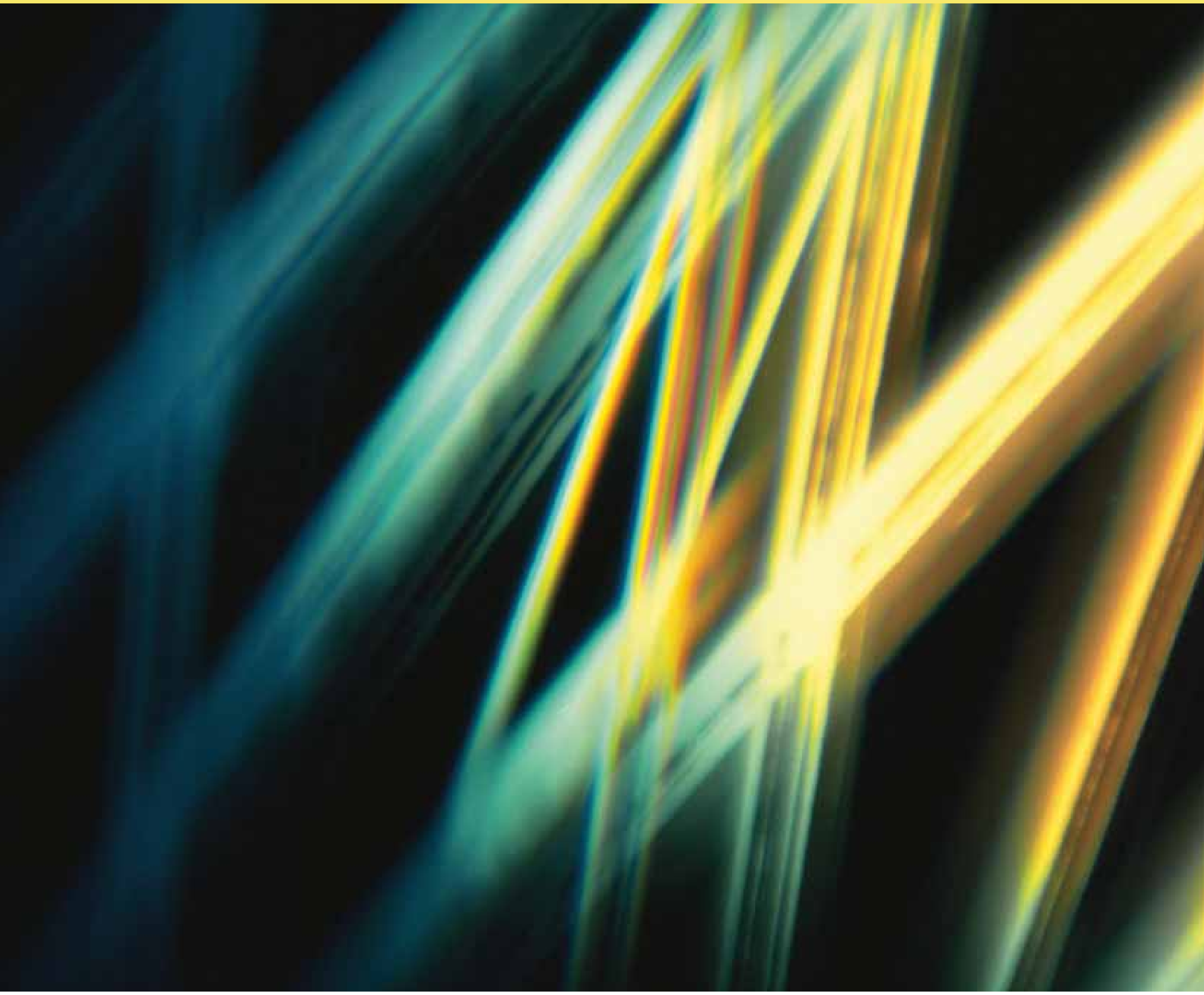
ANNEX 45

GUIDEBOOK ON ENERGY EFFICIENT ELECTRIC LIGHTING FOR BUILDINGS

SUMMARY REPORT

Espoo 2010
Edited by Liisa Halonen, Eino Tetri & Pramod Bhusal



Aalto University
School of Science
and Technology

Lighting Unit

International Energy Agency
Energy Conservation in
Buildings and Community
Systems Programme

Aalto University
School of Science and Technology
Department of Electronics
Lighting Unit

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GUIDEBOOK ON ENERGY EFFICIENT ELECTRIC LIGHTING FOR BUILDINGS

SUMMARY REPORT

Guidebook on Energy Efficient Electric Lighting for Buildings
IEA - International Energy Agency
ECBCS - Energy Conservation in Buildings and Community Systems
Annex 45 - Energy Efficient Electric Lighting for Buildings

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ABSTRACT

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. At the same time the savings potential of lighting energy is high, even with the current technology, and there are new energy efficient lighting technologies coming onto the market. Currently, more than 33 billion lamps operate worldwide, consuming more than 2650 TWh of energy annually, which is 19% of the global electricity consumption.

The goal of IEA ECBCS Annex 45 was to identify and to accelerate the widespread use of appropriate energy efficient high-quality lighting technologies and their integration with other building systems, making them the preferred choice of lighting designers, owners and users. The aim was to assess and document the technical performance of the existing promising, but largely under-utilized, innovative lighting technologies, as well as future lighting technologies. These novel lighting system concepts have to meet the functional, aesthetic, and comfort requirements of building occupants. The guidebook mostly concerns the lighting of offices and schools.

The content of the Guidebook includes an Introduction, Lighting energy in buildings, Lighting quality, Lighting and energy standards and codes, Lighting technologies, Lighting control systems, Life cycle analysis and life cycle costs, Lighting design and a survey on lighting today and in the future, Commissioning of lighting systems, Case studies, Technical potential for energy efficient lighting and savings, Proposals to upgrade lighting standards and recommendations, and a Summary and conclusions.

There is significant potential to the improve energy efficiency of old and new lighting installations even with the existing technology. The energy efficiency of lighting installations can be improved with the following measures:

- the choice of lamps. Incandescent lamps should be replaced by CFLs, infrared coated tungsten halogen lamps or LEDs, mercury lamps by high-pressure sodium lamps, metal halide lamps, or LEDs, and ferromagnetic ballasts by electronic ballasts
- the usage of controllable electronic ballasts with low losses
- the lighting design: the use of efficient luminaires and localized task lighting
- the control of light with manual dimming, presence sensors, and dimming according to daylight
- the usage of daylight
- the use of high efficiency LED-based lighting systems.

Annex 45 suggests that clear international initiatives (by the IEA, EU, CIE, IEC, CEN and other international bodies) are taken up in order to:

- upgrade lighting standards and recommendations
- integrate values of lighting energy density (kWh/m^2, a) into building energy codes
- monitor and regulate the quality of innovative light sources
- pursue research into fundamental human requirements for lighting (visual and non-visual effects of light)
- stimulate the renovation of inefficient old lighting installations by targeted measures

The introduction of more energy efficient lighting products and procedures can at the same time provide better living and working environments and also contribute in a cost-effective manner to the global reduction of energy consumption and greenhouse gas emissions.

PREFACE

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-eight IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

ENERGY CONSERVATION IN BUILDINGS AND COMMUNITY SYSTEMS

The IEA co-ordinates research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research.

The research and development strategies of the ECBCS Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Building Forum Think Tank Workshop, held in March 2007. The R&D strategies represent a collective input of the Executive Committee members to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy conservation technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in three focus areas of R&D activities:

- Dissemination
- Decision-making
- Building products and systems

THE EXECUTIVE COMMITTEE

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems:

ONGOING ANNEXES

Ongoing Annexes	
Annex	Title
55	Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO)
WG	Working Group on Energy Efficient Communities
54	Analysis of Micro-Generation & Related Energy Technologies in Buildings
53	Total Energy Use in Buildings: Analysis & Evaluation Methods
52	Towards Net Zero Energy Solar Buildings
51	Energy Efficient Communities
50	Prefabricated Systems for Low Energy Renovation of Residential Buildings
49	Low Exergy Systems for High Performance Buildings and Communities
48	Heat Pumping and Reversible Air Conditioning
47	Cost Effective Commissioning of Existing and Low Energy Buildings
46	Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
45	Energy-Efficient Future Electric Lighting for Buildings
44	Integrating Environmentally Responsive Elements in Buildings
5	Air Infiltration and Ventilation Centre

COMPLETED ANNEXES

Annex	Title
43	Testing and Validation of Building Energy Simulation Tools
42	The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM)
41	Whole Building Heat, Air and Moisture Response (MOIST-EN)
40	Commissioning of Building HVAC Systems for Improved Energy Performance
39	High Performance Thermal Insulation (HiPTI)
38	Solar Sustainable Housing
37	Low Exergy Systems for Heating and Cooling
36	Retrofitting in Educational Buildings - Energy Concept Adviser for Technical Retrofit Measures
36WG	Annex 36 Working Group Extension 'The Energy Concept Adviser'
35	Control Strategies for Hybrid Ventilation in New and Retorfitted Office Buildings (HybVent)
34	Computer-Aided Evaluation of HVAC System Performance
33	Advanced Local Energy Planning
32	Integral Building Envelope Performance Assessment
31	Energy Related Environmental Impact of Buildings
WG	Working Group on Indicators of Energy Efficiency in Cold Climate Buildings
30	Bringing Simulation to Application
29	Daylight in Buildings
28	Low Energy Cooling Systems
27	Evaluation and Demonstration of Domestic Ventilation Systems
26	Energy Efficient Ventilation of Large Enclosures
25	Real Time HEVAC Simulation
24	Heat, Air and Moisture Transport in Insulated Envelope Parts
23	Multizone Air Flow Modelling
22	Energy Efficient Communities
21	Environmental Performance of Buildings
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18	Demand Controlled Ventilating Systems
17	Building Energy Management Systems - Evaluation and Emulation Techniques
16	Building Energy Management Systems - User Interfaces and System Integration
15	Energy Efficiency in Schools
15WG	Working Group on Energy Efficiency in Educational Buildings
14	Condensation and Energy
13	Energy Management in Hospitals
12	Windows and Fenestration
11	Energy Auditing
10	Building HEVAC Systems Simulation
9	Minimum Ventilation Rates
8	Inhabitant Behaviour with Regard to Ventilation
7	Local Government Energy Planning
6	Energy Systems and Design of Communities
4	Glasgow Commercial Building Monitoring
3	Energy Conservation in Residential Buildings
2	Ekistics and Advanced Community Energy Systems
1	Load Energy Determination of Buildings

ACKNOWLEDGEMENTS

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The Summary Report and the Guidebook are the result of a joint effort by many countries. All those who have contributed to the project by taking part in the writing process or the numerous discussions are gratefully acknowledged. A list of the 20 participating and corresponding countries and members can be found in Chapter 14 of the Guidebook. Some of the Annex participants have taken more responsibility for collecting the information or writing the chapters in the Guidebook. They are:

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CONTENTS

1. INTRODUCTION

This publication is a Summary Report presenting and summarizing the contents of the Energy Efficient Electric Lighting for Buildings Guidebook.

The Guidebook is the achievement of the work done in the IEA ECBCS Annex 45.

HOW TO USE THE GUIDEBOOK

This Guidebook is the achievement of the work done in the IEA ECBCS Annex 45 *Energy Efficient Electric Lighting for Buildings*. The Summary of the Guidebook is available as a printed copy. The whole Guidebook is available on the internet (http://lightinglab.fi/IEAAnnex45, and http://www.ecbcs.org/). Additional information in the whole Guidebook includes Annex 45 newsletters, a brochure, appendices, etc.

This Guidebook is intended to be useful for lighting designers and consultants, professionals involved in building operation and maintenance, system integrators in buildings, end users/owners, and all others interested in energy efficient lighting.

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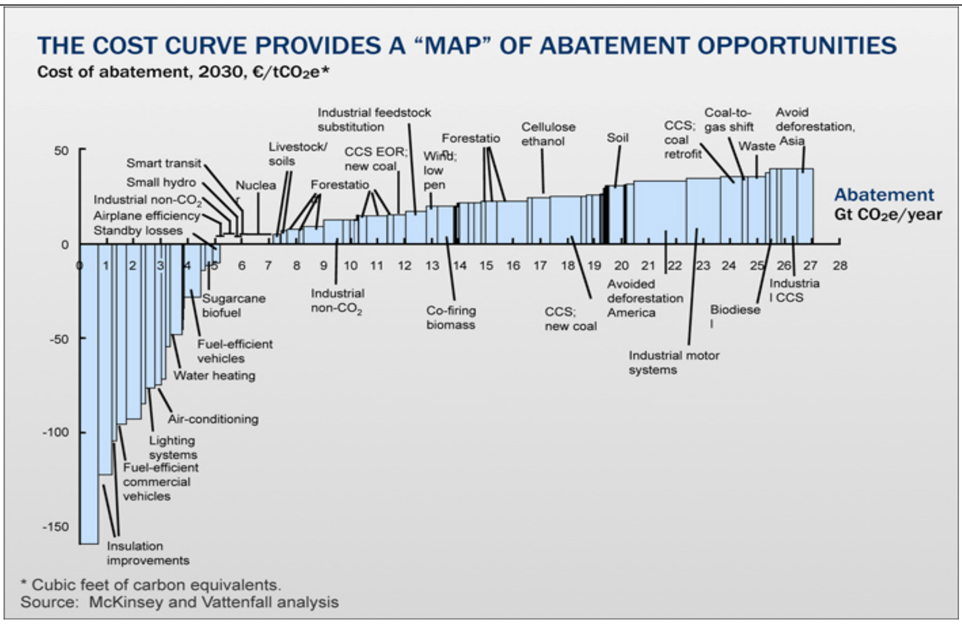
ABOUT ANNEX 45

BACKGROUND

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. In 2005 grid-based electricity consumption for lighting was 2650 TWh worldwide, which was about 19% of the total global electricity consumption. In addition, each year 55 billion liters of gasoline and diesel are used to operate vehicle lights. More than one-quarter of the world's population uses liquid fuel (kerosene oil) to provide lighting (IEA 2006). Global electricity consumption for lighting is distributed approximately 28% to the residential sector, 48% to the service sector, 16% to the industrial sector, and 8% to street and other lighting. In the industrialized countries, national electricity consumption for lighting ranges from 5% to 15%, on the other hand, in developing countries the value can be as high as 86% of the total electricity use (Mills 2002).

More efficient use of the energy used for lighting would limit the rate of increase of electric power consumption, reduce the economic and social costs resulting from the construction of new generating capacity, and reduce the emissions of greenhouse gases and other pollutants into the environment. At the moment fluorescent lamps dominate in office lighting. In domestic lighting the dominant light source is still the inefficient incandescent lamp, which is more than a century old. At present, important factors concerning lighting are energy efficiency, daylight use, individual control of light, quality of light, emissions during the life cycle, and total costs.

In different studies lighting has been found to be a cost-effective way to reduce CO_2 emissions. The Intergovernmental Panel on Climate Change for non-residential buildings concluded that energy efficient lighting is one of the measures with the largest potential and also providing the cheapest mitigation options. Among all the measures that have potential for CO_2 reduction in buildings, energy efficient lighting comes first largest in developing countries, second largest in countries with their economies in transition, and third largest in the industrialized countries (Ürge-Vorsatz, Novikova & Levine 2008).


THE COST CURVE PROVIDES A “MAP” OF ABATEMENT OPPORTUNITIES

Cost of abatement, 2030, €/tCO₂e*

* Cubic feet of carbon equivalents.

Source: McKinsey and Vattenfall analysis

Figure 1. Costs of different CO_2 abatement opportunities. (McKinsey 2008)

The global “carbon abatement cost curve” shows the lighting systems that have the cost-effective potential for reducing CO_2 emissions.

The report by McKinsey (2008) shows the cost-effectiveness of lighting systems in reducing CO_2 emissions: see Figure 1. The global "carbon abatement cost curve" provides a map of the world's abatement opportunities, ranked from the least-cost to the highest-cost options. This cost curve shows the steps that can be taken with technologies that either are available today or look very likely to become available in the near future. The width of the bars indicates the amount of CO_2 emissions that could be abated, while the height shows the cost per ton abated. The lowest-cost opportunities appear on the left of the graph.

OBJECTIVES AND SCOPE

The goal of Annex 45 was to identify and to accelerate the widespread use of appropriate energy efficient high-quality lighting technologies and their integration with other building systems, making them the preferred choice of lighting designers, owners, and users.

The aim was to assess and document the technical performance of the existing promising, but largely under-utilized, innovative lighting technologies, as well as future lighting technologies. These novel lighting system concepts have to meet the functional, aesthetic, and comfort requirements of building occupants.

The guidebook mostly concerns the lighting of offices and schools.

STRUCTURE

The work of Annex 45 was conducted during 2005-2009. The work of Annex 45 was divided into four subtasks.

Subtask A: Targets for Energy Performance and Human Well-Being

The objectives of this subtask were to set targets for energy use, lighting quality and human well-being. Another aim was to propose an upgrade of lighting recommendations and codes to improve the energy performance of indoor lighting installations. The performance criteria include the quality of light and user acceptance. The energy criteria include the energy efficiency of lighting, life cycle energy considerations, and the maintenance and control of light. The economic criteria include the initial costs and operating costs.

Subtask B: Innovative Technical Solutions

The objective of this Subtask was to identify, assess, and document the performance, energy, and economic criteria of the existing promising and innovative future lighting technologies. The purpose was to reduce the energy use of buildings

The work of IEA Annex 45 was conducted during 2005-2009. The work of Annex 45 was divided into four subtasks.

by investigating the saving potential by comparing the existing and future technologies and by providing information on concepts, products, and lighting solutions. The technical solutions cover connection devices (ballast, control gear, current sources, etc.), light sources, luminaires, and control techniques.

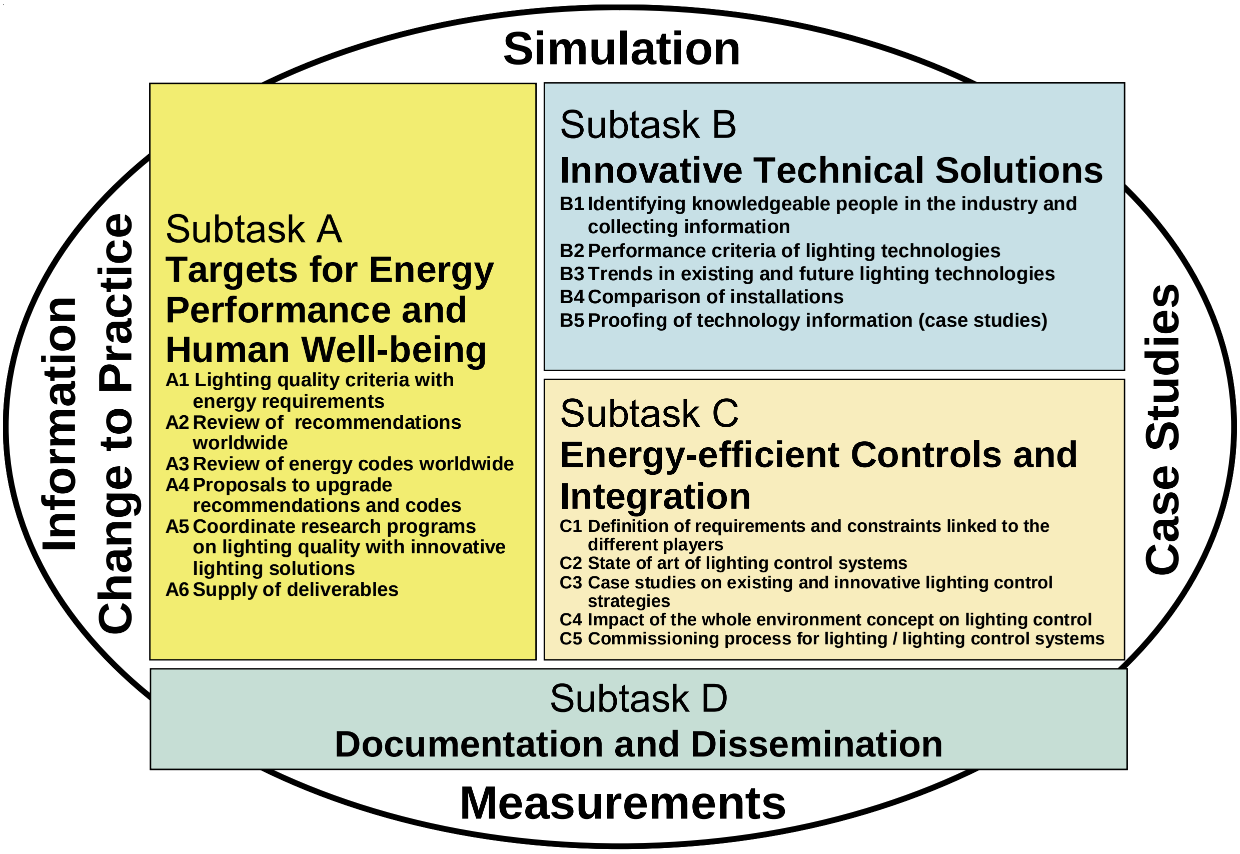
Subtask C: Energy-Efficient Controls and Integration

Subtask C focused on the optimal use of controls that enable energy savings to be made whilst the user (occupant, facility manager, operation and maintenance team) has the chance to adjust the electric lighting according to their personal needs and preferences, within acceptable building operation requirements.

Subtask D: Documentation and Dissemination

The objective of Subtask D was to compile and widely disseminate the results of Subtasks A, B, and C and to identify ways to influence energy policies and regulations in order to promote the use of energy efficient lighting. The aim of Subtask D was to improve current lighting practices in a manner that accelerates the use of energy efficient products, improves overall building performance, and enhances the occupants' environmental satisfaction.

Figure 2. Structure of Annex 45.



GLOBAL ENERGY CONSUMPTION

Energy is an essential commodity in our lives and the use of energy is increasing with industrial development. Energy security and the environmental impacts of energy use are major concerns worldwide.

Global energy consumption is rising continually every year. Total global primary energy consumption in 2006 was 472 quadrillion (10^{15}) British thermal units (BTUs) (1 BTU = 1055.1 joules), which is equivalent to 138330 TWh (EIA 2006).

Buildings, including residential, commercial, and institutional buildings, account for more than one third of primary global energy demand. The building sector is the biggest energy consumer among the three energy-using sectors: transportation, industry, and building. The global energy demand in the building sector has been increasing at an average of 3.5% per year since 1970 (DOE 2006). Urban buildings usually have higher levels of energy consumption per unit of area than buildings in rural areas. According to a projection by the United Nations, the percentage of the world's population living in urban areas will increase from 49% in 2005 to 61% by 2030 (UN 2005). Thus the growth of energy consumption in building is expected to continue in the long term as a result of population growth, and also as a result of urbanization.

Energy is consumed in buildings for different end use purposes: space heating, water heating, ventilation, lighting, cooling, cooking, and other appliances. Heating (space and water) is the leading energy consumer in the domestic and commercial building sectors in the EU followed by lighting. Lighting is the leading energy consumer (25%) in US commercial buildings, ahead of space cooling (13%), while lighting energy consumption is less than that of space heating, space cooling, and water heating in residential buildings (DOE 2009).

The global consumption of electricity has been increasing at a faster rate than the overall energy consumption because of the versatile nature of the production of electricity, as well as its consumption (EIA 2006). Worldwide electricity consumption in 2006 was 16378 TWh, which was 11.8% of the total primary energy consumption (EIA 2006). Because of losses in the generation process of electrical energy, the amount of input energy for electricity generation is much higher than the amount of electricity at its point of use. Worldwide electricity generation uses 40% of the world's primary energy supply (Hore-Lacy 2003).

Figure 3. Energy consumption by end use in US commercial and residential buildings. (DOE 2009)

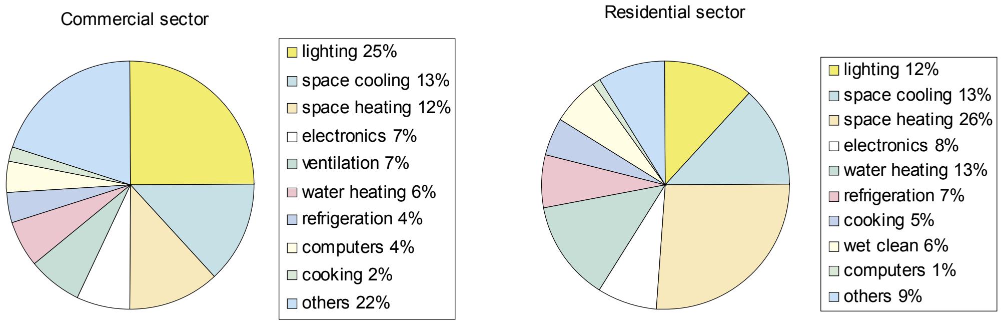
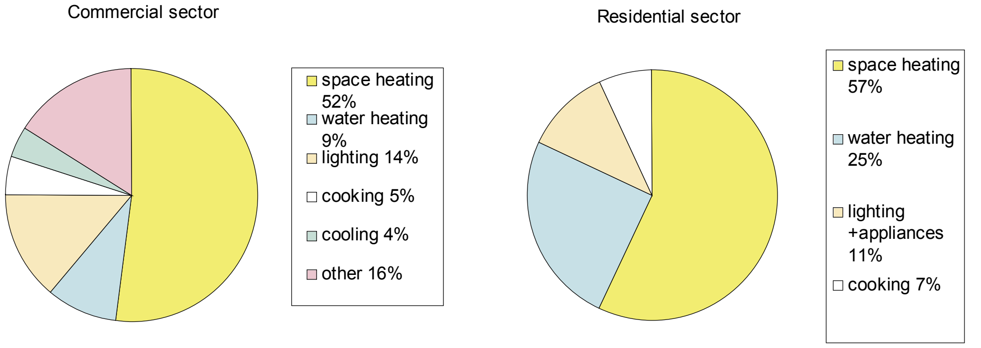


Figure 4. Energy consumption by end use in EU commercial and residential buildings. (EC 2007)



FACTS AND FIGURES ON LIGHTING ENERGY USAGE

Currently, more than 33 billion lamps operate worldwide, consuming more than 2650 TWh of energy annually, which is 19% of the global electricity concumption.

LIGHTING ENERGY USE

Globally, almost one fifth of the total amount of electricity generated is consumed by the lighting sector. The total electricity consumption of lighting is more than the global electricity produced by hydro or nuclear power plants, and almost the same as the amount of electricity produced from natural gas. More than 50% of the electricity used by lighting is consumed in IEA member countries, but this is expected to change in the coming years because of the increasing growth rate of lighting electricity use in non-IEA countries. (IEA 2006)

Almost half of the global lighting electricity (48%) is consumed by the service sector. The rest is distributed between the residential sector (28%), industrial sector (16%), and street and other lighting (8%). The share of electricity consumption of lighting of total electricity consumption varies from 5% to 15% in the industrialized countries, whereas the share is up to 86% (Tanzania) in developing countries (Mills 2002).

Lighting accounts for a significant part of electricity consumption in buildings. For example, in the US, over 10% of all energy is used for lighting in buildings (Loftness 2004). The amount of electricity used for lighting in buildings differs according to the type of buildings. In some buildings, lighting is the largest single category of electricity consumption.

The global residential lighting electricity consumption in 2005 was estimated by the IEA (IEA 2006) to be 811 TWh, which accounts for about 31% of total lighting electricity consumption and about 18.3% of residential electricity consumption. The household energy consumption for lighting varies greatly among different countries. The share of lighting electricity consumption of total electricity consumption in homes is very high in developing countries compared to OECD countries.

Residential lighting is dominated by the use of incandescent lamps but compact fluorescent lamps (CFLs) are taking their share gradually and LED lamps will do so in the future. The high purchase price of CFLs compared to incandescent lamps has been a major barrier to their market penetration, even though they last much longer, save energy, and have short payback periods.

Lighting is one of the single largest electricity users in most of the commercial buildings. In 2005, the global lighting electricity consumption of commercial buildings was equivalent to 43% of the total lighting electricity consumption and over 30% of total electricity consumption (IEA 2006). Offices, retail buildings, warehouses, and educational buildings were the largest users of lighting electricity in the commercial sector.

Most of the light delivered to commercial buildings is provided by fluorescent lamps. In OECD commercial buildings in 2005, linear fluorescent lamps provided 76.5% of the light output and the rest of the light output was provided by a mixture of incandescent, compact fluorescent, and HID lamps (IEA 2006). Similarly, fluorescent

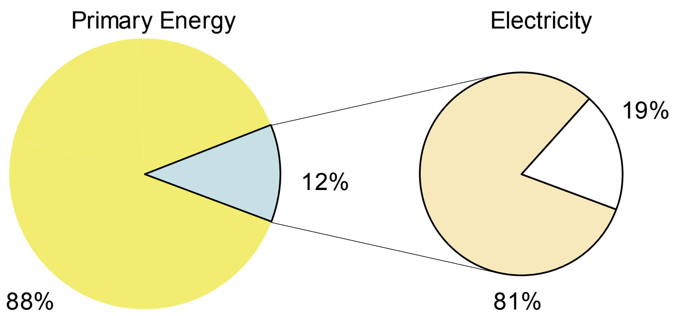


Figure 5. Global lighting energy use. (EIA 2006, IEA 2006)

The total lighting-related carbon dioxide (CO_2) emissions were estimated to be 1900 million tons (Mt) in 2005, which was about 7% of the total global CO_2 emissions from consumption and flaring of fossil fuels

Fuel based lighting used in developing countries is not only inefficient and expensive, but also results in 244 million tones of CO_2 to the atmosphere every year, which is 58% of the CO_2 emissions from residential electric lighting globally (Mills 2002).

lamps were the major light sources in US commercial lighting in 2001 (Navigant 2002).

Most of the electricity in industrial buildings is used for industrial processes. Although the share of lighting electricity of total electricity consumption in industrial buildings was only 8.7%, it accounted for about 18% of total global lighting electricity consumption in 2005 (IEA 2006).

Industrial lighting has the highest lumen efficacy among the three sectors: residential, commercial, and industrial. The electricity consumption for global industrial lighting was 490 TWh in 2005, which produced 38.5 Plmh of light with an average lumen efficacy of 79 lm/W (IEA 2006). This is due to the fact that most light in industrial buildings comes from efficient fluorescent lamps and HID lamps.

FUEL-BASED LIGHTING

Despite the dominance of lighting energy use by electric lighting, a significant amount of energy is also used in off-grid fuel-based lighting. More than one quarter of the world's population is still without access to electricity networks and uses fuel-based lighting to fulfill their lighting needs (Mills 2002). IEA (IEA 2006) estimates that the amount of energy consumed annually in fuel-based lighting is equivalent to 65.6 million tons of oil equivalent (Mtoe) of final energy usage.

The estimated amount of global primary energy used for lighting is 650 Mtoe. The fuel-based light sources include candles, oil lamps, ordinary kerosene lamps, pressurized kerosene lamps, biogas lamps, propane lamps, and resin-soaked twigs, as used in remote Nepali villages (Bhusal et al. 2007). In developing countries, the most widely used fuel-based lighting is ordinary wick-based kerosene lamps. For example, nearly 80 million people in India alone light their houses using kerosene as the primary fuel for lighting (Shailesh 2006).

IMPACT ON THE ENVIRONMENT

The environmental impacts of lighting are caused by the energy consumption of lighting, the materials used to produce lighting equipment, and the disposal of used equipment. Emissions during the production of electricity and also as a result of the burning of fuel in vehicle lighting and in fuel-based lighting are responsible for most of the lighting-related greenhouse gas emissions.

Lighting is one of the biggest causes of energy-related greenhouse gas emissions. The total lighting-related carbon dioxide (CO_2) emissions were estimated to be 1900 million tons (Mt) in 2005, which was about 7% of the total global CO_2 emissions from the consumption and flaring of fossil fuels (EIA 2007, IEA 2006). Energy efficient lighting reduces the lighting energy consumption and is a means to reduce CO_2 emissions.

Figure 6. Burning resin-soaked twigs as a light source in remote Nepali village.

3. LIGHTING QUALITY

Lighting quality cannot be expressed simply in terms of photometric measures, nor can there be a single universally applicable recipe for good-quality lighting.

Any attempt to develop an energy efficient lighting strategy should, as the first priority, guarantee that the quality of the luminous environment is as high as possible.

WHAT DOES LIGHTING QUALITY MEAN?

There is no complete definition of lighting quality. Lighting quality is dependent on several factors. It depends largely on people's expectations and past experiences of electric lighting. People who experience elementary electric lighting for the first time, for example, in remote villages in developing countries, have different expectations and attitudes towards lighting from office workers in industrialized countries. There are also large individual differences in what is considered comfortable lighting, as well as cultural differences between different regions.

Visual comfort is also highly dependent on the application; for example, lighting that is considered comfortable in an entertainment space may be disliked and regarded as uncomfortable in a working space (Boyce 2003). Lighting quality is much more than just providing an appropriate quantity of light. Other factors that are potential contributors to lighting quality include e.g. illuminance uniformity, luminance distributions, light color characteristics, and glare (Veitch and Newsham 1998).

There are many physical and physiological factors that can influence the perception of lighting quality. Lighting quality cannot be expressed simply in terms of photometric measures, nor can there be a single universally applicable recipe for good-quality lighting (Boyce 2003, Veitch 2001). Light quality can be judged according to the level of visual comfort and performance required for our activities. It can also be assessed on the basis of the pleasantness of the visual environment and its adaptation to the type of room and activity. There are also long-term effects of light on our health, which are related either to the strain on our eyes caused by poor lighting or to the effects of light on the human circadian system.

A number of different approaches have been suggested to define lighting quality (Bear and Bell 1992, Loe and Rowlands 1996, Veitch and Newsham 1998, Boyce and Cuttle 1998). The definition that seems most generally applicable is that lighting quality is given by the extent to which the installation meets the objectives and constraints set by the client and the designer (Boyce 2003). In this way lighting quality is related to objectives such as enhancing the performance of relevant tasks, creating specific impressions, generating desired patterns of behavior, and ensuring visual comfort. The constraints may be set by the financial budgets and resources available, set time-lines for completing the project and possible predetermined practices and design approaches that need to be followed.

Lighting quality is also a financial issue. In an office environment, poor lighting conditions can easily result in losses in the productivity of the employees and the resulting production costs of the employer can be much higher than the annual ownership cost of lighting. In the search for highly efficient lighting schemes, it is essential to fully understand the detailed lighting specification of the given environment and integrate this knowledge into lighting design, offering a combination of energy performance and lighting quality.

Figure 7. LEDs are used today to provide lighting in versatile applications, ranging from the lighting of homes in developing countries to the lighting of office buildings.

The traditional judgement of lighting on the basis of visibility is not adequate for describing the complex, but undeniable, effects lighting can have on humans. This opens up windows for designing healthier living and working conditions for people in the future.

LIGHTING QUALITY ASPECTS

VISUAL ASPECTS

One of the major aspects of the lighting practice and recommendations is to provide adequate lighting for people to carry out their visual tasks. Visual performance is defined by the speed and accuracy of performing a visual task. Light levels that are optimized in terms of visual performance should guarantee that the visual performance is reachable well above the visibility threshold limits.

Ensuring adequate and appropriate light levels is only an elementary step in creating good-quality luminous and visual environments. Lighting that is adequate for visual tasks should also avoid visual discomfort. In addition to adequate lighting for visual tasks, light distribution in a space, the limitation of glare, and the light color characteristics of the lighting that is provided are of great importance in good-quality lighting. Attention also needs to be paid to the elimination of veiling reflections and to the formation of shadows in the space.

The color characteristics of light in space are determined by the spectral power distribution (SPD) of the light source and the reflectance properties of the surfaces in the room. The color of light sources is usually described by two properties, namely the correlated color temperature (CCT) and general color rendering index (CRI). The general CRI of the CIE has its limitations. The shortcomings of the CRI may become evident when applied to LED light sources as a result of their peaked spectra.

Room surface reflectances are an important part of a lighting system and affect both the uniformity and energy usage of lighting. Compared to a conventional uniform office lighting installation with fluorescent lamps, LEDs provide opportunities to concentrate light more on actual working areas and to have light where it is actually needed. This provides opportunities to increase the energy efficiency of lighting in the future.

Glare is caused by high luminances or excessive luminance differences in the visual field. In indoor lighting the main concern is about discomfort glare. This is visual discomfort in the presence of bright light sources, luminaires, windows, or other bright surfaces.

LEDs are small point sources with high intensities and arrays of these individual sources can form luminaires with very different shapes and sizes. In illuminating the space with LEDs, special care has to be taken to avoid glare.

PSYCHOLOGICAL ASPECTS

People perceive their luminous environment through their eyes, but they process this information with their brain. Light scenes are therefore judged in connection with references and expectations. Variations of luminances and colours can strengthen attractiveness, trigger emotions, and affect our mood, the impact of lighting depending much on individuals and their state of mind. A lighting installation that does not meet the user's expectations can be considered unacceptable even if it provides the conditions for adequate visual performance. Unacceptable lighting conditions may impact on task performance and thus productivity through motivation. (Boyce 2003, Gligor 2004)

NON-VISUAL ASPECTS

Light also has effects that are fully or partly separated from the visual system. These are called the non-visual, non-image-forming (NIF) or biological effects of light and are related to human circadian photoreception.

The discovery of the novel third photoreceptor, the intrinsically photoreceptive retinal ganglion cell (ipRGC), in 2002 has aroused huge interest in both the circadian biology and lighting research communities (Berson et al. 2002). The ipRGC has been noticed to be the main photoreceptor responsible for entraining humans to the environmental light/dark cycle, along with other biological effects. It represents a missing link in describing the mechanism of biological effects as controlled by light and darkness. The human biological clock drives most daily rhythms in physiology and behavior. Light is thought of as an external cue that entrains the internal clock to work properly. Besides the shifting of the phase of the endogenous clock by light, there is evidence of the involvement of the ipRGC in pupillary reflex, alertness, mood, and human performance (Dacey et al. 2005, Duffy and Wright 2005, Whiteley et al. 1998).

With appropriate lighting the ability to perform visual tasks can be improved and visual discomfort can be avoided. This can provide conditions for better visual and task performance and finally productivity.

The biological effects of light and their effects on human performance are not yet very well known. A considerable amount of research work is still required before we can understand the non-visual effects of light and consider them in lighting practice. Research work is needed to generate an improved understanding of the interaction of the effects of different aspects of lighting on behavioral visual tasks and cortical responses and on how the biological effects of lighting could be related to these responses.

LIGHTING AND PRODUCTIVITY

Lighting should be designed to provide people with the right visual conditions that help them to perform visual tasks efficiently, safely, and comfortably. The luminous environment acts through a chain of mechanisms on human physiological and psychological factors, which further influence human performance and productivity.

The effect of lighting on productivity is ambiguous. The difficulty in finding the relations between lighting and productivity is that there are several other factors that simultaneously affect human performance. These factors include motivation, the relationships between the workers and the management, and the degree of personal control over the working conditions (Boyce 2003). With appropriate lighting the ability to perform visual tasks can be improved and visual discomfort can be avoided. This can provide conditions for better visual and task performance and, ultimately, productivity. The difficulty of field studies in working environments is the degree of experimental control required. In making changes to lighting, which lighting aspects are changed and whether there are other factors that are simultaneously changed in the working conditions need to be controlled and analyzed.

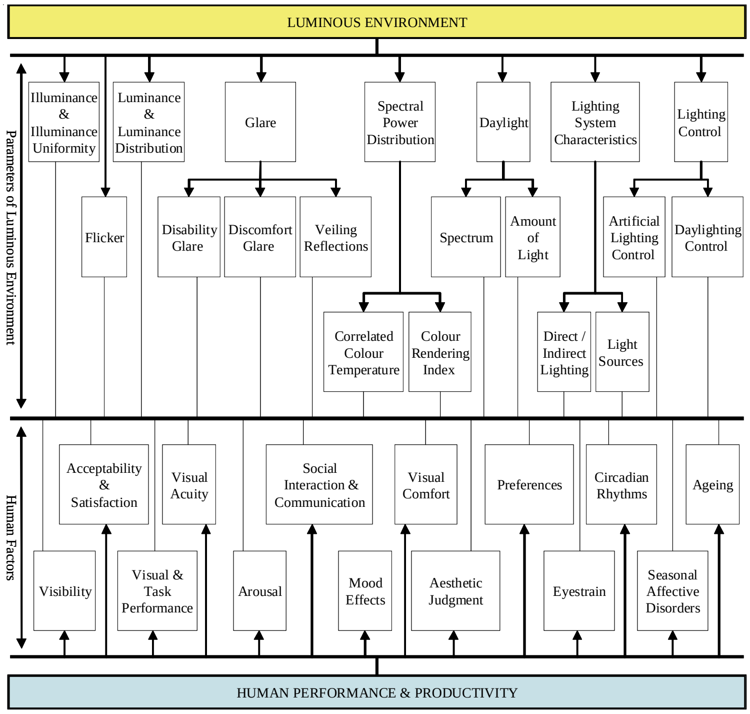


Figure 8. Luminous environment and human performance. (Gligor 2004)

WORLDWIDE LIGHTING STANDARDS

The CIE has published several recommendations for indoor lighting and has contributed to a joint ISO-CIE standard (ISO 8995-1) concerning indoor workplaces. The recommendations of the CIE have been interpreted in different manners in different countries.

The major international organization in charge of coordinating the management of standards, recommendations and technical reports in the field of lighting is the Commission Internationale de l'Eclairage (CIE). The CIE has published several recommendations for indoor lighting and has contributed to a joint ISO-CIE standard ISO 8995-1 (CIE, 2001/ISO 2002) concerning indoor workplaces.

The recommendations of the CIE have been interpreted in different manners in different countries. Hence some discrepancies exist among lighting recommendations worldwide. Furthermore, in North America, the Illuminating Engineering Society of North America (IESNA) is active in developing its own recommendations. The best known documents are the IES Lighting Handbooks which are regularly updated. The working groups of the IESNA have their own references and it is quite typical that some approaches differ from those of the CIE. For example, IESNA uses the term Visual Comfort Probability (VCP) for glare rating issues (Rea 2000), whereas the CIE glare rating is called the Unified Glare Ratio (UGR) (CIE 1995).

Comparisons of the lighting recommendations worldwide are presented in the Chapter 4.1 of the Guidebook. Most lighting recommendations include specifications on:

- minimum illuminance levels on a work plane
- minimum illuminance when working on computers
- minimum illuminance in the surroundings
- luminance ratios near task areas
- glare rating
- luminances on the ceiling and shielding angle
- indoor surface reflectance.

The comparison is useful in identifying the potential for amending these standards, considering the growing need for the increasing energy efficiency of lighting. The review focused on office buildings.

The summary of the lighting recommendations presented in the Guidebook indicates the following.

- Minimum values of illuminance on work planes for office work, drawing, and conference rooms vary from 200 to 500 lx, which leads to a total discrepancy of lighting power of 1:2.5 if the lighting uniformities delivered in the rooms are identical.
- Recommendations concern minimum horizontal and vertical illuminance values. The recommendations do not take into account the luminances of computer screens.
- Ratios of luminance in the field of vision are rather consistent and similar to the CIE recommendations.
- Glare ratings use either the Unified Glare Ratio (UGR) of the CIE or the Visual Comfort Probability (VCP) of the IESNA. These specifications are rather consistent.
- Ceiling luminance and shielding seem to be rather consistent. This is essential with the development of direct/indirect luminaires. However, no specification takes into account the risk of overhead glare, which is an issue under discussion at the CIE.

ENERGY CODES AND POLICIES

The measures recommended by the International Energy Agency to the G8 related to lighting energy efficiency are a) the use of best practice lighting and the phasing out of incandescent lamps, and b) ensuring least-cost lighting in non-residential buildings and the phasing out of inefficient fuel-based lighting.

Summaries of the lighting energy policies, codes, standards, and lighting-related energy programs in different countries and regions around the world are presented in Chapter 4.2 - 4.4 of the Guidebook.

In the European Union, many directives, regulations and other pieces of legislations, related to lighting energy use are in force or under development. The most important directives and other pieces of legislations at the European level regarding the lighting sector are:

- EuP, Energy-using Products Directive (EC 2005) which was recast in 2009 by a directive on ecodesign requirements for energy-related products.
- Ballast Directive (EC 2000)
- EPBD, Energy Performance of Buildings Directive (EC 2002)
- ESD, Energy Services Directive (EC 2006)
- EEL, Energy Efficiency Label (EC 1998)

In the United States, the Energy Policy Act (EPAct 2005), Energy Independence and Security Act (EISA 2007), and American Recovery and Reinvestment Act (ARRA 2009) require different standards and programs for energy efficient lighting in buildings.

China has set a target of improving energy efficiency in its 11th Five-Year Plan (Wang 2009). The key goal is that energy intensity relative to the country's gross domestic product should be reduced by 20% from 2005 to 2020. To achieve this goal, targets are set for the energy performance of buildings including lighting.

Similarly, Brazil and South Africa have laws and standards to improve the energy efficiency of buildings. These laws set out the general requirements for improving energy efficiency in all types of buildings. The South African energy strategy, created in 2004, aims to replace incandescent lamps in government buildings by energy efficient lighting by 2012.

Energy efficiency policy recommendations made by the International Energy Agency (IEA) to the G8 cover 25 fields of action across seven priority areas: cross-sectoral activity, buildings, appliances, lighting, transport, industry and power utilities. It is noted that making savings by adopting efficient lighting technology is very cost-effective and that buildings account for about 40% of the total energy used in most countries. The fields of action of lighting are suggested as:

- best practice lighting and the phasing out of incandescent lamps
- ensuring least-cost lighting in non-residential buildings and the phasing out of inefficient fuel-based lighting.

Examples of lighting-related energy programs are ENERGY STAR in the USA and Top Runners in Japan. In both programs target values for energy efficiency are set for products.

Table 1. European Commission regulation 244/2009 with regard to ecodesign requirements for non-directional household lamps: the regulation will phase out inefficient lamps from the European market.

Stage	Date	Lamps to be banned (i.e. can not be "placed on the market" anymore)
1	1 Sept 2009	All non-clear lamps not equivalent-class A (any power)
		Clear lamps equivalent-class D, E, F, G with luminous flux ≥ 950 lm (e.g. power ≥ 100 W incandescent lamps, 230 V >60 W halogen lamps)
		Clear lamps with luminous flux < 950 lm equivalent-class F, G
2	1 Sept 2010	Clear lamps equivalent-class D, E, F, G with luminous flux ≥ 725 lm (e.g. power≥ 75 W incandescent lamps, 230 V =60 W halogen lamps)
		Clear lamps with luminous flux < 725 lm equivalent-class F, G
3	1 Sept 2011	Clear lamps equivalent-class D, E, F, G with luminous flux ≥ 450 lm (e.g. power ≥ 60 W incandescent lamps, 230 V ≥ 40 W halogen lamps)
		Clear lamps with luminous flux < 450 lm class F, G or equivalent
4	1 Sept 2012	Clear lamps equivalent-class D, E, F, G any power
5	1 Sept 2013	Enhanced functionality requirements
6	1 Sept 2016	Poor efficiency halogens (C)

The best lamp, if coupled with poor or incompatible luminaire or ballast, loses most of its advantages. Combination of a good lamp, ballast and a luminaire but in a wrong installation may not meet the user needs or provide the lighting service in an inefficient way.

CHARACTERISTICS OF LIGHT SOURCES

Artificial lighting is being used more and more in the world. The usage is quite non-homogeneous. In developing countries, we can still find the widespread use of fuel-based lighting but nowadays the situation is changing and the demand for electricity-based lighting is growing. Electricity-based lighting accounts for about 19 % of the world's total electricity use. Improvements in the energy efficiency of lighting can have a great influence on global energy consumption and, indirectly, on the environment.

To provide the artificial lighting that is needed, it is important to search for the technological solutions which meet human needs with the lowest impact on the environment during operation, when most of the impacts take place. The environmental impacts also include the production and disposal of lamps and related materials.

Artificial lighting is based on systems: lamps, ballasts, starters, drivers, luminaires, and controls. Ballasts are needed for discharge lamps to connect the lamp to the mains. Lamps, ballasts, and starters are mounted in the luminaire with the wiring and lamp bases, reflectors distribute and redirect the light emitted from the lamp and louvers shield the user from glare. The best lamp, if coupled with a poor or incompatible luminaire or ballast, loses most of its advantages. The combination of a good lighting system in a well-designed installation derives a strong advantage from control devices to drive the lighting system according to, for instance, the availability of daylight, and occupancy. In the case of new buildings the integration of daylight is important in order to reduce the energy consumption.

In this chapter (Chapter 5) of the Guidebook, an overview of the current technologies of light sources, luminaries, and ballasts is presented. The chapter also illustrates their potential and describes the trends of the most promising technology. Integral lighting systems that utilize daylight together with electrical lighting systems are also presented.

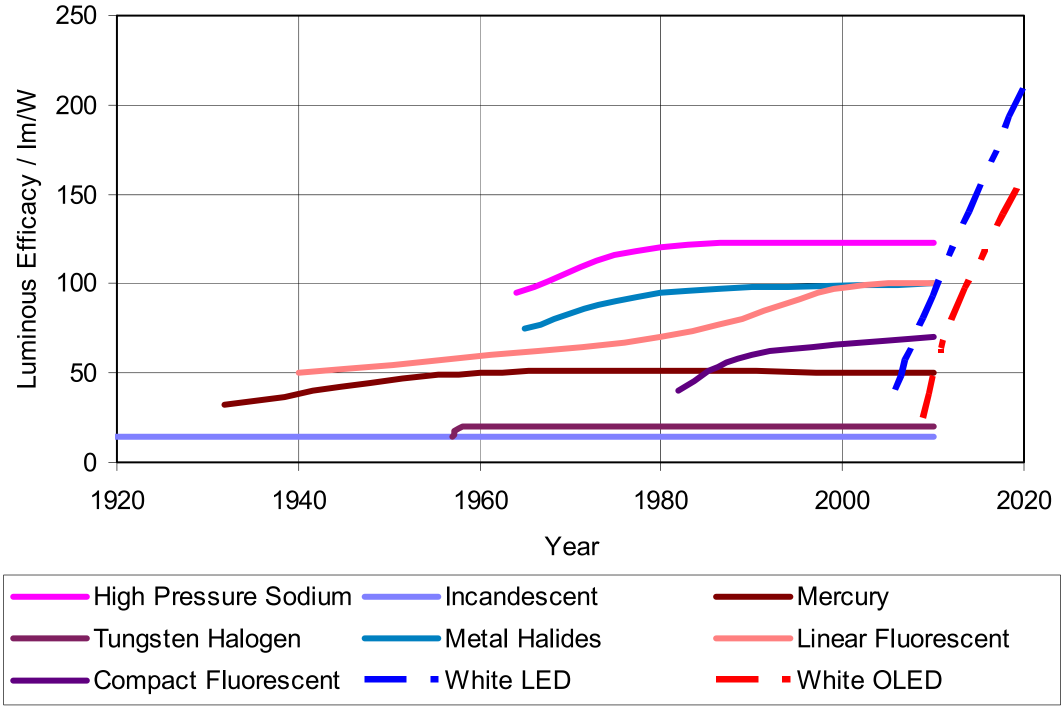
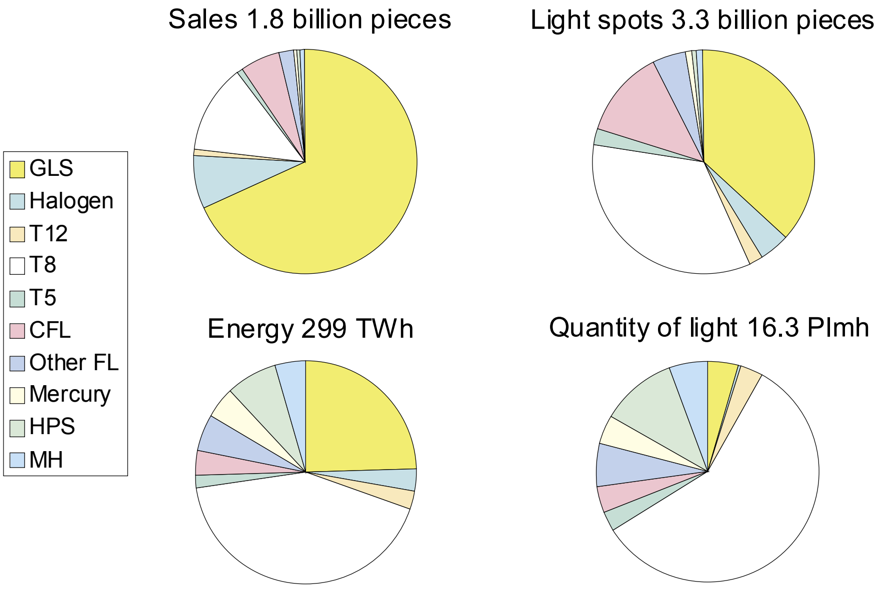


Figure 9. The development of luminous efficacies of light sources. (DOE 2010, Krames 2007)

Table 2. Lamp types and their typical characteristics.

Lamp type	Characteristics							
	Luminous efficacy (lm/W)	Lamp life h	Dimming control	Re-strike time	CRI	Cost of installation	Cost of operation	Applications
GLS	5-15	1000	excellent	prompt	very good	low	very high	general lighting
Tungsten halogen	12-35	2000-4000	excellent	prompt	very good	low	high	general lighting
Mercury vapour	40-60	12000	not possible	2-5 min	poor to good	moderate	moderate	outdoor lighting
CFL	40-65	6000-12000	with special lamps	prompt	good	low	low	general lighting
Fluorescent lamp	50-100	10000-16000	good	prompt	good	low	low	general lighting
Induction lamp	60-80	60000-100000	not possible	prompt	good	high	low	places where access for maintenance is difficult
Metal halide	50-100	6000-12000	possible but not practical	5-10 min	good	high	low	shopping malls, commercial buildings
High pressure sodium (standard)	80-100	12000-16000	possible but not practical	2-5 min	fair	high	low	Outdoor, streets lighting, warehouse
High pressure sodium (colour improved)	40-60	6000-10000	possible but not practical	2-6 min	good	high	low	outdoor, commercial interior lighting
LEDs	20-120	20000-100000	excellent	prompt	good	high	low	all in near future

Figure 10. EU member countries' lamp sales on 2004, the estimated number of light spots in use, the energy used by lamps, and the amount of light produced.



The future developments of the solid-state lighting technology are difficult to predict. However, the trend is towards the increasing and gradual adoption of this technology to replace conventional light sources, just as the transistor replaced the valve in the past.

SOLID-STATE LIGHTING (SSL)

Solid-state lighting (SSL) commonly refers to illumination where light-emitting diodes (LED) and organic light-emitting diodes (OLED) are used. Although there is still no official definition of solid-state lighting, the expression "solid-state" refers to a semiconductor crystal where charge carriers (electrons and holes) flow and originate photons (i.e. light) after radiative recombinations.

The history of commercially available LEDs started in the early 1960s with the first red LED, with its peak emission at 650 nm (Holonyak, Bevacqua 1962). Since then, LEDs have experienced fast technological development over the past four decades. Modern LED components cover peak wavelength regions from the ultraviolet to the infrared region.

White LEDs can be realized by mixing the emission of different colored LEDs or by the utilisation of phosphors. Phosphor-converted white LEDs are usually based on blue or ultraviolet LEDs. In the color mixing approach, usually only two colored LEDs are needed to produce white light. However, to achieve high color rendering properties, at least three colored LEDs are usually required.

The advantages of LEDs are:

- small size (heat sink can be big)
- good physical robustness
- long lifetime expectancy
- switching has no effect on life
- contain no mercury
- high luminous efficacy
- new luminaire design possibilities
- possibility of changing colors
- easy to dim.

Disadvantages of LEDs are:

- lack of standardization
- high price
- CRI can be low
- risk of glare as a result of small lamp size
- need for thermal management.

Similarly to inorganic light-emitting diodes, the organic light-emitting diode (OLED) promises the realization of highly efficient large-area light sources. Typically, an OLED is composed of one or several organic emissive materials sandwiched between two metal contacts. White OLEDs have been realized by piling three thin layers, emitting red, green, and blue light, respectively.

The main advantages of the OLED technology are the simplicity of their

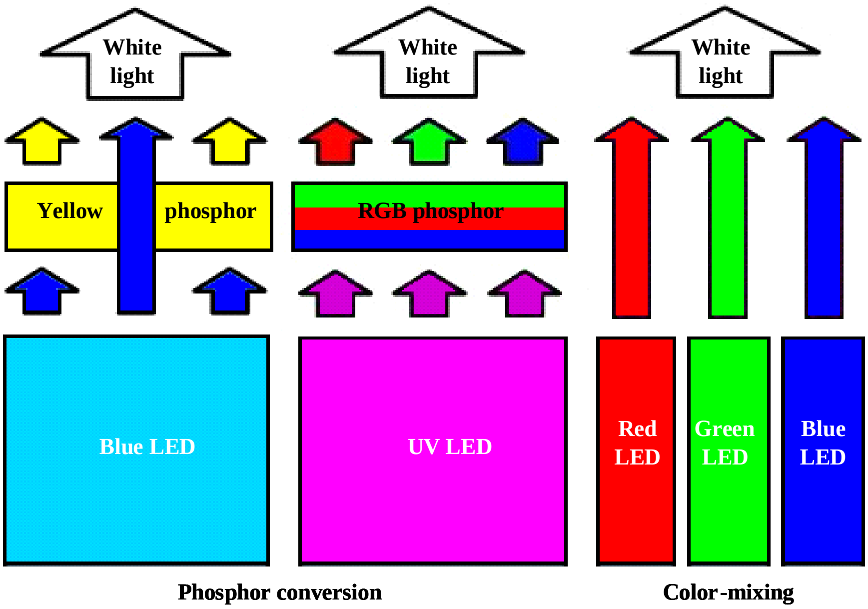


Figure 11. Schematic representation of the main approaches to creating white light using LEDs.

processing techniques, the availability of a wide range of organic luminescent materials and colors emitted, and the possibility of producing large and flexible surfaces. The disadvantages of the OLED technology are its low luminous efficacy and high price.

Further technological developments on electroluminescent light sources are forecast. These developments involve improvements in the efficiency and light output of the device and the cost of lumens per package. These developments will expand the possibilities of electroluminescent light sources being utilized in applications that were dominated until now by conventional lighting technologies.

LED ROADMAPS

The high energy-efficiency potential has been one of the main drivers for the fast technological development of LEDs during the last three decades. Currently, the main R&D trends in the LED technology are the improvement of their efficiency and the increase of their light output. The acceptance of solid-state lighting in niche applications such as horticultural lighting is dependent on future improvements in conversion efficiency and light output per package. The trend in LED light output and light cost is continuing to follow Haitz's law, according to which the evolution of red LEDs in terms of light output increases by a factor of 20 per decade, while the costs decrease by a factor of 10 (Haitz, Kish et al. 1999).

Theoretically, the LED technology can achive a conversion efficiency from electricity to light of 100%. Zukauskas et al. (2008) have also shown that, using phosphor-converted white LEDs, good color rendering can be attained at different color temperatures, while keeping luminous efficacies relatively high, i.e. 250 to 280 lm/W.

Table 3 shows LED package efficacy and luminaire efficiency projections. With an LED luminaire efficiency of 90% in 2020, and with an LED package efficacy of 243 lm/W (commercial cool white, color rendering index 70-80, CCT 4746-7040 K, current density 35 A/cm^2) LED luminaire efficacy would be 219 lm/W in 2020.

Figure 12. Haitz’s law, showing that every decade, the cost per lumen falls by a factor of 10, while the amount of light generated per LED package increases by a factor of 20.

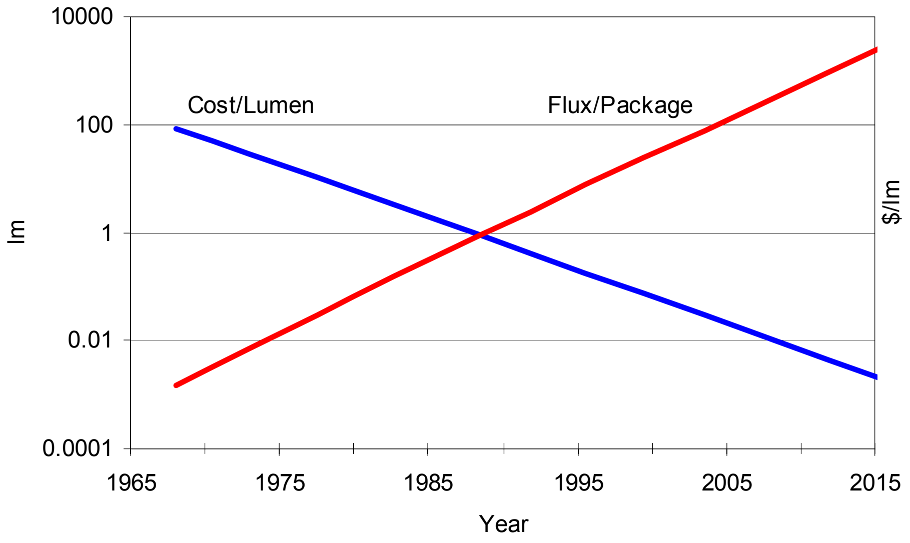


Figure 13. White LED package efficacy targets, laboratory and commercial. (DOE 2010)

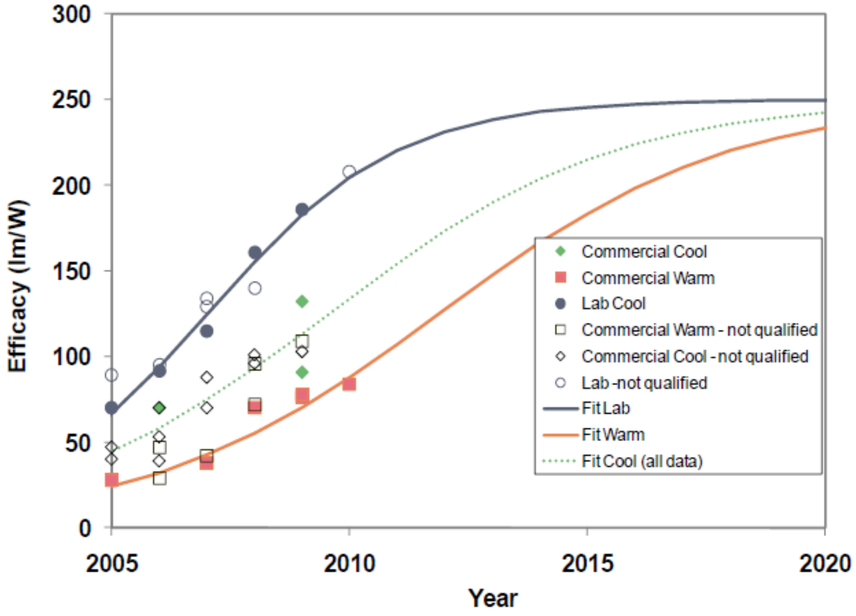


Table 3. Summary of LED luminaire performance and price projections. (DOE 2010)

Metric	2009	2010	2012	2015	2020
Package efficacy - commercial cool white (lm/W, 25 °C)	113	134	173	215	243
Cool white package price ($/klm)	25	13	6	2	1
Package efficacy - commercial warm white (lm/W, 25 °C)	70	88	128	184	234
Warm white package price ($/klm)	36	25	11	3.3	1.1
Thermal efficiency	87%	89%	92%	95%	98%
Efficiency of driver	86%	87%	89%	92%	96%
Efficiency of fixture	81%	83%	87%	91%	96%
Resultant luminaire efficiency	61%	64%	71%	80%	90%
Luminaire efficacy- commercial cool white (lm/W)	69	86	121	172	219
Luminaire efficacy- commercial warm white (lm/W)	43	56	91	147	211

6. LIGHTING CONTROL SYSTEMS

The main purpose of the use of lighting control systems is to reduce energy consumption while providing a productive visual environment. The lighting control system adopted should be able to allow the building operator to provide the right amount of light where and when it is needed.

The objective of lighting control systems and strategies is to provide optimal lighting for the tasks being performed using the most efficient light source suitable for application, and providing light only when and where it is needed. The main purpose of these systems is to reduce energy consumption while providing a productive visual environment.

Lighting control is a continuously-evolving matter because of the constant evolution of visual comfort and the increasing demand for lighting energy savings. The need for light control will depend on the lighting needs of thev zone being considered, the users' needs and the characteristics of the zone/area that is controlled. The Guidebook proposes a questionnaire in order to help the designer to identify the lighting control needs so that appropriate solutions can be adopted. The questionnaire, available in Appendix B of the Guidebook, provides information on:

- the different uses within the building
- the perception of the control barriers
- the control type needed
- the area that is controlled
- the flexibility and modularity of the lighting control system
- the maintenance scheme and needs.

The identification of the usages helps the designer to understand the way he has to design the installation. In a basic school, an On/Off system coupled with daylight dimming may be adequate but in some offices, it could be necessary to go one step further by integrating more advanced techniques. Similarly, asking the perception of the people on the barriers of lighting control may give information about the type and quality of lighting control system that can be used (basic On/Off system, advanced daylight dimming system, etc.).

An optimal system performance needs not only to reach a good performance with respect to saving electrical energy but also to be accepted by the end user. The end user may be disturbed by the operation of the system and disable it. A high level of user acceptance guarantees undisturbed operations and consequent energy savings.

OCCUPANT'S NEEDS TO CONTROL THE SYSTEM

Within the limits of comfort, it is difficult to define exactly what the occupant's needs and priorities are. They vary from one occupant to another. They also vary with time for the same occupant. For instance, some occupants can be concerned by energy savings, and some prefer a better algorithmic lighting scenes even if it requires more energy and generates higher costs. Therefore, it is recommended that the occupants should have the possibility to adapt the system's behaviour according to their will.

OCCUPANT'S NEEDS TO UNDERSTAND THE SYSTEM

The user acceptance of a lighting control system is better if the system and its working principle have been explained. On-site visits by practitioners and informal discussions with end-users showed that about 90% of them accept the operation of the system if they know/understand what its aims and working principles are. It has also been demonstrated that occupants react to a need (a specific condition) but do not necessarily react to the disappearance of this need. For example, if an occupant switches on the lights because of a sudden obstruction of the sun, the probability that he will switch them off under a high level of daylight level is low.

LIGHTING CONTROL SYSTEM MUST BE EASY TO USE

The usability of the system must be defined to address all the types of users (building operators, occupants, facility managers, maintenance teams, installers, etc.). Usability expresses the quality of a user's experience when interacting with a system. The combination of factors affecting the user's experience with the product or system have to be considered.

The coupling of different lighting control strategies results in the greatest energy gains; for instance, daylight harvesting and real occupancy achieves gains of more than 50% gains. These gains are the function of the room and window sizes, the orientation of the building, and the sensor position.

LIGHTING CONTROL STRATEGIES

A manual switch to turn luminaires on or off is the most widely used and simplest lighting control system.This kind of control is not robust enough with respect to energy efficiency. It relies solely on the behavior of the occupants, who are not necessarily concerned about energy savings. Lighting control strategies provide additional cost savings through real-time pricing and load shedding. Reducing lighting power during electricity peak-use periods when energy rates are at the highest can also be achieved through a Lighting Management System (LMS).

The energy efficiency of lighting control systems depends on the strategies implemented, as presented below.

PREDICTED OCCUPANCY CONTROL

The predicted occupancy control strategy (POCS) is used to reduce the operating hours of the lighting installation. It generates energy savings by turning lighting on and off according to preset daily time schedule. Schedules usually vary on a daily basis, according to the occupancy of the building. By automatically turning off lights at a preset time, the systems assist building operators/facility managers to avoid to leaving the luminaires to burn during unoccupied hours, mainly at night and at weekends. Different schedules can be programmed for different areas of the building on the basis of the occupant needs.

REAL OCCUPANCY CONTROL

Real occupancy control strategy (ROCS) limits the operating time of the lighting system on the basis of the occupancy time of a dedicated space. The system detects whether the room is occupied and then turns the lights on. If the system does not detect any activity in the room, it considers the room unoccupied and turns the lights off. Real occupancy control strategies are best used in applications where occupancy does not follow a set schedule and is not predictable. The savings potential of real occupancy control varies widely from 20 to 50 % (Maniccia et al. 2000, NBI 2003).

CONSTANT ILLUMINANCE CONTROL

The constant illuminance control strategy (CICS) uses a photocell to measure the lighting level within a space or determines the predicted depreciation (ageing) of the lighting level. If the light level is too high, the controller of the system reduces the lumen output of the light sources. If the light level is too low, the controller increases the lumen output of the light sources. The result is a system that minimizes lighting energy use while maintaining uniform and constant lighting levels.

DAYLIGHT HARVESTING CONTROL

The daylight harvesting control strategy (DHCS) allows facilities to reduce lighting energy consumption by using daylight, supplementing it with artificial lighting as needed to maintain the required lighting level.

The daylight harvesting control strategy uses a photocell to measure the lighting level within a space, on a surface or at a specific point. If the light level is too high, the controller of the system reduces the lumen output of the light sources. If the light level is too low, the controller increases the lumen output of the light sources. Sensors are often used in large areas, each controlling a separate group of lights in order to maintain a uniform lighting level throughout the area. The result is a system that minimizes lighting energy use while maintaining uniform lighting levels. This system can also provide the constant illuminance strategy.

Daylight harvesting systems are generally used in spaces that have relatively wide areas of windows or skylights. Typical applications include classrooms, high-rise office buildings and retail facilities. The savings potential varies from 20% (daylight harvesting alone) to more than 50% (daylight harvesting plus real occupancy). (NBI 2003)

Lighting control systems can easily be associated with a building management system (BMS). This facilitates the smart integration of lighting systems with heating, ventilation, air conditioning, security, etc.

LIGHTING AND BUILDING MANAGEMENT SYSTEMS

All the strategies described in the previous section can be applied in almost any building. They can be stand alone systems or part of a fully interoperable lighting management system (LMS). With an LMS one can monitor and schedule the light operations in any area within the building. The LMS gives facility managers the ability to remotely control building lighting energy consumption. It also enables the facility manager to perform load-shedding strategies in the event of high electricity demand in the building. The utilization costs are thus reduced as the control strategy turn off or dims some lights or lighting components during peak-use periods.

An LMS enables the building operators to be able to record lighting scenes or predefine scenarios. An LMS also provides the finest way to control lamps. Building operators will be able to manage lamps in one zone independently. An additional advantage of an LMS is their ability to monitor the operation of the lighting systems, such as the number of operating hours in a given area, the number of times the lights are switched on, etc. Using this information, maintenance operations such as like relamping can be scheduled.

If a building management system (BMS) is implemented, the management of the lighting system can be combined with heating, ventilation, air conditioning, security, etc. This type of integrated management system will allow the sharing of actuators and sensors.

LIGHTING CONTROL INTEGRATION

Lighting control systems can easily be associated with building management systems (BMS). This facilitates the smart integration of the lighting control systems with other technical equipment (e.g. HVAC and blinds). Three levels of integration can be distinguished for indoor lighting control:

- the first level takes into account the artificial lighting alone
- the second level takes into account artificial lighting and its control by external information such as daylighting, occupancy, etc.
- the third level takes into account artificial lighting and deals with artificial lighting plus external interaction with external elements such as HVAC systems and blinds.

Table 4. Lighting control strategy and integration analysis.

Strategy	Level 1 Artificial lighting alone	Level 2 Artificial lighting control based on external information	Level 3 Artificial lighting and daylight, and HVAC system
Complexity	Low	Intermediate	High
Potential for energy saving	Intermediate	High	High
Control strategies involved	Predicted occupancy Real occupancy	Predicted occupancy Real occupancy Constant illuminance Daylight harvesting (main)	Predicted occupancy Real occupancy Constant illuminance Daylight harvesting (main)
Management system	No LMS or BMS needed	LMS BMS (optional)	BMS needed

7. LIFE CYCLE ANALYSIS AND LIFE CYCLE COSTS

Usually, the energy use in the operating phase causes the biggest environmental impacts of the whole life cycle, especially when it comes to energy using products, such as lighting equipment.

Life cycle analysis (LCA) gives an overview of the usage of energy and raw materials of a product from cradle to grave. It also considers how much solid, liquid and gaseous waste and emissions are generated in each stage of the life of the product. (GDRC 2009)

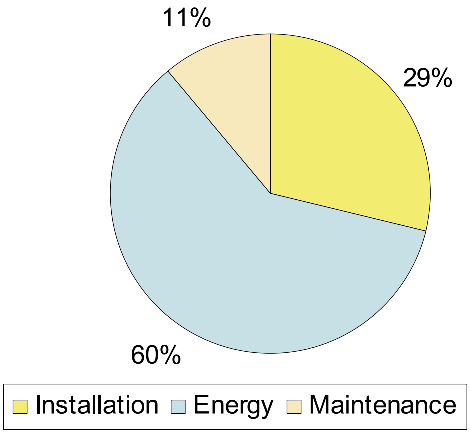
The definition of the scope is very crucial in LCA. It defines what is included in the analysis, for example if the transport or mining of the raw materials are included, if the analysis concentrates on a specific life cycle phase, or if the whole life cycle is considered. It is very important to be define the energy resources used in the operating phase. Usually, the energy use in the operating phase causes the biggest environmental impacts of the whole life cycle, especially when it comes to energy using products, such as lighting equipment.

The LCA is a useful tool in environmentally conscious product design. The results of the LCA can be used to compare different lighting technologies, and the results indicate what to concentrate on in eco-design. The results of an LCA are often given as environmental impact categories or as the so-called single-scale indices. Environmental impact categories are, for example, primary energy, toxicological impacts, global warming potential, and acidification potential. These allow the comparison from the point of view of one environmental impact. Single-scale indices weigh different environmental impacts and calculate them into one score to describe the total environmental performance of a product. This makes the comparison of the total environmental impact of the products easier.

Life cycle cost analysis has to be performed for the economic evaluation of different lighting solutions. It means that all cost categories, including initial and variable costs, must be considered over the lifetime of the whole lighting installation. Initial costs are e.g. the cost of the lighting design, lighting equipment, wiring and control devices, and the labour for the installation of the system. Variable costs may include the replacement of the burnt-out lamps (relamping), cleaning, energy, the replacement of other parts (reflectors, lenses, louvers, ballasts, etc.) or any other costs that are incurred. The energy costs of a lighting installation during its whole life cycle are often the largest part of the whole costs.

Examples of the LCA comparison of different lamp types are described in Chapter 7 of the Guidebook. An example of the distribution of life cycle costs in an office lighting installation is presented in Figure 14. Energy costs cover the majority of life cycle costs, as is usually the case. Other examples of the life cycle cost analysis of various lighting systems are also given in this chapter.

Figure 14. An example of the distribution of costs for office lighting.



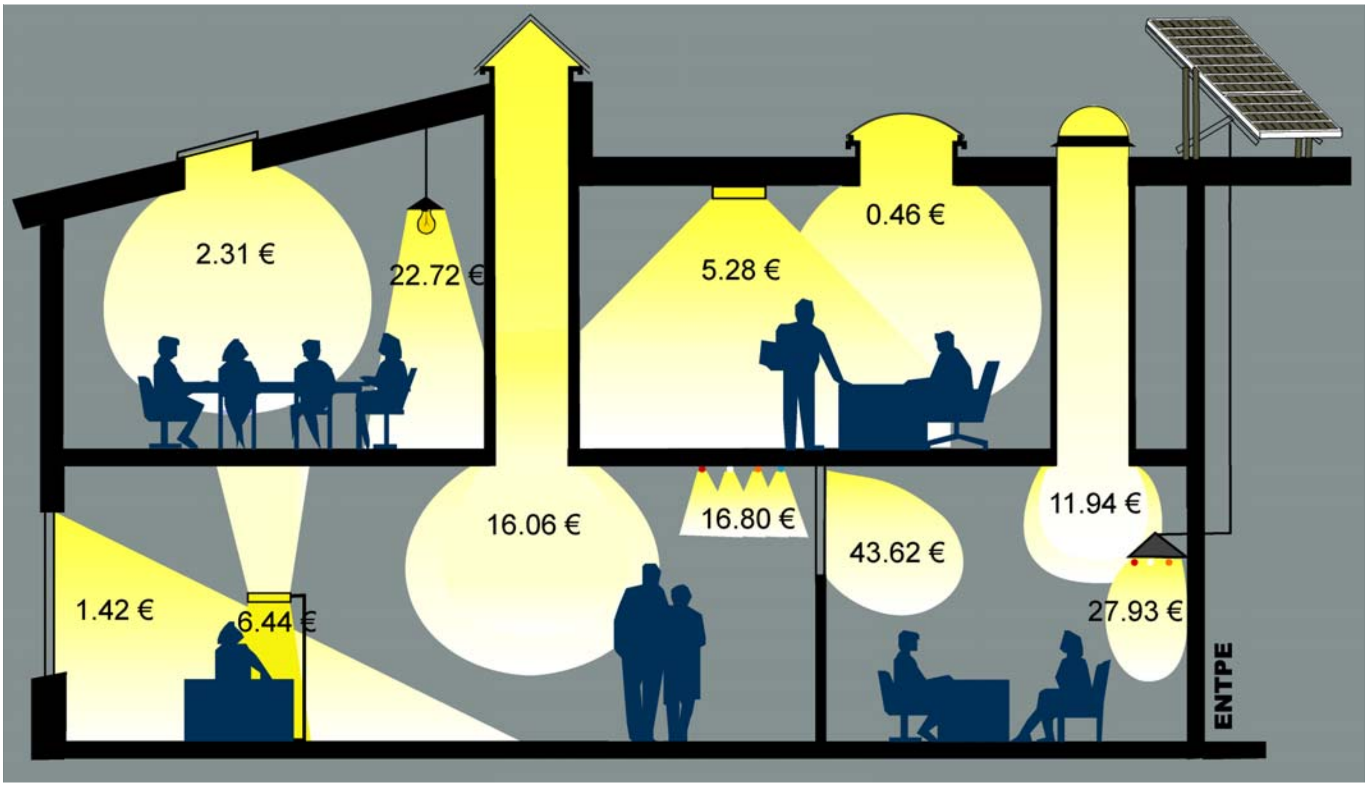
> Tungsten halogen lamps, when used continuously for lighting, are very expensive and need to be replaced by fluorescent lamps or LEDs.

Financial data have been studied for the comparison of the costs of various daylighting and lighting techniques over long time periods. The techniques are compared on the basis of the illumination delivered to the work plane per year. The selected day-lighting techniques were: roof monitors, façade windows, borrowed light windows, light wells, daylight guidance systems, and off-grid lighting based on LEDs powered by photovoltaics. These solutions were compared with electric lighting installations consisting of various sources: fluorescent lamps, tungsten halogen lamps and LEDs. Figure 15 shows the annual costs for various options (euro/Mlmh). (Fontoynont 2009)

The general results of the study were:

- Apertures in the envelope of the building are cost effective in directing light in the peripheral spaces of a building, particularly if they are durable and require little maintenance.
- Daylighting systems aimed at bringing daylight deep into a building are generally not cost effective, unless they use ready-made industrial products with high optical performance and low maintenance, and collect daylight directly from the building envelope.
- Tungsten halogen lamps, when used continuously for lighting, are very expensive and need to be replaced by fluorescent lamps or LEDs.
- Depending on the evolution of the performance and costs of LEDs and photovoltaic panels, there could also be options to generalize lighting based on LEDs and possibly to supply them with electricity generated directly from photovoltaic panels.

Figure 15. An example of Annual costs for various lighting and daylighting techniques (Fontoynont 2009).



LIGHTING DESIGN

The aim of an optimum lighting design is to achieve certain appearances and, at the same time, to fulfill the fundamental physiological and psychological visual requirements and to ultimately put the whole thing into effect in an energy efficient manner.

Lighting design is more than the planning of stipulated light intensities and luminance levels. Lighting design is also more than the fulfillment of the physiological visual requirements of visual perception. The fulfillment of these requirements belongs among the necessary prerequisites of illumination. Lighting design is more than just the fulfillment of normative guidelines. Lighting design means the creation of an appearance, which complies not only with the technical requirements but also with the emotional and aesthetic requirements of the user.

From an architectural point of view lighting is a mean to express and underline the desired character of the building space, which may be defined by an overall design style of the architect.

Different places need different types of lighting design.

- Environments designed for work and services to the public: places where functionality is the key element guiding the work of the designer, and the main aspects to satisfy are the rules of vision and ergonomics, safety and communication
- Environments designed for exhibitions and for sale purposes: places where the most important need is the image, be it faithful to the truth, or distant from the reality, virtual, and fascinating
- Environments designed for residence and tourism: places where light should satisfy the need for comfort, relaxation, aesthetic value, and status.

The aim of an optimum lighting design is to achieve certain appearances and, at the same time, to fulfill the fundamental physiological and psychological visual requirements and to ultimately put the whole thing into effect in an energy efficient manner.

From an energy point of view we can identify three groups of features that transform electrical energy into light: the lamp, the luminaire, and the room. The lamp transforms electrical power into luminous flux, the luminaire distributes the light in the room, and the room transforms this light into visible luminances by means of the surface reflections.

The energy consumption of the installation is further defined by the operating times, i.e. the need for artificial lighting should be minimized by intelligent architecture and daylight harvesting. To avoid needless operation of the artificial light proper controls (occupancy, daylight dependence, etc.) have to be installed.

The first key point for an energy efficient lighting installation is the choice of efficient lamps which produce the proper spectrum and offer the required operating features.

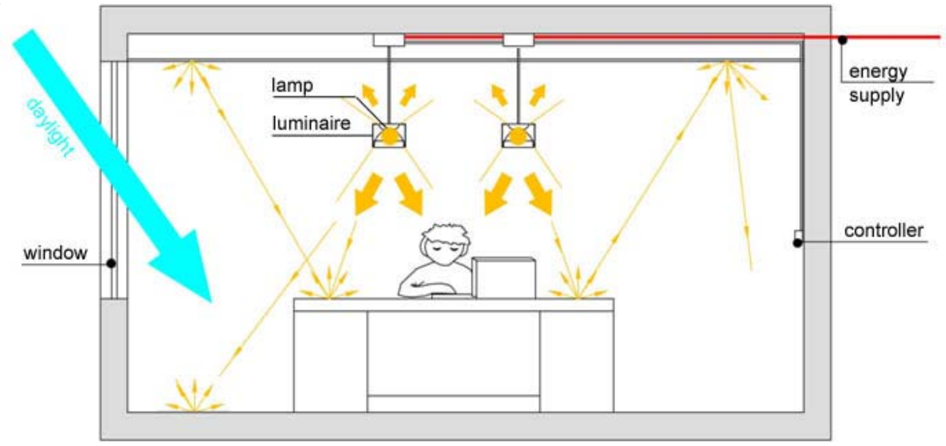


Figure 16. Supply chain from the electrical power grid to the visual environment.

Besides the use of energy efficient lamps, the application of high-quality luminaires, together with efficient room lighting concepts and clever controls, is important for the visual and ecological quality of the whole lighting installation.

The luminaire should not only be a decorative element, but rather a device to distribute the light of the lamp according to the illumination tasks in the room without causing glare, thus creating, together with the room surfaces, the desired visual environment.

With the emerging LED technology a new white light source is available which offers great potential for energy efficient lighting. With easy control and dimming possibilities, LEDs offer all the key features for energy efficient lighting. LEDs allow completely new designs and architectures for lighting solutions, thus opening a new and wide field of creativity for all lighting professionals. At the same time, some old rules and standards for a good lighting design are no longer applicable to LEDs.

Increased attention is being paid to the biological (non-visual) effects of lighting in the lighting community. For these different biological effects of light special light spectra may be needed. With a mixture of different LEDs it is possible to create almost any desired spectral distribution. This enables a lighting environment to be created with potential visual and biological effects for human beings.

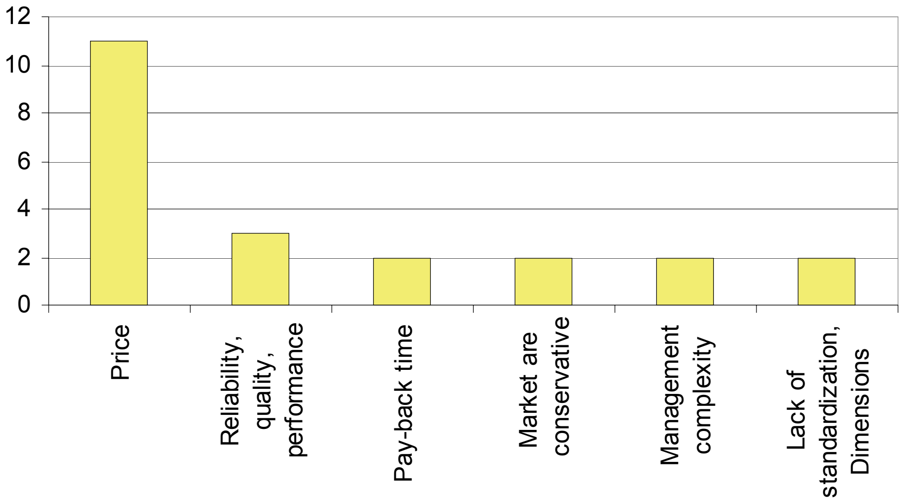
SURVEY ON LIGHTING TODAY AND IN THE FUTURE

The survey was conducted during 2006-2007 among knowledgeable people in the light community. The goal of the survey was to find out how lighting has developed in different countries within the last 5 to 10 years and how people see its development in the future.

Part of the Annex 45 work was to identify knowledgeable people in the lighting community and to conduct a survey for the collection of information about current lighting practices and future trends. The goal was to find out how lighting has been developed in different countries within the last 5 to 10 years and how people see its development in the future. The experts were also asked what kind of information about (energy efficient) lighting is needed and in what form this information should be provided.

A questionnaire template was sent to key contacts. The survey was conducted during 2006-2007 and the opinions presented in the Guidebook reflect those of the respondents. Altogether twenty-five answers were received from the following eleven countries: Austria, Belgium, Canada, China, Finland, France, Germany, Italy, Russia, Turkey and Sweden. The respondents were from the research, manufacturing, or application spheres.

Figure 17. Barriers to new light sources as selected by the number of experts participating in the survey.



According to the survey, the energy efficiency of lighting products has been increasing for the last 5 to 10 years, with new light sources, electronics, and control systems.

The view was that full advantage has not been taken of the new products which are already on the market, as the lighting market is conservative and the renovation rate is slow.

SUMMARY OF THE SURVEY

The survey indicated that the energy efficiency of lighting has been increasing during the last 5 to 10 years. This has happened through more efficient light sources, such as compact fluorescent lamps and T5-lamps, and also through the increase in the use of electronics (electronic ballasts) and controls. The problems of the current technology were seen to be its high price and reliability. On the other hand, it was seen that the market is slow and it takes time before a new technology can be established on the market. Further improvements in energy efficiency are still needed. When asked how manufacturers should improve their products, 14 respondents out of 25 said that they should improve their energy efficiency.

Human factors (well-being, health, productivity, and the visual environment) were considered very important. But the general opinion was that there is not enough knowledge about these and more research work is needed to understand the impact of lighting on human factors.

The survey indicated that in the future new light sources on the market will be LEDs and dimmable and/or low-wattage high-pressure discharge lamps with longer lifetimes. It was also perceived that electronics, intelligence, dimming, sensors and communication are becoming more commonly used. The view was that the efficiency of luminaires is increasing. The barriers to new products were seen as being their price, the long payback time, the lack of information on the total costs, their reliability, and the conservativeness of the market. It takes time before new products are approved and on the other hand, since volumes are big, it also takes time for the manufacturers to change their volumes.

The majority of the respondents answered that the payback time for the additional costs of energy efficiency should be less than 5 years (85% of answers) and, moreover, 37% answered that it should be less than 3 years. The attitude to the additional costs of environmentally friendly technology was parallel, 76% saying that the payback time should be less than 5 years and 36% said that it should be less than 3 years.

The respondents considered that in the future, energy efficiency will increase through technology and also because of increases in the price of electricity. Further causes of improvement in energy efficiency were seen as lying in the new directives and codes. Energy savings were found to be the most important factor to be gained from automation.

The respondents suggested that LEDs will be the light source of the future, with a broad field of applications. It was envisaged that LED luminaires will be smaller, and perhaps integrated in the furniture or construction elements. The main barriers to LEDs were seen to be their high price, thermal management issues, and their luminous efficacy. The lack of standards and glare and the durability of the installation were also mentioned as barriers.

The respondents' view was that education and also action on the part of society are needed to promote energy-efficient lighting; research institutes were seen as the best source of unbiased information. The survey indicated that information on the new technologies should be provided to the end users, and that action on the part of society and awareness are also needed to promote energy-efficient lighting technologies.

9. COMMISSIONING OF LIGHTING SYSTEMS

Commissioning is done for a number of different reasons: clarifying building system performance requirements set by the owner, auditing different judgments and actions by the commissioning-related parties to realize the performance, writing the necessary documentation, and verifying that the system facilitates proper operation and maintenance through functional performance testing.

The primary obstacles that impede the adoption of commissioning as a routine process for all buildings are the lack of awareness, the lack of time and too-high costs.

Commissioning is a quality-oriented process for achieving, verifying, and documenting whether the performance of a building's systems and assemblies meet defined objectives and criteria.

Commissioning is too often viewed as a task performed after a building is constructed and before it is handed over to the building owner to check its operational performance. A broader view is clearly favored, which starts at the predesign phase, goes through the construction process, and continues during operation. This broader view aims at bridging the gaps among four different visions, namely; the expectations of the building owner, the project of the designer, the assembled system of the contractor, and the running system of the operator.

In this broader view, the commissioning process begins at the inception of the project during the predesign phase, and continues for the life of the facility through the occupancy & operation phase. This global view aims at providing a uniform, integrated, and consistent approach to delivering and operating facilities that meet the owner's on-going requirements.

APPLYING COMMISSIONING TO THE LIGHTING SYSTEMS

The aim of the commissioning applied to lighting systems is to verify whether the performance of the system meets the defined performance and criteria. The first step consists of collecting the performance targets of the system and defining the criteria to assess those performances.

The lighting system should provide adequate and appropriate lighting for people to be able to perform visual tasks efficiently and accurately. The illumination can be provided by daylight, artificial lighting, or a combination of both. The level of illuminance and comfort required in a wide range of workplaces is governed by the type and duration of the activity. For good lighting practice, it is essential that qualitative and quantitative needs are satisfied, in addition to the required illuminance. Lighting requirements are determined by the satisfaction of three basic human needs: visual comfort, visual performance, and safety. The main parameters determining the luminous environment are: luminance distribution, illuminance, glare,the directionality of the light, the color rendering and color appearance of the light, flicker and stroboscopic effects, maintenance factors, energy considerations, and daylight. The methods for the calculation of all these parameters are available in the European standard EN 15251.

The key challenge when commissioning a building system is to follow a well-managed process.A central document for that purpose is the commissioning plan, which defines the actions to be performed. The purpose of the commissioning plan is to provide a direction for the commissioning process during the life-cycle of the building. It provides resolution for issues such as scheduling, roles and responsibilities, lines of communication and reporting, approvals, and coordination.

At each step of the process the commissioning plan defines the list of tasks to be performed to assess the performance of the system. Associated tools could also be used to help the commissioning provider to perform these tasks. The tasks defined in the commissioning plan could be divided into two parts, namely the organizational part and the technical part. The commissioning plan could also provide a general description of the commissioning team in order to identify the persons relevant to the commissioning process. An example of the tasks of a commissioning plan applied to a lighting system is given in Table 5.

Table 5. *Tasks of the Commissioning plan for lighting systems.*

Program step	*Cx Organizational*
	Check that the list of the relevant actions to take into account has been defined.
	Cx Technical
	Check that the occupant's lighting needs (Lighting requirement and calculation & lighting zone assumptions) have been defined.
	Check that the energy performance of the lighting system has been defined.
Working design step	*Cx Organizational*
	Check that the lighting system control method is defined.
	Check that each room has its own control system.
	Check that each local, luminaires in the row closest to the windows can be controlled separately.
	Check that the designer specified lighting equipment is suitable for the application environment.
	Cx Technical
	Check that the time delay and sensitivity are defined for each work space.
	Check that the sensitivity to change in daylight is defined for local room conditions.
	Check that the ranges of the reflectance for the major interior surfaces are in accordance with EN-12464.
	Check that lamps with a CRI lower than 80 are not used in interiors where people work or stay for longer periods.
	Check that the designer states the maintenance factor and lists all the assumptions made in the derivation of the value.
	Check that the designer prepares a comprehensive maintenance schedule to include frequency of lamp replacement, cleaning intervals for the luminaires and room, and the cleaning method.
	Check that the uniformity of the illuminance is superior to 0.7 for the work plane and 0.5 for its immediate surroundings.
	For offices check that the minimum shielding angles are applied for the specified lamp luminance.
Elaboration step	*Cx Organizational*
	Check that the plans of the offer answer the initial requirements.
	Check that the hypotheses of the calculations are justified.
	Check that the plans take into account the location of the components of the installation.
	Check that the plans take into account the access allowing maintenance.
	Check that the list of the tests and controls is included in the answer to the offer.
	Cx Technical
	Check that the description of the lighting system is complete (design, components, performance):
	a) List and description of the main components
	b) Location of the components
	Check that access to the sensors is easy but that they are not so accessible that unauthorized personnel can interfere with them.
	Check that incandescent or discharge lamps are of high frequencies.
	For offices check that the power installed in the interior is 2.2 $W/m^2/100$ lux and 2.5 $W/m^2/100$ lux for corridors.
Construction step	*Cx Organizational*
	Cx Technical
	Check that the lighting system controls are well connected.
	Check that the schedule of the lighting system is implemented into the energy management system of the building.
	For a sweep-off system, check that appropriate start and stop times are set to accommodate weekday, weekend and holiday operation.
	For daylight-linked systems be sure that all furnishings and interior surface materials are installed before calibration.
	For manual dimming, check that the dimmer has been installed in the correct position adjacent to the wall switch as per drawings.
Acceptance step	*Cx Organizational*
	Provide building maintenance personnel with all the necessary documentation and operatig instructions to re-commission and maintain the system.
	Check that a user's guide has been written.
	Check the periodicity of the maintenance inspection.
	Cx Technical
	Check that the placement and orientation of the sensors are correct according to the plans.
	Check that the sensitivity of the occupancy sensor is adjusted.
	Check that the time delay of the occupancy sensor is adjusted according to the room.
	Check that the schedule of the lighting system matches the effective functioning of the lighting system.
	Check that local and/or central overrides are well taken into account.
	Check that the lighting system is well controlled.
	For a dimming system, check burn in new lamps by operating the lamps at full power continuously for 100 hours.
	For a daylight-linked system, check that the light sensor is calibrated in order to obtain the desired light level at the work surface.
Post-Acceptance step	*Cx Organizational*
	Inform occupants about the functionality of the controls and, particularly, the overrides.
	Cx Technical
	Check that the operation of the lighting system meets the requirement defined in the book of specifications.
Post-post-acceptance step	*Cx Organizational*
	Check that the performance of the lighting equipment is evaluated yearly.
	Check that the sensors are cleaned up yearly (every six months for outside sensors).
	Cx Technical
	Check that the re-calibration of the sensors is performed if the environment of the building has changed (construction of a new building, for example)
	In the case of modification of the zone destination, check that the scheduling defined in the building energy management system still corresponds to the zone.

10. CASE STUDIES

The case studies conducted for a variety of buildings show the energy savings that are reached in real applications with current technology.

Case studies of different types of lighting systems were conducted within the Annex 45 work. The studies were conducted for twenty buildings, most of them being office buildings and schools in different locations around Europe.

The purpose of the case studies was to demonstrate the energy savings that are reached by real applications with current technologies. The case studies are presented in Chapter 10 of the Guidebook.

LIST OF CASE STUDIES

OFFICE CASE STUDIES

1. Optimizing of daylighting and artificial lighting in offices, Switzerland
2. Offices of a Finnish research unit
3. Rehabilitation of a German bank
4. Office buildings in France

Lighting power density 4.5W/m²

Saving lighting electricity by the use of occupancy and daylight-based dimming control systems

Lower power densities achieved with task/ ambient lighting solutions

OFFICE LED LIGHTING CASE STUDIES

5. Renovation of a cultural centre
6. Sture Library in Stockholm fully lit by LED lighting
7. Town Hall in Stockholm
8. Turning Torso
9. Office building in Finland (LED and fluorescent lamps)

Turning Torso, an apartment building in Malmö, Sweden: all the corridors lit by LED lighting

20 W tungsten halogen lamps above the doors replaced by 2 x 3 W LEDs

Lighting by a combination of LED and fluorescent lamps in the meeting room

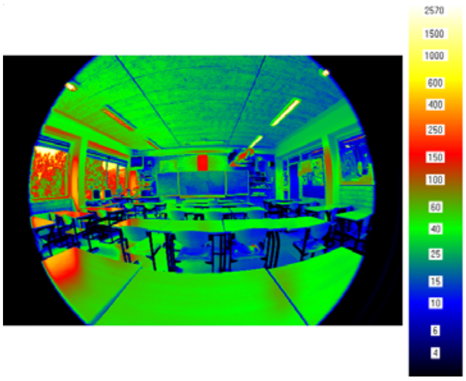
FACTORY CASE STUDIES

10. Factory in Netherlands
11. Factory in Italy

SCHOOL CASE STUDIES

12. School - lighting refurbishment
13. School - bright classroom
14. Primary school - bright classroom
15. Primary school Beveren-Leie - lighting refurbishment
16. High school of St Eligius - lighting refurbishment
17. Primary School in Rome (1)
18. Primary School in Rome (2)
19. Energy saving potential at a University
20. Renovation of an auditorium
21. Replacement of metal halide lamps by induction lamps

Increase in productivity and decrease in lighting energy consumption by task lighting and improved lighting control system



Luminance map showing the contribution of daylight and electric light in a classroom

Auditorium after the retrofit: 55% energy savings

MAIN RESULTS OF THE CASE STUDIES

The main results of the case studies are summarized briefly in the following paragraphs.

In office buildings, different case studies showed that it is possible to obtain both good visual quality and low installed power for lighting. It is possible to reach a normalized power density of 2 W/m^2.100 lx (even 1.5 W/m^2,100 lx in some cases) with the current technology. The studies also indicated that the best performance is reached in an office environment when the luminaires are shared between at least two persons. The development of LED technology is growing and the case studies show that the technology is already well suited to the task lighting applications and corridors.

The application of lighting control devices is another important aspect of improving the energy efficiency of the lighting systems. It was found that the use of a lighting control system to switch the lights on and off on the basis of occupancy sensors can reduce the lighting energy intensity of office buildings. Additionally, the use of dimming and control sensors for the integration of daylight and artificial light can yield further energy savings.

However, the design of the lighting system has to be performed carefully, so that the user can control and choose the visual environment of his/her choice. Allowing individual control of lighting enables the technology to be accepted by the users, as the lighting needs of people are different. Uniformity and glare have an effect on the acceptability of the lighting system. An uniformity of 0.6 was found to be acceptable in several case studies. The occupants also attributed importance to controlling the luminances of the light sources in the field of view of the workers.

The case studies in factories indicated that general lighting can be reduced by employing task lighting and individual control of the task lighting combined with automatic control of general lighting according to the working hours. This can lead to increases in productivity (as a result of better lighting) and to decreases in the lighting energy consumption. It is also possible to use dimming according to daylight in the factories. In one factory case dimming according to daylight could save about 50% of the energy used for lighting. The study showed that a normalized power density of 2.78 W/m^2,100 lx can be reached.

The case studies in schools indicate that it is possible to reach a normalized power density of 2 W/m^2,100 lx with the application of current technology, including the recommended black-board lighting. The refurbishment of old installations with new technology is an attractive way to improve energy efficiency in schools. One of the major problems related to the use of daylight in schools is daylight coming through the windows and falling on the work planes, blackboards etc. The design of a daylight utilization system must guarantee total protection against glare from the sun. Otherwise, people can move their desks or shade all the daylight with blinds.

11. TECHNICAL POTENTIAL FOR ENERGY EFFICIENT LIGHTING AND SAVINGS

This chapter presents the estimation of the global electric light consumption and lighting electricity consumption in 2015 and 2030 under different scenarios compared to the situation in 2005.

The prognosis of the electrical energy consumption for lighting presented in Chapter 11 of the Guidebook is based on the work of Annex 45. The figures presented in the Guidebook represent an estimation of the development of global electric light consumption in 2015 and 2030 under different scenarios compared to the situation in 2005.

The forecast of the electrical energy consumption for lighting is based on the following assumptions:

- Increasing light consumption of 25% (2015) and 55% (2030) by end user
- Increasing the efficiencies of the installations by 20% (2015) and 25% (2030) (light output ratio of luminaires and room utilance)
- Reduced operating time factors of 0.80 (2015) and 0.70 (2030) by daylight utilization and controls
- Phasing out incandescent lamps (mostly by 2015), T12 (2015) and T8 fluorescent lamps (2030), replaced by CFL, T5 and LED lamps
- In the scenarios 2015B and 2030B LEDs will take over the lamp market quickly and their luminous efficacy will develop fast.

LIGHT AND LIGHTING ENERGY CONSUMPTION IN 2005

The estimated global electric light consumption is calculated as the quantity of light which is the luminous flux over a duration of time; unit: lumen-hours. Since the light produced can not be stored, the light consumption and production are always equal; the light produced by lamps is consumed by the users.

In 2005, the estimated total global light consumption was 20 Mlmh/person,a and the total global energy consumption was 470 kWh/person,a.

The light production of incandescent lamps in the global residential sector was approximately equal to that of fluorescent lamps. However, the annual electrical energy consumption per person of incandescent lamps was approximately six times more than that of fluorescent lamps.

In the industrial sector, fluorescent lamps and HID (high-intensity discharge) lamps were the dominant light sources for the production of light, as well as for the consumption of lighting energy.

In the commercial sector, fluorescent lamps represent the largest share of electric light consumption and also electrical energy consumption. However, although incandescent lamps represent a small share of light consumption, their electricity consumption was almost 50% of that of fluorescent lamps. Compared to the other sectors, the commercial sector accounted for the highest share of both light consumption and electrical energy consumption.

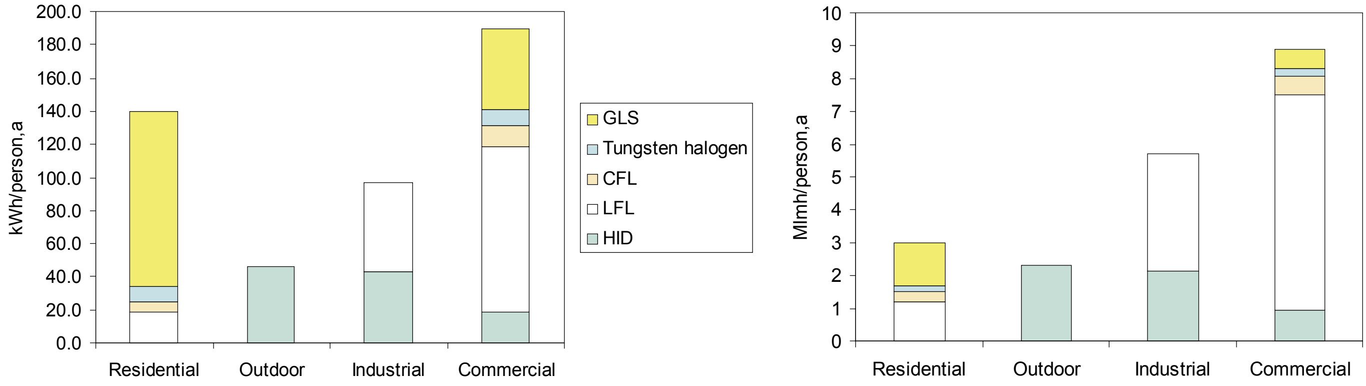


Figure 18. Worldwide estimated electric energy consumption kWh/ person,a (left) and light consumption Mlmh/person,a (right) in different sectors by lamp type in 2005. (IEA 2006)

LIGHT AND LIGHTING ENERGY CONSUMPTION IN 2015/2030

It is estimated that by 2030, incandescent lamps will account for only a very small share of the lamps in use. The share of LEDs will increase substantially.

In comparison to 2005, an increase in the global light consumption of approximately 25% is to be expected by 2015. It is estimated, however, that as a result of an improved facility utilization factor (light output ratio of a luminaire multiplied by room utilance, LOR x U) of 20% and reduced mean operating time (a factor of 0.8 as a result of improved daylight utilization and control systems), this will be compensated for. The increase in the facility utilization factor will reduce the need for light production since light will be waisted less in the luminaire and light will also be directed more efficiently to the task area. At the same time it is expected that there will be a clear reduction in the use of incandescent lamps as a result of legislation (step-by-step abolition of incandescent lamps), an increase in the use of CFLs and LED lamps, and the replacement of T12 and T8 lamps by T5 lamps.

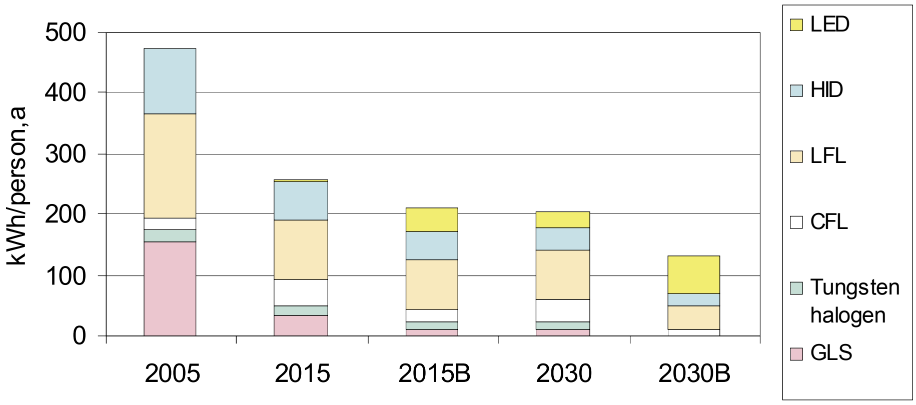
Compared to 2005, it is estimated that there will be an additional light demand (light consumption by end users) of 55% in 2030. Because of an improved facility utilization factor of 25% and reduced mean operating time (a factor of 0.7 as a result of improved daylight utilization and control), the overall electric light consumption will therefore be approximately the same as in 2015. Part of the electric light consumption will be replaced by daylight. Additionally, the energy consumption of fluorescent lamps will be reduced, as the luminous efficacy of the lamps in use will increase as a result of the replacement of obsolete technology.

Furthermore, in 2030, there will be a further reduction in the use of incandescent lamps as a result of their almost complete replacement by CFLs and LED lamps. LEDs will penetrate further into the market and will have a corresponding share of the market.

Figure 20 shows the reduction of electrical energy consumption in 2015 and 2030 compared to 2005. The reduction is based on the replacement of inefficient lamps and also on the increased luminous efficacy of all lamp types. The scenarios for 2015B and 2030B are based on the assumption of LEDs taking over the lamp market faster than in the scenarios for 2015 and 2030. Compared to scenario 2030, the light consumption remains the same in scenario 2030B, but the electrical energy consumption decreases because of the increase in the average luminous efficacy of LEDs.

On the basis of these assumptions, we can expect a decrease in electrical energy consumption for lighting to less than a half or even to one third of the consumption in 2005. These assumptions, and also the forecast of lamp efficacies, are rather conservative for the industrialized countries. The remaining unknown is the development in China, India, and Africa, which will define whether the predicted energy savings become reality.

Figure 19. Scenarios of electric energy consumption for lighting in 2005, 2015, 2015B, 2030, and 2030B by different lamp types. The scenarios 2015B and 2030B are based on the increased use of LEDs.



12. PROPOSALS TO UPGRADE RECOMMENDATIONS AND CODES

The possible obstacles and constraints that are set by the current regulations for horizontal illumination levels should be identified, and ways of designing and implementing more innovative lighting solutions should be sought.

The differences between the lighting standards and recommendations in different countries are related to the living standards, technological and economic capacity, and also to the influence of specific research or institutional organizations. A major future development of lighting recommendations is needed to address many other topics beyond the visual specifications associated with the satisfaction of specific activities. The following considerations are to be included in future indoor lighting recommendations.

- The minimum illuminance on a work plane in office lighting proposed by CEN Norm EN 12464-1 is 500 lx. The current recommendations concern mainly the level of illuminances on the desk area, but it should be remembered that what people perceive are luminances, i.e., light reflected from the surfaces. Therefore, discussions about the 500 lx minimum value should integrate a more luminance-based approach. Additionally, the individual and age-related differences in the required light levels should be considered.
- Since reading and writing are performed on a small part of the desk, and since a computer screen is now standard in workplaces, it is suggested that the recommended illuminance of 500 lx should be achieved only on the reading and writing area of the desk.
- The rest of the work plane would require a lower illuminance. Discussions about minimum illuminance values for the rest of the room would be useful.
- CEN Norm EN 12464-1 gives illuminance uniformity requirements as a minimum threshold of 0.7 on the task, and 0.5 for the immediate surroundings. Not much is said about the rest of the room. Tests performed on observers demonstrate that they respond positively to various kinds of modulation of the illuminance distribution. Discussions on the evolution of recommendations require evidence of the acceptable limits of this aspect.
- Indoor lighting design is based largely on providing more or less uniform levels of illuminance in the room, while the perception of the luminous environment is related mainly to light reflected from surfaces i.e., luminances. Thus innovative lighting design methods could be introduced which give a high priority to the quality of the luminous environment as our eyes perceive it.
- Luminaires with high luminance light sources, such as CFL, T5, or spot lamps (halogen, LEDs), have been found to be uncomfortable if the sources are visible, even if they are located above the head of the observers. Recommendations need to be updated to propose more restrictions on luminances and higher angles of observation.
- The reduction of the size of light sources (compact HID lamps, LEDs) may lead to an increased risk of glare. Standards and recommendations should be adapted accordingly.
- The balance of luminances in the field of view is expressed in the recommendations in order to reduce fatigue and eye stress. Recent findings suggest that the luminances of vertical surfaces facing the occupants also play a role in visual stimulation and alertness.
- The general CRI of the CIE has its limitations. The shortcomings of the CRI may become evident when applied to LED light sources as a result of their peaked spectra. It is recommended that a new colour rendering index should be developed, which should be applicable to all types of light sources, including white LEDs
- Practical metrics should be developed and mentioned in recommendations specifying the values and parameters related to daylighting.
- Glare from windows is not addressed, and there should be recommendations for sunshading systems to prevent glare.

13. SUMMARY AND CONCLUSIONS

Lighting accounts for 19% of the global electricity consumption and causes 7% of the total CO_2 emissions.

Energy-efficiency and the quality of lighting must go hand in hand. High-quality lighting does not mean high energy consumption if it is designed professionally.

The penetration of the lighting market by LEDs and legislative measures to phase out inefficient lamps will change the share of different light sources in the future.

Energy efficient lighting products and procedures can provide better living and working environments, and reduce the global energy consumption and greenhouse gas emissions.

Lighting is a large and rapidly growing source of energy demand and greenhouse gas emissions. Currently, more than 33 billion lamps operate worldwide, consuming more than 2650 TWh of energy annually, which is 19% of global electricity consumption. The total lighting-related carbon dioxide (CO_2) emissions were estimated to be 1900 million tons in 2005, which was about 7% of the total global CO_2 emissions from the consumption and flaring of fossil fuels.

More than one quarter of the world's population is still without access to electricity networks and uses fuel-based lighting to fulfil its lighting needs. While electrification is increasing in the developing countries, it is more important to adopt energy efficient light sources and lighting systems in the developing countries. Solid-state lighting combined with renewable energy sources has already reached some remote villages in developing countries, where it brings affordable, safe, healthy, and energy efficient lighting to the people.

Any attempt to develop an energy efficient lighting strategy should, as the first priority, guarantee that the quality of the luminous environment is as high as possible. The results presented in the Guidebook demonstrate that this is achievable, even with high savings in electricity consumption. While it is important to provide adequate light levels for ensuring optimized visual performance, there are always light levels above which a further increase in the light level does not improve performance.

Innovative and efficient lighting technology is already available on the market; very often, however, the current installations are dominated by inefficient technology that does not utilize control systems, sensors, or efficient light sources. Today, 70% of the lighting energy is consumed by inefficient lamps. Low retrofitting rates in the building sector (and thus also in lighting installations) are the main barrier to the market penetration of adequate and modern lighting technologies. It is estimated that 90% of all buildings are more than 20 years old, and 70-80% are older than 30 years. In order to increase the knowledge and use of energy efficient lighting, it is essential to increase dissemination and education, as well as to get new standards and legislation.

Energy efficient lighting also includes considerations of the control of light and the use of daylight. A sustainable lighting solution includes an intelligent concept, high-quality and energy efficient lighting equipment suitable for the application, and proper controls and maintenance. Further energy savings can be achieved with smart lighting control strategies. These can lead to energy savings that vary from 10% with a simple clock to more than 60% with a total integrated solution (occupancy plus daylight plus HVAC).

It is foreseen that LEDs will revolutionize the lighting practices and market in the near future. The benefits of LEDs are their long lifetime, color-mixing possibilities, spectrum, design flexibility and small size, easy control, and dimming. The special features of LEDs are prompting luminaire manufacturers to develop new types of luminaires and designers to adopt totally new lighting practices. The key success factor for the broad penetration of the general lighting market by LEDs is a light source with high system efficacy and high quality at moderate prices. One barrier to the broad penetration of the market by LED applications is the lack of industrial standards.

The expert survey conducted during 2006-2007 within the Annex 45 work indicated that among the lighting community there is a lack of knowledge of the characteristics and performance of new lighting technologies. Another major topic that was raised was the lack of awareness of the total life-cycle costs. The survey also indicated resistance to the adoption of new technology. It is essential that in future lighting design practice, maintenance schedules and life-cycle costs will become as natural as e.g. illuminance calculations already are.

Case studies of different types of lighting systems were conducted within the Annex 45 work. The studies were conducted for twenty buildings, most of which were offices and schools. In office buildings different case studies showed that it is possible to obtain both good visual quality and low installed power for lighting. In offices and schools it is possible to reach a normalized power density of 2 W/m^2,100 lx (even 1.5 W/m^2,100 lx in some office cases) with the current technology. It was found that the use of lighting control systems to switch the lights on and off according to data provided by occupancy sensors can reduce the lighting energy intensity of office buildings. Additionally, the use of dimming and control sensors for the integration of daylight and artificial light can yield further energy savings. The case studies also show that LEDs can be used in the renovation of lighting in commercial buildings.

It is expected that the share of different light sources producing the total electric light output will change in the future. This is due to the development of light source luminous efficacies, legislative measures to phase out inefficient light sources in many countries, and the penetration of the lighting market by LEDs. In the Annex 45 work forecasts for the consumption of lighting energy were made. On the basis of the most optimistic scenario, according to which LEDs will take over the lamp markets quickly and their luminous efficacy will develop fast, the lighting energy consumption in 2015 will be reduced to half, and in 2030 to one third, of the values in 2005. The remaining unknown is the developments in China, India, and Africa, which will define whether the predicted energy savings become reality.

Annex 45 recommends the introduction of innovative lighting design methods which give a high priority to the quality of the luminous environment as our eyes perceive it. Both the design of electric lighting and the use of daylight have a major impact on lighting quality and energy efficiency. The present lighting recommendations do not specify recommended values of daylight factors or other daylight parameters. This is a field where practical metrics could be developed and mentioned in the recommendations. A reduction in the size of light sources (compact HID lamps, LEDs) may lead to an increased risk of glare. Standards and recommendations should be adapted accordingly. One parameter to assess the quality of lighting is the color rendering index, the CRI. The current CRI is not suitable for LEDs because of their peaked spectra. The CIE recommends the development of a new color rendering index (or a set of new color rendering indices) which should be applicable to all types of light sources, including white LEDs.

A major future development of lighting recommendations is that beyond the visual requirements they should also address the non-visual effects of light.

There is a significant potential to improve the energy efficiency of old and new lighting installations, even with the existing technology. The energy efficiency of lighting installations can be improved with the following measures:

- The choice of lamps. Incandescent lamps should be replaced by CFLs or LEDs, mercury lamps by high pressure sodium lamps, metal halide lamps, or LEDs, and ferromagnetic ballasts by electronic ballasts.
- The usage of controllable electronic ballasts with low losses.
- The lighting design. The use of efficient luminaires and localized task lighting.
- The control of light with manual dimming, presence sensors and dimming according to daylight.
- The usage of daylight.
- The use of high-efficiency LED-based lighting systems.

Annex 45 suggests that clear international initiatives (by the IEA, EU, CIE, IEC, CEN, and other legislative bodies) are taken to:

- Upgrade lighting standards and recommendations
- Integrate values of lighting energy density (kWh/m^2, a) into building energy codes
- Monitor and regulate the quality of innovative light sources and products
- Pursue research into fundamental human requirements for lighting (visual and non-visual effects of light)
- Stimulate the renovation of inefficient old lighting installations by targeted measures

The introduction of more energy efficient lighting products and procedures can, at the same time, provide better living and working environments, and also contribute in a cost-effective manner to the global reduction of energy consumption and greenhouse gas emissions.

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ANNEX 45

ENERGY EFFICIENT ELECTRIC LIGHTING FOR BUILDINGS

GUIDEBOOK ON ENERGY EFFICIENT ELECTRIC LIGHTING FOR BUILDINGS

is the achievement of the work done in the
IEA – International Energy Agency
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Globally, almost one fifth of total electricity generated is consumed by lighting. There is a significant potential for improving the energy efficiency of old and new lighting installations, even with the existing technology. The introduction of more energy-efficient and ergonomic lighting products and procedures can, at the same time, providebetter living and working environments and also contribute in a cost-effective manner to the global reduction of greenhouse gas emissions. The energy efficiency of lighting installations can be improved with the choice of efficient lamps, luminaires, and electronic ballasts with low losses, lighting design, the control of light, the usage of daylight, and the usage of highly efficient LED-based lighting systems.

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