Project Summary Report

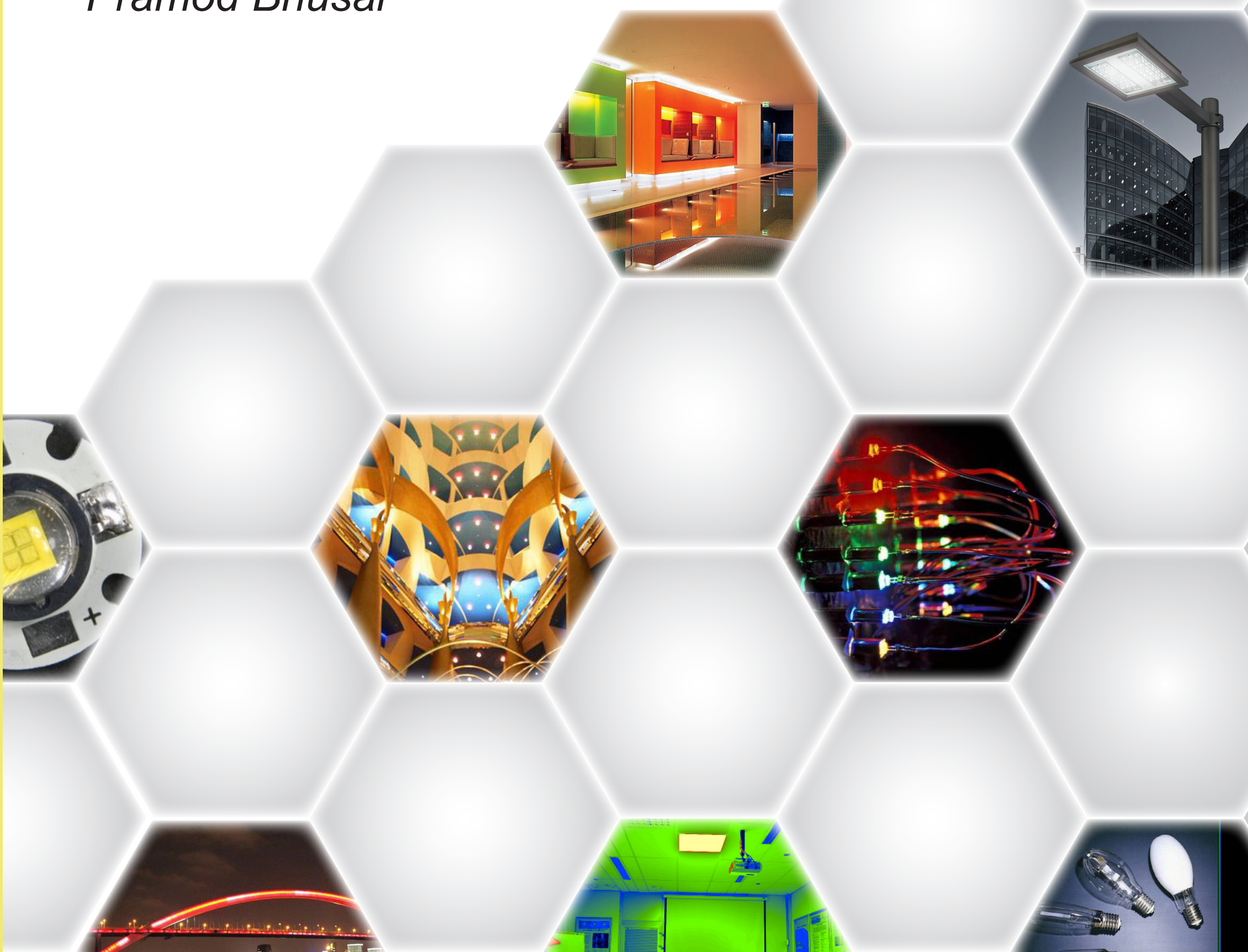
International Energy Agency
Energy Conservation in Buildings and Community Systems Programme

ECBCS Annex 45

Energy Efficient Electric Lighting for Buildings

Liisa Halonen, Eino Tetri,

Pramod Bhusal



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Published by AECOM Ltd, AECOM House, 63 - 77 Victoria Street, St Albans, Hertfordshire AL1 3ER, United Kingdom

ISBN 978-0-9562808-7-9

Participating countries in ECBCS:
Australia, Austria, Belgium, Canada, P.R. China, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Republic of Korea, the Netherlands, New Zealand, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

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Web: www.ecbcs.org/annexes/annex45.htm

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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 (**www.ecbcs.org**), 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 (completed projects are identified in grey):

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Annex 2:	Ekistics and Advanced Community Energy Systems
Annex 3:	Energy Conservation in Residential Buildings
Annex 4:	Glasgow Commercial Building Monitoring
Annex 5:	Air Infiltration and Ventilation Centre
Annex 6:	Energy Systems and Design of Communities
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Working Group - Energy Efficiency in Educational Buildings
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings
Working Group - Annex 36 Extension: The Energy Concept Adviser
Working Group - Energy Efficient Communities

General Information

Project leader: **Dr. Liisa Halonen, Aalto University, Finland**
Project duration: **2004 - 2008**
Further information: **www.ecbcs.org/annexes/annex45.htm**

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, with current technology and 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 the ECBCS project **'Annex 45: Energy Efficient Electric Lighting for Buildings'** 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 project has generally examined lighting of offices and schools. The main outcome of the project was the 'Guidebook on Energy Efficient Electric Lighting for Buildings'.

The Guidebook starts with an overview on lighting energy consumption in buildings. In addition to the equipment used (light sources and luminaires), the total lighting energy use depends also on the lighting design and the room itself. Energy efficient lighting further includes the control of light and good use of daylight. As well as lighting design, lighting technologies and control strategies are covered in the Guidebook. Visual and non-visual aspects of lighting and lighting quality are discussed. A worldwide review is presented about lighting and energy standards and codes. The Guidebook contains chapters on commissioning and life cycle cost calculations, since it is expected that in future maintenance schedules and life cycle costs will become as commonplace as e.g. illuminance calculations already are. Case studies conducted for a variety of buildings show the energy savings that were achieved in real applications with current technology. Finally, a scenario is given to show the technical potential for energy efficient lighting and energy savings, along with proposals to upgrade lighting standards and recommendations.

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

- The choice of lamps: Incandescent lamps should be replaced by compact fluorescent lamps (CFLs), infrared coated tungsten halogen lamps or light emitting diodes (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 use of daylight;

- The use of high efficiency LED-based lighting systems.

The project suggests that clear international initiatives (by the IEA – International Energy Agency, EU – European Union, CIE – International Commission on Illumination, IEC – International Electrotechnical Commission, CEN – European

Participating Countries:

Australia
Austria
Belgium
Canada
China
Finland
France
Germany
Italy
Japan
Netherlands
Norway
Poland
Sweden
Switzerland
Turkey
UK
USA

Observers: Russia and Singapore

Committee for Standardization and other international bodies) should be taken up 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 simultaneously 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.

The Guidebook on Energy Efficient Electric Lighting for Buildings is available from: lightinglab.fi/IEAAnnex45 or www.ecbcs.org.

Project Outcomes

Project leader: Dr. Liisa Halonen, Aalto University, Finland
Project duration: 2004 - 2008
Further information: www.ecbcs.org/annexes/annex45.htm

Project Objectives and Scope

The goal of the ECBCS project **'Annex 45: Energy Efficient Electric Lighting for Buildings'** 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 project has generally examined lighting of offices and schools.

The Guidebook on Energy Efficient Electric Lighting for Buildings

The 'Guidebook on Energy Efficient Electric Lighting for Buildings' is the culmination of the work done in the ECBCS project 'Annex 45: Energy Efficient Electric Lighting for Buildings'. More than 30 organisations from 20 countries participated in the project.

The Guidebook starts with an overview on lighting energy consumption in buildings. In addition of the equipment used (light sources and luminaires), the total lighting energy use also depends on the lighting design and the room itself. Energy efficient lighting further includes the control of light and usage of daylight. Lighting technologies and control strategies as well as lighting design are covered in the Guidebook. Visual and non-visual aspects of lighting and lighting quality are discussed. A worldwide review is presented on lighting and energy standards and codes. The Guidebook contains chapters on commissioning and life cycle cost calculations, since it is expected that in future maintenance schedules and life cycle costs will become as commonplace as e.g. illuminance calculations already are. The case studies conducted for a variety of buildings show the energy savings that were achieved in real applications with current technology. Finally, a scenario is given to show the technical potential for energy efficient lighting and energy savings, along with proposals to upgrade lighting standards and recommendations.

The full Guidebook is available from either lightinglab.fi/IEAAnnex45 or www.ecbcs.org. Additional information in the Guidebook includes project 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.

Lighting Energy Consumption

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. More than one-quarter of the world's population uses liquid fuel (kerosene oil) to provide lighting. 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.

Lighting accounts for a significant part of electricity consumption in buildings. For example, in the US, over 14% of all primary energy is used for lighting in buildings. The amount of electricity used for lighting differs according to the type of building. In some buildings, lighting is the largest single category of electricity consumption.

The global residential lighting electricity consumption in 2005 was estimated to be 811

TWh, which accounts for about 31% of total lighting electricity consumption and about 18% 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 gradually increasing in their share and light emitting diode (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. In European Union, inefficient household lamps are being phased out from the market by regulations.

Lighting is one of the single largest uses of electricity in most 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. 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 77% of the light output and the rest of the light output was provided by a mixture of incandescent, compact fluorescent and high intensity discharge (HID) lamps. Similarly, fluorescent lamps were the major light sources in US commercial lighting in 2001.

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.

Industrial lighting has the highest luminous 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 luminous efficacy of 79 lm/W. This is due to the fact that most light in industrial buildings comes from efficient fluorescent lamps and HID lamps.

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 inefficient incandescent lamps, a technology 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.

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 for vehicle lighting and in fuel-based lighting are responsible for most of the lighting-related greenhouse gas emissions.

The total lighting-related carbon dioxide (CO_2) emissions were estimated to be 1900 million tonnes (Mt) in 2005, which was about 7% of the total global CO_2 emissions from the consumption of fossil fuels. Energy efficient lighting reduces the lighting energy consumption and is therefore a means to reduce CO_2 emissions.

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 for reducing CO_2 emissions and also provides the cheapest mitigation options. Among all the measures that have potential for CO_2 reduction in buildings, energy efficient lighting ranks first in developing countries, the second largest potential in countries with their economies in transition, and third largest in the industrialized countries.

Project Outcomes

Technical Potential for Energy Efficient Lighting and Savings

An estimation of the growth of global electric light consumption in 2015 and 2030 was made in the project under different scenarios compared to the situation in 2005. These forecasts of the electrical energy consumption for lighting were based on the following assumptions:

- Increasing light demand of 25% (2015) and 55% (2030) by end users;
- Increasing the efficiencies of the installations by 20% (2015) and 25% (2030) (light output ratio of luminaires and room utilance, utilance is the ratio of the luminous flux received by a reference surface to the sum of the individual total fluxes of the luminaries of the installation);
- 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 B-scenarios (2015B and 2030B) LEDs will take over the lamp market quickly and their luminous efficacy will develop fast. The efficacy of LEDs in use is estimated to be 80 lm/W by 2015 (100 lm/W by 2015B) and 120 lm/W by 2030 (160 lm/W by 2030B).

The estimated global electric light consumption was calculated as the quantity of light, which is the luminous flux over duration of time; unit: lumen-hours. In 2005, the estimated total global light consumption was 20 Mlmh/(person•a) and the total lighting related 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.

In comparison to 2005, an increase in the global light consumption of approximately 25% is to be expected by 2015. It is estimated, however,

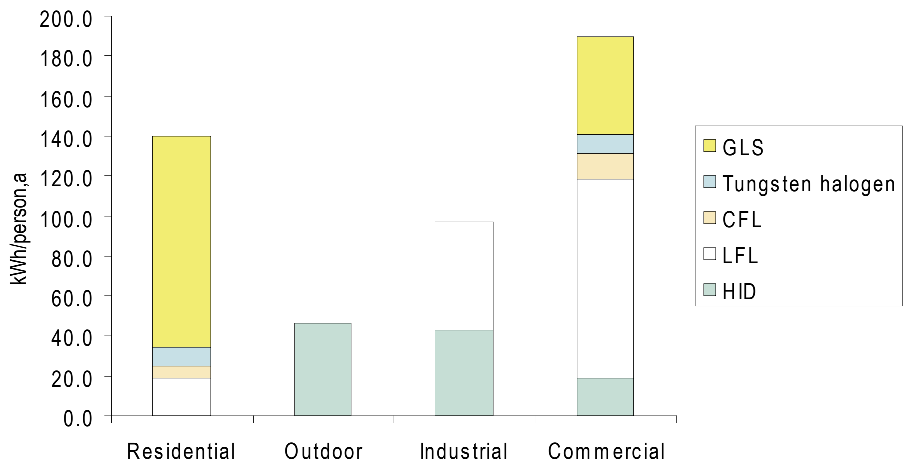
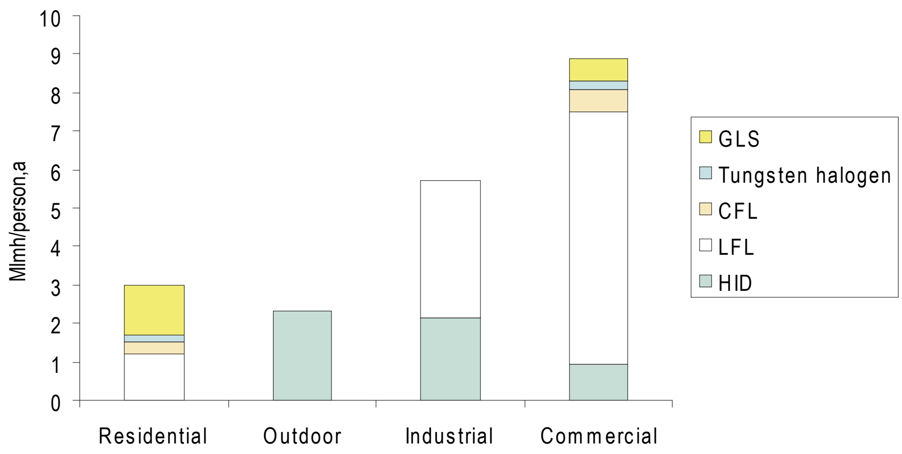


Figure 1. Worldwide estimated electric energy consumption kWh/(person a) in different sectors by lamp type in 2005.

Figure 2. Worldwide estimated light consumption Mlmh/(person•a) (right) in different sectors by lamp type in 2005.



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 compensate for the increase. The improvement in the facility utilization factor will reduce the need for light production since light will be wasted 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. T5 lamps are used only with electronic ballasts. Electronic ballasts have lower losses than magnetic ballasts, which are still widely used with T12 and T8 lamps.

Compared to 2005, it is estimated 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 will increase as a result of the replacement of obsolete fluorescent technology (replacement of T8 lamps and magnetic ballasts with T5 lamps and electronic ballasts).

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 3 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 of China, India, and Africa, which will define whether the predicted energy savings become a reality.

Proposals to Upgrade Recommendations and Codes

The growing concern about the energy performance of buildings leads to a search for a 'reasonable' optimum in installed lighting power. On one hand, visual requirements related to visual acuity have led to rather high illuminance levels (500 lx to read), and even higher if we consider the population above 60 years of age. On the other hand, general ambient lighting is more related to balance of luminances and absence of glare and minimum illuminances could be lower than 500 lx.

The difference between the lighting standards and recommendations in different countries has been attributed to the economic context and the geographical zone of the country. The differences are related to living standards, technological and economical capacity and also to the influence of specific research or institutional organizations in the individual countries. The following considerations are to be included in future indoor lighting recommendations.

- The minimum illuminance on a work plane in office lighting proposed by the European Committee for Standardization (CEN) 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 of people 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

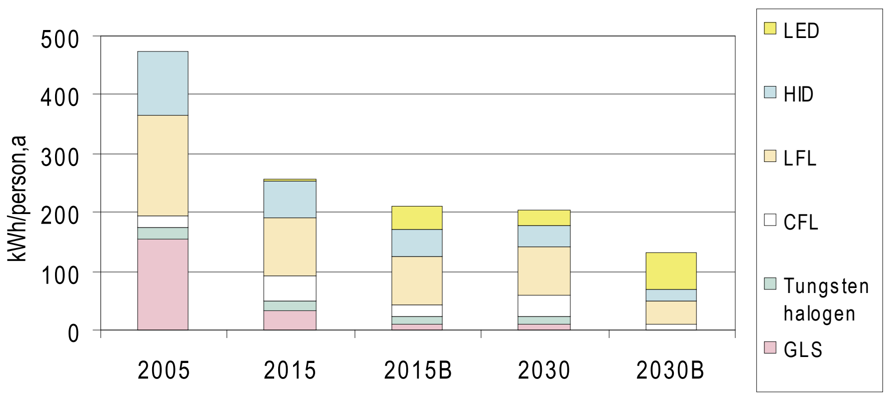


Figure 3. Scenarios of electric energy consumption for lighting in 2005, 2015, 2015B, 2030, and 2030B by different lamp types. The scenarios 2015B and 2030B are based on the increased use of LEDs.

of the illuminated 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 illuminated 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 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 colour rendering index (CRI) of the International Commission on Illumination (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.

Discussion and Conclusions

Any attempt to develop an energy efficient lighting strategy should, as the first priority, guarantee that the quality of the illuminated environment is as high as possible. Through professional lighting design, energy efficient and high quality lighting can be achieved. Better lighting quality does not necessarily mean higher consumption of energy. While it is important to provide adequate light levels for ensuring optimised visual performance, there are always light levels above which further increases do not improve performance.

The increased possibilities to control both the intensity and spectrum of light sources should allow the creation of more appropriate and comfortable illuminated environments. Also, the use of lighting control systems, based on presence detection and the integration of electric lighting with daylight, can lead to substantial energy savings. New technologies such as LEDs offer high flexibility in the control of light spectra and intensities, which enhance their attractiveness besides their growing luminous efficacy.

It is important to search for technological lighting solutions which meet human needs with the lowest impact on the environment during their life cycle. The environmental impacts of lighting include production, operation and disposal of lamps and related materials. The total lighting energy used depends, in addition to the lighting equipment used (lamps, ballasts, drivers, luminaires, control devices), on the lighting design and the room characteristics. There are several characteristics that need to be considered when choosing the lamp. These include e.g. luminous efficacy (lm/W), lamp life (h), spectrum and other colour characteristics (CRI, CCT), dimming characteristics, and the effects of ambient circumstances on the lamp performance. For all lamp types, even the best lamp, if coupled with poor or incompatible luminaire, ballast or driver, loses most of its advantages.

It is foreseen that LEDs will revolutionise the lighting practices and market in the near future. The long lifetime, colour mixing possibilities, spectra, design flexibility and small size, easy control and dimming are the benefits of LEDs. For LEDs huge technological development is expected to continue. The maximum luminous efficacy of phosphor converted cool-white LEDs is expected be around 200 lm/W by 2015. (The stated value is for high-power LEDs with 1 mm^2 chip size at a 350 mA drive current at 25°C ambient temperature without driver losses.) The special features of LEDs provide luminaire manufacturers with the capability to develop new types of luminaires and designers to adopt totally new lighting practices. The key success factor for the broad penetration of LEDs into the general lighting market is a light source with high system efficacy and high quality at moderate prices. One barrier for broad penetration of LED applications to the market is the current lack industrial standards.

Currently, there is a global trend to phase out inefficient light sources from the market through legislation and voluntary measures. Two EU regulations for lighting equipment entered into force in April 2009 and they will result in gradual phasing out of e.g. incandescent, mercury and certain inefficient fluorescent and HID lamps from the EU market. Similar legislative actions are being implemented around the world: Australia has banned the import of incandescent lamps from February 2009, and USA has enacted the Energy Independence and Security Act of 2007 that does not phase out incandescent lamps specifically in 2012 - 2014, but requires higher efficacy of all light sources. Other countries and regions have also banned, are on their way to ban, or are considering banning inefficient light sources.

There are already innovative and efficient lighting technologies available in the market. Very often, however, current installations are dominated by inefficient technology not utilising 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) is a main barrier for 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. To increase knowledge and use of energy efficient lighting, it is essential to increase dissemination and education, as well as to create new standards and legislation.

Energy efficient lighting further 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. At present, the most common form of control (the standard wall switch) is being replaced by automatic components based on occupancy or daylight harvesting. Examples of this technology are occupancy sensors which turn the lights off when the area is unoccupied, time-based controls and the dimmer plus photocell combination. 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).

For economic evaluation of different lighting solutions, a life cycle cost analysis has to be made. Usually, only the initial (investment) costs are taken into account. People are not aware of the variable costs, which include energy costs, lamp replacement costs, cleaning, and maintenance costs. In commercial buildings, the variable costs are very often paid by those who rent space, and the initial (investment) costs are usually paid by the investor who chooses the system. The energy costs of a lighting installation during the whole life cycle are very often the largest part of the lifetime costs. It is essential that in future lighting design practice, maintenance schedules and life cycle costs will become as commonplace as illuminance calculations already are.

The aim of an optimum lighting design is to achieve a certain appearance and, at the same time, to fulfill fundamental physiological and psychological visual requirements, and to ultimately put the whole thing into effect in an energy efficient manner. LEDs allow for 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 just as applicable to LEDs (e.g. glare assessment, colour rendering, light distribution, etc.).

The expert survey conducted during 2006 - 2007 within the project 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 adopting new technologies.

Commissioning is carried out for various 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 necessary and sufficient documentation, and verifying that the system enables proper operation and maintenance through functional performance testing. Commissioning should be applied through the whole life cycle of the building. The Guidebook presents an example of a commissioning process applied to a lighting control system.

Case studies of different types of lighting systems 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 the normalized power density of 2 W/(m^2 100 lx) (even 1.5 W/(m^2 100 lx) in some offices) with current technology. It was found that the use of lighting control system to switch lights on and off based on 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 show examples of LEDs in task, general and corridor lighting. LED lighting requires a new approach to lighting design. The case studies show that LEDs can be used in renovation of lighting in commercial buildings.

The evolution of standards has generally followed the development of lighting technologies, cost of lighting and increased scientific understanding of vision. The recommended values of illuminances have followed the development of light sources. For instance, in the second half of the 20^{th} Century the evolution of fluorescent lamps led to increases in the recommended illuminance levels. The difference between the lighting standards and recommendations in different countries has been attributed to the economic context and the geographical zone of the country. Current indoor lighting design is based largely on providing more or less uniform levels of illuminances in the room, while the perception of the illuminated 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 illuminated environment as our eyes perceive it. Both the electrical lighting design 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 in which practical metrics could be developed and stated in the recommendations. Reduction of the size of light sources (compact HID lamps, LEDs) may lead to increased risk of glare. Standards and recommendations should be adapted accordingly. One parameter to assess the quality of lighting is the colour rendering index CRI.

The current CRI is not suitable to LEDs due to their peaked spectra. The CIE recommends the development of a new colour rendering index (or a set of new colour 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 address also the non-visual effects of light. Light has effects that are fully or partly separated from the visual system. These are called the non-visual, non-image-forming or biological effects of light and are related to human circadian photoreception. Non-visual effects of light can e.g. have an effect on alertness in people.

There is already a significant potential to improve energy efficiency of old and new lighting installations with 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 compact fluorescent lamps (CFLs), infrared coated tungsten halogen lamps or light emitting diodes (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 use of daylight;
- The use of high efficiency LED-based lighting systems.

The project suggests that clear international initiatives (by the IEA – International Energy Agency, EU – European Union, CIE – International Commission on Illumination, IEC – International Electrotechnical Commission, CEN – European Committee for Standardization and other international bodies) should be taken up to:

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

The introduction of more energy efficient lighting products and procedures can simultaneously 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.

The Guidebook on Energy Efficient Electric Lighting for Buildings is available from: lightinglab.fi/IEAAnnex45, or www.ecbcs.org.

Further Information

Liisa Halonen, Eino Tetri & Pramod Bhusal, Guidebook on Energy Efficient Electric Lighting for Buildings, Aalto University, 2010

Liisa Halonen, Eino Tetri & Pramod Bhusal, Guidebook on Energy Efficient Electric Lighting for Buildings - Extended Summary, Aalto University, 2010

Project Reports

www.ecbcs.org/annexes/annex45.htm

Project Participants

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Canada	University of British Columbia
China	Fudan University Shanghai Hongyuan Lighting & Electric Equipment Co
Finland	Helsinki University of Technology
France	Ecole Nationale des Travaux Publics de l'État CSTB Ingélux Consultants Lumen Art ADEME Veolia Environnement R&D
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Italy	Università di Roma "La Sapienza" ENEA Ispra Politechnico di Torino
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Poland	WASKO S.A.
Russia	Russian Lighting Research Institute Svetotehnika
Singapore	National University of Singapore
Sweden	School of Engineering, Jönköping WSP Ljusdesign BAS Bergen School of Architecture
Switzerland	Solar Energy and Building Physics Lab, EPFL University of Applied Sciences of Western Switzerland
Turkey	Istanbul Technical University
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