SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Daylighting and lighting retrofit to reduce energy use in non-residential buildings: A literature review

T50.D2

A Technical Report of IEA SHC Task 50

A condensed version of this report was published in:
Dubois M-C, Bisegna F, Gentile N, Knoop M, Matusiak B, Osterhaus W, Tetri E (2015). Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: a literature review. Energy Res. J. 6, 25–41. doi:10.3844/erjsp.2015.25.41

March 2016

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 members 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 54 such projects have been initiated, 44 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- 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 – working agreement with solar thermal trade organizations
- Workshops and seminars

Country Members

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

Sponsor Members

European Copper Institute	Gulf Organization for Research and Development
ECREEE	RCREEE

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

Daylighting and lighting retrofit to reduce energy use in non-residential buildings: A literature review

A Technical Report of Subtask D (Case Studies), T50.D2

IEA SHC Task 50: Advanced Lighting Solutions for Retrofitting Buildings

February 2016

AUTHORS

Primary:
Marie-Claude Dubois (Lund University, Sweden)
Niko Gentile (Lund University, Sweden)

Additional (in alphabetical order):
Fabio Bisegna (Sapienza University of Rome, Italy)
Martine Knoop (Technische Universität Berlin, Germany)
Barbara Matusiak (NTNU, Norway)
Werner Osterhaus (Aarhus University, Denmark)
Sophie Stoffer (Aarhus University, Denmark)
Eino Tetri (Aalto University, Finland)

Distribution Classification: Unrestricted

This report was printed and is available at:

Fraunhofer-Institut für Bauphysik
Nobelstrasse 12
70569 Stuttgart
Germany

Price: [xx,-] EUR

AUTHORS (in alphabetical order)

Fabio Bisegna
Department of Astronautical Electrical and Energetic Engineering
Faculty of Engineering, SAPIENZA University of Rome
Via Eudossiana 18-00184
Rome, Italy
fabio.bisegna@uniroma1.it

Marie-Claude Dubois and Niko Gentile
Lund University
Division of Energy and Building Design
Box 118, 221 00
Lund, Sweden
marie-claude.dubois@ebd.lth.se
niko.gentile@ebd.lth.se

Martine Knoop
Technische Universität Berlin
Einsteinufer 19, 10587
Berlin, Germany
martine.knoop@tu-berlin.de

Barbara Matusiak
NTNU Norwegian University of Science and Technology, Faculty of Architecture
Alfred Getz vei 3, 7491
Trondheim, Norway
barbara.matusiak@ntnu.no

Werner Osterhaus
(with assistance of Sophie Stoffer)
Lighting Design Research Laboratory
Department of Engineering
Aarhus University
Inge Lehmanns Gade 10
8000 Aarhus C, Denmark
Werner.Osterhaus@eng.au.dk

Eino Tetri
Aalto University
PO Box 13340
00076 Aalto, Finland
eino.tetri@aalto.fi

KEYWORDS

Lighting retrofit, energy-efficiency, luminaires, lamps, lighting controls, daylighting systems, occupant behavior.

ACKNOWLEDGEMENTS

The authors thank Jan de Boer and Anna Hoier from the Fraunhofer Institute for Building Physics (Stuttgart) for reviewing the last version of this report and providing fruitful comments and discussion.

The authors also thank their respective funding agencies for supporting their work as part of IEA Task 50:

- Denmark: Danish Energy Agency (Energistyrelsen), Danish Ministry of Climate, Energy and Building (Klima-, Energi- og Bygningsministeriet), Energy Technology Development and Demonstration Program (energiudviklings- og demonstrationsprogram - EUDP), contract number 64012-0150;
- Finland: Finnish RYM Indoor Environment Program, (*http://www.rym.fi/en/programs/indoorenvironmentprogram/);*
- Germany: Bundesministerium für Wirtschaft und Technologie;
- Norway: The Research Council of Norway;
- Sweden: Swedish Energy Agency (Statens energimyndighet).

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

ABSTRACT

This report presents a literature review about energy-efficient retrofit of electric lighting and daylighting systems in buildings. The review, which covers around 160 research articles, discusses the following energy retrofit strategies: replacement of lamp, ballast or luminaire; use of task-ambient lighting design; improvement in maintenance; reduction of maintained illuminance levels; improvement in spectral quality of light sources; improvement in occupant behavior; use of control systems; and use of daylighting systems. The review indicates that existing general knowledge about lighting retrofit is currently very limited and that there is a significant lack of information concerning the actual energy performance of lighting systems installed in the existing building stock. The resulting key directions for future research highlights issues for which a better understanding is required for the spread and development of lighting retrofit.

EXECUTIVE SUMMARY

Electric lighting is one of the major sources of electricity consumption in buildings with a high saving potential. The production of electric light consumes approximately one fifth of the global electric energy consumption and generates a large amount of CO2. Projections by the International Energy Agency show that if governments only rely on current policies, global electricity use for lighting will grow to about 4250 kWh by 2030, an alarming increase of more than 40%. Higher costs of electricity compared to most other energy sources justifies ranking lighting retrofit measures high on the list of options. Recent studies point out that investment in energy-efficient lighting is one of the most cost-effective ways to reduce CO2 emissions. Many studies demonstrate that energy retrofit of lighting equipment have a typical pay-back period of less than two years. However, some authors warn about the so-called rebound effect, which means that with the reduced system power in lighting – and fixed energy prices – the tendency is to use more light because it is cheaper and by that absolute consumption is ultimately increased.

Most energy is consumed in existing buildings while the replacement rate of existing buildings by new built is less than 3% per year and current renovation and refurbishment rates are not significantly higher. Linking retrofit with energy-efficiency in lighting, the IEA-Task 50 ‘Advanced Lighting Solutions for Retrofitting Buildings’ pursues the goal to accelerate retrofitting of daylighting and electric lighting systems in the non-residential sector using cost-effective, best practice approaches.

The aim of the present report, which is under the activities of Subtask D (Case studies), is to analyze the existing information found in the scientific literature, previous European and international research projects, websites of national projects etc. in order to:

- Identify the already existing databases of case studies;
- Identify previous scientific studies or projects about lighting or daylighting retrofit;
- Update key information regarding energy saving strategies and solutions demonstrated in the past by research, monitoring or demonstration projects;
- Summarize the energy saving potential according to measure or strategy.

This review, which covers around 160 research articles, is based on information found in peer-reviewed scientific journal articles, conference articles, reports, relevant past IEA projects, relevant past European projects, relevant national projects (published 1993-2013, 20 years).

The main conclusions of this review are that electric lighting is one of the major sources of electricity consumption in buildings representing 15-60% of the final energy use. It has a high saving potential at a reasonable pay-back period, especially due to the development of new lighting technologies with lower cost and higher luminous efficacies. Reported energy savings through lighting retrofit vary widely depending on initial energy use, building type, usage, etc. Energy savings measures should be considered in a holistic way since electric lighting reductions normally entail an increase in heating demand. Improvements in lighting should thus be planned along with building envelope improvements to compensate for the consequent increase in heating loads.

Replacement of lamp, ballast and luminaire is the most common lighting retrofit strategy, with a great saving potential. The most common existing lighting installations consist of fluorescent lighting (with conventional ballasts) and most commonly retrofitted fixtures are the 4-lamp T12 and parabolic and lenses troffers with T12 or older T8 lamps (data from the USA). Compared to fluorescent lighting, LED lamps have reduced energy consumption

(approximately 50%) and a longer life time. Although good products are available, this review outlines that lighting quality aspects such as unsatisfactory color rendering, low light load, flicker and poor light distribution have been reported and need to be considered seriously to ensure user satisfaction.

Reducing maintained illuminance levels is another promising strategy since previous research indicated lower preferred illuminance levels compared to those recommended by the standards particularly in areas where computers are used. There are indications of a tendency to reduce the number of lamps (by ‘delamping’) partly due to the education around proper light levels and the fact that many facilities are currently overlit.

The review outlines that although improvements in user behaviour and use of task-ambient lighting design have both proven to provide significant potential energy savings, studies focusing on these retrofit strategies are scarce.

In contrast, a large number of studies addressed the topic of lighting control. The use of electric lighting control systems can significantly reduce the consumption of electric lighting but the saving potential varies greatly according to context and building, which leads to difficulties in estimating the payback time of a lighting retrofit. Simulations generally overestimate the savings compared to field studies; especially when the control system involves advanced automation and/or technology, such as daylight harvesting technologies. Manual control systems, such as door switches, manual task lamps and manual dimmers, can offer unexpectedly high energy savings with increased occupant satisfaction and productivity. Occupancy based lighting control systems are also very promising with high expected savings (20-93%). However, using a presence (on/off) control system could yield higher energy use for lighting than a simple manual switch at the door combined with absence detection (switch off), especially in individual or small offices. Daylight-linked control systems can result in significant lighting savings, but several studies reported difficulties in real installations and in estimating the payback period at the design stage.

Building facades, by their glass area ratio, shading or daylighting systems, can greatly affect electricity use for lighting provided that electric lights are switched off in presence of sufficient daylight. However, payback times for daylighting systems are typically extensive while passive daylighting or shading systems have a poorer performance, but are typically cheap, simple and require less maintenance, leading to better payback times.

This review discussed several strategies for reducing electricity use in lighting and/or daylighting retrofit projects. The review was limited to the topic of energy efficiency but the reader should be reminded that retrofitting a lighting installation offers several advantages besides energy savings: improvement in lighting quality, occupant satisfaction and productivity, improved corporate image, energy security, etc. The review generally shows that studies of lighting retrofit in real context with monitored data are extremely rare and most of the existing studies target either lamp-ballast-luminaire replacement or implementation of advanced control systems. Monitoring studies, where simple and robust retrofit strategies such as task-ambient lighting design, improved occupant behavior, improvement in the spectral quality of light sources, or even a simple reduction of maintained illuminance levels, have not been reported extensively in the literature despite their great energy saving potential. This review suggests that research efforts addressing these specific strategies should be emphasized in the future taking into consideration the context of retrofitting buildings.

TABLE OF CONTENTS

ABBREVIATIONS

CFL	Compact fluorescent lamps
DHW	Domestic hot water
DLQ	Designers’ lighting quality
EC	Electrochromic
ECBCS	Energy Conservation in Buildings and Community Systems
ECM	Energy conservation measure
EPBD	Energy performance of buildings directive
ERM	Energy retrofit measures
HEP	High efficiency plasma
HF	High frequency (ballasts)
HID-MH	High intensity discharge, metal halide
HPS	High pressure sodium
HVAC	Heating, ventilation, air conditioning
IEA	International Energy Agency
IES	Illuminating Engineering Society
IES-VE	Integrated environmental solutions – virtual environment
LCC	Life-cycle cost
LED	Light emitting diode
LPD	Lighting power density
MH	Metal halide
SHC	Solar Heating and Cooling
SPBP	Simple payback period
SSL	Solid state lighting
UNEP	United Nations Environment Programme

FIGURES

TABLES

1. Introduction

1.1. Increasing energy use in non-residential buildings

The building sector consumes 20-40% of the final energy used in most countries (Janda, 2009; US DOE, 2005 via, Itani, Ghaddar, & Ghali, 2013; Perez-Lombard, Ortiz, & Pout, 2013), and a very significant share of global electricity (Janda, 2009), in addition to using 40% of the materials entering the global economy and generating 40–50% of the total output of greenhouse gases (Prasad & Hill, 2004 via, Ardente et al., 2011). In Europe, for instance, commercial and residential buildings account for 38.7% of total energy consumption (Europe's Energy Position, 2009 via, Boyano, Hernandez & Wolf, 2013). It is estimated that around 26% of the European final energy is used by residential buildings and 13% by non-residential buildings (EU Energy and Transport, 2009 via Boyano, Hernandez & Wolf, 2013). In the United States, the commercial (non-residential) building sector consumes over one-third of the nation's primary energy (Krarti, 2000; Krarti, Erickson & Hillman, 2005).

In addition, the tertiary sector (non-residential buildings and agriculture) is among the fastest growing energy demand sectors and is projected to be 26% higher in 2030 than it was in 2005, compared to only 12% higher for residential buildings (Capros et al., 2008 via, Boyano, Hernandez & Wolf, 2013). It is also expected that energy consumption in the service sector in non-developed countries will double in the next 25 years due to an average growth rate of 2,8% (Perez-Lombard, Ortiz & Pout, 2013). For the past decades, building energy use in China for instance has increased at more than 10% each year, going from 20.7% of national energy consumption in 2004 to 33% by 2010 (Xu, Chan & Qian, 2011). According to THUBERC (2007, via Xu, Chan & Qian, 2011), building energy use in large-scale public buildings and commercial buildings such as offices, hotels, retails, hospitals, and schools, is up to 70-300 kWh/m^{2}yr, which corresponds to 5-15 times that of urban residential buildings. The US Energy Information (WBCSD (2007) compiled the energy use in buildings for China, India, Brazil, US, Europe and Japan and showed that although the residential sector is dominant, the commercial (also called non-residential) sector is substantial and likely to grow more rapidly in coming decades, see Figure 1.

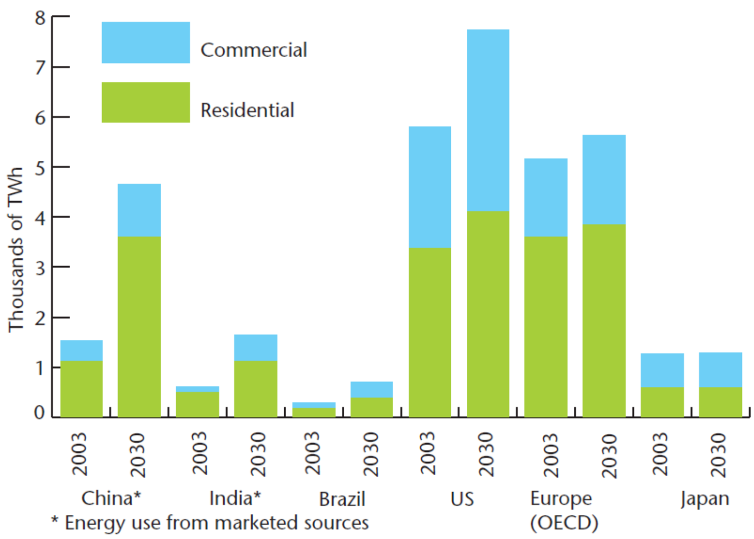

Figure 1 Building energy projection by region 2003-2030, according to WBCSD, 2007.

1.2. Increasing electricity use in non-residential buildings

Electrical energy consumption in non-residential buildings has also exhibited a constant rise over the last years due to the extensive use of HVAC and office equipment (especially electronic devices and computers) and is expected to increase from 42% in 2005 to almost 50% of the total energy consumption by 2030 (Spyroupoulos & Balaras, 2011, via Boyano, Hernandez & Wolf, 2013). According to Janda (2009), electricity use in commercial buildings is driving peak demand in the USA, Japan, and in some of the wealthiest developing countries in the global south. As countries in the global south raise their standards of living and develop their service sector, the electricity use of buildings is expected to continue to increase, and this, especially in the non-residential sector (Janda, 2009).

According to Perez-Lombard, Ortiz & Pout (2013), the rapidly growing world energy use is raising concerns over supply difficulties, exhaustion of energy resources and serious environmental impacts (ozone layer depletion, global warming, climate change, etc.). The International Energy Agency has gathered frightening data on energy use trends: during the last two decades (1984–2004) primary energy has grown by 49% and CO2 emissions by 43%, with an average annual increase of 2% and 1.8% respectively, see Figure 2 (Perez-Lombard, Ortiz & Pout, 2013). According to the same authors, recent predictions have also indicated that this trend will continue.

Population growth, increasing demand for building services and high comfort levels, together with the rise of time spent in buildings, sustain the upward trend in energy demand. Moreover, with a projected 70% of the global population living in urban areas by 2050 (Eames et al., 2013), the United Nations Environment Programme (UNEP) has pointed out the need to promote a low carbon, resource efficient and socially inclusive ‘green’ economy (UNEP, 2011, via Motta Cabrera & Zareipour, 2013). Current energy systems and socio-economic systems are clearly unsustainable, according to UNEP (2011 via Motta Cabrera & Zareipour, 2013) and therefore, highly energy-efficient buildings, which reduce both emissions and waste are of significant interest. Energy efficiency in buildings is today one of the prime objectives for energy policy at regional, national and international levels as outlined by Perez-Lombard, Ortiz & Pout (2013). Buildings have a very long life cycle so their effect on the environment is a long and continuing issue to consider, which further justifies that urgent actions are taken to reduce their energy use (WBCSD, 2007).

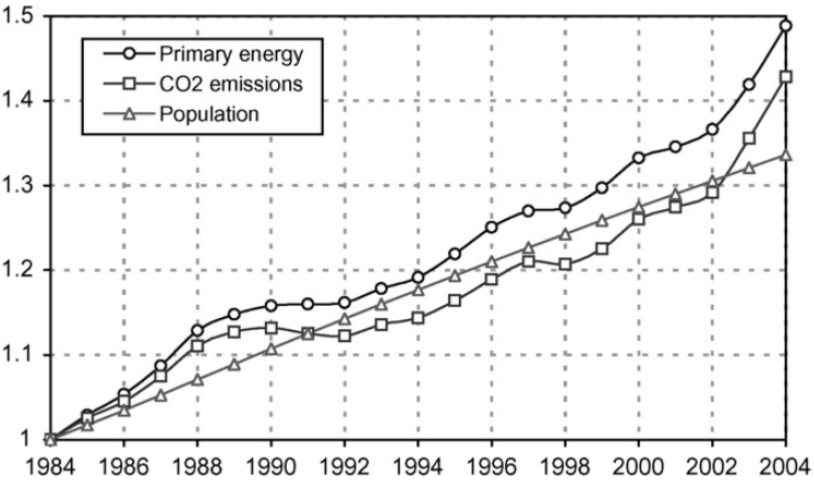

Figure 2 Primary energy consumption, CO2 emissions and world population, International Energy Agency (IEA) via Perez-Lombard, Ortiz & Pout (2013).

1.3. Electricity use in the lighting sector

More than four-fifths of site energy use typically occurs in the operational phase of a building's life (WBCSD, 2007). Among the great energy end-uses, lighting is identified as one of the major sources of energy consumption corresponding to 15-60% of the final energy use in buildings according to Spyropoulos & Balaras (2011), a wide variation, which depends on many factors such as building type, function, technology used, climate, etc. But electric lighting also presents a high energy saving potential, which has recently been highlighted in numerous side events that took place during the United Nation Climate Change Conference (UN Climate Change Conference, 2012, via Boyano, Hernandez & Wolf, 2013).

Previous research suggests that the potential for savings in electric lighting depends significantly on the initial energy demand for lighting and on the building type. Higher initial lighting load and more compact building shapes generally present higher saving potential since these cases generally have higher electric lighting demand compared to other installations and building types (Dascalaki & Santamouris, 2002). Note that daylight provisions are also less likely to be sufficient in such buildings.

The production of electric light consumed (in 2005) roughly 6.5 percent of total global primary energy and 0.72 percent of world gross domestic product according to Tsao & Waide (2010). It was also responsible for approximately 19% (i.e. 2900 TWh) of the global electric energy consumption, which generated 1900 million tons of CO2 emissions (IEA, 2006). In the United States, lighting was one of the three dominant end uses in 2010 together with space heating, space cooling, and accounting for close to half of all energy consumed in the building sector (US Department of Energy, 2013). In post-secondary education, for example, a significant portion of the energy consumption is for lighting (Motta Cabrera & Zareipour, 2013). In office buildings, previous studies have also demonstrated the importance of lighting in relation to the total energy consumption, see Figure 3 (from Boyano, Hernandez & Wolf, 2013). Kofoworola & Gheewala (2009, via Itani, Ghaddar & Ghali, 2013) reported that electricity used for lighting and HVAC systems were the most significant posts in the buildings' life cycle energy use in the operation phase of a manufacture of concrete and steel in Thailand. These findings were also confirmed by results obtained by other researchers (Chirarattananon et al, 2010, and Saidur, 2010, via Itani, Ghaddar & Ghali, 2013). Crawley et al. (2013) reported that 30–50% of the electricity consumption is used to provide lighting in typical office buildings. In contrast to these data for the rich countries, it is worth noting that more than one quarter of the world's population living in the developing countries, does not have access to electric light, and are largely dependent on kerosene lamps for their lighting, a highly polluting method to produce light (Mills, 2005; Zahnd, Eloholma & Halonen, 2007).

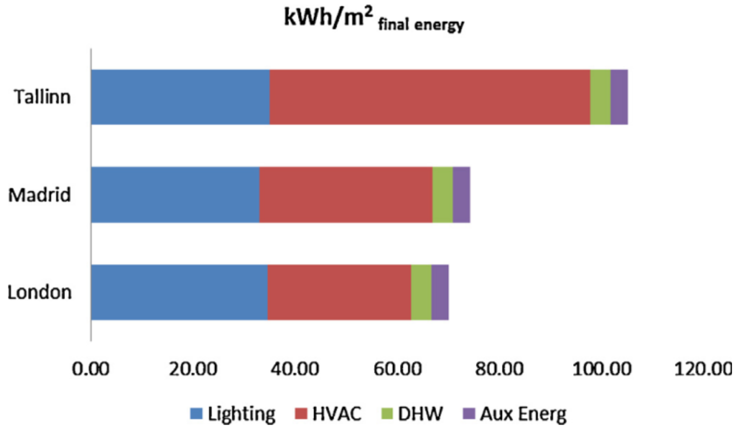

Figure 3 Breakdown of the average energy consumption of different end-uses in a typical European office building depending on locations (results by simulation), according to Boyano, Hernandez & Wolf, 2013.

Projections by the IEA (2006) show that if governments only rely on current policies, global electricity use for lighting will grow to around 4250 TWh by 2030, an alarming increase of more than 40%. Due to the world's growing population and the increasing demand for electrically driven services in emerging economies, this increase will occur despite constant improvements in energy efficiency of lighting systems. Indeed, it has been demonstrated (Tsao & Waide, 2010) that there is a massive potential for growth in the consumption of light if new lighting technologies are developed with higher luminous efficacies and lower cost of light.

Many authors have warned about this so-called rebound effect. Porritt et al. (2013), for instance, claimed that the direct rebound effect means that with the reduced system power in lighting – and fixed energy prices – the tendency is to use more light because it is cheaper and by that ultimately consumption is increased. Increase in efficiency will thus not necessarily produce an absolute reduction of energy use, as observed by Jevons in 1865. The Jevons Paradox, which was first expressed in relation to use of coal, states that an increase in efficiency in using a resource leads to increased use of that resource rather than to a reduction (Polimeni et al., 2007). Also economic productivity is stimulated by broader adoption of 'general purpose technologies', like lighting, triggered through increased affordability due to less costs. Increase of human productivity and quality of life often leads to increased consumption of light.

Tsao & Waide (2010) linked the demand to factors like (i) average illumination a person chooses for its direct surroundings, (ii) the number of hours lighting is being used and (iii) the amount of lighting spent to unshared areas. From empirical data of the last three centuries, a linear relation with increasing GDP is deduced, which gives at least indications about the potential proportion of the counter-effect of the 'rebound': the world has always spent ~0.72% of its GDP on light according to Tsao & Waide (2010). Also with newest LED technologies, this is expected to continue; though massive reductions in energy consumption per LED lamp are accomplished, new features and applications enabled e.g. by the small form factor and reduced heat generation will even stimulate further demands. In a IEA report (2005), the rebound effect for lighting efficiency measures is estimated to 5-12% in the residential and 0-2% in the commercial sector. The authors criticize that in energy-efficiency policies, most analyses and forecasts use linear relations between increase in efficiency and reduction in energy consumption. The evidence for rebound effects at societal and individual level means that the effect of energy efficiency measures is grossly overestimated and overstated in many policies. New policies are suggested to limit the overall consumption in lighting rather than encouraging the use of a specific technology. For deep energy reduction, making maximal use of the potential of SSL and advanced lighting controls enforcement by higher electricity prices or even rationing of energy is to be considered. Light-as-a-Service models that could keep control on agreed service levels, and by that keeping rebound effect under control are also discussed as the Light-as-a-Service model puts more responsibility and incentive to the providers of such service. The authors suggest additional research, because potential rebound effects in such business models have not been studied so far. Note that Saunders & Tsao (2012) argued that even though the rebound effect is an established fact, the increase in efficiency should be pursued because it will at least lead to economic benefits.

In summary, there is a high saving potential with new lighting technologies. High quality lighting can be achieved in energy-efficient and more sustainable ways with appropriate retrofits. However, awareness of possible rebound effects is important; therefore, actions to raise awareness, measures targeting absolute energy savings and understanding of the potential to improve lighting quality in existing buildings are all urgently needed. This report focuses on the available energy saving strategies in lighting or daylighting (façade and roofs) retrofit and their potential as described in the scientific literature.

1.4. Energy saving potential in the lighting sector

Research and developments in the field of energy efficient lighting techniques can contribute significantly to reduce worldwide electricity consumption and C02 emissions. Recent studies (Enkvist, Nauclér & Rosander, 2007; Motta Cabrera & Zareipour, 2013) have pointed out that investments in energy - efficient lighting is one of the most cost-effective ways for improving energy efficiency in buildings and reduce CO2 emissions. Higher costs of electricity in comparison to most other energy sources (e.g. natural gas) further justifies ranking lighting retrofit measures high on the list of options as pointed out by Boyano, Hernandez & Wolf (2013). One report (America's Energy Future Panel on Energy Efficiency Technologies, 2010 via Motta Cabrera & Zareipour, 2013) even states, for example, that the cost of saving 1 kWh lighting energy through efficiency is less than 20% of the average price of 1 kWh electricity in the United States.

Lighting has been pointed out as one of the areas with significant improvement potential (Boyano, Hernandez & Wolf, 2013). According to Krarti (2000), and Krarti, Erickson & Hillman (2005), energy retrofits of lighting equipment are very cost-effective with typical payback periods of less than two years in most cases. In a recent article, Dubois & Blomsterberg (2011) presented key energy use figures and investigated the energy saving potential for electric lighting in office buildings based on a literature review, with special emphasis on a North European context. This review outlined that theoretical calculations, measurements in full-scale rooms and simulations with validated lighting programs indicate that an energy intensity of around 10kWh/m^2 yr. is a realistic target for electric lighting in future low energy office buildings. According to these authors, this target would yield a significant reduction in energy intensity of at least 50% compared to the actual average electricity use for office lighting (21kWh/m^2 yr. in Sweden).

1.5. Importance of retrofitting the existing building stock

In recent years, the need to 'retrofit' existing buildings and the built environment in response to the long term challenges of climate change and resource constraints has gained increasing importance (Dawson, 2007, Kelly, 2009, and Sustainable Development Commission, 2010 via Eames et al., 2013). According to Dixon & Eames (2013), the term 'retrofit' originated in the United States in the late 1940s and early 1950s, as a blend of the words, 'retroactive' (applying or referring to the past) and 'fit' (to equip).

In Europe, energy-efficient buildings, mostly built after 1980, represent about 20 % of the building stock but only 5 % of the energy consumption, as outlined by Erhorn-Kluttig, Erhorn, & Wössner, 2004). Thus, in order to meet the objectives of the Energy Performance of Buildings Directive (EPBD, in Europe) and other stringent directives, codes and compliances in the USA and in the rest of the world, it is crucial to concentrate on improving the energy-unefficient building stock. According to Zhenjun et al. (2012), retrofitting should be considered as one of main approaches to achieving sustainability in the built environment at relatively low cost and high uptake rates. These authors point out that most energy is consumed by existing buildings while the replacement rate of existing buildings by the new-build is only around 1.0–3.0% per annum (also suggested in Eames et al., 2013; Itani, Ghaddar & Ghali, 2013) and it is 2.2% per year only for the commercial building sector (Zhenjun et al., 2012). Current renovation and refurbishment rates are somewhat higher (between 2.9% and 5% in the UK of existing stock for domestic buildings and 2–8% for commercial stock, depending on the sector (Stafford et al., 2011). In the UK, for instance, some 70% of total 2010 building stock is expected still to be in use in 2050 (Better Buildings Partnership, 2010 via Eames et al., 2013). Therefore, rapid improvement of energy efficiency in existing buildings is needed for a timely reduction in global energy use and promotion of environmental sustainability, as suggested by Zhenjun et al. (2012).

Table 1 SWOT analysis of the lighting retrofit situation.

Strengths	▪ High demonstrated energy savings of new lighting technologies and control systems ▪ Demonstrated short payback times ▪ Minimal disruption of lighting retrofit compared to many other retrofit measures
Weaknesses	▪ Lack of knowledge and hands-on experience about many retrofit strategies in a retrofit context (e.g. reduced illuminance, task-ambient lighting design, improvement of spectral quality of light source, improved occupant behavior etc.) ▪ Uncertainty of predicted energy savings and lack of reliability of some control systems(i.e. occupancy and photoelectric dimming)
Opportunities	▪ Retrofit of the existing building stock for timely reduction of energy use and promotion of environmental sustainability ▪ General need to improve and modernize indoor environmental quality including lighting quality ▪ Obsolescence of existing lighting installations in developed countries
Threats	▪ Potential increase of lighting energy use by 40% in 2030 ▪ Rebound effect

Paradoxically, a survey of the references in the scientific literature indicates a substantial lack of studies specifically focused on building retrofit and refurbishment actions, according to Ardente et al. (2011). In addition, Lowe & Oreszczyn (2008, via Menezes et al., 2012) pointed out that there is a significant lack of information concerning the actual energy performance of the existing building stock.

Dixon & Eames (2013) outlined the different challenges in retrofitting different building stocks in different regions of the world. In the global south, for instance, the pressing need is to retrofit the vast informal developments in response to the challenges of poverty and housing, economic development, climate change, and energy insecurities. On the other hand, in countries with a long history of urbanization like in Europe and the USA, the challenge is often to deal with an ageing building stock and urban infrastructure (Dixon & Eames, 2013). In the USA, it has been estimated that large-scale retrofitting could yield US$1 trillion of energy savings and create 3.3 million new job years (DB Climate Change Advisors, 2012, via Dixon & Eames, 2013). Besides, retrofitting a building offers great opportunities besides improved energy efficiency: increased staff productivity, reduced maintenance costs and better comfort, improvement of a nation's energy security, corporate social responsibility, and reduction of exposure to energy price volatility, creation of job opportunities and more liveable buildings.

During the last decade, many governments and international organizations (e.g. IEA) have put significant efforts towards energy efficiency improvement in existing buildings (Zhenjun et al., 2012). For instance, the International Energy Agency (IEA) launched a series of Annex projects (Annex 46, 50, 55, 56) to promote energy efficiency of existing buildings. In the field of lighting, the IEA launched Annex 45 titled 'Energy efficient electric lighting for buildings' under the umbrella of the Energy Conservation in Buildings and Community Systems (ECBCS) programme.

Table 1 summarizes some of the key ideas presented in the introduction as outlined by this literature review.

1.6. Objectives of this literature review

This report presents a literature review carried out as part of the activities of Subtask D of IEA Task 50. Subtask D concerns Case Studies as a means to provide and disseminate valuable inspiration, insight and experience from energy renovation projects carried out in different countries and under different constraints. This report is the second of six activities of Subtask D:

D.1 Building stock analysis
D.2 State-of-the-art (literature review)
D.3 Assessment and monitoring protocol
D.4 Case study assessment
D.5 Overall conclusions, lessons learned
D.6 Case study book / e-documentation

This literature review under activity D.2 pursued the aim to analyze and summarize existing information found in the scientific literature, previous European and international research projects, websites of national projects, etc. The specific objectives of this literature review are listed below:

- Identify existing databases of case studies;
- Identify previous research about lighting and/or daylighting retrofit;

- Update key information regarding energy saving strategies and solutions demonstrated in the past by research, monitoring or demonstration projects;
- Summarize the energy saving potential according to measure or strategy.

2. Method

This literature review is based on an analysis of the following types of documents (published 1993-2013, 20 years):

- Scientific journal articles;
- Conference articles;
- Reports;
- Relevant past IEA projects;
- Relevant past European projects;
- Relevant national projects.

The articles were identified by first performing a search in several databases (Science Direct, Compendex, Inspec, etc.) with the following keywords: lighting retrofit, energy-efficient lighting, relamping, luminaires, lamps, lighting control, light sensors, dimming, daylight retrofit, daylighting systems, etc. Subsequently, the bibliography of each article was scrutinized to find other relevant sources. The authors also asked all experts of IEA Task 50 for articles related to retrofitting and lighting. The main journals consulted were:

- Applied Energy
- Energy and Buildings
- Energy Engineering
- Solar Energy
- Building and Environment
- Energy Policy
- Renewable Energy
- Renewable and Sustainable Energy Reviews
- Lighting Research and Technology (UK)
- Leukos, the Journal of the Illuminating Engineering Society (USA)
- Journal of Light & Visual Environment (JLVE) (Japan)

Finally, the main author registered for automatic email alerts in various fields in order to get updates on new relevant articles. This thorough process allowed finding more than 350 publications of which about half were judged directly or indirectly relevant and further classified after reading the abstract. This article thus summarizes information found in some 160 research articles on lighting and/or daylighting retrofit.

3. Results

3.1. Whole building retrofits to reduce energy use

A large amount of research has been previously carried out to develop and analyse different energy efficiency measures with the aim to improve energy performance of existing buildings (Zhenjun et al., 2012). Zhenjun et al. (2012) have schematically illustrated the main categories of building retrofit technologies, see Figure 4.

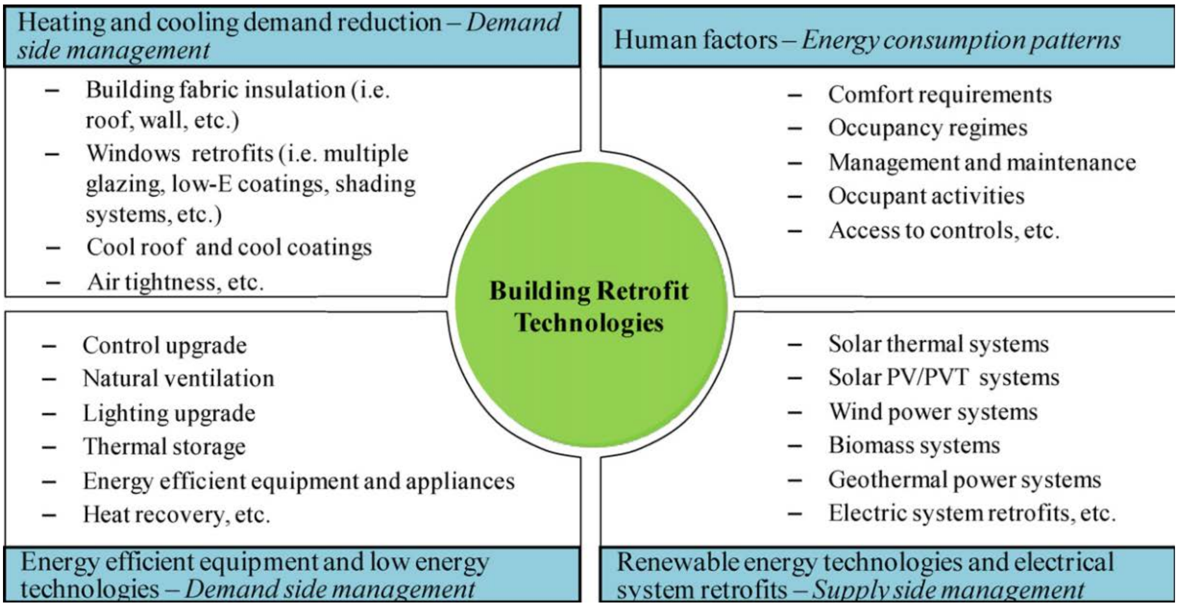

Figure 4 Main categories of building retrofit technologies.

The results of previous research have generally indicated that energy use in existing buildings can be reduced significantly through proper retrofitting or refurbishment (Zhenjun et al., 2012). As pointed out by Ernst & Young (2010) and Sweatman & Managan (2010), retrofitting a building offers great opportunities besides improved energy efficiency: increased staff productivity, reduced maintenance costs and better (...) comfort, improvement of a nation's energy security, corporate social responsibility, reduction of exposure to energy price volatility, creation of job opportunities and more liveable buildings. However, Zhenjun et al. (2012) claimed that most previous studies have been based on numerical simulations; the actual energy savings due to the implementation of the selected retrofit measures have rarely been reported. These authors emphasized that more research and application work with practical case studies on commercial office building retrofits is essentially needed, which could help to increase the level of confidence of building owners to retrofit their buildings for better performance.

Zhenjun et al. (2012) also provided a systematic approach to proper selection and identification of the best retrofit options for existing buildings besides presenting a detailed and comprehensive literature review about building retrofitting. They proposed that the overall process of a building retrofit can be divided into five major phases, as illustrated in Figure 5.

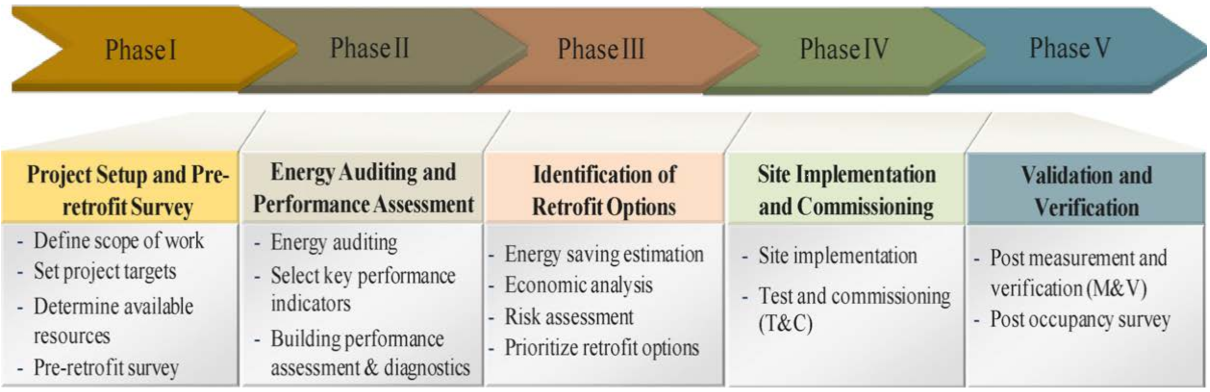

Figure 5 Key phases in a sustainable building retrofit programme.

They also claimed that the success of a building retrofit programme depends on many key elements, such as policies and regulations, client resources and expectations, retrofit technologies, building specific information, human factors and other uncertainty factors, see Figure 6. They finally proposed their systematic approach to identifying, determining and implementing the best retrofit measures for existing buildings (see original article).

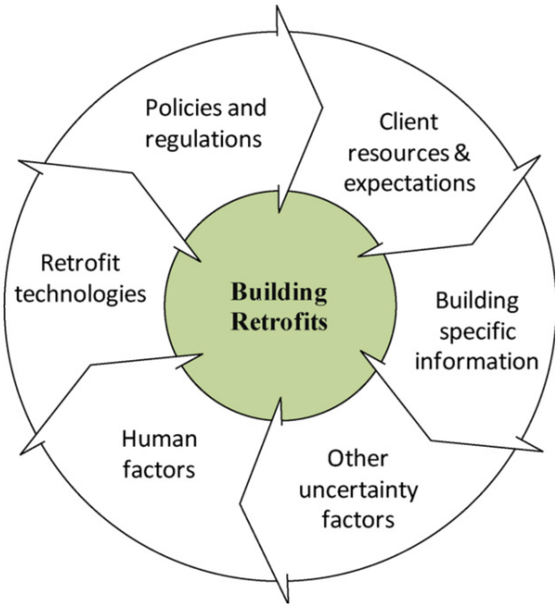

Figure 6 Key elements influencing building retrofits.

The IEA-ECBCS programme has launched a series of research projects to promote energy efficiency of existing buildings:

- Annex 36 – Retrofitting of educational buildings (REDUCE);
- Annex 46 – Holistic assessment toolkit on energy efficient retrofit measures for government buildings;
- Annex 50 – Prefabricated systems for low energy renovation of residential buildings;
- Annex 55 – Reliability of energy efficient building retrofitting;
- Annex 56 – Energy and greenhouse gas optimised building renovation.

IEA- ECBCS Annex 36 – Retrofitting of educational buildings (REDUCE)
One previous IEA project (Erhorn-Kluttig, Erhorn & Wössner, 2004) called 'Annex 36 – Retrofitting of educational buildings (REDUCE)' focused on energy-optimised retrofit measures for existing educational buildings (see www.annex36.com). This project, which

involved researchers from ten participating countries from Europe and the US, compared and analysed more than 30 case study retrofit projects from nine European countries and the USA, and developed a software tool (Energy Concept Adviser) to support the decision makers and their technical staff in designing energy efficient retrofit measures.

In this project, the collection of case studies was achieved in two rounds: existing and new case studies. A format was developed according to which existing case studies were reported. A total of eleven existing case studies concerned lighting systems, eight concerned daylighting technologies and ten concerned control systems. The cases showed that it was the traditional energy technologies (e.g. new efficient electrical lighting and control) that have been applied the most. In approximately one third of the projects, daylighting principles and improved control of electric lighting systems were also applied.

BRITA in PuBs
The IEA-Annex 36 on educational buildings was subsequently extended to all public buildings through a European project called 'BRITA in PuBs' (Bringing Retrofit Innovation to Application in Public Buildings). The BRITA in PuBs project has documented case studies of different public building types, summarising special energy-efficient retrofit measures and adding on benchmarks for different public building types (see www.brita-in-pubs.com). In addition, the calculation engine of the Concept Adviser has been adapted to all public buildings in a new IEA-ECBCS Annex 46 – EnERGO.

According to information found in Erhorn-Kluttig, Erhorn & Wössner (2004), the EU 'BRITA in PuBs' Project with 23 European partners from public administration, research, design and consultancies aimed to (1) increase the market penetration of innovative and effective retrofit solutions; (2) improve energy efficiency; and (3) implement renewable energy in public buildings all over Europe (Ardente et al., 2011). This was realised firstly by the exemplary retrofit of nine demonstration public buildings in four participating European regions, including public buildings of different types such as colleges, cultural centres, nursery homes, student houses, churches etc. In this project, the technology applications included, amongst others, energy-efficient lighting and integrated solar application. The overall goal of the demonstration buildings was the reduction of the primary energy demand for heating, cooling, ventilation, domestic hot water and lighting by at least 50 % in addition to improving the comfort so that the percentage of the dissatisfied users (investigated by questionnaires before and after the retrofit) was halved. In this project, the retrofit concepts of all buildings were evaluated through a one-year monitoring period. The project also highlighted the role of the life cycle approach for selecting the most effective options during the design and implementation of retrofit actions (Ardente et al., 2011).

ECBCS Annex 46 - EnERGO
Based on the results of Annex 36, the International Energy Agency subsequently initiated a new Annex, which included the further development of the Energy Concept Adviser on public buildings. Whilst the work of BRITA in PuBs was mainly concentrated on developing new case studies, work on the retrofit measure part and add benchmarks for the whole group of public buildings, Annex 46 extended the calculation part to all public buildings. This was achieved by using the new CEN codes for the implementation of the EPBD for the calculation of heating, cooling, ventilation, lighting and domestic hot water consumptions.

OFFICE project – Passive retrofitting of office buildings to improve their energy performance and indoor working conditions

A European research project (Hestnes & Kofoed, 2002) evaluated energy retrofitting strategies designed for office buildings, considered combinations of energy retrofit measures (ERMs) i.e. building envelope improvements, HVAC improvements, use of passive cooling technologies, and lighting improvements. The results showed that the selection of ERMs should be based on the particular energy characteristics of the building and that measures need to be carefully selected to avoid using measures that attempt to save the same energy and therefore have no additional impact on total energy reduction.

3.2. Whole building retrofit including lighting and daylighting measures

As part of the OFFICE project, Dascalaki & Santamouris (2002) investigated the energy conservation potential of combined retrofit measures for five different building types in four climatic regions of Europe. The measures included interventions on the building envelope, HVAC and electric lighting systems as well as integration of passive components for heating and cooling. The potential of the measures was assessed through energy simulations using advanced computer models and climatic data from different European climate zones. Relying on a previous study of office building typology, the monitored buildings were classified into five categories:

- Free standing/heavy/core dependent/open plan,
- Enclosed/heavy/skin dependent/cellular,
- Free standing/heavy/skin dependent/cellular,
- Free standing/light/skin dependent/open plan and
- Enclosed/light/skin dependent/cellular.

Computer models were built with accurate description of each building using information from the thermal monitoring in each building. Contrary to expectations, the results indicated that buildings of the type ‘enclosed/light/skin dependent/cellular’ had the lowest energy use. These buildings typically had highly insulated opaque elements and airtight double glazed surfaces in the building envelope often combined with atria to allow for deeper daylight penetration. The energy use for electric lighting was only 16% of total energy use. In contrast, the first type ‘free standing/heavy/core dependent/open plan’ was characterized by a high volume-to-envelope surface ratio, open plan internal structure, massive floors and ceilings and large glazing areas on the outer envelope with a high LPD (lighting power density) and number of operating hours for electric lighting. This building type had a higher energy use than all other building types studied under all climatic conditions. In this building, 39% of energy was used for electric lighting alone; daylight penetration was inadequate which made the use of electric lighting necessary throughout the working day. This resulted in increased energy use for lights and high cooling loads. On the other hand, the potential energy savings by retrofit was high for this building type especially regarding possible improvements in heating and lighting systems.

A number of scenarios for retrofitting actions were assessed for each building type and climate and common trends were extracted indicating the most suitable retrofitting interventions in each case. In general, the results indicated that global retrofitting was found to generate the highest reduction of the total energy consumption in all climatic regions and all building types. For the highest energy consuming building (‘free standing/heavy/core dependent/open plan’), combined measures on the building envelope reduced energy use for heating by up to 21% and 66% for electric lights. Due to the reduction of the internal gains resulting from the use of energy-saving luminaires, cooling was reduced by 17%, but the heating energy was increased by up to 16% in the North Coastal climatic region. Consequently, the reduction in the total energy consumption was not significant i.e. the total energy use was reduced by an average of 13% in all climates. Application of the lighting scenario was found to have a SPBP (simple payback period) of nine years, while a simple measure like a reduction of the installed LPD from 121 to 20 W/m^2 was found to have a SPBP of five years. For the low energy consumer building type (‘enclosed/light/skin dependent/cellular’), the highly glazed outer envelope allowed for a deep daylight penetration and the use of electric lighting was usually controlled by the occupants. Thus, despite the fact that the lighting scenario yielded a significant reduction in the lighting energy use, the corresponding reduction in the total energy use was not significant. Overall, this research demonstrated two important facts:

- The potential for energy savings depends significantly on the building type; more compact building shapes demand more energy for electric lighting and thus present a higher energy saving potential than other building types.
- It is necessary to look at energy savings in a holistic way (for the whole building) since electric lighting reductions normally entail an increase in heating loads (and reduction in cooling), which can make lighting retrofit measures less cost effective considering all other end-uses.

Another article (Hestnes & Kofoed, 2002) about the OFFICE project reports some additional findings. According to this article, the retrofitting strategies prioritised activities on three levels:

1. Individual retrofitting measures, such as improved insulation, use of shading devices, reduced air change rates, and improved heating and cooling systems.
2. Combinations of retrofitting measures (called scenarios) within each of the following categories:
   - Building envelope improvements,
   - Use of passive cooling techniques,
   - Lighting improvements,
   - HVAC improvements.
3. Combinations of the different retrofitting scenarios (called packages), including building envelope improvements, the use of passive cooling techniques, and lighting and HVAC improvements.

The lighting scenarios included measures to increase the admittance of daylight, such as replacement of windows and the use of light shelves. Measures aimed at reducing unnecessary use of electric light, such as occupancy sensors, daylight responsive controls, the use of task lighting, and reduced general light levels were also investigated. Other measures studied consisted of improvements in the efficiency of the electric lighting system, such as the use of HF-ballasts and modern luminaires and reflectors. The results of the evaluation of the daylighting and electric lighting scenarios indicated that significant reductions in total energy use could be obtained when the initial lighting energy use was very high. In other cases, the reductions in total energy consumption were relatively small due to the fact that the reduction in electric energy use in many cases resulted in an increase in thermal energy use. Consequently, the authors concluded that improvements to reduce energy use for lighting ought to be combined with improvements on the building envelope to reduce thermal energy use. In their conclusions, the authors also mentioned that the choice of technologies to consider should be based on the specific characteristics of the existing building. The combination of technologies must be carefully selected to avoid the use of measures that cancel the benefit of another measure, which increases the cost of the retrofitting action. In all climates, potential reductions in lighting energy use are limited except for buildings with very high initial lighting energy use. However, the authors mention that since electricity is usually more expensive than thermal energy, any saving in electricity use is a significant improvement.

Much earlier, Zmeureanu & Peragine (1999) investigated the net energy impact of lighting system retrofit taking into account the interactions with HVAC systems since lighting retrofit can lead to an increased heating demand while reducing the cooling demand of buildings. Their study was carried out by parametric study with computer simulations with MICRO-DOE2 of an existing, 28-floors, 100 000 m^2 office building built in 1983 in a very cold climate (Montreal, Canada). This building had an annual energy use summing up to 315.0 kWh/m^2yr with an installed electric power density for lighting and office equipment varying between 25-

45 W/m^2 depending on the floor. The breakdown of electricity use in this building showed that 29.7% was used for lighting only (18.3% for office equipment, 28.1% for fans and pumps, 11.6% for chillers and cooling towers).The authors calibrated the initial base case computer model using the utility bills and demonstrated acceptable differences between measured and simulated annual values. In the parametric study, the following effects were investigated:

1. Type of fixtures for fluorescent lamps;
2. Installed electric power density for lighting;
3. Proportion of heat generated by the lighting fixtures released into the space;
4. Proportion of heat directly eliminated by the return air circulated through the lighting fixture.

They also performed a second parametric study for a different location i.e. Phoenix, Arizona to check the effect of climate on the results. In the case of suspended fluorescent fixtures, which entirely release the heat into the space, the net energy savings (heating, cooling, and lighting) obtained were 6.3% larger than the gross energy savings (lighting only) due to the important reduction of cooling loads and corresponding reduction of energy use by the mechanical cooling system. There was no negative effect of this lighting retrofit because the heating loads did not increase. When the original fixture was of a recessed unvented type and about 40% of the heat generated by the fixtures was released into the space, the net savings were about 67% to 73% the gross savings, for all levels of reduction of the electric installed power density due mainly to the increased heating demand. The authors noted that the larger the reduction in installed LPD, the smaller the net savings due to the increase in heating load. Changing to a warmer climate (Phoenix) produced net energy savings which were greater and closer to the gross lighting savings since the contribution of heating in annual energy use was not significant. They found that the net savings were greater than the gross lighting savings only if a large portion of heat generated by the light fixture was released into the space. Overall, the results indicated that the net energy savings were only about 70% of the gross lighting energy savings for most cases of recessed fluorescent fixtures. They discussed that in other less energy-efficient buildings, the net energy savings will be even smaller with respect to the gross lighting savings. They argued that the improvement of the lighting system might thus be less cost effective than expected initially when only considering the gross energy savings by the lighting system alone.

In a recent article, Lopez-Paleo & Negron (2013) presented a detailed case study for a holistic energy audit and energy-efficiency project together with results from the post-installation verification. The study was accompanying the energy-efficiency project for the Professional Colleague of Engineers and Land Surveyors of Puerto Rico (CIAPR) of San Juan, Puerto Rico. Based on a contracted energy audit, the energy consumption of the building was precisely analysed and disaggregated to individual domain contributions. Lighting contributed about 15.5% of the facility's energy consumption. The detailed lighting survey distinguished installations in conditioned/cooled and unconditioned areas in order to determine the amount of luminaires that have an effect on the HVAC load. The baseline lighting technology was predominantly fluorescent (~90%), followed by Metal Halide technology (~8%). The lighting retrofit assessment identified saving potential based on better reflectors and optics, allowing for lamps with lower lumen output. Furthermore, the potential of lamp upgrades (T12 to T8) and the ballast exchange towards HF ballasts was used. For some areas, occupancy-based lighting controls were implemented. Overall savings in the yearly lighting consumption were predicted to 39.4 MWh (27.7%). For the HVAC cooling system, a new variable refrigerant flow VRF system (inverter technology) for the whole building was proposed. Total annual savings were predicted to 235.1MWh and 55.500$. Simple payback of the combined retrofit measures (HVAC and lighting) was calculated to 6.25 years. The post-installation monitoring via monthly consumption bills revealed higher savings than predicted, which further shortened the payback period. Energy costs for the CIAPR building are now about 55% lower than previous energy expenses.

In an earlier paper, Ardente et al. (2011) reported some of the results of the Brita in Pubs project. They addressed the issue of expected life span of retrofit technologies, showing that lighting had the shortest expected life span compared to other strategies, which has many implications for life-cycle cost and analysis calculations, see Table 2 (Ardente et al., 2011). They showed that the case studies of Hol Church, Gol (Norway), and a Nursing Home in Stuttgart all have implemented some retrofitting strategy regarding electric lighting or daylighting. In the case of the Gol Church, the introduction of efficient lighting provided relatively small savings compared to other retrofit measures, i.e. about 90 MJ (or 25 kWh/m^{2}year, primary energy). In the case of the Nursing Home in Stuttgart, the installation of an efficient lighting system together with the improvement of the daylight transfer saved 163.6 MJ (45.4 kWh/m^2 yr., primary energy). In their conclusions, they stated that substitution of insulation, lighting and glazing components provided particularly efficient solutions. In all the case studied, the renovation of HVAC plants and lighting systems provided significant energy benefits according to these authors.

Table 2 Assumed life span for each component/technology/equipment.

Component	Lifetime (years)
Lighting equipments	3
Small wind turbines	15
HVAC systems	15
Solar thermal plants	15
PV plants	20
Building components	35

The same year, Chidiac et al. (2011) investigated by simulation the interactive effects of applying multiple energy retrofit measures (ERMs) to representative office buildings of different years and constructions located in three Canadian cities (Ottawa, Vancouver, Edmonton), with the goal of assessing the changes in energy consumption that occur due to the application of various ERM combinations. Their results showed that the reductions in energy use were not necessarily a linear addition of the savings from each ERM. For example, the implementation of light dimming features with more efficient lighting fixtures was not as effective in reducing consumption as a linear addition would indicate. In fact, the authors found that for the majority of measure combinations studied, the overall reduction in energy consumption was generally less than the linear addition of the individual ERMs. Only two retrofit measures applied together resulted in a larger reduction in energy consumption than the sum of each measure: a new HVAC system and an improvement in building envelope U-values. The largest difference between additive and modelled electrical consumption reductions occurred for combinations of measures that reduced lighting loads while adding light dimming controls with daylighting. If the electricity use of the lighting system is reduced through the implementation of more efficient lighting, then the reduction in consumption due to daylighting technique is paradoxically decreased, as a whole, on the building level. The authors also showed that when lighting upgrades are combined with heating efficiency improvements, the benefits gained from the higher efficiency heating system neutralizes the increases in natural gas energy resulting from the reduced heat gain from the more efficient lights. In addition, the integration of a daylighting retrofit measure reduces the internal heat gains, which results in reduced cooling demand while the heating demand is increased. Some of the conclusions of this paper are worth mentioning:

- The implementation of a retrofit that reduces the lighting load can have a significant negative impact on the effectiveness of a light dimming strategy when applied concurrently.

- For a post-1975 building type (LV) located in Vancouver only, the reduction in electrical consumption due to ERMs combinations that include daylighting and/or reduction in lighting load and high efficiency boiler was found to be greater than the linear additions of these measures.

In the Greek context, Spyropoulos & Balaras (2011) analysed six-year data from 39 representative offices used as bank branches from all the climatic zones of Greece. In addition, they carried out an in-depth analysis of information from energy audits performed in eleven buildings. In the investigated buildings, electricity was the main energy source for almost all branches using heat pumps for HVAC, except for a small number of branches located in the North, where oil fired boilers were used for heating. The data analysis showed that the average total energy consumption (including thermal energy) was about 346 kWh/m^2 (102 kWh/m^3). The contribution of final end-uses to the final energy use ranged for lighting between 15% and 60% with an average value of 35%, for office and electronic equipment
between 13% and 22% with an average value of 17%, and for HVAC between 22% and 69% with an average value of 48%. The authors examined three different ECMs (energy conservation measures) for lighting:

1. Replacing the conventional starters (old type electromagnetic ballasts) in the luminaries with new HF electronic ballasts, along with the replacement of any incandescent lamps (75 W), with more energy efficiency CFL lamps having the same or better output (lm/W);
2. Reducing the operating hours of the external marquee sign;
3. Reducing the number of luminaries (using DIALux simulations).

The authors stated that electric lighting system in almost all the bank branches in Greece consists of lighting fixtures with conventional ballasts. Almost all branches in their investigation use typical 4×18W T8 and 2×26W TCL lighting fixtures along with a small number of incandescent lamps. They found that the average light power density (LPD) was about 34 W/m^2 (24.2 W/m^2 excluding the external marquee sign). The replacement of incandescent lamps and the installation of electronic ballasts reduced the installed LPD to 28.9 W/m^2 and 19 W/m^2 respectively, resulting in an average reduction of 15% and 22% respectively. The average energy savings and accordingly the CO2 emission reductions resulting from the installation of electronic ballasts was estimated to yield about 6.5% (min 4%, max 11%) and 12% (min 4%, max 19%) of the total final energy consumption accounting for an average energy savings of 22 kWh/m^2 and 29 kWh/m^2 with and without the use of the external marquee sign, respectively. Reducing the operating hours of the external marquee sign from 10 h per day throughout the year to 8 h in winter (from 18:00 to 02:00) and 6.5 h in summer (from 20:30 to 03:00) yielded an average reduction of 12% for the lighting energy demand and about 5% for the total final energy consumption. They calculated that the potential energy savings for the investigated eleven typical bank branches averaged 16 kWh/m^2 (average reduction in CO2 emissions of about 14.8 kg/m^2). Reducing the number of installed luminaries in the working areas allowed reducing the installed LPD from 34 W/m^2 (or 24.2 W/m^2 if the external marquee sign is not considered) to 26.6 W/m^2 (or 17.6 W/m^2 excluding external marquee sign), but still maintaining the appropriate illuminance levels (400 lux). Based on these results, the average annual energy consumption for lighting in the investigated 11 typical bank branches with the existing installations dropped from 79.9 kWh/m^2 (or 46.7 kWh/m^2 if the external marquee sign is not considered) to 63.5 kWh/m^2 (or 31.7 kWh/m^2 not considering the marquee sign) by reducing the amount of luminaires only. Thus, on average, total energy use was reduced by up to 7% (or 12% excluding the external marquee).

In an earlier study, Mahlia et al. (2005) investigated the potential electricity savings, emission reduction and cost-benefit analysis of lighting retrofit policy in the Malaysian residential sector at a national level. The aim of this research was to encourage the authority and policymakers to implement this simple strategy to reduce rapid electricity consumption growth in the residential sector, after the successful experimentation conducted in the commercial sector. Their research method was based on a randomly conducted survey and on calculation of energy consumption/savings, emissions reduction, cost analysis. The results indicated that lighting retrofit could provide a significant impact on residential electricity consumption at a national level.

Much earlier, Lee (2000) reported a verification study of the annual electrical energy savings associated with lighting retrofits using short- and long-term monitoring in three facilities: a four-story (13936 m^2) office building, an industrial manufacturing plant, and a city hospital (23,226 m^2). The objective of the measurement and verification work was to quantify the annual energy savings associated with the proposed lighting retrofit measures. The short-term monitoring of the energy savings involved the measurements of the fixtures' power before and after the retrofit. Instantaneous demand metering was conducted on 10% of the fixtures, in accordance with the utility's measurement and verification protocol. For long-term monitoring, run time loggers were installed on 10% of the fixtures of each type after installation and were read quarterly for one year. These procedures are similar to the standard performance measurement and verification protocols established by the US Department of Energy (U.S. DOE, 1997). For the office building, they obtained that replacing all existing lighting with high efficiency lighting yielded energy savings of 497,200 kWh, which was 16.1% more than the projected energy savings. For the industrial manufacturing plant, the actual energy savings were 360,700 kWh, which was 17.9% more than the projected savings. For the city hospital, the actual energy savings were 1,330,300 kWh, which was 29.7% more than the projected savings. The lighting baseline operating hours were estimated by interviewing the building maintenance manager. The results show that the run hours for many energy conservation measures (ECMs) were significantly under-estimated, implying that the estimated run hours provided by the building maintenance manager were inaccurate or erroneous. However, in all three cases, the energy savings measured exceeded the projected energy savings by 16±30%. The study also allowed showing that the monitoring cost was about 2±3% of the total project cost, which is consistent with the projections of the International Performance Measurement and Verification Protocols (U.S. DOE, 1997).

The same year, Stefano (2000) assessed the potential to save electricity and reduce electricity-related CO2 emissions at Melbourne University, Australia, by modeling four alternatives of energy efficient lighting technologies. The four alternatives were easy to install and had the potential to save substantial amounts of energy. The method was based on a lighting survey within five studied buildings, and five room categories. Estimation of electricity consumption and cost, as well as the economic analysis was conducted. In order to do this, the initial monetary costs and 20 year cash flows were estimated for each technology option in each room category. Electricity costs, material and labor costs and disposal costs were taken into account. Three economic techniques were used to determine cost effectiveness of different lighting technology alternatives: simple payback time, net present value, cost of conserved energy. The results indicated that there is a large potential to reduce the amount of electricity used at Melbourne University, and that this potential would result in a substantial reduction in CO2 emissions associated to electricity usage. However, all these savings are unlikely to occur because of the prohibitive costs of installing new energy efficient lighting technology. The study identified three main factors influencing the cost effectiveness: operating hours, electricity prices and initial costs. The first one cannot be changed by external forces, the other two are controlled by market forces and government policies. The results of the study consequently supports the conclusion that low electricity prices and high component costs represent the social and political (non technical) barriers to the cost effective installation of energy efficient lighting technology in Australia.

3.3. Lighting retrofit strategies

3.3.1. Lamp, ballast and luminaire replacement

Studies about energy-efficient lighting retrofit generally suggest that most existing lighting installations consist of fluorescent lighting (with conventional ballasts). One American study (Baker, 2013) reported that the most commonly retrofitted fixtures (in the USA) are the four-lamp T12 while parabolic and lenses troffers with T12 or older T8 lamps are the primary lamp types to replace. This study also outlined that energy savings are generally decreasing over time, due to increases in new construction baselines and decreases in the number of existing very inefficient lighting systems (‘low-hanging fruit’).

According to another American author (Vogel, 2012), specifiers have four traditional options to consider in lighting retrofit:

1. Relamp and reballast;
2. Delamp and reballast;
3. One-for-one fixture replacement;
4. Complete redesign.

Options 3 and 4 represent a higher investment since entry into the plenum is required-a key factor affecting the cost of retrofitting-but they also present a higher saving potential. A new generation of lighting retrofit kits is available in energy efficient LED options. According to Vogel (2012), these kits enable component parts to be installed in 15 minutes or less into the housing of old fixtures, provide better quality and better looking fixtures and involve minimal disruption because they are installed below the ceiling.

Retrofits with LED Lamps

The hottest topic in lighting today is probably the possible replacement of different lamp types by highly efficient LED lamps. Rapid developments in the area of Solid-State Lighting (SSL) technology have created a real reorganization of the lighting industry worldwide with great emphasis on enormous potential savings. An analysis of LED retrofit lamps offered on the market (as alternative and equivalent to linear fluorescent solutions) carried out as part of IEA Task 50 Subtask B indicated that these lamps have a reduced energy consumption (approximately 50%), a life time typically two to three times higher, a comparable color rendering and a beam angle of around 140°.

Labayrade & Avouac (2013) recently evaluated the performance of 10 000 samples of a customized LED solutions, which were optimized to replace low voltage halogen lamps (4 W equivalent to a 20 W halogen and a 5,5 W equivalent to a 35 W halogen lamp). A total of 9300 retrofits were evaluated in uncontrolled environments (restaurants, cafes and shops), in which more than 85% of the users were satisfied with the light produced by the LED spots and would consider replacing their halogen lamps with it.

However, the CALIPER study in the USA (U.S. DOE, 2010) investigated 14 LED retrofit downlights that were equivalent to typical CFL downlights (32 W) and incandescent downlights (65 W), which are typically applied for ambient lighting in normal ceiling heights. This study indicated that the luminous flux was too low for all tested ‘MR16 equivalent’ LED retrofit solutions, having a product efficacy of 16-35 lm/W. Color rendering ranged from 61 to 96 and color temperature was not near the target CCT or Planckian locus. This study also 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. However, note that this study is already six years old, a period with much development in SSL technology.

A more recent study (Poplawski & Miller, 2013) nevertheless showed that a wide variation in flicker performance and unfamiliar flicker characteristics can still be found amongst LED lighting solutions (also in Lehman et al., 2011; U.S. DOE, 2010). Their study was based on the evaluation of 22 traditional lighting technology sources (incandescent, halogen, metal halide and fluorescent lamps) and 93 LED products (mainly retrofit lamps). Since flicker can affect well-being and performance, it seems to be a relevant quality criterion to take into consideration in the choice of LED retrofit solutions. The IES (2010) recommends a minimum driver output frequency of 120 Hz to avoid perceptible flicker, but the analysis by Poplawski & Miller (2013) indicates that this is insufficient to ensure quality. As no standard procedure for evaluation of flicker is currently available (CIE, 2013; Lehman et al., 2011), Poplawski & Miller (2013) proposed a light source evaluation using a flicker frequency dependent maximum flicker index. Another author (Osterhaus, 2014) stressed the need for appropriate combinations of LED sources and LED drivers. Inappropriate combinations can lead to flicker problems, which motivates the need to test sources and drivers as a unit, not as two separate components.

In addition, a study performed by Navigant Consulting (2012) indicated that LED lamps and equivalent compact fluorescent lamps have comparable average life-cycle energy consumption (approximately 3,900 MJ per 20 million lumen-hours). For the purpose of the analysis, a LED lamp luminous efficacy of 64 lm/W was used. But as the efficacy of LED lamps increases, the life-cycle energy consumption will diminish, since the energy consumption in use represents the significant portion of the total life-cycle energy consumption (approximately 90 percent).

Earlier, Ryckaert et al. (2011) evaluated 12 different brands of LED retrofit lamps as alternative for a linear fluorescent solution (T8/36W, 3500-4000 K, 3350 lm). They assessed the quality of the retrofit lamps through laboratory measurements at the beginning of the project and after 2000 h. The lamp efficacy of the LED retrofit was between 50,8 lm/W and 89,5 lm/W, compared to 75 and 95 lm/W for the linear fluorescent solution, depending on the ballast chosen. The majority of the retrofits had a CRI below 80 and would therefore not be suitable for office applications. Lumen depreciation over 2000 h varied from -38,7 % to +7,1% amongst the different brands. In addition to the product evaluation, the application of three selected retrofits was studied in a small office room. The authors concluded that, at that time, replacing T8 fluorescent lamps with ‘equivalent’ LED retrofits would indeed bring energy savings up to 70%, but would reduce at the same time the illuminance levels by about 50%, which is consistent with findings from a recent field study (Osterhaus, 2014). The latter was noticed by nearly all of the 44 subjects that evaluated the lighting conditions in the small office room. In addition to this major limitation, they noted that the luminous intensity distribution of the luminaire with all three retrofits changed considerably, which affected the illuminance distribution and uniformity as well as the impression of the room.

In summary, despite the promising savings that LED retrofits may bring in the future, many serious issues such as flicker, low illuminance levels, poor beam distribution and color rendering have been reported and should be given serious consideration in real retrofit projects.

Retrofits with T8 and T5 Lamps

In the context of Malaysia, Mahlia, Abdul Razak & Nursahida (2011) investigated the potential energy savings, Life Cycle Cost (LCC) and payback period of the lighting system in the campus buildings of the University of Malaya, by using theoretical calculations and standard cost and payback equations. They compared retrofitting the existing standard fluorescent lighting systems (T12) with T8 magnetic (18/36W), T8 electronic (18/36W), HPT8 electronic (17/32W) and T5 electronic (14/28W) ballasts. According to these authors, T8 lamps can replace the old T12 fluorescent lamps without any modification of the fixture while the use of T5 system requires electronic ballasts with high efficiency version that can reach a lamp luminous efficacy superior to 100 lm/W. However, the reader should consider that replacement to T5 tubes might require more controlled luminaire outputs (e.g. more louvers or baffles) to prevent glare due to the higher luminance of the light source, thus perhaps reducing end-use efficacy.

According to Mahlia, Abdul Razak & Nursahida (2011), T5 lamps can last at least 18,000 h with 5% reduction of lumen output in the lifetime. In contrast, a T8 light tube usually lasts about 20,000 h but it loses about 20% output in its life. The authors found that using T8 electronic system, HPT8 system and T5 lamps with electronic ballasts could reduce the energy consumption and LCC by 17%, 31% and 40% respectively at 100% retrofitting. Assuming an increase in electricity tariff of 2% per year, they also found that if retrofitting was fully done (100%), the payback period for T8 electronic would only be 0.689 years while it would be 1.24 years for HPT8 and 1.95 years for T5 electronic alternative.

Table 3 summarizes the potential energy savings reported with replacement of lighting technology.

Table 3 Potential energy savings by using more energy-efficient lighting technology in retrofit projects.

Technology	Potential energy savings	Issues	Source
Linear fluorescent[a] to LED	50%	Flicker, reduced illuminance, poor beam distribution, and color rendering	IEA Task 50, Subtask B
T8 to LED	70%		Ryckaert et al. (2011)
T12 to T8[b]	17%		Mahlia et al. (2011)
T12 to HPT8	31%		
T12 to T5	40%		

a unspecified
b electronic

3.3.2. Task-ambient lighting design

Loe (2003, 2009) suggested an alternative approach to lighting design which consists of separating the elements of task lighting and building or amenity lighting and to control them both independently, but in an integrated way. According to the author, this is not a new approach as it was used in the early part of the 20th century when lighting was extremely expensive, both in terms of the electricity it consumed and the cost of equipment, particularly lamps.

This task-ambient lighting approach was investigated by Veitch & Newsham (1999), who studied nine light conditions including three levels of LPDs (9, 14, 25 W/m^2) and three levels of designers' lighting quality (DLQ). These lighting conditions were evaluated by temporary office workers. They showed that lighting systems incorporating both task and ambient lighting (9W/m^2, measured LPD including task lighting) were rated as providing better quality lighting than systems without task lighting (14 W/m^2).

More recent experiments carried out in Denmark (Johnsen et al., 2009), assessed lighting installations combining low level general daylighting/lighting levels with task lighting achieving total LPDs of 5.4 W/m^2, including the task lamp and respecting the Danish code DS700[1]. This installation resulted in 25% reduction in electricity use compared to a standard energy-efficient installation with reduced user satisfaction concerning light levels. Loe (2003) also presented theoretical calculations showing energy savings of around 22% (compared to fixed general lighting solution) by simply using a combination of general lighting level (200 lx) combined with task lighting.

No other article was found specifically addressing the issue of retrofit and change in lighting design using the task-ambient lighting approach even though this approach seems to present a high energy saving potential.

3.3.3. Improvement in maintenance

According to Hanselaer et al. (2007), a high maintenance factor (cleaning) together with an effective maintenance programme promotes energy efficient design and limits the installed lighting power requirements.

Gasparovsky & Raditschova (2013) studied the luminous properties of old type luminaires after decades of their operation. They measured their efficacy in their actual conditions and after cleaning, with inserted and reference lamps. The measurements included luminous flux, luminous efficiency (in integrating sphere), luminous intensity distribution curve (with goniophotometer), spectral transmittance of diffuser in order to assess the yellowish effect of UV radiation (using a spectrophotometer) and electrical characteristics of the lamp-ballast system. They concluded that luminaires from the 1980s have significant non-recoverable losses of about 10% in case of interior luminaires. Pollutants (e.g. dust) collecting on the surfaces of the luminaire are responsible for another 10-20% reduction in performance, but these can be recovered through cleaning. The luminous efficacy of old-type T12 fluorescent lamps is 15% lower than catalogue values but in comparison with recent technology their efficacy was only half.

Mucklejohn et al. (2013) reported on fundamental basics of lighting design and the dimensioning of lighting taking the specific factors and aspects of light conversion and delivery into account. They presented case studies for a warehouse area (70m □54m) without any windows or skylights. In six configurations, HID-MH (High-intensity discharge metal halide) luminaires were compared with High Efficiency Plasma (HEP) light sources. Under the same maintenance conditions, they claimed that HEP light sources can fulfil the lighting design requirements with a total installed power of 22 kW while the design with HID-MH light sources requires 38.6kW. Assumptions on the cleaning interval, e.g. extending the cleaning interval from one to three years led to an increase of 9.5% in the installed power in order to always guarantee the required light levels. Changes in the reflectances and their impact were demonstrated by changing the wall reflectance from 50% to 10%. For the HID-MH configuration for instance this again asked for a design with more fittings and therefore an increased installed power by 4.8% compared to the base case.

3.3.4. Reduction of maintained illuminance levels

Boyce et al. (2006) claimed that lighting practice that uses 500 lx in offices as the target for maintained illuminance is excessive. According to these authors, by using 400 lx as a design

[1] 500 lx on task, 200 lx in immediate surroundings, 100 lx in remote surroundings and 50 lx for general lighting.

criterion, a 20% decrease in energy consumption could be gained together with a likely increase in the percentage of office workers who are within 100 lx of their preferred illuminance.

No study was found where the issue of reduced illuminance level was specifically addressed in a retrofit context. However, Baker (2013) discussed trends in new construction and retrofit lighting projects as seen in four years of energy efficiency incentive programs in Texas, USA and reported that in most cases, the number of lamps was reduced, which is partly due to the 'education around proper light level as many facilities are currently over-lit'.

Indeed, many studies (e.g. Galasiu et al., 2007; Boyce et al., 2006; Moore et al., 2002; 2001; Veitch and Newsham, 2000; Newsham et al., 2008) indicated that office workers generally prefer illuminance levels that are lower than recommended by the standards particularly if they work with a computer most of the time (Escuyer & Fontoynont, 2001). For example, a Canadian study (Veitch & Newsham, 2000) conducted in an open-plan office laboratory where forty-seven matched pairs of participants spent a day completing various simulated office tasks and questionnaires showed that individually preferred light levels varied widely (mean desktop illuminance 423 lx, s.d. 152 lx, min. 83 lx, max 725 lx), but on average required 10-15% less power than prevailing energy code recommendations. Another study (Schuler, 1995) in a computer hardware and software distribution company, where each of the offices contained at least two computers, showed through measurements that most employees felt comfortable with a lighting level of around 100 lux (as opposed to the standard regulations of workplaces demanding 300 to 500 lux at desk level). Meanwhile, a French field study (Escuyer & Fontoynont, 2001) involving worker interviews in three office buildings, distinguished between two distinct groups: a small group spending more than 70% of their time working on the computer, for which light levels were low (100-300 lux) and a bigger group spending less than 70% of their time working on the computer for which light levels were higher (300-600 lx). Note that these results are in line with those of an earlier French study by Berrutto et al. (1997).

However, in a more recent Finnish study by Viitanen et al. (2013), lighting quality parameters were studied in an office lighting setting for three different luminaire types: 1) square LED panel luminaire (Sq_LED); 2) round LED downlight luminaire (Ro_LED); and 3) rectangular recessed T5 fluorescent lamp luminaire (Re_T5). Re_T5 lighting was compared to Sq_LED lighting at 300, 600 and 1000 lx. Ro_LED lighting was studied at three different color temperatures: 3000, 4500 and 6000 K. The subjects evaluated 600 lx to be equally pleasant to 1000 lx and the reading task was evaluated to be equally easy at these two illuminance levels. However, 1000 lx caused slightly more glare and 300 lx was considered to be less pleasant. Visual performance regarding reading and detail distinction on the wall was more difficult at 300 lx than at higher illuminance levels. At 600 lx, the amount of light was considered to be more optimal than at 300 or 1000 lx. When the users adjusted illuminance, the overall average preferred illuminance was 648 lx for Re_T5 lighting and 517 lx for the LED lighting; but the authors noted that there were large variations in the preferred illuminances between subjects.

Finally, it might be worthwhile pointing out the potential impact of vertical illumination, rather than just horizontal illuminance: if vertical surfaces appear well-lit, lower horizontal illuminance values might be tolerated more easily.

3.3.5. Improvement in spectral quality of light sources

Better match between the lighting system's spectral qualities and the user's visual response can provide an optimal, energy-efficient lighting solution. Rea et al. (2009) have shown, for instance, that they could achieve energy savings (of the order of 37% according to Rea,

2010) in outdoor lighting applications by using Metal Halide (MH) lamps instead of the more common High-Pressure Sodium (HPS) since MH spectra are better tuned to the spectral sensitivity of the human retina at mesopic light levels. Note that the illuminance ratio between an MH and an HPS light source has been measured to be about 0.7 for equivalent brightness perception in the high end of the mesopic luminance range (>0.1 cd/m2) (Rea, 1996; Fotios & Cheal, 2007). The same logic can be applied to indoor lighting situations. Rea (2010) indicated, for instance, that at the same brightness level, 6500 K T8 fluorescent lamps use 35% less energy than 3000 K T8 fluorescent lamps due to a better match between the human eye's sensitivity and the lamp's spectrum.

Along these lines, a recent field study by Osterhaus (2014) carried out at Horsens Hall in Denmark, where 2700 K fluorescent lamps were retrofitted with 6000 K LED panels, indicated that the 6000 K lamps were judged to be brighter than the 2700 K source despite the fact that they provided slightly lower illuminance values on the work surface. Although this retrofit case involved two different types of light sources, it still suggests that the spectral light distribution of the light source is very critical in terms of subjective brightness perception and it should thus be an important factor to consider in lighting retrofit.

3.3.6. Occupant behavior

Masoso & Grobler (2010) claimed that 'behavioural change has energy saving potential comparable and in most cases higher than that of technological solutions'. The most salient feature of behavioural change is that it is largely no cost, it needs no hi-tech knowledge, it is readily applicable to both new and existing buildings, it is largely appreciated by many (though not practiced) and it has a self-perpetuating potential in that once occupants of a building have developed an energy conservation culture, they spread it to their new comers as well as take it with them to other places. It might even be worthwhile addressing the need for good user manuals for buildings and their systems. When occupants know how the systems are designed and how they are supposed to operate and when they know how to get short-comings of a system rectified, they will be less likely to disable systems and become more aware of the energy-saving mentality. Manuals should also explain the purpose of the light energy saving technology or control system.

Unfortunately, only a few studies have been found addressing the energy saving potential related to occupant behavior or evaluating the consequences for human performance, health and well-being of energy-saving lighting strategies in a retrofit context.

One study (Mahdavi et al., 2008) analyzed occupants' operation of lighting and shading systems by monitoring three office buildings from nine months to a year. They found that the probability of switching the light on upon arrival increased significantly when the horizontal illuminance at the proximity of the workstation was less than 200 lx. The same authors also obtained a probability model for switching the lights off as a function of the duration of absence from the offices.

Another study (Coleman et al., 2013) demonstrated that an installed wireless system was found to help individuals evaluate their energy-related behaviors and identify personal actions that are not apparent from aggregated building-level feedback. Neither study provides clear data about the potential energy savings achievable through improved occupant behavior.

Table 4 provides a summary of the potential energy savings achievable with the lighting retrofit strategies discussed in the last sections of this literature review.

Table 4 Potential energy savings by using specific lighting retrofit strategies.

	Potential energy savings	Retrofit studies	Source
Task-ambient lighting design	22-25%	No	Dubois & Blomsterberg (2011) Loe (2003, 2009)
Improved maintenance	5-20%[a]	Yes	Gasparovsky & Raditschova (2013)
Reduced maintained illuminance	20%[b]	No	Boyce et al. (2006)
Improved spectral quality of light source	35%[c]	No	Rea (2010)
Improved occupant behavior	unknown	No	Mahdavi et al. (2008) Coleman et al. (2013)

a light loss if no maintenance program is applied
b from 500 to 400 lux
c for a specific lighting technology

3.3.7. Use of Control Systems

The use of electric lighting control systems - in order to provide light exactly at the right time, to the right level and in the right place - can significantly contribute to reduce the consumption of electricity for lighting. Recently, Boyano, Hernandez & Wolf (2013) presented key energy use figures and explored the energy saving potential in office buildings across Europe by simulating (with Energy Plus) several currently available Energy Conservation Measures (ECMs) for three representative locations across Europe (cold, mild and warm climate). With partial daylight-linked dimming control (on 50% of office building facilities), they obtained a potential energy saving between 9 and 37% of the total energy consumed and 18 to 37% with total lighting control (100% of office building facilities).

Earlier, Fostervold et al. (2010) investigated the potential for energy savings and possible consequences for the workers by implementing new luminaires and a new lighting control system in a large hospital building. They obtained reductions in lighting energy use by 55-75% (depending on the control system) with neither positive nor negative effect on individual well-being and concentration or negative outcomes of adaptive lighting systems due to reduced degree of perceived control.

Prior to this, Granderson & Agogino (2006) developed an intelligent lighting dimming system in order to balance user comfort, energy savings and retrofit costs using an influence diagram approach. This system utilized wireless sensing and actuation technology to relieve much of the expense associated with retrofitting. In contrast to traditional systems that use a single ceiling-mounted photosensor per control zone, the intelligent system uses Smart Dust motes placed directly on each work surface. Illuminance sensing is performed with photodiodes embedded on the motes, while occupancy sensing is accomplished with mote accelerometers fixed to occupants' chairs, or with commercial personal occupancy sensors. Validation and fusion algorithms are used to mitigate interference from the users. Smart dust motes offer significantly reduced retrofit costs since they are wireless and directly interfaced with ballasts. They avoid the need to access power lines behind the walls and ceiling of an office. The authors (Granderson & Agogino, 2006) tested this system by simulation and found that replacing the existing non-dimming system designed under previous Illuminating Engineering Society (IES) guidelines with a commercial dimming system would generate 13% energy savings and a 15% cost savings. On the other hand, the intelligent system increased the energy savings to 26% and the cost savings to 20%.

In general, the saving potential varies greatly according to context and building: different studies show different energy savings, which leads to difficulties in calculating the payback time of a lighting retrofit action. Williams et al. (2012) tried to overcome this difficulty through a meta-analysis based on the review of 88 scientific papers and reports which included the potential savings from lighting control systems. The authors categorized the different strategies and listed the study typology as well as the key features of each document. Applying increasing restrictive filters, they concluded that there is a potential saving of 24-38% for different lighting control systems in actual installation. The study also pointed out that the simulations generally overestimate the savings compared to field studies. The effect, in this case, is higher when the lighting control system has a higher level of automation and/or technology, such as daylight harvesting technologies. The authors also found that there is a consistent effect of the switch-off delay in the occupancy strategies.

It might be worthwhile pointing out that Simpson (2003) claimed that office buildings are probably the most important application for lighting control systems, but also an application where individuals will likely have strong opinions about lighting control. While systems might have been installed with the best of intentions, he states that some ‘have been unsuccessful to the extent that users have disconnected the automatic element or even the entire lighting control system’. He argues that specifiers of lighting control systems need to be aware of various factors when selecting a lighting control system:

- People behave differently when lighting is under central control;
- People of different ages and visual abilities have different requirements and even those with the same age and ability might have different preferences;
- Occupancy times of spaces vary widely, especially for private office and other work spaces;
- Unpredictability of lighting system behaviour is generally disliked;
- Very quick and very large changes in illuminance levels are difficult to handle for the human eye;
- The extent of daylight contributing to the workplace illumination typically varies significantly with the distance to windows;
- The orientation of the workspace’s daylight openings can result in highly seasonal or diurnal problems affecting the users;
- The introduction of blinds and other shading devices affects the way in which automated lighting control systems work;
- Appropriate placement of light and/or presence sensors is crucial for achieving user satisfaction and energy savings;
- The type of occupancy of the space is a considerable ‘human’ factor.

Manual Controls

Manual control systems, such as door switches, manual task lamps and manual dimmers, can offer an unexpectedly high saving potential. For example, a survey conducted in France (IEA, 2006) reported energy savings of up to 77% by installing more manual switches in open plan offices. Besides energy savings, the possibility of controlling the light environment has a positive effect on the users’ mood according to Moore et al. (2002), which is also related to monetary savings. Juslén et al. (2007) have shown an increase of 4,5% in productivity in a factory hall where manually dimmable task lights were provided to the workers.

In an earlier study carried out in the USA (Jennings et al., 2000), five different lighting control scenarios were tested in an office building located in San Francisco. Among these scenarios, two considered the use of manual controls. In the first case, a bi-level switching gave the possibility to choose to turn on only a part of the light fixtures. In the second scenario, the electric lighting was turning on automatically when people were entering the offices, but it could be manually dimmed afterwards. The bi-level switching offered about 23% energy savings compared with a classic switch, while the second scenario (automatic on with dimming) provided about 26% energy savings. Nevertheless, the authors analysed the behaviour of the users and found quite important differences in individual preferences. For example, in the bi-level switching case, about 63% of the occupants used mostly the full-light setting, 13% used mainly 2/3 of the light fixtures and the remaining used mostly 1/3 of the light fixtures.

In general, the saving potential is not predictable because it largely depends on individual behaviours according to Boyce et al. (2000). In small office rooms, the occupants tend to adjust the light level, which leads to both a more pleasant lighting environment and energy savings (see also Love, 1998; Gentile, Laike & Dubois, 2013). In open space offices, a strategy could be to provide manually adjustable task lighting, while keeping some automatic controls for the general electric lighting.

Recently, a solution that combined automation with individual preferences was proposed by Wen & Agogino (2011). They proposed a lighting design method enabling dynamic, personalized and optimal horizontal illumination of open-plan offices by using an elaborated control mechanism to tune each lamp in the office according to each occupant's preference and need. The prototype lighting system was tested in an open-plan office. The overall energy savings for the year analyzed was 51% compared to the original all on/off lighting configuration.

Occupancy Controls

One of the most effective approaches to minimize energy use in the non-residential sectors is by using occupancy based lighting control systems (IEA, 2006; Garg & Bansal, 2000; Galasiu et al., 2007). As a result of occupants not turning the lights off when they no longer need them, more energy is spent on non-working hours than during scheduled time as emphasized by Masoso & Grobler (2010).

A recent article by Motta Cabrera & Zareipour (2013) presented an experimental research aiming to quantify and understand lighting energy waste patterns in a post-secondary educational institute located in Calgary, Canada. They collected data over a full academic year in three typical classrooms. Data association mining was used in order to extract association rules and explore lighting waste patterns. They made an energy assessment to account for the amount of energy, money and CO2 emissions spent by each classroom throughout the year and obtained energy wastes of 126.4 kWh/seat, 49.2 kWh/seat and 62.8 kWh/seat respectively for the three classrooms. The average number of waste instances for all three classrooms was 44.24%, which means that the lights were turned on with no one in the classroom for 10.6 h in an average day. They finally demonstrated by simulation that if the waste patterns were avoided, significant savings, up to 70% of the current energy use, could be achieved.

Another recent article (Itani, Ghaddar & Ghali, 2013) concerned the effect of Energy Conservation Measures (ECMs) for an existing eight-storey building located in Beirut, Lebanon. The authors analysed the impact of low investment and minimal disruption ECMs that can maintain thermal comfort and good indoor air quality. The ECMs were investigated by using a commercial energy analysis software (IES-VE) and varying the indoor temperature cooling set point, lighting control, etc. They used a standard system audit methodology and advanced energy modelling techniques to replicate the existing building base case. The lighting energy use in the building studied used less percentage of total energy compared to most ordinary office buildings due to the use of efficient lights (T5 and CFLs with an average LPD of 10.23 W/m^2) and the large daylighting available from the glazed façade. Substantial energy savings were achieved by implementing scheduled lighting controls and by placing occupancy sensors in meeting rooms and private offices. The schedule of lighting was also adjusted by turning off some lights during unoccupied and low occupancy hours, which yielded reductions in the lighting energy corresponding to 11.8% savings in lighting energy or a 2.6% saving in overall building energy consumption due to a simultaneous decrease in lighting and cooling loads. The economic analysis showed that lighting control and increasing temperature set point are two ECMs that should be implemented because of short payback period of 1.3±0.2 years, respectively.

According to Motta Cabrera & Zareipour (2013), one obstacle of implementing an occupancy-based lighting-control is the uncertainty on the amount of energy that could be saved. Previous research papers report differences in expected savings, typically ranging from 25% to 75% (Garg & Bansal, 2000; Moore et al., 2003; Richman et al., 1995; Granderson & Agogino, 2006). This could be due to the fact that each space has a different occupancy profile based on the schedules and activities of people in the building (see e.g. Guo et al., 2010; Rubinstein et al., 2003).

In addition to this, the switching strategy seems to play a significant role. The occupancy control system could automatically turn on/off the electric lighting when the presence is detected (presence switches), or only switch off a manually turned on system when any movement is recognized (absence switches). The differences in savings between these two approaches could be high, especially in individual or small offices, as shown by Gentile, Håkansson & Dubois (2012). These authors showed that using a presence (on/off) control system in small offices would yield higher energy use for lighting than a simple manual switch at the door with an absence detector (switch off), confirming results from previous research (Voss et al., 2006).

In an earlier study, Garg & Bansal (2000) found that by optimizing the time delay, energy savings from using an occupancy sensor increased from 20% to 25%. In another study in eight buildings (Richman et al., 1995), which included conference rooms, mail room, restrooms, one training room and laboratory areas, it was found that occupancy sensors had the potential to save between 24% and 79% of energy consumption by using a 10-min time delay. When the time delay was decreased to a 2-min setting, the potential savings range increased to 76-93%, with negative impact on user comfort.

Guo et al. (2010) presented a review of occupancy-based lighting control systems where they analyzed the typologies of sensors generally used for this kind of lighting control systems, as well as the settings generally applied during the installation. Regarding the sensors, while several technologies are available, the market often offers only PIR (Passive Infrared), ultrasonic or hybrid PIR/ultrasonic presence sensors, which are offering a good compromise between feasibility, accuracy and costs. Each of these systems presents some limitation regarding the position of the sensor, the room area, the geometry, etc. This makes the savings conditioned by proper installation and post-installation commissioning. Guo et al. (2010) concluded that a cheap and feasible solution could be to have a network of sensors rather than a single expensive one. With focus on the settings, this review shows that the savings with 20 minutes of delay could be as high as 46%, while it increases up to 86% when the delay is reduced to 5 minutes.

As mentioned previously, shorter time delays for the switch-off reduce the energy consumption, but could be unacceptable for occupants. The general recommendation is to keep 10-20 minutes time delay, never accepting shorter time delays than 7 minutes. Note also that the effectiveness of those systems is largely dependent on the pattern of use of the space. Generally, irregularly occupied spaces offer higher saving potential.

Daylight-Linked Control Systems

Several studies have indicated that daylighting can provide a cost-effective alternative to electrical lighting for commercial and institutional buildings (Ihm et al., 2009). In addition, it is generally acknowledged that daylight is preferred to electric light, fosters higher productivity and performance (Plympton et al., 2000; Säter, 2010). According to many authors, simulation studies as well as field monitoring, daylighting controls can result in significant lighting savings ranging from 30 to 77% (Doulos et al., 2008; Li et al., 2006; Lee & Selkowitz, 2006; Onaygil & Guler, 2003; Ihm et al., 2009; Kobav & Bizjak, 2010). However, previous surveys have indicated that daylighting control strategies are not commonly integrated in buildings (Li and Lam, 2003). According to Ihm et al. (2009) and Krarti, Erickson & Hillman (2005), this may be explained by the lack of simplified prediction tools.

A recent field study (Chow et al., 2013) considered a corridor space adjacent to a large skylight atrium. The combination of high daylight availability and low illuminance requirements for corridor spaces, suggested the use of daylight-linked control system with efficient T5 light fixtures. The solution led to an overall energy saving of 93% compared to the existing lighting installation. The payback period for the proposed solution was calculated to be 3.42 years.

Another study achieved in Hong Kong (Li et al., 2006) investigated a fully air conditioned side-lighted open plan office with an initial power density for lighting of 16.7 W/m2. The original two rows of fluorescent lamps closer to the window were improved by adding new high frequency ballasts and a photo sensor for daylight harvesting. A single photo sensor served all the upgraded fixtures. The authors obtained average energy savings of 33% compared to the non-dimmable fixtures, with better performances during the central part of the day and the summer months.

In the Canadian climate, Galasiu et al. (2004) tested different combinations of lighting and shading control systems. For the electric lighting, the authors used dimmable and on/off daylight systems, which were combined with photo controlled blinds as well as with different cases of static positions of the blinds. The best case scenario offered possible energy savings of 50-60% with windows without blinds, which dropped by 5-80% with different static (predefined blind positions, not automatically controlled) window blinds settings.

An Italian study (Gugliermetti & Bisegna, 2005) performed in the Mediterranean area investigated the luminous and energy aspects related to the integration of control systems with different Electro Chromic (EC) and double glazed systems equipped with motorized internal shading devices. On/off and linear control strategies were used to change the transparency of EC systems from clear to dark state and to close the indoor curtains, while dimming and on/off strategies for managing the electric lighting. The study showed the significant impact of highly flexible controls of both electric and natural light also in climates where overheating and visual comfort problems are of great importance owing to the high level of daylight. They found that the difference in lighting electric power demand can be largely affected by the variation in the number of dimming zones. And still more important are the different situations obtained by changing the daylighting control: a finer regulation, such as that obtained by the linear control, involves a more uniform and continuous, but lighter, presence of electric lights with respect to simpler and less flexible regulation. This has been proved for both internal curtain control and ECs, from both energy efficiency and visual comfort points of view.

In an earlier study in a sub-tropical environment, To et al. (2002) considered a side-lit classroom with two rows of fluorescent tubes parallel to the windows. The closest row to the windows was replaced with a high frequency electronic daylight linked dimming system. In addition, the general horizontal illuminance was reduced from about 1000 lux to around 800 lux. The authors extrapolated the potential annual savings using a 16-weeks data collection period, which demonstrated savings of the order of 40% compared to the full-power scenario. Considering the actual installation costs, the energy savings led to a payback period of 4.9 years for the tested installation, with projection of possible reduction up to 2.2 years for larger spaces.

Table 5 Potential energy savings by using different types of lighting control systems.

	Potential energy savings	Retrofit studies	Source
Manual controls	23-77%	Yes	IEA (2006); Jennings et al. (2000)
Scheduling	12%	No	Itani, Ghaddar & Ghali (2013)
Occupancy control	20-93%[a]	Yes	Motta et al. (2013); Garg & Bansal (2000); Moore et al. (2003); Richman et al. (1995); Guo et al. (2010)
Daylight-linked dimming	10-93%	Yes	Boyano et al. (2013); Doulos et al. (2008); Li et al. (2006); Lee & Selkowitz (2006); Onaygil & Guler (2003); Ihm et al. (2009); Kobav & Bizjak (2010); Chow et al. (2013); To et al. (2002); Koyle & Papamichael (2010).
Combined daylight-linked and occupancy	26%	No	Granderson & Agonino (2006)

a Highly dependent on space occupancy and time delay

Koyle & Papamichael (2010) installed an innovative dual-loop photo sensor control system in a 150000 ft^2 retail store. The system received readings from both open- and closed-loop sensors. It combined the information through an algorithm and determined the relative requested electric light output. Over a 12-month observation period, the authors found that the system was able to match the requested light levels 63.7% of the time and saved 36.6% energy compared to a retail store without daylight harvesting strategy. The payback time of this installation was determined to be 2.4 years.

In addition to the uncertainty in predicting the energy saving potential, several studies reported difficulties in real installation of daylight-linked dimming systems (e.g. Lee & Selkowitz, 2006; Gentile, Håkansson & Dubois, 2012). The practical difficulties regard mainly the performance of the photo sensor (Ehrlich et al., 2002), since the whole system is based on its reading of the light environment. Frequent light switching under unstable sky conditions may compromise the savings (Li et al., 2006). In addition, difficulties in matching the illuminance design levels because of overestimated number of light fixtures, changes in the space purpose (Choi & Sung, 2000) or actual occupancy rate of the space (Roisin et al., 2008) are also factors that may compromise the efficiency of the systems. A lack of awareness by the designers about the comprehensive performance of the real installations has also been identified (Ehrlich et al., 2002). Gentile, Laike & Dubois. (2013) also pointed out the need for training installers to calibrate these systems properly or simply to be trained about the calibration settings of the systems they install.

Table 5 summarizes the findings regarding potential energy savings using lighting control systems.

3.3.8. Use of Daylighting Systems

Building facades and roofs, by their glass area ratio, shading or daylighting systems, may greatly affect electricity use for lighting, provided of course that electric lighting is switched off in the presence of daylight. Many studies report results related to daylight utilisation i.e. the replacement of electric light by daylight.

Sanati & Utzinger (2013) examined the effect of an interior light shelf system fixed in the upper part of windows on occupants' use of blinds in the lower part and on the consumption of electric lighting. The results suggest that in otherwise identical environmental conditions, occupants working in the 'light shelf zone' demonstrated a lower window occlusion than those located in the area with conventional windows. Light shelves distributed daylight more evenly, consequently, occupants in the 'light shelf zone' used less electric lighting.

Previously, daylighting systems have been developed to enhance daylight penetration or utilization. A large number of daylighting systems were evaluated within IEA Task 21 'Daylight in Buildings' (IEA, 2000) based on their ability to block or redirect daylight. Depending on the geographical location and its predominant daylighting conditions different daylighting systems seem to be suitable. Energy savings for electric lighting can be achieved with (angular) selective systems, such as anidolic solar blinds, using direct sunlight without glare, which is of specific relevance for mild and sunny climates. Sunlight-redirecting daylighting systems positioned in the upper part of the window plane, such as laser-cut-panels and prismatic panels, present energy saving potential as well, but need consideration with respect to position and angle to avoid glare. These systems are typically applied in sunny climates according to Edmonds & Greenup (2002), even though the laser-cut panel has shown its applicability in temperate climates as well (IEA, 2000).

Other, more invasive, light redirecting systems, like light shelves and anidolic systems, redirect both diffuse and direct light. Both can increase daylight penetration, but might reduce the sunlight and daylight contribution near the façade. They have limited application in high-latitude countries, because of the additionally required shading device for a prevalent time of the year. The most efficient daylighting systems for moderate climates seem to be automatically controlled blinds and louvres, because of their flexibility to respond to different daylighting conditions.

Ehling (2000) investigated the energy savings potential and economical aspects of daylighting systems under moderate climate conditions and concluded the pay back times for daylighting systems are typically extensive therefore also pleading for simple, cost effective, daylighting systems, such as blinds and louvres. These systems perform well under predominant sunny sky conditions as well.

A recent literature review (Nair et al., 2013) concluded that active systems, with for example sun tracking mirrors or lenses, can optimally collect daylight and with this offer high energy saving potential. Nonetheless, they are typically complex and relatively expensive and require regular maintenance. Passive systems have a poorer performance, but are typically cheap, simple and require less maintenance. Positive attributes of a good daylighting enhancement system are said to be passiveness, ease of installation, visual acceptance, solar shading against direct radiation and well-controlled output distribution.

4. Conclusion

As part of the International Energy Agency research ‘IEA-Task 50 Advanced Lighting Solutions for Retrofitting Buildings’, this literature review pursued the aim to analyze information found in the scientific literature, previous international, European and national research projects in order to summarize the state of knowledge on lighting and daylighting retrofit. Key conclusions that should be remembered from this literature review are summarized below.

4.1. General

- Electric lighting is one of the major sources of electricity consumption in buildings representing 15-60% of the final energy use. It has a high saving potential at a reasonable pay-back period, especially due to the development of new lighting technologies with higher luminous efficacies and lower cost of light.

- Reported energy savings through lighting retrofit vary widely depending on initial energy use, building type, usage, etc.

- The so-called rebound effect may create a tendency to use more light because it is cheaper and by that absolute consumption could be ultimately increased.

- Energy savings measures should be considered in a holistic way since electric lighting reductions normally entail an increase in heating demand. Improvements in lighting should be planned along with building envelope improvements to compensate for the related increase in heating loads.

- Reductions in energy use are not necessarily a linear addition of the savings from individual Energy Retrofit Measures (ERMs). The overall reduction in energy consumption is generally less than the linear addition of the individual ERMs.

4.2. Specific to electric lighting

- Replacement of lamp, ballast and luminaire appears as the most often reported lighting retrofit strategy, with a great saving potential. The most common existing lighting installations consist of fluorescent lighting (with conventional ballasts) and most commonly retrofitted fixtures are the four-lamp T12 and parabolic and lenses troffers with T12 or older T8 lamps (data from the USA).

- Compared to fluorescent lighting, LED lamps have reduced energy consumption (approximately 50%) and a longer life time. Although good products are available, lighting quality aspects such as unsatisfactory color rendering, low light load, flicker and poor light distribution have been reported and need to be considered seriously to ensure user satisfaction.

4.3. Reduced maintained illuminance

- Reducing the maintained illuminance level is another promising strategy since previous research indicated lower preferred illuminance levels compared to those recommended by the standards particularly in areas where computers are used. There are indications of a tendency to reduce the number of lamps (by ‘delamping’) partly due to the education around proper light levels and the fact that many facilities are currently overlit.

4.4. Task-ambient lighting

- Use of task-ambient lighting design has proven to provide better quality lighting and a 22-25% reduction in electricity use compared to a standard general energy-efficient lighting installation but no study has been found about task-ambient lighting design approach in a retrofit context.

4.5. Occupant behavior

- Occupant behavior offers substantial energy saving potential but this strategy has not been sufficiently explored in retrofit context.

4.6. Lighting control

- The use of electric lighting control systems can also significantly reduce the consumption of electric lighting but the saving potential varies greatly according to context and building, which leads to difficulties in estimating the payback time of a lighting retrofit.

- Simulations generally overestimate the savings compared to field studies; especially when the control system involves advanced automation and/or technology, such as daylight harvesting technologies.

- Manual control systems, such as door switches, manual task lamps and manual dimmers, can offer an unexpectedly high saving potential with increase in occupant satisfaction and productivity:

- Occupancy based lighting control systems are also very promising with high expected savings (20-93%).

- Irregularly occupied spaces offer higher saving potential.

- Optimizing the time delay has a significant impact on the energy savings.

- Using a presence (on/off) control system could yield higher energy use for lighting than a simple manual switch at the door combined with absence detection (switch off), especially in individual or small offices.

- Daylight-linked control systems can result in significant lighting savings, but several studies report difficulties in real installations and in estimating the payback period at the design stage.

4.7. Daylighting Systems

- Building facades, by their glass area ratio, shading or daylighting systems, may greatly affect electricity use for lighting provided that electric lights are switched off in presence of sufficient daylight.

- Payback times for daylighting systems are typically extensive while passive daylighting or shading systems have a poorer performance, but are typically cheap, simple and require less maintenance, leading to better payback times.

This review discussed several strategies for reducing electricity use in lighting retrofit projects. The review was limited to the topic of energy efficiency but the reader should be reminded that retrofitting a lighting installation offers several advantages besides energy savings: improvement in lighting quality, occupant satisfaction and productivity, improved corporate image, energy security, etc. The review generally shows that studies of lighting retrofit in real context with monitored data are surprisingly rare and most of the existing studies target either lamp-ballast-luminaire replacement or implementation of advanced control systems. Monitoring studies where simple and robust retrofit strategies such as task-ambient lighting design, improved occupant behavior, improvement in the spectral quality of light sources, or even a simple reduction of maintained illuminance levels have not been reported extensively in the literature despite their promising saving potential. This review suggests that research efforts addressing these specific strategies should be emphasized in the context of retrofitting buildings.

5. References

Ardente F, Beccali M, Cellura M, & Mistretta M (2011). Energy and environmental benefits in public buildings as a result of retrofit actions. Renewable and Sustainable Energy Reviews, 15:460–470.

Baker S C (2013). A Bright Future: market Transformation in Texas Lighting Efficiency Incentive Programs. Energy Engineering, 110(2): 35-36.

Berrutto V, Fontoynont M & Avouac-Bastie P (1997). Importance of wall luminance on users' satisfaction: Pilot study on 73 office workers. Proceedings of the 8th European Lighting Conference, Amsterdam, The Netherlands.

Boyano A, Hernandez P & Wolf O (2013). Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations. Energy Buildings, 65: 19-28. DOI: 10.1016/j.enbuild.2013.05.039.

Boyce P R, Eklund N H & Simpson S N (2000). Individual lighting control: Task performance, mood and illuminance. J. Illuminating Eng. Society, 29: 299-311. DOI: 10.1080/00994480.2000.10748488.

Boyce P R, Veitch J A, Newsham G R, Jones C C & Heerwagen J M (2006). Occupant use of switching and dimming controls in offices. Lighting Res. Technol., 38 (4): 358-378. DOI: 10.1177/1477153506070994.

Chidiac S E, Catania E, Morofsky E & Foo S (2011). Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings. Energy, 36(2011): 5037–5052.

Choi A S & Sung M K (2000). Development of a daylight responsive dimming system and preliminary evaluation of system performance. Building Environ., 35: 663-676. DOI: 10.1016/S0360-1323(99)00055-4.

Chow S K, Li D H, Lee E W & Lam J C (2013). Analysis and prediction of daylighting and energy performance in atrium spaces using daylight-linked lighting controls. Applied Energy, 112: 1016-1024. DOI: 10.1016/j.apenergy.2012.12.033.

CIE (2013). Review of lighting quality measures for interior lighting with LED lighting systems. Proceedings of the CIE Lighting Quality and Energy Efficiency Conference, Mar. 3-5, Central Bureau, Vienna, Austria.

Coleman M J, Irvine K N, Lemon M & Shao L (2013). Promoting behaviour change through personalized energy feedback in offices. Building Res. Inf., 41: 637-651. DOI: 10.1080/09613218.2013.808958.

Crawley D B, Hand J W, Kummert M, Griffith B T (2008). Contrasting the capabilities of building energy performance simulation programs. Building and Environment, 43 (4), 661–673.

Dascalaki E, & Santamouris M (2002). On the potential of retrofitting scenarios for offices. Building and Environment, 37(2002): 557–567.

Dixon T, & Eames M (2013). Scaling up: the challenges of urban retrofit. Building Research & Information, Special Issue on Urban retrofitting for the transition to sustainability, 41(5): 504-516.

Doulos L, Tsangrassoulis A & Topalis F (2008). Quantifying energy savings in daylight responsive systems: The role of dimming electronic ballasts. Energy Buildings, 40: 36-50. DOI: 10.1016/j.enbuild.2007.01.019.

Dubois M.C. & Blomsterberg Å (2011). Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: A literature review. Energy Buildings, 43: 2572-2582. DOI: 10.1016/j.enbuild.2011.07.001.

Eames M, Dixon T, May T & Hunt M (2013). City futures: Exploring urban retrofit and sustainable transitions. Building Res. Inf., 41(5): 504-516. DOI: 10.1080/09613218.2013.805063.

Edmonds IR & Greenup P J (2002). Daylighting in the tropics. Solar Energy, 73(2): 111-121. DOI: 10.1016/S0038-092X(02)00039-7.

Ehling K (2000). Tageslichtsysteme: Lichttechnische Bewertung und Wirtschaftlichkeit. 1st Edn., VDI-Verlag, Berlin, ISBN-10: 318316504X.

Erhorn-Kluttig H, Erhorn H & Wössner S (2004). Exemplary retrofit concepts in Europe: Energy-efficient public buildings (results from IEA/EU-projects).

Ehrlich C, Papamichael K, Lai J & Revzan K (2002). A method for simulating the performance of photosensor-based lighting controls. Energy Buildings, 34: 883-889. DOI: 10.1016/S0378-7788(02)00064-6.

Enkvist PA, Nauclér T & Rosander J (2007). A Cost Curve for Greenhouse Gas Reduction. 1st Edn., McKinsey Quarterly, pp: 1-7.

Ernst & Young. (2010). Business opportunities in a low carbon economy, final report. Industry and Investment NSW.

Escuyer S & Fontoynont M (2001). Lighting controls: a field study of office workers' reactions. Lighting research and technology, 33(2): 77-96. DOI: 10.1177/136578280103300202.

Fostervold K I, Larsen P J, Lillelien E, Mjøs T & Berg M O (2010). Energy efficient lighting control systems: Consequences for lighting quality, environment, health and human factors. Proceedings of the CIE Lighting Quality and Energy Efficiency, (CLQ' 10), Vienna, Austria, pp: 368-375.

Fotios S A & Cheal C (2007). Lighting for subsidiary streets: Investigation of lamps of different SPD, Part 2 - Brightness. Lighting Res. Technol., 29: 233-252. DOI: 10.1177/1477153507080805.

Galasiu A D, Atif M R & MacDonald R A (2004). Impact of window blinds on daylight-linked dimming and automatic on/off lighting controls. Solar Energy, 76(5): 523-544. DOI: 10.1016/j.solener.2003.12.007.

Galasiu A D, Newsham G R, Suvagau C & Sander D M (2007). Energy saving lighting control systems for open-plan offices: A field study. J. Illuminating Eng. Society North Am., 4:

7-29. DOI: 10.1582/LEUKOS.2007.04.01.001. also published as Technical Report. Institute for Research in Construction, Canada, 2007.

Garg V & Bansal N (2000). Smart occupancy sensors to reduce energy consumption. Energy Buildings, 32(1): 81-87. DOI: 10.1016/S0378-7788(99)00040-7.

Gasparovsky D & Raditschova J (2013). Lighting properties and efficiency of luminaires exceeding their lifetime. Proceedings of CIE Centenary Conference, Paris, France, pp. 317-326.

Gentile N, Håkansson H & Dubois M-C (2012). Lighting control systems in individual offices at high latitude: measurement of lighting conditions and electricity savings. Proceedings of the International Conference on Energy Efficiency in Commercial Buildings, (IEECB '12), Frankfurt, Germany, pp: 333-344.

Gentile N, Laike T & Dubois M-C (2013). Lighting control systems in peripheral offices rooms at high latitude: Measurements of electricity savings and users' preferences. Energy Procedia, 57: 1987-1996. DOI: 10.1016/j.egypro.2014.10.063.

Granderson J & Agogino A (2006). Intelligent office lighting: demand-responsive conditioning and increased user satisfaction. Leukos Journal of the Illuminating Engineering Society of North America, 2(3): 185-198.

Gugliermetti F & Bisegna F (2005). A model study of light control systems operating with Electrochromic Windows. Lighting Res. Technol., 37: 3-20. DOI: 10.1191/1365782805li123oa.

Guo X, Tiller D K, Henze G P & Waters C E (2010). The performance of occupancy-based lighting control systems: A review. Lighting Res. Technol., 42: 415-431. DOI: 10.1177/1477153510376225.

Hanselaer P, Lootens C, Ryckaert W R, Deconinck G & Rombauts P (2007). Power density targets for efficient lighting of interior task areas. Lighting Res. Technol., 39: 171-184. DOI: 10.1177/1365782807076737.

Hestnes A G & Kofoed N U (2002). Effective retrofitting scenarios for energy efficiency and comfort: results of the design and evaluation activities within the OFFICE project. Building and Environment, 37(2002): 569–574.

IEA (2000). Daylight in Buildings: A Source Book on Daylighting Systems and Components. A Report of IEA SHC Task 21, ECBCS Annex 29. 1st edition, International Energy Agency, Washington.

IEA (2006). LIGHT'S LABOUR'S LOST Policies for Energy-efficient Lighting. International Energy Agency, OECD.

IES (2010). Guideline for the application of general illumination ("white") light-emitting diode (LED) technologies. New York, N.Y: Illuminating Engineering Society of North America.

Ihm P, Nemri A & Krarti M (2009). Estimation of lighting energy savings from daylighting. Building Environ., 44(3): 509-514. DOI: 10.1016/j.buildenv.2008.04.016.

Itani T, Ghaddar N & Ghali K (2013). Strategies for reducing energy consumption in existing office buildings. Int. J. Sustainable Energy, 32: 259-275. DOI: 10.1080/14786451.2011.622765.

Janda K (2009). Worldwide status of energy standards for buildings: a 2009 update. . ECEEE 2009 Summer Study, Act! Innovate! Deliver! Reduce Energy Demand Sustainability.

Jennings J D, Rubinstein F M, DiBartolomeo D & Blanc S L (2000). Comparison of control options in private offices in an advanced lighting controls testbed submitted to the offices. Illuminating Eng. Society, 29: 39-60. DOI: 10.1080/00994480.2000.10748316.

Johnsen K, Rasmussen H F, Iversen A, Fischer C, Larsen C P, & Traberg-Borup S (2009). Kontorbelysning baseret på energieffektive arbejdslamper. Hoersholm, Denmark: Statens Byggeforskningsinstitut.

Juslén H, Wouters M & Tenner A (2007). The influence of controllable task-lighting on productivity: A field study in a factory. Applied Ergonomics, 38: 39-44. DOI: 10.1016/j.apergo.2006.01.005.

Kobav M B & Bizjak G (2010). Long term study: Energy savings obtained with use of daylight sensor and dimming ballasts. Proceedings of the CIE Lighting Quality and Energy Efficiency, (CLQ’ 10), Vienna, Austria, pp: 618-621.

Koyle B & Papamichael K (2010). Dual-loop photosensor control systems: Reliable, cost-effective lighting control for skylight applications. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, (ASSE’ 10), Pacific Grove, California, pp: 157-166.

Krarti M (2000). Energy audit of building systems: an engineering approach. 1st ed. Boca Raton: CRC Press LLC.

Krarti M, Erickson P M & Hillman T C (2005). A simplified method to estimate energy savings of artificial lighting use from daylighting. Building and Environment, 40(6): 747-754.

Labayrade R & Avouac P (2013): Visual quality assessment of LED spots in comparison to low-voltage halogen spots. In: Proceedings of CIE Centenary Conference "Towards a New Century of Light", 348-377. Vienna: CIE Central Bureau (x038).

Lee E S & Selkowitz S E (2006). The New York times headquarters daylighting mockup: Monitored performance of the daylighting control system. Energy Buildings, 38: 914-929. DOI: 10.1016/j.enbuild.2006.03.019.

Lee H (2000). Verification of electrical energy savings for lighting retrofits using short- and long-term monitoring. Energy Conversion and Management, 41(18), 1999-2008.

Lehman B, Wilkins A J, Berman S M, Poplawski M E & Miller N J (2011). Proposing measures of flicker in the low frequencies for lighting applications. Proceedings of the Energy Conversion Congress and Exposition, Sept.17-22, IEEE Xplore Press, Phoenix, pp: 2865-2872. DOI: 10.1109/ECCE.2011.6064154. also published in Leukos 7 (3), S. 189–195.

Li D H, Lam T N & Wong S L (2006). Lighting and energy performance for an office using high frequency dimming controls. Energy Conversion Manage, 47: 1133-1145. DOI: 10.1016/j.enconman.2005.06.016.

Loe D (2009). Energy efficiency in lighting - considerations and possibilities. Lighting research and technology, 41, 209-218.

Loe D (2003). Energy efficiency in lighting - an overview. London, UK: Action Energy, Society of light and lighting, Editor.
Lopez-Paleo & Negron (2013)

Love J (1998). Manual switching patterns in private offices. Lighting Res. Technol., 30: 45-50. DOI: 10.1177/096032719803000107.

Mahdavi A, Mohammadi A, Kabir E & Lambeva L (2008). Occupants' operation of lighting and shading systems in office buildings. J. Building Performance Simulation, 1: 57-65. DOI: 10.1080/19401490801906502.

Mahlia T, Abdul Razak H & Nursahida M (2011). Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. Renewable and Sustainable Energy Reviews, 15(2011): 1125-1132.

Mahlia T, Said M, Masjuki H & Tamjis M (2005). Cost-benefit analysis and emission reduction of lighting retrofits in residential sector. Energy and Buildings, 37(6): 573–578.

Masoso O & Grobler L (2010). The dark side of occupants behaviour on building energy use. Energy and Buildings, 42(2): 173–177. DOI: 10.1016/j.enbuild.2009.08.009.

Menezes A C, Cripps A, Bouchlaghem D & Buswell R (2012). Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. Applied Energy, 97.

Mills E (2005). Environment – the specter of fuel-based lighting. Science, 308 (5726): 1263-1264.

Moore T, Carter D J & Slater A I (2003). Long-term patterns of use of occupant controlled office lighting. Lighting Res. Technol., 35: 43-57. DOI: 10.1191/1477153503li061oa.

Moore T, Carter D J & Slater A I (2002). User attitudes toward occupant controlled office lighting. Lighting Res. Technol., 34: 207-219. DOI: 10.1191/1365782802lt048oa.

Moore T, Carter D J & Slater A I (2001). A comparative study of user opinion in offices with and without individually controlled lighting. Proceedings of the 9th European Lighting Conference Lux Europa, (ELC' 01), Reykjavik, Iceland.

Motta Cabrera D F & Zareipour H (2013). Data association mining for identifying lighting energy waste patterns in educational institutes. Energy and Buildings, 62: 210-216.

Mucklejohn S A, Whittaker A L & Gore J (2013). Unrevealing efficacy, maintenance and lighting energy for the end user. Proceedings of the CIE Centenary Conference, (CC' 13), Paris, France.

Nair M G, Ramamurthy K & Ganesan A R (2013). Classification of indoor daylight enhancement systems. Lighting Res. Technol., 46: 245-267. DOI: 10.1177/1477153513483299.

Navigant Consulting, Inc. (2012). Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part I: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps. Department Energy. online: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf

Newsham G R, Mancini S & Marchand R G (2008). Detection and acceptance of demand-responsive lighting in offices with and without daylighting. LEUKOS: J. Illuminating Eng. Society North Am., 4: 139-156. DOI: 10.1582/LEUKOS.2007.004.03.001.

Onaygil S & Guler O (2003). Determination of the energy saving by daylight responsive lighting control system with an example from Istanbul. Building Environ., 38: 973-977. DOI: 10.1016/S0360-1323(03)00034-9.

Osterhaus W (2014). Daylight and electric light monitoring at Horsens Hall in Denmark. Internal report, IEA Task 50 Advanced Lighting Solution for Retrofitting Buildings.

Perez-Lombard L, Ortiz J & Pout C (2013). A review on buildings energy consumption information. Energy and Buildings, 40(2008): 394–398.

Plympton P, Conway S & Epstein K (2000). Daylighting in schools: improving student performance and health at a price schools can afford. Golden, CO: National Renewable Energy Laboratory (NREL).

Polimeni J, Mayumi K, Giampietro M & Alcott B (2007). The Jevons Paradox and the Myth of Resource Efficiency Improvements. Routhledge, Earthscan Research Edition.

Poplawski M E & Miller N M (2013). Flicker in solid-state lighting: Measurement techniques, and proposed reporting and application criteria. Proceedings of CIE Centenary Conference "Towards a New Century of Light". Vienna: CIE Central Bureau (x038), pp. 188–202.

Porritt J, Tulej S & Mucklejohn S A (2013). The rebound effect-an overview of the implications for lighting energy. Proceedings of the CIE Centenary Conference, Paris, France.

Rea M S (1996). Essay by invitation. Lighting Design and Application, 26: 15-16.

Rea M S (2010). Energy-efficient lighting. Energy efficient lighting in a human perspective. Proccedings of conference CEEBEL (Centrum för energieffektiv belysning), Katrineholm, Sweden.

Rea M S, Bullough J D & Akashi Y (2009). Several views of metal halide and high-pressure sodium lighting for outdoor applications. Lighting Res. Technol., 41: 297-320. DOI: 10.1177/1477153509102342.

Richman E E, Dittmer A L & Keller J M (1995). Field Analysis of Occupancy Sensor Operation: Parameters Affecting Lighting Energy Savings. Illuminating Engineering Society of North America, 25.

Ryckaert W R, Roelants I A A, van Gils M, Durinck G, Forment S, Audenaert J & Hanselaer P (2011): Performance of LED linear replacement lamps. In: CIE 197-2011 Proceedings of the 27th Session of the CIE. Sun City, South Africa, 9 - 16 July 2011. CIE. Vienna: CIE, pp. 643–652.

Ryckaert W R, Smet K A G, Roelandts I A A, van Gils M, Hanselaer P (2012). Linear LED tubes versus fluorescent lamps: An evaluation. Energy and Buildings 49, pp. 429–436. DOI: 10.1016/j.enbuild.2012.02.042.

Sanati, L. and M. Utzinger, 2013. The effect of window shading design on occupant use of blinds and electric lighting. Building Environ., 64: 67-76. DOI: 0.1016/j.buildenv.2013.02.013

Roisin B, Bodart M, Deneyer A & D'Herdt P (2008). Lighting energy savings in offices using different control systems and their real consumption. Energy Build., 40 (4): 514–523.

Rubinstein F, Colak N, Jennings J & Neils D (2003). Analyzing occupancy profiles from a lighting controls field study. Proceedings of CIE Session. San Diego, California.

Saunders H D & Tsao J Y (2012). Rebound effects for lighting. Energy Policy, 49: 477-478.DOI: 10.1016/j.enpol.2012.06.050.

Schuler M (1995). Building simulation in application: Developing concepts for low energy buildings through co-operation between architects and engineer. Proceedings of the Solar World Congress, International Solar Energy Society (ISES), Harare, Zimbabwe.

Spyropoulos G N & Balaras C A (2011). Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches—A case study,. Energy and Buildings, 43(4): 770-778.

Stefano J D (2000). Energy efficiency and the environment: the potential for energy efficient lighting to save energy and reduce carbon dioxide emissions at Melbourne University, Australia. Energy, 25: 823–839.

Sweatman P & Managan K (2010). Financing Energy Efficiency Building Retrofits: International Policy and Business Model Review and Regulatory Alternatives for Spain. Spain: Climate Strategy and Partners.

Säter M (2010). Psychological, physiological and visual responses to electromagnetic radiation in natural and artificial light. Proceedings of CIE Lighting Quality and Energy Efficiency", Vienna, Austria, pp. 422-425.

Simpson R (2003) Lighting Control: Technology and Applications. Focal Press, Oxford. ISBN-13: 978-0240515663.

Stafford A, Gorse C & Shao L (2011). The Retrofit Challenge: Delivering low carbon buildings. Centre for Low Carbon Futures, Leeds, UK.

To D W, Sing L K, Chung T M & Leung C S (2002). Potential energy saving for a side-lit room using daylight-linked fluorescent lamp installations. Lighting Res. Technol., 34: 121-132. DOI: 10.1191/1365782802li038oa.

Tsao J Y & Waide P (2010). The world's apetite for light : Empirical data and trends spanning three centuries and six continents. LEUKOS: J. Illuminating Eng. Society North Am., 6: 259-281.

U.S. Department of Energy (2010). DOE solid-state lighting caliper program. Summary of results: Round 11 of product Testing. Pacific Northwest National Laboratory.

U.S. DOE. (1997). International performance measurement and verification protocol, DOE Report. Washington DC: US Department of Energy.

Veitch J A & Newsham G R (1999). Lighting that benefits people and the environment. Newsletter of the International association for energy-efficient lighting (IAEEL), pp. 4-6.

Veitch J A & Newsham G R (2000). Preferred luminous conditions in open-plan offices: Research and practice recommendations. Lighting Res. Technol., 32: 199-212. DOI: 10.1177/096032710003200404.

Viitanen J, Lehtovaara J, Tetri E & Halonen L (2013). User preferences in office lighting: A case study comparing LED and T5 lighting. LEUKOS: J. Illuminating Eng. Society North Am., 9: 261-290.

Vogel K (2012). Strategies for Lighting Retrofits. LD+A, The magazine of the Illuminating Engineering.

Voss K, Löhnert G, Herkel S, Wagner A & Wambsganß M (2006). Bürogebäude mit Zukunft: Konzepte-Analysen-Erfahrungen. 2nd Edn., Solarpraxis, Berlin, Germany.

WBCSD (2007). Energy efficiency in buildings: Business realities and opportunities. Geneva, Switzerland: World Business Council for Sustainable Development.

Wen Y J & Agogino A M (2011). Personalized dynamic design of networked lighting for energy-efficiency in open-plan offices. Energy Buildings, 43(8): 1919-1924. DOI: 10.1016/j.enbuild.2011.03.036.

Williams A, Atkinson B, Garbesi K, Page E & Rubinstein F et al. (2012). Lighting controls in commercial buildings. J. Illuminating Eng. Society North Am., 8: 161-180.

Xu P P, Chan E & Qian Q K (2011). Success factors of energy performance contracting (EPC) for sustainable building energy efficiency retrofit (BEER) of hotel buildings in China. Energy Policy, 39: 7389–7398.

Zahnd P, Eloholma M & Halonen L (2007). Replacing fuel based lighting with light emitting diodes in developing countries: energy and lighting in rural Nepali homes. The Journal of the Illuminating Engineering Society of North America, 3(4).

Zhenjun M, Cooper P, Daly D & Ledo L (2012). Existing building retrofits: Methodology and state-of-the-art. Energy and Buildings, 55: 889-902.

Zmeureanu R & Peragine C (1999). Evaluation of interactions between lighting and HVAC systems in a large commercial building. Energy Conversion and Management, 40(11): 1229-1236.