Catalogue of Criteria to rate highly differentiated Lighting Retrofits Technologies

T50.B1

A Technical Report of IEA SHC Task 50

July 2015

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

Country Members

Australia	Germany	Portugal
Austria	Finland	Singapore
Belgium	France	South Africa
China	Italy	Spain
Canada	Mexico	Sweden
Denmark	Netherlands	Switzerland
European Commission	Norway	United States

Sponsor Members

ECI	ECREEE	RCREEE

Further information:

For up to date information on the IEA SHC work, including many free publications, please visit www.iea-shc.org.

Catalogue of Criteria to rate highly differentiated lighting retrofits technologies

A Technical Report of Subtask B (Daylighting and Electric Lighting Solutions), T50.B1

IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings

July 2015

AUTHORS

Primary:
Martine Knoop (Technische Universität Berlin, Germany)
Patrick Prella (Technische Universität Berlin, Germany)
Wilfried Pohl (Bartenbach GmbH, Austria)
Arnaud Deneyer (Belgian Building Resaerch Institute, Belgium)

Additional (in alphabetical order):
Berat Aktuna (Fraunhofer Institute, Germany)
Stanislav Darula (Slovak Academy of Sciences, Slovakia)
David Geisler-Moroder (Bartenbach GmbH, Austria)
Kjeld Johnsen (SBi, Aaborg University Copenhagen, Denmark)
Marta Malikova (Slovak Academy of Sciences, Slovakia)
Luo Tao (China Academy of Building Research, China)
Eino Tetri (Aalto University, Finland)

Distribution Classification: Unrestricted

AUTHORS (in alphabetical order)

Berat Aktuna
Fraunhofer-Institut für Bauphysik
Abteilung Wärmetechnik
Nobelstr. 12; 70569 Stuttgart, Germany
berat.aktuna@ibp.fraunhofer.de

Stanislav Darula
Institute of Construction and Architecture, Slovak Academy of Sciences
Dubravska cesta 9,
SK-845 03 Bratislava 45, Slovakia
usarsdar@savba.sk

Arnaud Deneyer
Belgian Building Research Institute
Avenue Pierre Holoffe, 21,
1342 Limelette, Belgium
arnaud.deneyer@bbri.be

David Geisler-Moroder
Bartenbach GmbH
Rinner Strasse 14
6071 Aldrans, Austria
david.geisler-moroder@bartenbach.com

Kjeld Johnsen
Statens Byggeforskningsinstitut
Aalborg Universitet
Afdelingen for Energi og Miljø
A C Meyers Vænge 15, 4. sal
2450 København SV
kjj@sbi.aau.dk

Martine Knoop
Technische Universität Berlin
Faculty of Electrical Engineering
Einsteinufer 19; 10587 Berlin, Germany
martine.knoop@tu-berlin.de

Marta Malikova
Institute of Construction and Architecture, Slovak Academy of Sciences
Dubravska cesta 9,
SK-845 03 Bratislava 45, Slovakia
malikova.marta@savba.sk

Wilfried Pohl
Bartenbach GmbH
Rinner Strasse 14
6071 Aldrans, Austria
wilfried.pohl@bartenbach.com

Patrick Prella
Technische Universität Berlin
Faculty of Electrical Engineering
Einsteinufer 19; 10587 Berlin, Germany
patrick.prella@tu-berlin.de

Luo Tao
China Academy of Building Research
No.30 Beisanhuan Road,
Beijing, China
luotao@chinaibee.com

Eino Tetri
Aalto University
PO.Box 13340 (Otakaari 7B, Espoo)
00076 Aalto, Finland
eino.tetri@aalto.fi

KEYWORDS

retrofit solutions, daylight, electric lighting, lighting controls, energy efficiency, lighting quality

ACKNOWLEDGEMENTS

The authors thank their respective funding agencies for supporting their work:

- bmvit - Bundesministerium für Verkehr, Innovation und Technologie and FFG - Die Österreichische Forschungsförderungsgesellschaft, Austria
- Bundesministerium für Wirtschaft und Technologie, Germany.
- China Academy of Building Research, China.
- Danish Energy Agency, Energy Technology Development and Demonstration Program, Denmark.
- Finnish RYM Indoor Environment Program, Finland. (http://www.rym.fi/en/programs/indoorenvironmentprogram/)
- Service Public de Wallonie, DGO4, Belgium.
- Slovak Academy of Sciences - international scientific cooperation scheme (MVTS – medzinárodná vedecko-technická spolupráca), Slovakia.

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

EXECUTIVE SUMMARY

Simple retrofits 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 retrofit approaches that might cost more but offer a (further) reduction of energy consumption while improving lighting quality to a greater extend. In order to do so, a Catalogue of Criteria was developed to describe the overall quality of daylighting and electric lighting solutions (Chapter 3 “Catalogue of Criteria”), which can be used to compare retrofit solutions with a set baseline condition, or amongst each other (Chapter 4 “Comparison of retrofit solutions”).

All material is included in the Technology Viewer of the Lighting Retrofit Adviser (Chapter 5 “Implementation of Technology Viewer in the Lighting Retrofit Adviser”) to convey the information to the relevant target groups: building owners, authorities, designers and consultants, as well as the lighting and façade industry. The Technology Viewer offers a user-friendly representation of the product quality, allowing for easy comparison of different lighting retrofit solutions and providing detailed background information on each solution.

List of figures

Table of Contents

1. Introduction

This document is drawn up as part of the work conducted in Subtask B.1 “Definition - system characterisation” of Subtask B “Daylighting and Electric Lighting Solutions“ within IEA Task 50 “Advanced lighting solutions for retrofitting buildings”.

The work presented in this report aims at promoting state-of-the-art and new retrofit approaches that might cost more but also offer more benefits: further reduction of energy consumption while improving lighting quality to a greater extend. For this, the document offers a list of quality criteria to assess the effectiveness of electric lighting and daylighting retrofit solutions to reduce energy consumption and running costs as well as improve lighting quality. The document provides information for those involved in the development of retrofit products and those involved in the decision making process of a retrofit project, buildings owners, authorities, designers and consultants, as well as the lighting and façade industry.

The document consists of two parts. The first part describes the quality criteria included in the Catalogue of Criteria, a list of over 30 quality measures that can be used to describe the performance of lighting retrofit solutions, qualitatively and to some degree quantitatively. The second part of the document describes the so called Technology Viewer of the Lighting Retrofit Adviser, a tool developed within IEA Task 50 to convey detailed information about retrofit solutions and compare highly differentiated retrofit solutions on a mutual basis.

2. Quality assessment of lighting retrofit solutions

In retrofitting a building, lighting related solutions can be applied with the aim to save energy, to reduce costs, and / or to increase lighting quality. 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. 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. However, retrofit approaches that take into account the usage of other components or a new design of the lighting installation often allow a (further) reduction of energy consumption while improving the lighting quality to a greater extend.

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, Subtask B of IEA Task 50 developed a matrix (see Figure 1) 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,

  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.

Another hurdle to take in considering alternative solutions in the 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 for both electric lighting as well as daylighting solutions.

	Upgrade of existing situation	Use new components in existing situation	Redesign
Façade & daylighting technology	Add on to window plane: add simple daylighting system (e.g. light redirection blinds)	Window replacement: Add daylighting system (construction fits in existing window frame)	Redesign façade or façade elements, increase window size, add skylight, add daylighting systems
Blinds & shading technology	Add on to window plane: add shading devices (static or dynamic)	Window replacement: Improve glazing (e.g. electrochromic glazing, smart windows, double glazing with blinds)	Redesign façade or façade elements, add architectural shading elements Link to BMS – blind control to optimize with heating and cooling
Electric lighting solutions	Lamp replacement: improvement in lamp technology, or ballast technology, improvement of spectral quality of the light source, increase luminous flux	Luminaire replacement: improvement in lamp or ballast technology that requires a new luminaire, improvement in luminaire technology	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: controls for dimmable luminaires: use of sensors for presence detection – dimming, daylight dimming, manual dimming	install building management system to link electric lighting to heating and cooling (e.g. demand control), 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

→ for the retrofit solutions from the left to the right →
in most cases: an increase of energy efficiency or visual comfort, as well as initial costs

Figure 1: Matrix of retrofit solutions

3. Catalogue of Criteria

In order to evaluate a large variety of retrofit solutions, on an equal and holistic basis, Subtask B "Daylighting and Electric Lighting Solutions" of IEA Task 50 "Advanced lighting solutions for retrofitting buildings" defined a Catalogue of Criteria, that can be used to:

- describe the holistic performance of retrofit approaches
- function as a basis for the Technology Viewer, a tool that allows for a quantitative comparison of retrofit possibilities.

The quality measures 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
- the impact of the lighting retrofit on the overall retrofit process
- the thermal behaviour of daylighting systems and thermal impact of electric lighting solutions
- the geographical and climatological applicability.

Figure 2: Product and application related quality criteria collected within activities of IEA Task 50

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 concludes with 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 a evaluation of both daylighting and electric lighting solutions on the main features, potential energy savings for electric lighting, lighting quality, costs and the retrofit process, a comparison of distinct different retrofit approaches on a common basis seems to be feasible.

3.1. Baseline

In order to describe the performance of the retrofit lighting 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 ((τ_v = 0.8, g value = 0.6, providing

- a clear view out (classification according to EN 14501: 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 facades (East, South or West orientated façades on the Northern hemisphere, East, North and West orientated facades 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 electric lighting solution depends on the application 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[1]) = 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,

[1] R_a or CRI

- 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 = 4000 K, 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 personal, occupancy or daylight harvesting controls.

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.

3.2. Quality measures

As indicated before, the Catalogue of Criteria contains over 30 quality measures that primarily focus on the following reasons to retrofit:

- reduce energy consumption,
- improve the lighting quality, and
- reduce the operational costs.

A detailed description of the criteria included in the Catalogue of Criteria can be found in § 3.2.1 - 3.2.5.

An overview of the numbered criteria (referred to #) can be found in Appendix A.

3.2.1. 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 achieved in field studies (Williams et al. 2011)

	Office	Warehouse	Lodging	Education	Retail, other than mall	Healthcare, outpatient	Public assembly
Personal control	35 %			6 %			
Daylight harvesting	27 %	28 %		29 %	29 %		36 %
Occupancy sensing	22 %	31 %	45 %	18 %		23 %	36 %
Tuning[2]	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 under **direct sunlight** (# 9). 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.

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.

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

3.2.2. 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 thermal energy consumption of the building as well.

The energy consumed by the electric lighting can be considered as internal load of the building. Internal loads lead to a reduction of the heating needs of the building and have an influence of the cooling needs of buildings: In cold climate and/or in winter, internal loads may benefits but too high internal loads may be a disadvantage in hot climate and/or in summer.

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 can impact the internal gains and the cooling needs.

Daylighting use combined to efficient control system, may also lead to a large reduction of the internal gains. At the same time the use of daylight can also raise the external loads which influences negatively the cooling especially in hot climate and/or in summer.

The interaction between lighting and HVAC, and its effect on the annual heating and cooling requirements should then 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.

Thermal impact of electric lighting solutions is evaluated by means of **system efficacy** (# 1, in lm/W).

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 smart window solutions or switchable glazing, that can change light and heat transmission properties according to changing needs, such as (re)moveable shading systems, electrochromics, thermochromics, and liquid crystals,
- 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 advanced lighting 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).

3.2.3. Lighting quality

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). 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 by means of 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 guaranteed **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.

3.2.4. 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 pool 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 L90 or L70). By, denotes the LEDs rate which is expected to fail for given bounder conditions (e.g. reach the admissible lumen output (x) for a given lifetime) (see Appendix D). 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 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.

3.2.5. Costs

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 1), 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 electric lighting solutions, which should be considered in the comparison of payback periods of retrofit solutions.

3.3. Use of the Catalogue of Criteria

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.

In the use of the Catalogue of Criteria, it needs to be assumed that the systems are optimally operated, in line with the intended operation as defined by the manufacturer of the given system 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.

Comparison of a retrofit solution with the baseline situation using the quality criteria included in the Catalogue of Criteria (overview in Appendix A, Appendix B and Appendix C:) systematically reflects the advantages and disadvantages of the retrofit solution quantitatively and qualitatively.

The assessment can be made with the main features (e.g. “the lighting solution offers a high energy savings potential”) or on a detailed level, addressing specific topics (e.g. “the system does not provide glare protection during winter time”). The Technology Viewer of the Lighting Retrofit Advisor (as discussed in Chapter 5 ”Implementation of Technology Viewer in the Lighting Retrofit Adviser”) distinguishes similarly in the representation of product quality, as illustrated with examples in Figure 3. In the upper part is the performance on a high level included for the topics ‘energy efficiency’, ‘lighting quality’ and ‘operational costs’. In the lower part, the product specific advantages and disadvantages are included.

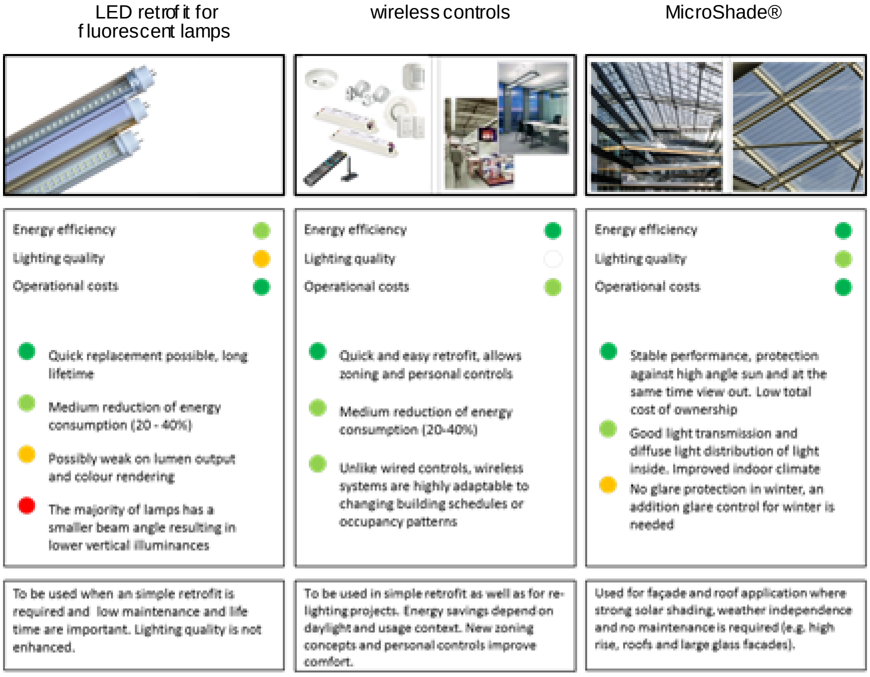


Figure 3: Draft version of performance assessments for different retrofit solutions
(dark green: much better than baseline, light green: better than baseline, white: similar to baseline or not applicable, orange: worse than baseline, red: much worse than baseline)

Table 2: Example for LED retrofit for CFL downlights for the Catalogue of Criteria as included in Appendix C:
(dark green: much better than baseline, light green: better than baseline, white: similar to baseline or not applicable, orange: worse than baseline, red: much worse than baseline)

	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 ≤ 28 lm/W for CFL downlights (replacement)	28 lm/W < component efficacy ≤ 36 lm/W for CFL downlights (replacement)	36 lm/W < component efficacy ≤ 44 lm/W for CFL downlights (replacement)	44 lm/W < component efficacy ≤ 52 lm/W for CFL downlights (replacement)	component efficacy > 52 lm/W for CFL downlights (replacement)
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

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
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 (R_a)	$R_a \leq 65$	$65 < R_a \leq 75$	$75 < R_a \leq 85$	$85 < R_a \leq 95$	$95 < R_a \leq 100$
CCT	negative deviation of standard	-	standard	-	dynamic
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
Costs					
Ease of retrofit according to Figure 1	redesign		use new components in existing situation		upgrade of existing situation
Initial costs	€€€		€€		€
Operational costs	€€€	€€	€		no costs
Lamp life (requirements for specific solution)	lamp life of replacement for CFL downlights ≤ 5000 h	5000 h < lamp life of replacement for CFL downlights ≤ 8000 h	8000 h < lamp life of replacement for CFL downlights ≤ 10000 h	10000 h < lamp life of replacement for CFL downlights ≤ 15000 h	lamp life of replacement for CFL downlights > 15000 h
Lumen depreciation over lifetime	lumen depreciation > 30 %	20 % < lumen depreciation ≤ 30 %	10 % < lumen depreciation ≤ 20 %	5 % < lumen depreciation ≤ 10 %	0 % ≤ lumen depreciation ≤ 5 %

3.4. Drawbacks of the Catalogue of Criteria

The Catalogue of Criteria includes relevant, broadly applicable quality criteria. As indicated in paragraph 3.2.1 “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 and orientation** 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. In line with this, 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 to look into increased productivity, academic results, sales or user comfort due to the applied (day)lighting solution.
- 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.

4. Comparison of retrofit solutions

4.1. Project specific comparison of retrofit solutions

The Catalogue of Criteria is used to create descriptive performance assessments of all retrofit lighting solutions (e.g. Figure 3).

Comparison of systems 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 impact of daylighting retrofit solutions.

Again, baseline conditions are 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.

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 upmost 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.

The relevance of each item within the main categories should be defined in a project and be reflected in weighting factors per item. For now, a general weighting of quality measures for the different main categories ‘energy efficiency’, ‘lighting quality’, and ‘costs’ as presented in Table 3 is included.

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.

Table 3: Predefined weighting factors for quality criteria

	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 1)	25 %	Ease of retrofit (acc. Figure 1)	25 %
	Initial costs	25 %	Initial costs	25 %
	Operational costs	50 %	Operational costs	50 %
Thermal considerations	Minimum g value	25 %	System efficacy	100%
	Variable thermal consideration	25 %		
	Visible to thermal ratio (LSG)	25 %		
	Secondary heat transfer	25 %		

4.2. Representation of product performance

The quality assessment including the weighting factors according to Table 3 allows for a representation as shown in Figure 4. The representation will support in the decision making process of suitable retrofit lighting 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 product representation, having a prominent role in the decision making process already, and therefore not reflected in the performance icon of the retrofit solutions (see Figure 4).

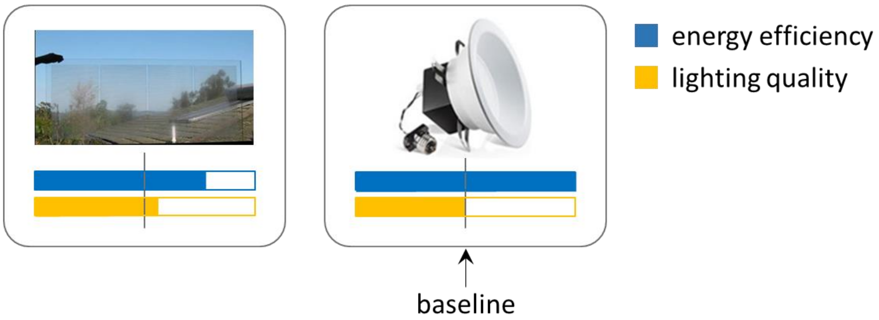


Figure 4: Representation of retrofit quality of differentiated lighting retrofit solutions

5. Implementation of Technology Viewer in the Lighting Retrofit Adviser

Material collected and developed within IEA Task 50 is included in the Lighting Retrofit Adviser, an electronic interactive source book, created to provide buildings owners, authorities, designers and consultants, as well as the lighting and façade industry with relevant lighting retrofit information.

Based on the Catalogue of Criteria and the resulting instrument, a tool to evaluate and compare lighting retrofit solutions was developed: the Technology Viewer. The primary objective of the tool is to present the solutions clearly, practically relevant and user-friendly. The operation should be intuitive and attractive, to ensure that even non-experts can get appropriate support in planning with retrofit technologies.

5.1. Structure

The presentation of all retrofit solutions included in the Technology Viewer of the Lighting Retrofit Adviser is in line with the matrix used to cluster lighting retrofit solutions (see Figure 1). Daylighting and electric lighting solutions are combined in one representation.

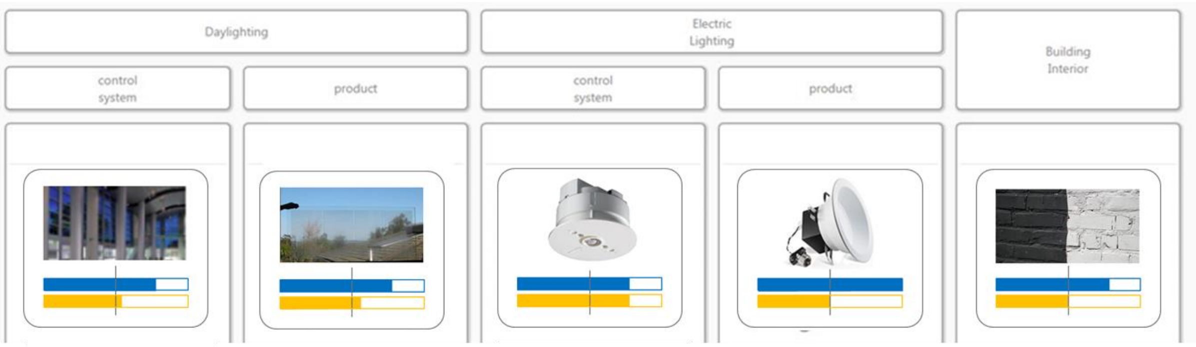


Figure 5: Representation of retrofit solutions included in the Technology Viewer of the Lighting Retrofit Adviser

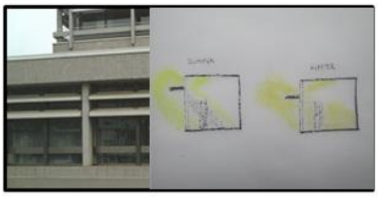
In order to select a retrofit solution, the user can directly choose the specific solution or search for possible solutions. The search for solutions can be based on:

- Filtering on climate, retrofit strategy and cost will be used to select specific solutions, which will reduce the amount of proposed solutions.
- Sorting on energy efficiency, lighting quality or thermal impact is used to bring more suitable solutions in the upper part of the matrix (Figure 1).

For each solution, three layers of information are available:

1) The least detailed level of information includes the overall performance on energy efficiency and lighting quality, as reflected in Figure 4 and Figure 5).
2) The second level of information includes the assessment of the system on all quality aspects included in the Catalogue of Criteria.
3) Detailed information on the retrofit solution can be found in the Technology Fiche of the product (see Figure 6). It includes the overall performance on energy efficiency, lighting quality and thermal considerations, as well as the two main advantages and the two main disadvantages of the retrofit solution. Additionally to that, it includes a description of the solution's working principle, background information, relevant references, as well as information on additional benefits, restrictions and considerations.

Comparison of retrofit solutions is possible on each information level.



External Light Shelves
An external light shelf is designed to shade and reflect light on its top surface. An external light shelf is usually positioned above eye level, the lower the light shelf height, the greater the glare potential as well as the amount of light reflected to the ceiling.

Energy efficiency
Lighting quality

Shading device reduces thermal gain

Enhances the quality of light

Applicability depends on ceiling height.

High maintenance, resulting in higher running costs

Performance of External Light Shelves
External light shelves can be an effective element to reduce energy consumption and enhance quality of light in tropical buildings, if designed and located properly. They produce higher levels of illuminance deeper inside a space, energy savings are modest. Field studies showed an energy reduction for electric lighting of 19 to 41%. A room with the optically treated light shelf can increase energy savings potential, thus using less total annual electricity for lighting than one with a conventional light shelf. Movable light shelves are more expensive (especially if motorized) than fixed light shelves, but movable systems are more flexible in control and application.
Light shelves affect the architectural and structural design of a building and must be considered at the beginning of the design phase because they require a relatively high ceiling in order to function effectively.
Light shelves require regular cleaning. External light shelves can become dirty, collect snow, and provide nesting places for birds or insects. A specular surface requires maintenance to maintain its reflective properties, which will increase running costs.
They can be applied in climates with significant direct sunlight and are applicable for deep spaces with south orientation in the northern hemisphere (north orientation in the southern hemisphere). Light shelves do not perform as well on east and west orientations and in climates dominated by overcast sky conditions.
The costs for the system and its installation are relatively effective but maintenance costs can be high.

External light shelves are effective in situations with high ceilings. They perform best with direct sunlight, and need to be positioned above eye level.

IEA (2000) : Daylight in Buildings.
Perez 2009 : Climatic considerations in school building design in the hot-humid climate for reducing energy consumption.
Joarder 2009 : A Simulation assessment of the height of light shelves to enhance daylighting quality in tropical office buildings under overcast sky conditions in Dhaka, Bangladesh.

Figure 6: Technology Fiche of a retrofit solution

5.2. Evaluated retrofit solutions within IEA Task 50

The Technology Viewer of the Lighting Retrofit Adviser includes a number of retrofit solutions, identified and selected by the members of Subtask B of IEA Task 50 as relevant retrofit solutions from a lighting point of view. These solutions are listed below:

Electric lighting solutions:

- LED replacement lamps for T8
- LED luminaire replacements
- LED retrofit for CFL downlights

- LED replacements for halogen / incandescent lamps
- 1 to 1 luminaire replacement to reduce light levels
- Task – Ambient lighting with free floor standing luminaires
- Task – Ambient lighting with task luminaires

Lighting controls and drivers:

- Occupancy controls
- Wireless lighting Controls
- Electronic ballast (HF+)
- Daylight harvesting controls
- Constant illuminance control
- Scheduling
- Lighting controls that consider zoning
- Demand driven controls
- Controls for algorithmic lighting using CCT change and dynamic lighting
- Scheduling of the solar shading systems
- Building Management System solutions

Daylighting solutions:

- Sun protection film
- Different types of blinds
- Light shelves
- Louvres
- MicroShade®
- Lamella
- Microstructure glazing
- New glazing types
- Laser cut panels
- Fixed systems with redirecting elements
- Sky lights
- Light tubes
- Overhang
- Sun screens
- Awning
- Shutters
- Louvre (glass, wood, metal / horizontal and vertical)
- Electrochromic glazing
- Prismatic elements
- Micro sunshading

Interior changes:

- Change of reflection coefficients
- Add book shelves
- Add partitions
- Remove walls or replace with glass walls
- Rearrangement of work places

5.3. Drawbacks of the Technology Viewer

For now, it is not possible to evaluate products not included in the Technology Viewer. To evaluate these retrofit solutions, please use the Catalogue of Criteria as included in Appendix A, Appendix B and Appendix C:.

The Technology Viewer works with product families, and gives an overall performance assessment for a retrofit solution type. As an example, LED solutions for T8 replacement are available in large variety. The products considered in the performance assessment are replacement lamps offered by larger, well-known, manufacturers. Resulting, the performance icon (see Figure 4) and the representation of the main features in the Technology Fiche (as presented in on the left side of Figure 6) will not reflect the performance of all LED solutions for T8 replacement available on the market. The text part of the Technology Fiche can include relevant information about outliners in performance, pointing out possible quality restrictions, whenever this information is available. Even though the Technology Fiche might increase awareness for product quality flaws, 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.

6. Conclusions and Recommendations

Using 30 quality measures, the Catalogue of Criteria can describe the performance of highly differentiated lighting retrofit solutions, qualitatively and to some degree quantitatively. It allows for comparison of state-of-the-art, new and future retrofit solutions on an equal and holistic basis. This approach promotes lighting retrofits that might cost more but also offer more benefits, which is reflected in the solutions' quality defined by means of the Catalogue of Criteria.

The Technology Viewer of the Lighting Retrofit Adviser is developed to convey the collected information within IEA Task 50, including approximately 50 different retrofit solutions. This tool within the Lighting Retrofit Advisor offers both a 'quick glance' on the retrofits' performance for easy comparison, as well as detailed information on the selected solutions. When using the Catalogue of Criteria, future retrofit solutions can be compared with the currently available solutions as well.

Even though the Technology Viewer includes detailed information on product families, the performance single products can deviate from it. It remains of importance to assess the actual performance of a specific product before implementation in a retrofit project. This performance again, can be assessed, for example, by means of the Catalogue of Criteria.

7. References

Bordass WT, Leaman AJ, Willis STP (1994) Control strategies for building services: the role of the user. Proceedings of CIB Conference on Buildings and the Environment. Building Research Establishment, Watford, May 1994.

Boyce PR, Eklund NH, Simpson SN (2000) Individual lighting control: task performance, mood, and illuminance, Journal of the Illuminating Engineering Society, Winter 2000

Bullough JD, Sweater Hickcox K, Klein TR, Lok A, Narendran N (2012) Detection and acceptability of stroboscopic effects from flicker Lighting Research and Technology 44(4):477-483.

CEN (2005) EN 14501 Blinds and shutters – Thermal and visual comfort – Performance characteristics and classification, published by the European Committee for Standardization CEN

CEN (2007) EN 15193: Energy performance of buildings - energy requirements for lighting, published by the European Committee for Standardization CEN.

CEN (2011) EN 12464-1:2011 Light and lighting — Lighting of work places — Part 1: Indoor work places, published by the European Committee for Standardization CEN.

CIE (2013): CIE 205-2013 Review of Lighting Quality Measures for Interior Lighting with LED Lighting Systems. Vienna: Commission Internationale de l'Eclairage

Dubois MC, Knoop M, Matusiak Szybinska B, Tetri E, Gentile N, Fuhrmann P, Bisegna F (2014) Lighting retrofits: a literature review A Technical Report of Subtask D (Case Studies), T50.D2 IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings. IEA Solar Heating and Cooling Programme

Galasiu AD, Newsham GR, Suvagau C, Sander DM (2007), Energy saving lighting control systems for open-plan offices: a field study, NRCC-49498, also published in Leukos, v.4, no.1 July 2007, pp. 7-29.

Jennings JD, Rubinstein FM, Dibartolomeo D (2000) Comparison of control options in private offices in an advanced lighting controls testbed, Journal of the Illuminating Engineering Society, Summer 2000.

Kirsch RM (2015) Lighting quality and energy efficiency in office spaces, PhD Thesis Technische Universität Berlin

Lehman B, Wilkins AJ, Berman SM, Poplawski ME, Miller NJ (2011) Proposing metrics of flicker in the low frequencies for lighting applications. Leukos 7(3):189-195.

Loe DL, Mansfield KP, Rowlands E (1994) Appearance of lit environment and its relevance in lighting design: Experimental study. Lighting Research and Technology 1994 26: 119-133

Maniccia D, Rutledge JB, Rea MS, Morrow W (1999), Occupant use of manual lighting controls in private offices, Journal of the Illuminating Engineering Society, Summer 1999, 42-56

Moore T, Carter DJ, Slater A (2002) A field study of occupant controlled lighting in offices, Lighting Research and Technology, 34,3:191-205

Moore T, Carter DJ, Slater AL (2004) A study of opinion in offices with and without user controlled lighting, Lighting Research and Technology 36,2(2004):131-146 Building Use Studies Ltd (1993) summarised in Leaman A. Dissatisfaction and office productivity. Facilities 1995; 13: 13–19.

Newsham G.R., Richardson C, Blanchet C, Veitch JA (2005) Lighting quality research using rendered images of offices. Lighting Research and Technology 2005 37: 93-115

Newsham G.R., Aries MBC, Mancini S, Faye G (2008) Individual control of electric lighting in a daylit space Lighting Res. Technol. 2008; 40: 25–41

Ruck N, Aschehoug Ø, Christoffersen C, Jakobiak R, Johnsen K, Lee E, Selkowitz S (2000) Daylight in Buildings; A Source Book on Daylighting Systems and Components, A Report of IEA SHC Task 21 / ECBCS Annex 29, LBNL Berkeley

Tregenza P, Romaya S, Dawe S, Heap L, Tuck B (1974) Consistency and variation in preferences for office lighting, Lighting Research and Technology 6:205-11

Williams AA, Atkinson BA, Garbesi K, Rubinstein FM, Page E (2011) A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings In LBNL-5095E.,

Appendix A: List of Criteria

Energy efficiency (§ 3.2.1, page 16)

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 (§ 3.2.2, page 18)

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 (§ 3.2.3, page 18)

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 (§ 3.2.4, page 20)

25 lamp life [h]
26 lumen depreciation over lifetime [%]
27 re-commissioning (descriptive)

Costs (§ 3.2.5, page 21)

28 operational costs [€]
29 initial costs [€]
30 ease of retrofit (according to Figure 1)

Appendix B: 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 %
Primarily using diffuse skylight	no		yes		performs well under both diffuse skylight as well as direct sunlight
Primarily using direct sunlight	no		yes		performs well under both diffuse skylight as well as direct sunlight
Visual comfort					
Provides glare protection (overcast sky conditions)	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 conditions)	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 conditions)	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 selectivity (for D65) (overcast sky conditions)	affects R_a considerably (R_a< 80)		affects R_a slightly ($80 < R_a < 90$)		maintains R_a ($90 < R_a < 100$)
Colour distortion / fidelity (for D65) (direct sunlight)	affects R_a considerably ($R_a < 80$)		affects R_a slightly ($80 < R_a < 90$)		maintains R_a (90 < CRI < 100)
Privacy at night	minimal (or EN 14501 - Class 0)		medium (or EN 14501 - Class 1 & 2)		high (or EN 14501 - Class 3 & 4)

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
Providing a good distribution (light deeper in the room, higher uniformity, luminance distribution on the wall)	worse distribution	no	depends on sky condition		yes
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 ≥ 0.50 (EN14501 Class 0) / highly increased solar heat gain (larger window plane)	0.35 ≤ g < 0.50 (EN14501 Class 1) / increased solar heat gain (slightly larger window plane)	0.15 ≤ g < 0.35 (EN14501 Class 2) / similar to baseline	0.10 ≤ 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 ≥ 0.30 (EN 14501 Class 0)	high difference between room and surface temperature 0.20 ≤ qi < 0.30 (EN 14501 Class 1)	similar to baseline 0.10 ≤ qi < 0.20 (EN 14501 Class 2)	small difference between room and surface temperature 0.03 ≤ qi < 0.1 (EN 14501 Class 3)	very small difference between room and surface temperature qi ≤ 0.03 (EN 14501 Class 4)
Costs					
Ease of retrofit according to Figure 1	redesign		use new components in existing situation		upgrade of existing situation
Initial costs	€€€		€€		€
Operational costs	€€€	€€	€		no costs
Need for tracking	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

Appendix C: 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 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 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 (R_a)	R_a ≤ 65	65 < R_a ≤ 75	75 < R_a ≤ 85	85 < R_a ≤ 95	95 < R_a ≤ 100
CCT	negative deviation of standard	-	standard	-	dynamic
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
	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline

	much worse than baseline	worse than baseline	similar to baseline or not applicable	better than baseline	much better than baseline
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 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
Costs					
Ease of retrofit according to Figure 1	redesign		use new components in existing situation		upgrade of existing situation
Initial costs	€€€		€€		€
Operational costs	€€€	€€	€		no costs
Lamp life	lamp life of replacement for fluorescent luminaires < 10500 h tungsten halogen luminaires < 2100 h CFL downlights < 5000 h luminaires with metal halogen < 5600 h	lamp life of replacement for fluorescent luminaires: 10500 - 13500 h tungsten halogen luminaires: 2100 - 2700 h CFL downlights: 5000 - 8000 h luminaires with metal halogen: 5600 - 7200 h	lamp life of replacement for fluorescent luminaires: 13500 - 16500 h tungsten halogen luminaires: 2700 - 3300 h CFL downlights: 8000 - 10000 h luminaires with metal halogen: 7200 - 8800 h	lamp life of replacement for fluorescent luminaires: 16500 - 19500 h tungsten halogen luminaires: 3300 - 3900 h CFL downlights: 10000 - 15000 h luminaires with metal halogen: 8800 - 10400 h	lamp life of replacement for fluorescent luminaires > 19500 h tungsten halogen luminaires > 3900 h CFL downlights > 15000 h luminaires with metal halogen > 10400 h
Lumen depreciation over lifetime	lumen depreciation > 30 %	20 % < lumen depreciation ≤ 30 %	10 % < lumen depreciation ≤ 20 %	5 % < lumen depreciation ≤ 10 %	0 % ≤ lumen depreciation ≤ 5 %

Appendix D: LED Lifetime

White paper by Bartenbach GmbH (28/04/2015/ MF)

Traditional light source lifetime is calculated according to the B50 standard. In this standard, the lifetime of the source is the number of operating hours after which 50% of the tested population fail.

Since LED is a semiconductor, it will not burn out like a Halogen or a CFL. Instead, lighting output will decline over time. As a result, other kinds of standards based on luminous flux degradation, as the L70 B50 (testing methods IES LM 80-08, + TM 21-11), have been developed to evaluate the LED lifetime in relation to the fulfillment of determined lighting requirements.

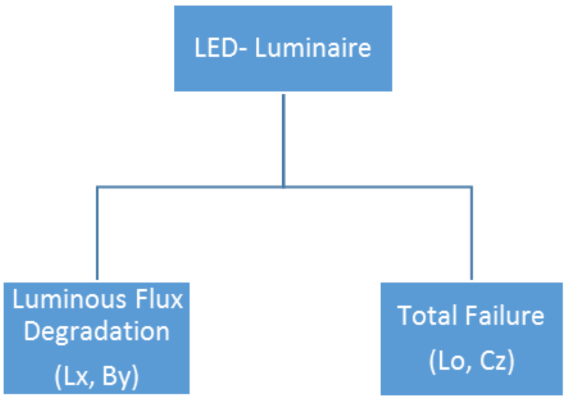
The Lifetime of LED and LED luminaires/modules have to be provided by the manufacturer. Main factors for the LED lifetime evaluation are the electrical power and the operating temperature. The lifetime specification results from a defined decrease of the luminous flux bzw. LED failure rate in a given period (ex. 50.000h) at defined operating conditions. This period defines the lifetime of LED and is indicates as EOL (End of Lifetime. After this period the largest part of LED should be completely replaced.

What does it mean 50.000h?

Street lighting	10h / day	ca. 14 years
Shops lighting	10h / day	ca. 14 years
House application	6h / day	ca. 22 years

Definition

There is not a recognized definition of LED lifetime. In line with the ZVEI document “Planungssicherheit in der LED-Beleuchtung“ and the CELMA guiding paper “Apples & Pears a CELMA guiding paper”, we can define LED Lifetime as the period in which a LED light source provides an acceptable light level for a given application.



Two main parameter Lx and By are used to evaluate the amount of light that we will get after a specified lifetime (burning hours) and allow to define maintenance and replacement times.

Measuring of LED Lifetime

Lx Lumen Maintenance

It 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.

Quality levels: from L90, L80 to L70.

For example, the value L70 indicates the number of hours before light output of those LEDs, which have survived (not totally failed), drops down to 70% of the initial output. In common applications, such as general lighting in office environment, research has indeed shown that the majority of occupants in a space will accept light level reductions of up to 30% with little notice, particularly if the reduction is gradual. Therefore, a level of 70% of initial light output could be considered an appropriate threshold.

For LEDs used for decorative purposes, a value of 50% (L50) can be accepted. For some applications, a level higher than 70% may be required.

(Source: Alliance for Solid State Illumination Systems and Technologies (ASSIST))

By Failure rate (LED)

The parameter “By” denotes the LEDs rate which not reach the admissible lumen output (x) for a given lifetime. It is expressed in percentage (%). “B50” for example, indicates that the 50 % of the LEDs is expected to fail for given bounder conditions.

Together with the parameter Lx, By is used to define the LEDs expected 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; L70B50 is hence referred to the average of tested LEDs.

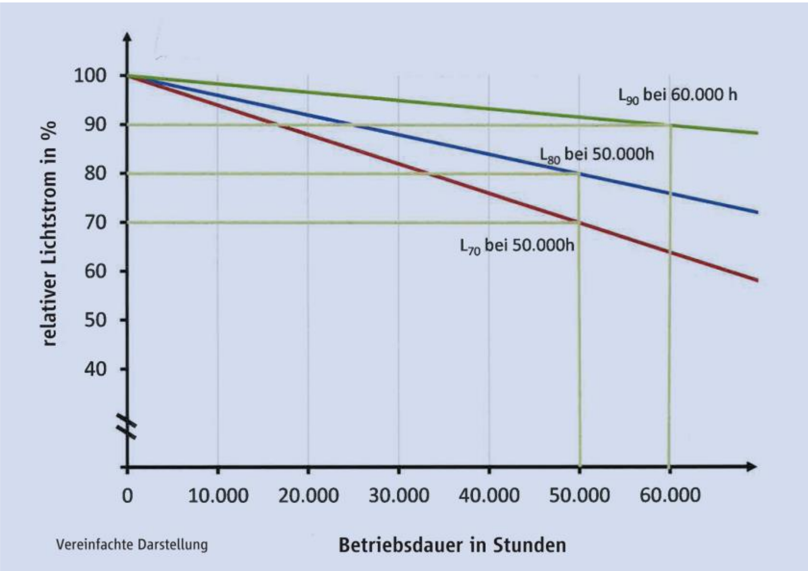


Figure 7: Variation of LED lumen output in relation to the burning hours
Source: ZVEI - Zentralverband Elektrotechnikund Elektronikindustrie

Cz Total failure rate

The parameter “Cz” (expressed in percentage) denotes the amount of LEDs with a total failure at the end of the given lifetime. The total failure rate is mainly considered to evaluate a LED module expected lifetime.

Measuring of LED Modules Lifetime

Luminaire lifetime refers to the lumen maintenance projections of the LED light sources integrated into that luminaire, the number of hours that a LED luminaire will deliver a sufficient amount of light in a given application. LED luminaire life according to the IEC/PAS 62722 should always be published as a combination of life at lumen maintenance (Lx) and failure fraction (Fy).

Fy "Failure fraction" (LED Module) corresponds to the rated life[3] of the LED module in the luminaire. The percentage (y) of a number LED modules of the same type at their rated life designates the percentage (fraction) of failure. This failure fraction expresses the combined effect of all components of a module including mechanical, as far as the light output is concerned. The effect of the LED could either be less light than claimed or no light at all. The notation **"LxFy"** is used to indicate the lifetime of the lighting system.

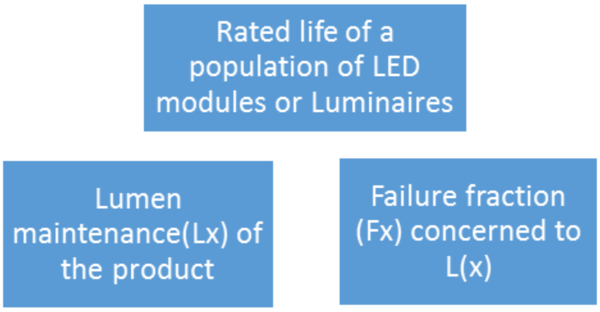


Figure 8: LED luminaire life according to IEC/PAS 62722

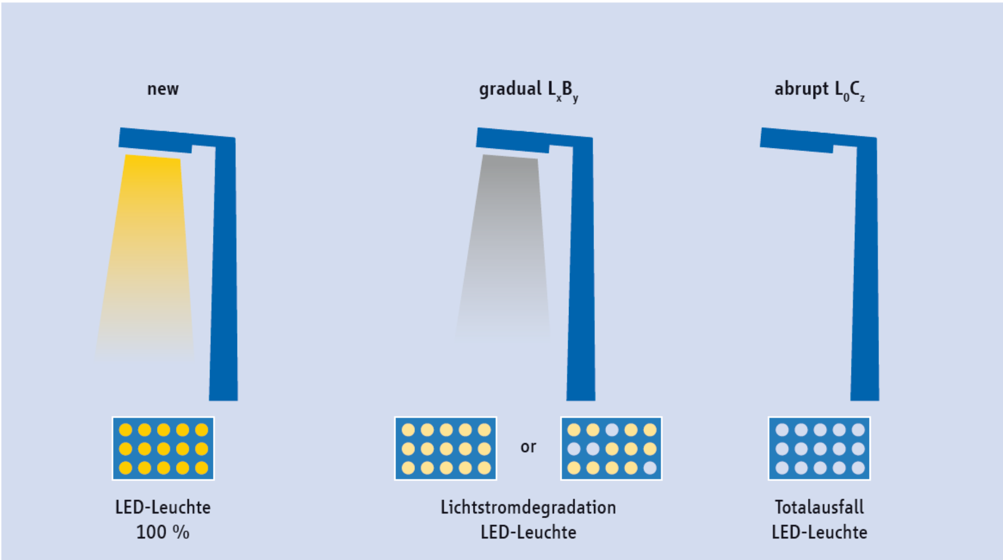


Figure 9: LED Module lifetime
Source: ZVEI Planungssicherheit in der LED-Beleuchtung

[3] Rated life of LED module and the associated rated lumen maintenance Lx (of the whole system) is defined by CELMA as the length of time during which a population of LED modules provides more than the claimed percentage of the initial luminous flux always published in combination with the failure fraction. It is expressed in hours.

Currently many LED luminaire manufacturers use test results typically provided by LM-80 as the L90, L70 and L50 lumen maintenance thresholds of LED luminaires. But there is a disconnection between the LM-80 test results usually made by the LED manufacturer and the results on a LED luminaire where for example the thermal management can change the actual performance.

Main constraints in translating LED test results into LED luminaire performance are:

- The catastrophic failures of individual LEDs and other failure modes participate to the light output depreciation of a population of LEDs in a LED-luminaire are not taken into consideration;
- There is no validated way to translate the lumen maintenance curve of an individual LED-light source into a curve for the LED-luminaire.

Note:

The LED lifetime doesn´t indicate the lifetime of the luminaire/LED module, which depends on more components (controls, mechanical housing, electrical connections ecc.).

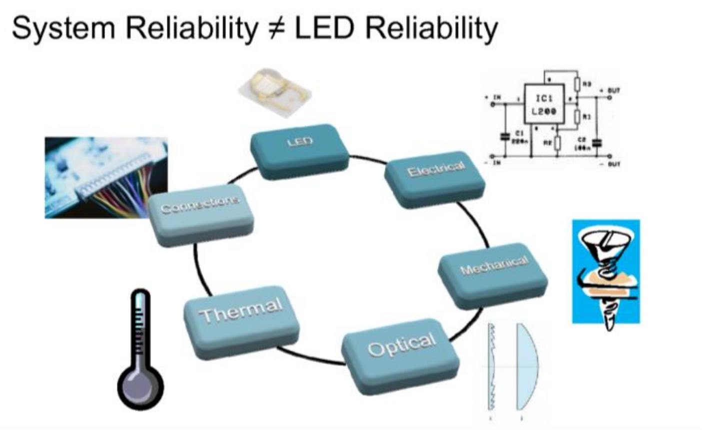


Figure 10: Luminaire life is about system reliability

Recommendations

In the evaluation of the LED lifetime Bartenbach advices to specify a “L- value” in relation to a “B value” of 50%. The single-LED failure is not contained in the lifetime calculation; it should be eventually taken into account in the maintenance factor.

Advice:

- The lifetime of the whole system (incl. electronic, optic system, etc.): should be minimum 50.000h.
- **Minimum quality values for used LED:**

  This value should be postulated for all LED typologies in order to ensure a minimum quality of reliability of the LEDs presented on the market. The value should be documented with diagrams and tables.

  L70 > 50.000h (in line with LM80-08 / TM21-11) *for given operating bounder conditions*

- **Requirements for recognized LED Typologies with higher expected lifetime:** For recognized LED typologies an L value higher than 70 could be requested. The value should be documented with diagrams and tables.
  L85 > 50.000h (in line with LM80-08 / TM21-11) *for given operating bounder conditions*

IES Standards – LED lifetime

LM-79-08

Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products – Illuminating Engineering Society of North America, 2008

LM-79 prescribes uniform test methods under controlled conditions for photometric and colorimetric performance as well as electrical power measurements for LED-luminaires manufactured for production. This can be used to measure the initial electrical and photometrical specifications of a LED-luminaire.

LM-80-08

It is the Illuminating Engineering Society of North America (IESNA) approved standard for measuring lumen maintenance of LED light sources. LM-80-08 apply to the LED package, array, or module alone, not a complete system, it is testing a component level. The standard does not provide guidance for extrapolation of testing results.

The testing report issued according to a standard format will provide luminous flux for a given current over a 6,000 hours period with interval measurements. Luminous flux will be measure for 3 different LED case temperatures: 55ºC, 85ºC and a third temperature to be selected by manufacturer. Besides, the lumen maintenance, the chromaticity shifts over the measured period.

TM-21-11

It is the Illuminating Engineering Society of North America (IESNA) approved method for taking LM-80 data and making useful LED lifetime projections. The standards apply to lifetime projection of LED package, array or module alone. The results can then be used to interpolate the lifetime of an LED source within a system (luminaire or integrated lamp) using the in-situ LED source case temperature.

In line with the TM-21-11:

- If total LM-80 data period is between 6,000 and 10,000 hours, we consider the last 5,000 hours
- If total data period is above 10,000 hours, we use the last half of collected data.
- In situ case temperature interpolation using Arrhenius equation between LM-80 temperature.
- Projections are limited to 6 times the available LM-80 data period so projected and reported lifetime may or not be the same.

Life notation results will then use the following standardized nomenclature: **Lp (Yk)**

- P: Lumen maintenance percentage. For LED luminaire we consider L70 to be the standard. After 30% lumen depreciation, we consider the system is not performing its duty anymore and should be replaced.
- Y: Length of LM-80 data period in thousands of hours. Example: L70 (6k) = 36 000 hours

References

- ZVEI - Zentralverband Elektrotechnikund Elektronikindustrie e. V. Fachverband Licht, Planungssicherheit in der LED-Beleuchtung, November 2013
- IES- Illuminating Engineering Society, Addendum A for LM-80-08 IES Approved Method: Measuring Lumen Maintenance of LED Light Sources
- IES- Illuminating Engineering Society, Measuring Lumen Maintenance of LED Light Sources standard by Illuminating Engineering Society, Sept. 2008
- U.S. Department of Energy, Lifetime of White LEDs, Sept.2009
- Alliance for Solid State Illumination Systems and Technologies (ASSIST)- LED lifetime, 2005
- CELMA: Apples & Pears a CELMA guiding paper: Why standardization of performance criteria for LED luminaires is important, Sept. 2011