personal control over the electric lighting is offered to the user. Climate or the predominant weather condition should be respected in the choice of a daylighting retrofit solutions. Systems that redirect or reflect sunlight, avoid overheating, and allow sky light provision in the building are preferred in sunny conditions. In temperate climates, flexible systems that offer one of these two functionalities, but can be retracted under conditions without direct sunlight should be used.

The review was concluded in 2015. It is expected that the development of LEDs will lead to a further reduction of price and increase of efficacy of both retrofit lamps and luminaires. These solutions will remain good retrofit solutions with an even shorter payback period. It is not likely that the payback period for lighting control solutions and daylighting solutions will become significantly shorter in the near future. Lighting control systems are expected to reduce in cost, but the absolute energy saving for electric lighting will diminish, due to the use of more efficient components. Therfore, the effectiveness of controls to save energy is smaller. It has to be noted, that the use of non renewable resources will still be reduced. The costs for daylighting retrofit solutions might only slightly reduce in the near future. The performance of these retrofits will stay the same. Therefore, conclusions and guidelines as can be found in this source book, or the source book of IEA Task 21 (Ruck et al. 2000), will remain applicable.

Generally, lighting control solutions and daylighting solutions offer a higher potential to increase user comfort and lighting quality. With the current public interest in light for health and well-being, which is typically addressed with lighting conditions that vary in luminance distribution, light level and / or colour temperature over time, these solutions gain in value at present. Daylight is preferably integrated as it is a very effective light source to cause non-visual responses, due to its availability in large amounts during the day and the strong blue component in its spectrum. Additionally to that, daylight utilization can increase the energy efficiency of lighting installations for health and well-being. Lighting controls should be applied to harvest these saving potentials and to control the electric lighting to realize the required varying lighting conditions.

Summarizing, the development as well as the application of lighting retrofit solutions follows a two-way approach. The majority of electric lighting retrofit solutions will further focus on reduced price and increased efficacy to achieve short payback periods, whereas high end electric lighting solutions, and the majority of lighting controls and daylighting solutions are developed and applied to increase user comfort and lighting quality. The current performance of the selected retrofit technologies is in line with this. The reason to perform a lighting retrofit will determine the appropriate solution.

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54	Application of prismatic elements	Bartenbach GmbH
55	Application of prismatic elements	Bartenbach GmbH
56	Laser cut panel	TU Berlin
57	Application of laser cut panel, façade view	TU Berlin
58	Application of laser cut panel, indoor view	TU Berlin
59	Sun protection film	mzacha @morguefile http://mrg.bz/c4e0fd
60	Sun protection film, partial glare reduction	Martine Knoop
61	Sun protection film	emahluver3 @morguefile http://mrg.bz/7d8a2d
62	Exterior blinds	mjas @morguefile http://mrg.bz/c25fd4
63	Blinds, sun protection, blocked view	hotblack @morguefile http://mrg.bz/096d89
64	Blinds, partial view	MikiBrhanu @morguefile http://mrg.bz/3b9bea
65	Vertical blinds (“curved windows”)	Christopher Charles @flickr (CC BY-NC-SA 2.0, unadapted) https://www.flickr.com/photos/neonman/ 2690658525
66	Application of blinds (“lamellen dünn”)	David Kasparek @ flickr (CC BY 2.0, cropped) https://www.flickr.com/photos/dave7dean/ 436816856
67	Redirecting blinds	Patrick Prella
68	Redirecting blinds	Bartenbach GmbH
69	Redirecting blinds	Bartenbach GmbH
70	Fixed redirecting elements	Martine Knoop
71	Fixed redirecting elements	Martine Knoop
72	Fixed elements, partial glare reduction	Martine Knoop
73	Application of stainless steel roller shutters	Fraunhofer Institut für Solare Energiesysteme
74	Application of stainless steel roller shutters	Fraunhofer Institut für Solare Energiesysteme
75	Sunscreens	Martine Knoop
76	Sunscreens	Martine Knoop
77	Sunscreens, partial glare reduction (“The Noise Made When Textile Fibres Meets the Unforgiving Sun”)	Mattias @flickr (CC0 1.0, unadapted) https://www.flickr.com/photos/mnsc/ 5957983540
78	Renovation project (“empty office”)	Robbie Sproule @flickr (CC BY 2.0, unadapted) https://www.flickr.com/photos/robbie1/ 2718022465/
79	Task - ambient lighting	Bartenbach GmbH
80	Task - ambient lighting (“Desk Light”)	Yu Morita @flickr (CC BY-SA 2.0, unadapted) https://www.flickr.com/photos/securecat/ 3256065104

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81	Lecture hall with warm white lighting	Martine Knoop
82	Lecture hall with cool white lighting	Martine Knoop
83	Virtual roof light	Coelux S.r.l.
84	Vitrual roof light	Coelux S.r.l.
85	Demand driven lighting control, task lighting	Fraunhofer Institut für Bauphysik
86	Demand driven lighting control, task lighting	Fraunhofer Institut für Bauphysik
87	Demand driven lighting control, general lighting	Fraunhofer Institut für Bauphysik
88	Daylight responsive lighting controls	Patrick Prella
89	Luminaire based sensor for daylight responsive lighting control	Philips
90	Luminaire based sensor for daylight responsive lighting control	Philips
91	Room based sensor for daylight responsive lighting control	Philips
92	LED retrofit for a recessed fluorescent luminaire	Philips
93	Surface mounted LED luminaire	Bartenbach GmbH
94	LED ceiling solution	Peter Bartenbach
95	LED retrofits for CFL downlights	Bartenbach GmbH
96	LED retrofits for CFL downlights	Bartenbach GmbH
97	LED retrofits for CFL downlights	Bartenbach GmbH
98	Occupancy sensor	Philips Lighting
99	Room without (l) and with (r) occupancy sensing ("Occupancy Sensor")	Gramophone Maryland @flickr (CC BY-NC-ND 2.0, unadapted) https://www.flickr.com/photos/gramophone- maryland/8287294863
100	Time scheduling	Patrick Prella
101	Wireless controls	Patrick Prella
102	Wireless controls	Philips Lighting
103	Retrofit of ballast ("Lighting Retrofit Project - Re-wiring Light Fixtu")	Christine Rosalin, NAVFAC Pacific Public Affair @flickr (CC BY 2.0, cropped) https://www.flickr.com/photos/navfac/ 8594162546
104	Retrofit of ballast ("Lighting Retrofit Project - Installing New Ballasts")	Christine Rosalin, NAVFAC Pacific Public Affair @flickr (CC BY 2.0, cropped) https://www.flickr.com/photos/navfac/ 8594162504
105	Fluorescent lamps (T8, T5, CFL)	Philips Lighting
106	Retrofit of fluorescent solution (before)	Cláudia Amorim

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107	Retrofit of fluorescent solution (after)	Cláudia Amorim
108	LED retrofits for incandescent lamps (“An assortment of LED lamps commercially available as of 2010 as replacements for screw-in bulbs, including floodlight fixtures (left), reading light (center), household lamps (center right and bottom), and low-power accent light (right) applications”)	Geoffrey.landis @wikipedia (CC-BY-3.0, unadapted) https://en.wikipedia.org/wiki/LED_lamp#/media/File:LED_bulbs.jpg
109	LED retrofit for incandescent lamps	Philips Lighting
110	LED retrofit for incandescent lamps (“230-volt LED filament light bulb, with a E27 base. The filament is visible as the eight yellow vertical lines”)	Liebeskind @wikipedia (CC-BY-SA-4.0, unadapted) https://en.wikipedia.org/wiki/LED_lamp#/media/File:LEDfilamentLightBulbE27.jpg
111	LED retrofit for fluorescent lamps (“A 17 W tube of LEDs which has the same intensity as a 45 W fluorescent tube”)	Mcapdevila @wikipedia (CC-BY-SA-3.0, unadapted) https://en.wikipedia.org/wiki/LED_lamp#/media/File:Fluo-45W_LED-17W.jpg
112	LED retrofit for fluorescent lamps	Philips Lighting
113	Representation of technology performance (summary)	Martine Knoop
	All technology sketches	Patrick Prella

Energy efficiency (section 2.1.2, page 6)
1 system efficacy [lm/W]
2 luminous flux [lm]
3 luminous intensity distribution (descriptive)
4 emitting angle [°]
5 dimmable [yes / no]
6 power factor [-]
7 zoning possible [yes / no]
8 performs best under diffuse sky conditions [yes / no]
9 performs best under direct sunlight [yes / no]

Thermal considerations (section 2.1.3, page 8)
10 g value (classified according to EN 14501)
11 maximum g value variation [-]
12 light to thermal ratio [-]
13 qi value (classified according to EN 14501)
1 system efficacy [lm/W]

Lighting quality (section 2.1.4, page 9)
14 personal control [yes / no]
15 Unified Glare Rating, UGR_R [-]
16 colour rendering index, R_a [-]
17 correlated colour temperature, CCT [K]
4 beam angle [°] or directionality (descriptive)
18 directionality of the lighting solution (descriptive)
19 availability of flicker (descriptive)
20 daylight glare protection (descriptive)
21 light distribution in the room (descriptive)
22 light transmittance [-]
23 view out (classified according to EN 14501)
24 privacy at night (classified according to EN 14501)

Maintenance (section 2.1.5, page 10)
25 lamp life [h]
26 lumen depreciation over lifetime [%]
27 re-commissioning (descriptive)

Costs (section 2.1.6, page 11)
28 operational costs [€]
29 initial costs [€]
30 ease of retrofit (according to Figure 4)