SINTEF Building and Infrastructure

TORE KOLÅS

LECO – Energy efficient lighting

Technologies and solutions for significant energy savings compared to current practice in Norwegian office buildings

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LECO er et kompetanseprosjekt med brukermedvirkning (KMB).
Prosjektet ledes av SINTEF Byggforsk og gjennomføres i samarbeid med SINTEF Energiforskning AS, Erichsen & Horgen AS, Entra Eiendom AS, YIT AS, Entro AS, Hunter Douglas AS, Per Knudsen Arkitektkontor AS, Rambøll AS, Skanska AS, og OptoSense AS.
Prosjektet ble igangsatt høsten 2008 og vil pågå til utgangen av 2011.

Vi takker prosjektets partnere og Norges forskningsråd for finansiering av prosjektet

Summary and outline

This report addresses the potential for energy savings in lighting in buildings. The main emphasis is on office buildings but most of the solutions are applicable for other commercial buildings as well. Several means directed at reducing the lighting loads are discussed. The most important of these are the use of efficient light production equipment (chapter 4), occupancy scheduling (chapter 5) and daylight harvesting (chapter 6). But also the potential of lesser known energy saving means such as improved lighting maintenance (chapter 7) and the application of a non-uniform electric lighting scheme (chapter 8) are briefly discussed.

A typical non-efficient lighting installation that provides annual energy consumption for lighting of 47 kWh/m^2 is described in chapter 11 and used as a base-case for introducing the different energy saving measures. In chapter 12, a step-by-step approach for reducing the energy consumption is outlined and the energy saving potential from each step is roughly estimated.

It is further shown that the results from each of the energy saving measures can be combined in order to achieve substantial energy savings. The combination of more efficient lighting equipment, occupancy scheduling, daylight harvesting, improved lighting maintenance and the application of a non-uniform electric lighting scheme could provide lighting energy savings of up to 90% compared to the reference situation (47 kWh/m^2).

Furthermore, in the near future, solid state lighting (LED and OLED) can be utilized in order to provide even higher energy savings.

A practical example of energy efficient lighting from Miljøbygget in Trondheim is discussed in chapter 13. The main conclusions from the report are summarized in chapter 14.

Contents

1 Introduction

This report has been prepared within the research project LECO (Low Energy Commercial buildings). The main purpose of LECO is to collect existing knowledge and to develop knew knowledge about energy efficient solutions for reduction of energy usage in commercial buildings. A main goal is to produce guidelines for obtaining energy savings of 50%, 75% and 90% respectively (factor 2, 4 and 10) for a typical office building of today with an energy consumption of 300 kWh/m^2 (Wigenstad and Grini 2010).

This report addresses the potential for energy savings in lighting in buildings. The main emphasis is on office buildings but most of the solutions are applicable for other commercial buildings as well. The most important issues discussed in the literature include the light production equipment, the lighting intensity distribution, occupancy scheduling, daylight harvesting and integrated control strategies. In addition to reduced lighting loads, energy efficient lighting solutions also influence the need for heating and cooling. This secondary effect is important but is not discussed in this report.

As indicated above, the most ambitious target for the project is to reduce the energy consumption of a typical office building with a factor 10. A key question to be addressed in this report is whether or not this target is feasible with respect to electric lighting loads. Therefore, the most promising technologies and solutions will be addressed and the corresponding energy saving potential will be roughly estimated. The estimated savings are mainly derived from information found in the literature on energy efficient lighting. Two of the most recent literature sources are an IEA Guidebook on Energy Efficient Lighting (Halonen, Tetri et al. 2010) and a new publication on lighting and energy by Lyskultur (Mjøs 2010). In addition, Enova has published a useful guide to energy efficient lighting in commercial buildings (Birkeland and Bruun 2008).

2 Energy usage in Norwegian office buildings

Lighting energy loads constitute a significant part of the energy budget for an office building. According to the standard NS3031 (TEK 07) the annual lighting load is 25 kWh/m^2. However, for the reference building used in the LECO project, the energy consumption is much higher. For the reference building, the annual lighting load is 47 kWh/m^2. The table below shows the annual energy consumption as well as the associated annual lighting loads for various energy efficient buildings, including factor 2, factor 4 and factor 10.

Table 1: Annual energy consumption for office buildings in Norway.

Annual energy consumption	Reference 300 kWh/m^2	TEK 07 165 kWh/m^2	**Factor 2** 150 kWh/m^2	Low-energy 100 kWh/m^2	**Factor 4** 75 kWh/m^2	**Factor 10** 30 kWh/m^2
Lighting	47 kWh/m^2	25 kWh/m^2	24 kWh/m^2	16 kWh/m^2	12 kWh/m^2	5 kWh/m^2

3 Human needs and energy efficient lighting

Lighting affects several human needs, including visual ability, psychological factors, well-being and health. A good interior lighting design should therefore not only be energy efficient, but also meet the human needs in a satisfactory manner. The elements in the provision of light and lighting that needs to be considered for enhanced human performance and energy efficiency are discussed by Loe (2009). The main aspects are showed in figure 1. In the discussion that follows energy efficiency is the main issue, but human needs are also an important consideration, and energy saving should not be obtained at the expense of human well-being and health.

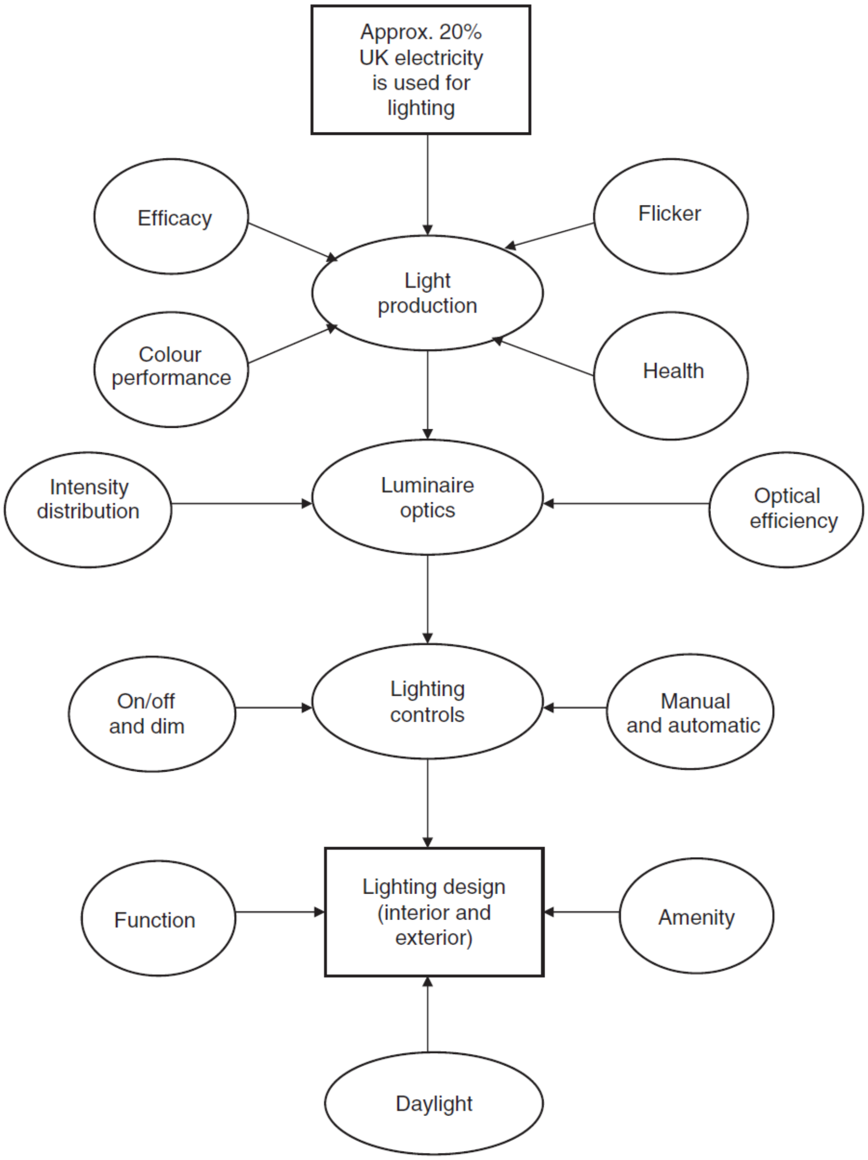

Figure 1: The elements in the provision of light and lighting that needs to be considered for enhanced human performance and energy efficiency. Illustration from Loe (2009).

4 Equipment for light production

The efficiency of the lighting equipment can be regarded as the cornerstone of an energy efficient lighting installation. This includes the luminous efficacy of the light source, the output ratio of the luminaire, as well as the efficiency of auxiliary equipment such as ballasts, starters, dimmers and transformers.

4.1 Light sources

A good overview of light sources (or lamps) is provided by the IEA Guidebook on Energy Efficient Lighting (Halonen, Tetri et al. 2010). Table 2 summarizes the typical characteristics of the main electric light sources.

Table 2: Lamp type and their typical characteristic. Table reprinted from IEA Guidebook on Energy Efficient Lighting (Halonen, Tetri et al. 2010).

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

As can be seen in Table 2, there is a large difference in the luminous efficacy of different light sources. The incandescent lamp (also called General Lighting Service Lamp; GLS) is the least energy efficient, but even today the most widely used. According to the IEA Guidebook, two thirds of the lamps sold are incandescent lamps, yet these lamps only produce 4% of the light (Halonen, Tetri et al. 2010). At present there is a trend to phase out inefficient light sources such as the incandescent lamp through legislation.

The various lamp types and their applicability for domestic lighting are discussed by Jacob (2009). Jacob also discusses why there is a need for legislation to phase out the least efficient lamps. He argues that the incandescent lamp has a number of advantages to compensate for its poor luminous efficacy and short lamp life: *"It is cheap, has good colour rendering properties, provides full light output almost immediately and is easily dimmed."*

Today, the fluorescent lamp is the benchmark for energy efficient electric light sources. As shown in Table 2, this light source can provide high luminous efficacy, good dimming control, and very good colour rendering (CRI).

Solid state lighting (SSL) is regarded as the lighting for the future. Solid state lighting refers to lighting based on semiconductor technology where light is produced by radiative recombinations of electric charge carriers. Solid state lighting includes light-emitting diodes (LED) and organic light-emitting diodes (OLED).

LED is the most developed of the solid state lighting technologies. The current trend is that LED continues to find new lighting applications for energy efficient and cost-efficient performance. At present however, LED is still less energy efficient than fluorescent lighting and provides poorer colour rendering and much higher installation costs. But these shortcomings might change in only a few years time. Projections made by Navigant Consulting (2009) indicate that warm white LEDs with good colour rendering (CRI above 85) can reach luminous efficacy values of 160 lm/W in the year 2017. Cool white LEDs with CRI between 70 and 80 are expected to surpass 200 lm/W in the same year. Such efficiencies will enable significant energy savings compared to all lamp types used today. Today the initial costs for LED lighting is high compared to e.g. a fluorescent lighting installation. It is therefore of great importance that the cost per lumen from LEDs so far has decreased according to Haitz's law with a factor of 10 per decade (Haitz, Kish et al. 1999).

OLEDs are organic based solid state lighting. The main advantages of OLEDs are a simplified processing technique and the possibilities for producing large and flexible light emitting surfaces. The energy-efficiency potential of OLEDs is equally high as for LED technology. At present however, the OLED technology is less developed and the luminous efficacies for OLEDs are lower than for LEDs. Even so, luminous efficacies as high as 90 lm/W has been reported for laboratory OLED samples (Reineke, Lindner et al. 2009).

4.2 Luminaries

The energy efficiency of a luminaire is given by its light output ratio (LOR). The light output ratio is the ratio between luminous flux of the light source installed in a luminaire to that of the light source alone. In recent years, the development of highly reflective reflector materials (available at an acceptable cost) has improved the light output ratio of luminaires for fluorescent lamps. In addition, the smaller diameter of for example T5 fluorescent lamps as compared to T8 allows for more efficient luminaires.

The LED source is more compact than traditional light sources and the light is distributed in the forward direction. This makes it easier to produce even more efficient luminaire optics based on light refraction rather than reflection. It is expected that LEDs will revolutionise the luminaire practise in the near future. The long lifetime, colour mixing possibility, spectrum, design flexibility and small size, easy control and dimming are the main benefits of LEDs. One important challenge for LED-based luminaires is the sensitivity to heat conditions of the LED source. Excessive heat loads can negatively affect the spectral distribution, intensity as well as lamp life.

4.3 Auxiliary equipment

Auxiliary equipment includes starters, dimmers, transformers ballasts and drivers. A good overview regarding starters, dimmers and transformers are provided by the IEA Guidebook on Energy Efficient Lighting (Halonen, Tetri et al. 2010). These technologies will not be discussed further here.

Ballasts are an essential component in a discharge dependant lighting system, as it provides a controlled current to the lamp. Electromagnetic ballasts are the old standard. They operate at the 50 Hz or 60 Hz frequency of the AC voltage. Electromagnetic ballasts are known to produce a (barely perceptible) flicker and a noticeable humming sound. The new standard is the electronic ballast, operating at about 25 kHz. High frequency operation eliminates flicker and humming and removes the associated health concerns. Electronic ballasts also provide improved energy efficiency, using about 25% less energy than electromagnetic ballasts. On the negative side it should be noted that electronic ballasts are more difficult to recycle.

Electronic drivers are important components in a majority of LED-based systems. According to the IEA Guidebook, a small improvement on the driver efficiency often results in big improvements in the system level efficiency. Therefore, in order to take advantage of the many positive aspects of LEDs, the drivers should perform accordingly. Today, IC switching regulators, microcontrollers or programmable microcontrollers are often being used in LED-drivers. According to the IEA Guidebook digitally managed power supplies may be the best solution to drive a broad range of LED systems both now and in the future.

5 Occupancy scheduling

Light is normally only needed in buildings at times when people are present. In most commercial buildings significant savings can be obtained by the use of occupancy scheduling.

Several different control strategies can be implemented to save energy when spaces are not occupied. The least energy efficient "strategy" is the *"lighting always on strategy"*. This strategy can hardly be recommended but is still, unfortunately, often used in practice. The next strategy often used is that of manual switching. The effectiveness of this solution depends on the behavior of the building occupants and how concerned they are with energy savings. It is also likely that manual switching provides less energy savings in office landscape areas compared to for example private offices, where it is easier to switch off light when you leave the space and where occupants are more likely to feel ownership to the lighting. Manual switching can also be combined with a timer switch in what has been labeled as the *predicted occupancy control strategy*. This approach saves energy by turning lighting on and off on a preset daily time schedule. The most energy efficient approach is the *real occupancy control strategy*. Here sensors are used in order to detect if the room is occupied and only then the lighting is turned on. If no presence is detected the lighting is turned off. To prevent the system from turning lights off while the space is still occupied, a delay time (typically from 5 to 20 minutes) can be programmed.

The energy savings that are possible with a real occupancy control strategy varies according to the occupancy rates of each location. This can differ according to building type, room type, type of work carried out, cultural differences, et cetera. Many of the older international occupancy studies carried out are therefore not necessarily relevant for current practice in Norway. One of the most detailed studies was carried out in USA by the Lighting Research Center (VonNeida, Maniccia et al. 2000). A total of 158 rooms with manual switching control were monitored, including 37 private offices. The study was conducted on 60 different organizations in 24 different states. The following four conditions were recorded: (1) room occupied with the lights on, (2) room occupied with the lights off, (3) room unoccupied with the lights on, and (4) room unoccupied with the lights off. An important conclusion from this study was that the majority of the energy waste occurred during the weekdays, and not during the weeknights or over the weekends. As noted by Von Neida, *"this pattern of energy waste is particularly suited to control by occupancy sensors."* The main results from this study are extracted and summarized in Table 3. The results show the lighting energy saving potential for the *real occupancy control strategy* compared to that of manual switching. As would be expected the saving potential varies greatly both with room type and with the delay time.

Table 3: Lighting energy saving for the *real occupancy control strategy* compared to manual switching. Results extracted from VonNeida (2000).

Room type	Lighting energy saving potential [%]		
	No delay	5 min. delay	20 min. delay
Restroom	72	68	47
Classroom	59	58	52
Conference room	55	50	39
Private office	48	38	28
Break room	40	29	17

A limited number of studies have been carried out in Norway. A study in 10 offices in Statens Hus in Trondheim was carried out more than 15 years ago (Opdal and Brekke 1995). The study concluded that the average presence during office hours (08.00 to 16.00) was as low as 28% over the three month monitoring period. In other words, the offices were empty for about 72% of ordinary working hours. More recently, a study was carried out in Asker Kulturhus (Larsen and Ursin 2005). Data-loggings were carried out in 32 private offices in the library section of the building. The results showed occupancy rates of 47% during the working hours (08.00 to 16.00).

More studies are needed to get a better understanding of the energy saving potential in Norway from occupancy scheduling for different building categories, different room types and for different applications of the rooms. It seems clear however, that the saving potential in office buildings is much larger than the 20% indicated by the Norwegian Standard NS3031 (2007).

6 Daylight harvesting

Systems for daylight harvesting are described thoroughly in an IEA Sourcebook on Daylighting Systems and Component (Ruck, Aschehoug et al. 2000). Only a brief overview of such systems is given here.

Daylight harvesting can be achieved by many different means. As indicated in the figure below, the costs for the light provided by different types of daylight harvesting systems and electric lighting systems varies greatly (Fontoynont 2009). The various techniques are compared on the basis of illumination delivered on the work plane per year over long time periods. The selected daylighting techniques given are: roof monitors, facade windows, borrowed light windows, light wells, daylight guidance systems as well as off-grid lighting based on LEDs powered by photovoltaics. The electric lighting installations given are; fluorescent, tungsten and LED.

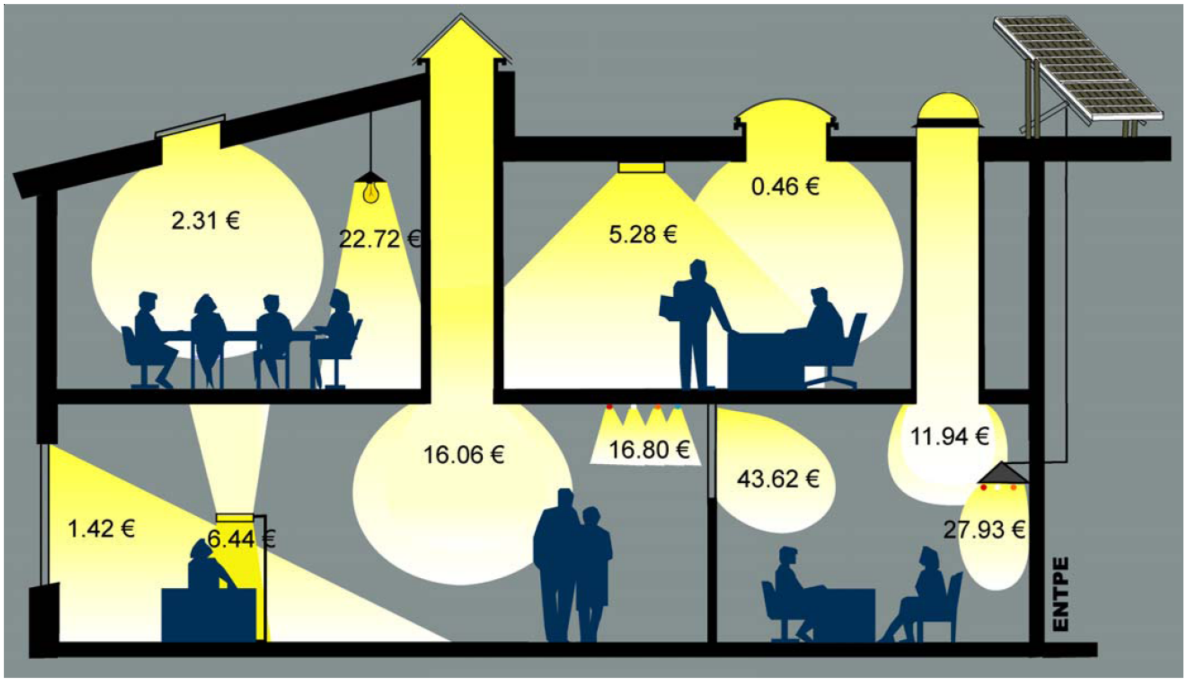

Figure 2: Cost of providing light on the working plane by different means. The cost includes the cost of initial construction and operation/maintenance for the expected lifetime of a building prorated on an annual basis (€/Mlmh). (Fontoynont 2009).

The least expensive means of providing daylight is achieved for top floors through the roof. It is interesting to note that this way of providing lighting is much less expensive than electric lighting. A recent overview of this technology is provided by Kim (2009).

Daylight through vertical window openings can be provided at a somewhat higher cost, but still lower than the cost for electric lighting. Daylight provided in this way is limited to the perimeter areas of the building. To be able to utilize daylight further from the window wall, daylight redirection systems can be used in the window facade. These systems typically redirect incident daylight to the deeper interiors via the ceiling. Daylight redirecting systems include lightshelves, anidolic systems (Scartezzini and Courret 2002), laser-cut panels (Edmonds 1993), sun directing glass (Beck, Körner et al. 1999) as well as daylight redirecting venetian blinds. An overview of daylight redirection systems is provided by Ruck (2000).

The energy savings from daylight harvesting depend on several factors, such as the type of daylighting system, building location and orientation, etc. For daylight through windows, the saving potential also depends strongly on the type of solar shading used and on the operation of the solar shading. Assuming that the solar shading is operated to prevent glare and overheating, the two most important factors determining the daylight harvesting potential through windows is the size of the window (A_{win}) relative to the perimeter floor area (A_{per}) and the light transmission properties of the window (τ_{win}). A simplified model for the lighting energy saving potential has been developed by Krarti (2005). He defines the *daylight aperture* as the product of window to perimeter floor area and window transmittance. For small daylight apertures the energy saving potential increases almost linearly with window area and window transmittance, as illustrated in Figure 3.

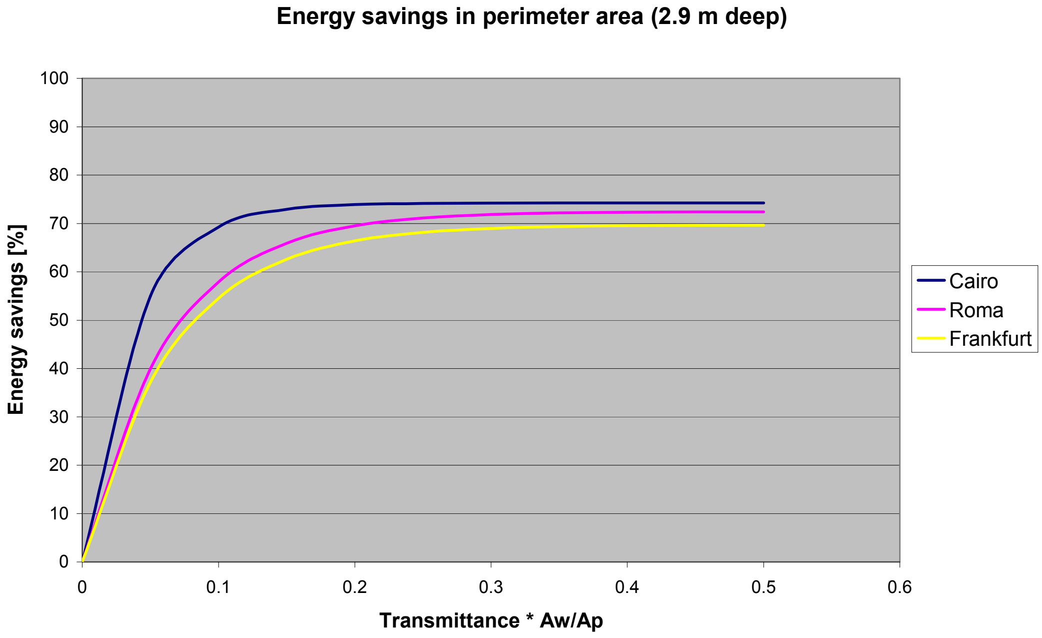

Figure 3: A simplified model by Krarti shows that lighting energy saving in the perimeter zone from utilization of daylight through windows depend strongly on window area and window transmittance. Graphs made according to numbers provided by Ihm (2009).

It should be noted that the energy saving potential is quite large also for northern latitudes (Frankfurt). The energy saving potential given by Krarti (2005) is calculated for a vertical window opening without any daylight redirecting components. Therefore, the perimeter zone where significant energy savings can be obtained is limited to a short distance from the window wall. The energy savings provided in Figure 3 are thus limited to the perimeter zone extending only 2.9 m from the window facade. However, with daylight redirection technologies, the daylit zone can be increased. Daylight redirection technologies also enable better utilization of the direct sunlight component of the daylight. In the simplified model by Krarti direct sunlight is mostly excluded through the use of shading and contributes little to the lighting energy saving potential.

Several field studies have shown significant lighting energy savings from utilization of daylight through windows in the perimeter zone of a building. The energy savings from four different studies (Opdal and Brekke 1995; Lee and Selkowitz 2006; Bülow-Hübe 2007; Ihm, Nemri et al. 2009) are provided in Table 4.

Table 4: Lighting energy savings from utilization of daylight through windows.

Ref.	Location	Daylight aperture*	Area depth	Shading system	Lighting control system	Annual lighting energy savings
Ihm 2009	Boulder, USA	0.105	2.9 m	Automatic interior shades	Dimming (500 lux)	All orientations: 64%
Opdal 1995	Trondheim, Norway	0.101	4.25 m	Manual curtains / blinds	Dimming (500 lux)	South: 29% North: 22.5%
					On / off 500 / 900 lux	South: 35% North: 2.5%
Lee 2006	New York, USA	0.077 – 0.135	7.0 m	Automated roller blinds	Dimming (500 lux)	West: Febr. to Sept; 23%
Bülow-Hübe 2007	Lund, Sweden	0.195	4.1 m	Automated interior white blinds	Dimming (500 lux)	South: May: 77% Nov.: 5%

* The daylight aperture is defined as: $T_{win} * (A_{win}/A_{per})$

The reported savings should only be taken as rough estimates to indicate the saving potential that can be expected. It is important to realize that several factors affect the energy savings; including the orientation of the facade, the daylight aperture (as given by Krarti), the depth of the area to be lighted, the type of shading system (or daylight redirection system) that is applied and also the type of lighting control system. For example, the study by Opdal showed that an on/off lighting control gave very small savings on a north oriented office in Trondheim, while it was quite effective in a south oriented office.

7 Maintenance factor

If the recommendation is 500 lux for e.g. a private office, the initial value in the new installation has to be higher, maybe 650 lux, in order to ensure the 500 lux at the critical time just before lamp replacement and cleaning. The ratio between the maintained and the initial value is the maintenance factor (MF). With the above mentioned values MF is 500/650 = 0.77. The maintenance factor depends on:

- Lamp data
  - lumen maintenance curve
  - lamp survival curve
- Dirt aspects
  - luminaire
  - room

    - surroundings
- Maintenance procedure
    - spot replacement or group replacement
    - time between group replacements

It is clear that MF-values will increase and energy consumption decrease with shorter lamp replacement intervals. From an economical point of view this has to be balanced against higher costs for lamps and replacements. According to Jacobsen (1997) the energy saving potential from taking measures to increase the maintenance factor can be as high as 15-20 % for a typical fluorescent lighting installation.

8 Lighting intensity distribution

In office buildings it has been a general practice to seek a uniform horizontal illuminance level over the entire working plane. Most modern lighting installations in offices comprise a regular array of ceiling mounted or suspended luminaires. This is generally considered to provide excellent working conditions. Nevertheless, it has also been argued that this approach is far from optimal with respect to energy efficiency. Loe (2009) remarks that; *"because this approach provides a uniform lighting condition with little flexibility, energy can be wasted through illumination being provided to a level, or at a location not required."* It has also been suggested that occupants prefer a space not only to appear 'visually light', but also prefer an element of "visual interest" that can be obtained through non-uniform intensity levels. According to Veitch et al. (2008) a more interesting and stimulating space could in turn enhance human performance.

A lighting design that combines the use of task lighting with a general building lighting (or ambient lighting) has been proposed as more energy efficient. Loe (2003) describes an approach where *"the task lighting only illuminates the task and the general building lighting illuminates the areas in between to a lower level as well as ensuring appropriate lit appearance for space as a whole."* According to Loe, such an approach will usually use less energy because the task area will only occupy a fraction of the total area. A non-uniform distribution is also supported by the often suggested ratio of 3:1 on the level of task light versus surroundings.

This is an area where little work has been carried out to provide solutions and to estimate energy savings. It is important to implement solutions that meet all the human needs required for the application. Work carried out by Veitch et al. (1998) indicates that savings around 50% are possible, while Loe (2003) provides a more conservative estimate of up to 25%.

Solid state lighting opens up new and interesting possibilities to provide non-uniform light distributions that can result in significant energy savings while also meeting other relevant requirements to lighting. In the future, OLEDs in walls and ceilings are likely to enable a bright appearance of the interior surfaces and thus avoid a gloomy interior in a very energy efficient manner.

9 Interior surface reflectance

The reflectance values of the interior surfaces strongly affect the resulting illuminance levels within the interiors. For lighting installations based on a large component of indirect lighting the reflectance values of ceiling and walls are of particular importance. A ceiling with a high reflectance will reflect a large fraction of the incident light back towards the work plane. In addition, a highly reflective ceiling will maintain a bright appearance even under low light levels and thereby reduce the need for indirect lighting.

The interior reflectance values also affect the potential for daylight utilization in a space. Computer simulations have been carried out to estimate the average floor illuminance for a sidelighted space under overcast sky conditions. In Figure 4 the results are shown for different reflectance values of floor, walls and ceiling respectively.

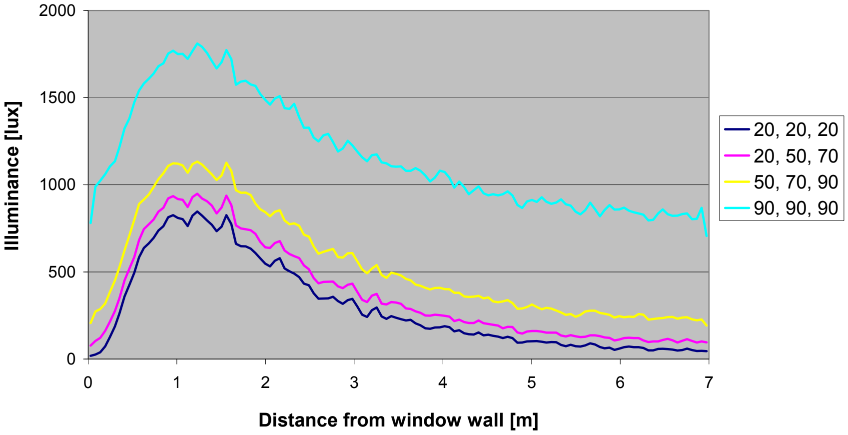

Figure 4: Average illuminance on the floor for different interior reflectance values (on floor, walls and ceiling) as a function of the distance from the window wall for a sidelighted room under overcast sky conditions.

The label “20, 20, 20” illustrates the case of “very low interior reflectance”. Here, all interior reflectance values (of floor, walls and ceiling) are set to 20%. The label “90, 90, 90” illustrates another case where all reflectance values are set to 90%. This extreme case is provided in order to illustrate the effect of “very high interior reflectance”. In-between these two special cases lies the “standard” case where floor, walls and ceiling reflectance’s are set to 20%, 50% and 70% respectively, as well as a realistic “high interior reflectance” case where the reflectance values are set to 50%, 70% and 90%.

As expected, the case where all values are set to 20% provides the lowest illuminance values. The improvement when wall and ceiling reflectances are increased to 50% and 70% respectively is not very large. Providing the space with high reflective surfaces (50%, 70% and 90% for floor, walls and ceiling) gives a significant increase in illuminance values, especially in the innermost parts of the space. As could be expected, the case where all surface reflectances are set to 90% provides the highest illuminance values. In this case the relative decrease in illuminance with distance from the window wall is much smaller. Thus, these high reflectance values not only provide high illuminance levels but also a more uniform distribution of the daylight.

10 Integrated controls

Integrated control strategies are important for energy savings. Both electric lighting and daylight affects the heat loads in a building. This means that the controls for electric lighting, daylighting and solar shading should be integrated with controls for heating ventilation and air conditioning (HVAC). A recent study indicated that the integration of HVAC, lighting and shading can provide up to 50% of energy savings during the summer periods for a building located in France (Halonen, Tetri et al. 2010).

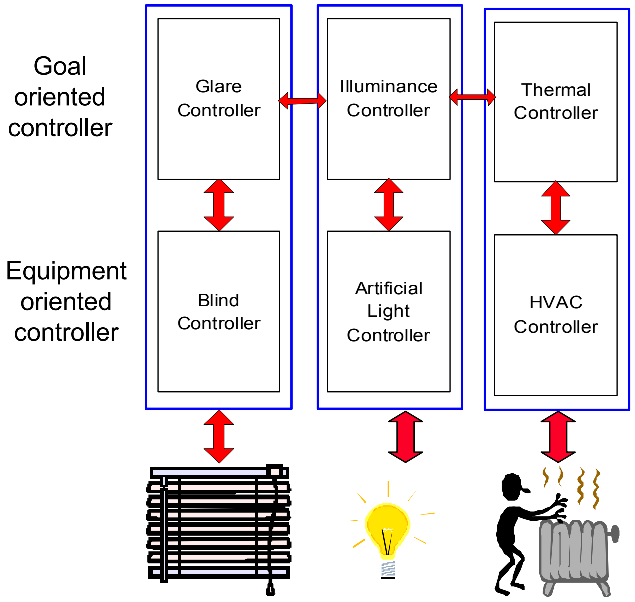

Figure 5: ***An example of an integrated control strategy for HVAC, lighting and solar shading. Illustration from IEA Guidebook (Halonen, Tetri et al. 2010).***

11 Reference conditions for lighting (47 kWh/m^2)

In this chapter an example of the lighting conditions in the reference building are given. These lighting conditions represent an example of a 15 years old lighting installation for an office building in Norway. The lighting conditions presented here will serve as a base-case for introduction of energy saving measures.

It should be emphasized that the lighting conditions given here do not in any way represent today's practice for energy efficient office lighting but rather an old and non-efficient lighting installation that can be improved upon by several means.

The reference conditions are summarized below:

- Regular array of suspended T8 fluorescent luminaires.
- Luminaire efficiency (light output ratio) of 0.6.
- 30% of the light is directed towards the ceiling (indirect lighting).
- Electromagnetic ballasts.
- Near uniform horizontal work plane illuminance of 500 lux.
- Little use of individual task lighting.
- Manual control of lighting - no daylight or occupancy sensors, and no timer.
- Little flexibility – few possibility for individual lighting adjustments.
- Surfaces reflectance values for floor, walls and ceiling are 20%, 50% and 70% respectively.

12 Discussion of energy saving potential for lighting

This chapter will provide a discussion of the energy saving potential for electric lighting. Starting from the annual lighting loads assumed for the reference building (see Table 1) the feasibility of obtaining lower energy consumption corresponding to factor 2, factor 4 and factor 10 will be discussed. The lighting conditions given in the previous chapter will be used as a base-case for introduction of several energy saving measures. A step-by-step approach is suggested and the energy saving potential for each step is estimated (Table 5).

Step 1: Better luminaire
The first step in order to reduce the energy consumption could be to replace the fluorescent luminaries with more modern luminaires for T5 fluorescent lamps. The T5 lamps typically have a higher luminous efficacy than the T8 lamps and the saving potential from this factor alone is estimated to 15%. In addition, the T5 lamp runs on electronic ballasts, and these are generally about 25% more energy efficient than electromagnetic ballasts. Assuming that the new luminaire has a light output ratio of 0.9 (as compared to the reference luminaire with LOR=0.6) further savings of about 33% can be obtained.

Step 2: Occupancy scheduling
The second step could be to introduce presence detectors in order to dim or switch off lighting when no occupants are present in the space to be illuminated. The studies of occupancy in office buildings indicate that lighting energy savings of at least 40% can be obtained compared to the manual switching approach often used today. More research is needed to get better data for the expected energy saving potential for the Norwegian practice within different building categories, room types and applications of the rooms.

Step 3: Daylight dimming
The third step could be to apply daylight dimming for the electric lighting. Daylight harvesting is an environmentally friendly and economically interesting approach to obtain lighting energy savings. The energy saving potential depends on many different factors, but for typical conditions expected energy savings in the perimeter zone of the building are at least 30%. If we assume that the daylit (perimeter) area accounts for half of the lighting energy in the building, the average savings for the whole building is 15%

Step 4: Automatic sun shading
The forth step could be to apply sun shading that is controlled automatically. Combined with daylight dimming, additional savings of at least 30% are feasible, but again only in the perimeter zone of the building. Assuming as before that half of the lighting in the building is needed for the perimeter area, the average saving potential for the whole building can be estimated to 15% with automatic shading.

Step 5: Daylight redirection systems
The fifth step could be to apply daylight redirection systems. By redirecting daylight from window openings via the ceiling, the area where daylight can be utilized is significantly increased. Also, with daylight redirection systems, a larger fraction of the direct sunlight can be utilized. Care should be taken in order to avoid discomfort glare for the building occupants. The energy saving potential from application of daylight redirection systems depends on a number of factors. A conservative estimate is that the application of such systems can provide average lighting energy savings in the order of 20% for the whole building (and higher savings in the daylit areas).

Step 6: Improved maintenance procedures

The sixth step could be to take a close look at the lighting maintenance procedures. Following from the discussion in chapter 7, the saving potential is here conservatively estimated to 10%.

Step 7: Non-uniform illuminance distribution

The seventh step could be to change the lighting design from a constant illuminance scheme to a lighting design that combines the use of task lighting with a general building lighting. As discussed in chapter 8 it is important that human needs are taken into account in addition to energy issues. A conservative estimate of potential energy savings from such a change in lighting design is 25%.

Step 8: Brighter interior surfaces

The eighth step could be to consider the reflectance values of the interior surfaces (floor, walls and ceiling). The reflectance of the ceiling is especially important when indirect lighting solutions are used since in this case the ceiling acts as a secondary "reflector". If the reflectance values of floor (0.2), walls (0.5) and ceiling (0.7) are increased to 0.5, 0.7 and 0.9 respectively, energy savings in the order of 25% can be expected. However, care should be taken in order to assure that this does not introduce discomfort glare for the building occupants.

Future savings

The eight steps discussed above could be introduced with the technology that is available today. In the near future, energy efficient light sources based on solid state lighting are expected to emerge as cost-effective and energy efficient alternatives to traditional light sources. Up to 50% additional energy savings can be expected from LED-based lighting solutions within the next 10 years.

Table 5 Lighting energy saving measures and estimated saving potential.

Step	Measure	Saving potential [%]	Accum. savings [%]	Energy consumption [kWh/m^2]
	Reference conditions (no measure)	-	-	47
1	Better light source (T8•T5)	15	15	40
1	Switch from electromagnetic to electronic ballasts	25	36	30
1	Better luminaires (LOR 0.6•0.9)	33	57	20
2	Presence detectors (real occupancy control strategy)	40	74	12 (factor 4)
3	Daylight dimming	15*	78	10
4	Automatic shading (+ daylight dimming)	15*	81	8.7
5	Daylight redirection systems (+ daylight dimming)	20*	85	7.0
6	Improved maintenance procedures	10	87	6.3
7	Non-uniform illuminance distribution for electric lighting	25	90	4.7 (factor 10)
8	Brighter interior surfaces	25	93	3.5
	LED with 200 lm/W (future savings)	50	96	1.8

* Numbers refer to average savings for the whole building. Higher savings can be obtained in the daylit areas.

13 Lighting in Miljøbygget

In this chapter a practical example of energy efficient office lighting is discussed. Lighting measurements and lighting energy estimates have been carried out for parts of the areas in Miljøbygget (Proffesor Brochs gate 2) in Trondheim. The measurements have been compared to the estimated values for lighting energy.

13.1 Description of the studied area

The studied area lies in the 2nd floor (3. etasje) of Miljøbygget, on the western part of the building. The studied area has been used by Enova as an open office landscape since 2009. The area has been fully occupied during the period of lighting measurements.

Two lighting meters have been installed in the studied area, labeled 433.33 and 433.35. Drawings of the two areas are shown in Figure 6 and in Figure 7 respectively. In the drawings private offices are seen in the perimeter zone close to the window façades. However, in actual fact there are no private offices in these areas but rater a large office landscape.

The area measured by meter 33 (Figure 6) is approximately 450 m^2 and has window facades facing east, west and north. The east façade lies inside an atrium. On this façade no solar shading is needed and the supply of daylight is rather limited. An outside view of the east façade is provided in Figure 8.

Also on the north façade no solar shading is provided. However, on the west façade the solar shading is provided by exterior louvers that are operated automatically. The louvers are raised and lowered according to solar irradiation and solar position. Additionally the louvers are tilted automatically according to the solar position. No manual override is possible for the operation of the solar shading. It was noted that the operation of the solar shading allowed some sunlight to enter into the interiors between the louver slats. This allows more daylight into the interiors but direct sunlight can also be a source of glare for the office workers. An outside view of the north and west façade is provided in Figure 9.

The area measured by meter 35 (Figure 7) is approximately 250 m^2 and has window façades facing south and west. Both façade orientations are provided with automatically operated exterior louvers, as described above. An outside view is provided in Figure 10.

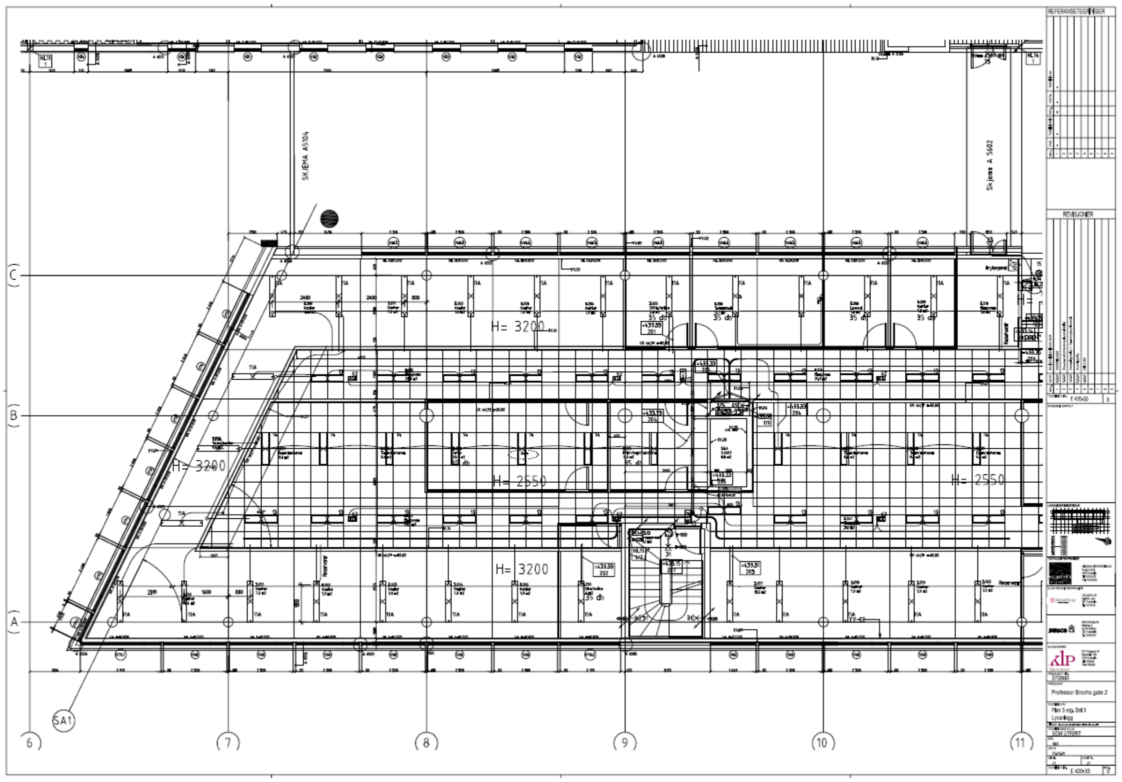

Figure 6: Drawing of the space measured by lighting meter 433.33.

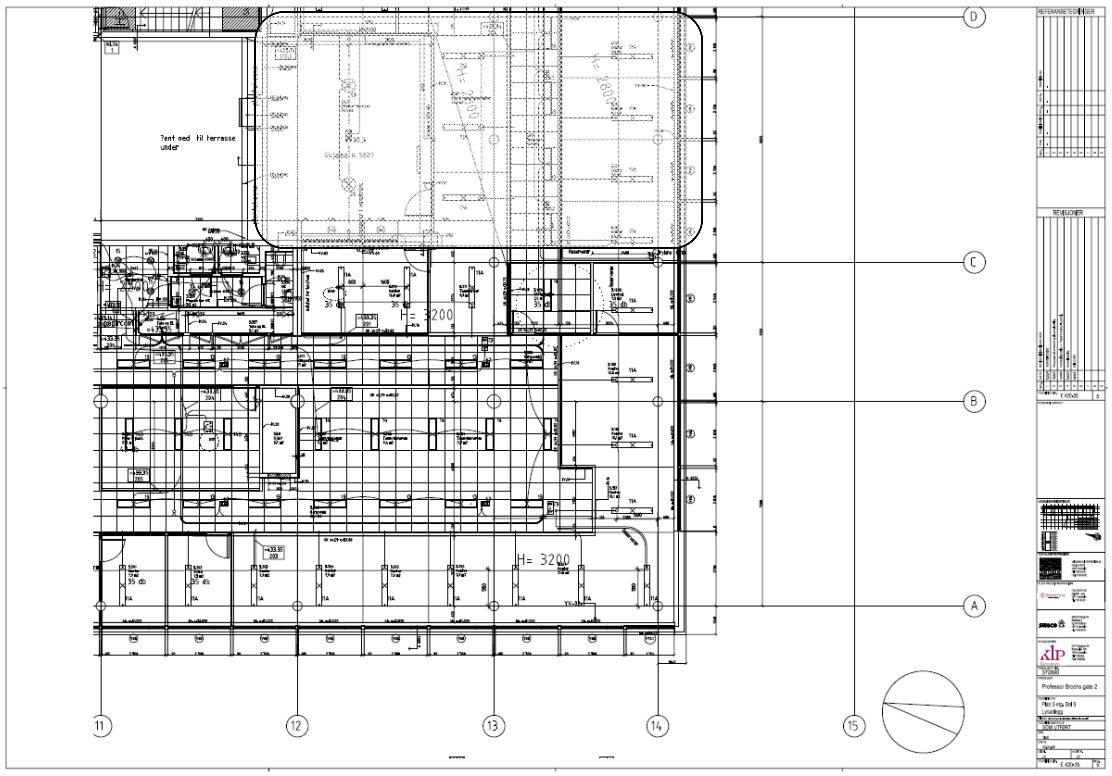

Figure 7: Drawing of the space measured by lighting meter 433.35.

Figure 8: East façade of area measured by meter 33 (2nd floor).

Figure 9: North and west façade of area measured by meter 33 (2nd floor).

Figure 10: West and south façade of area measured by meter 35 (2nd floor).

13.2 Description of lighting installation

A modern lighting installation has been used in Miljøbygget.

A suspended T5 fluorescent luminaire of type C10-P1 235 SU has been widely used in the building. This luminaire has a light output ratio (LOR) of 0.8. The luminaire has two T5 tubes and directs 64% of the output downwards and 36% upwards as shown in Figure 11.

In the corridor areas a ceiling mounted luminaire of type C20 R300 SL has been used. This luminaire has a light output ratio (LOR) of 0.83. The luminaire has one T5 tube of 28W, and directs 100% of the output downwards as shown in Figure 12.

In the space occupied by Enova (3. etasje) the originally planned private offices are replaced by an open office landscape. For the work areas near the windows, both daylight dimming and occupancy sensors have been applied, as well as a timer that switches off the lighting outside working hours. A non-uniform lighting scheme has been applied in these areas. Therefore, the illuminance target is 500 lux only at the work places located near the luminaires.

Pictures of the office landscape zones located near the various façade orientations are provided in Figure 13 (east façade), Figure 14 (south façade), Figure 15 (west façade) and Figure 16 (west and north façade). These pictures were taken on a sunny afternoon between 14.30 and 15.00 on November 3rd 2011.

The pictures show that the automatic tilting of the louver slats allows for direct sunlight to enter the interiors between the louver slats on the western façade. This might result in glare for the building occupants.

The pictures also show that several of the luminaires are lit even though no workers are present in the nearby area. This could be related to the 15 minute delay period before the luminaire is switched off when no people are detected. Also, it is possible that nearby people could trigger the sensor and activate the lighting.

For the spaces further away from the windows, including the corridor areas occupancy sensors have not been widely used, and the lighting is typically operated by a timer as well as manual switching (Figure 17). The illuminance target in the corridor areas are slightly above 200 lux.

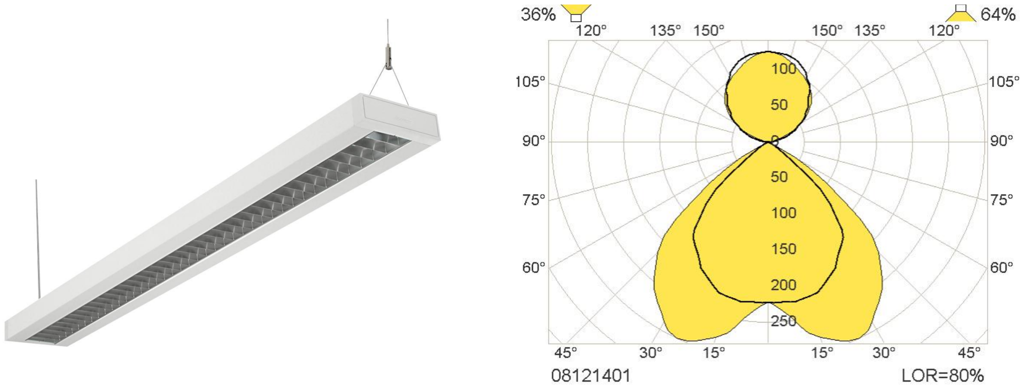

Figure 11: Suspended luminaire of type C10-P1 235 SU with 2 T5 tubes.

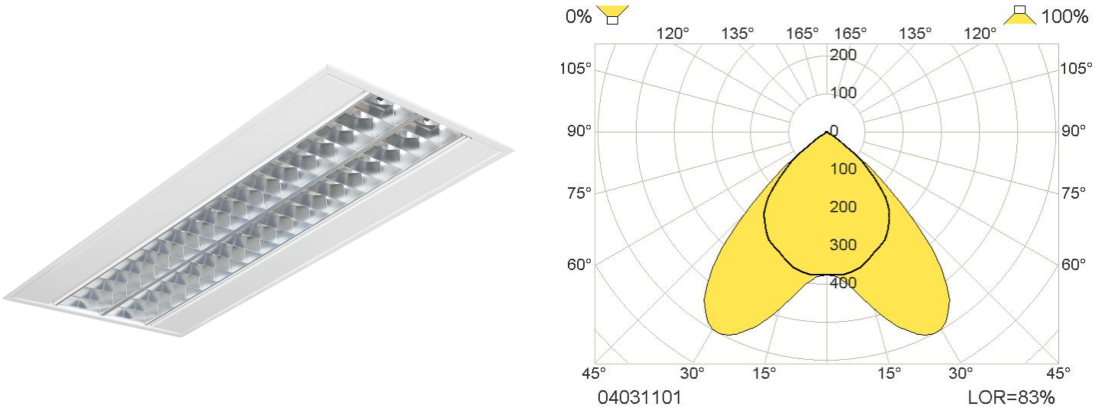

Figure 12: Ceiling mounted luminaire of type C20 R300 SL.

Figure 13: Interior view of the office landscape zone close to the east façade.

Figure 14: Interior view of the office landscape zone close to the south façade.

Figure 15: Interior view of the office landscape zone close to the west facade.

Figure 16: Interior view of the office landscape zone close to the west façade (left) and the north façade (right).

Figure 17: Interior view of the corridor space (left picture). Outside working hours the corridor lighting may be operated by a manual switch with a timer (right picture).

13.3 Lighting measurements

Measurements of lighting energy use have been carried out over an extended period of time. The results presented below are from the time period November 2010 to November 2011. Unfortunately, the meter has not been recording continuously. For periods of non-operation, values from the previous year have been used, or a simple interpolation.

The energy usage from meter 33 and 35 are shown in Figure 18 and Figure 19 respectively. It is evident that the energy usage for lighting is less during the summer months than during the winter months. The reduction during the summer months is about 25-30% compared to the winter months. This clearly shows that the daylight levels affect the lighting consumption and that the daylight dimming installed reduces the lighting energy usage.

The annual energy consumption for the two areas that have been measured are 5725 kWh for meter 33 and 4085 kWh for meter 35. This gives an average energy use of 14.3 kWh/m^2 per year and 16.2 kWh/m^2 per year respectively for the two areas.

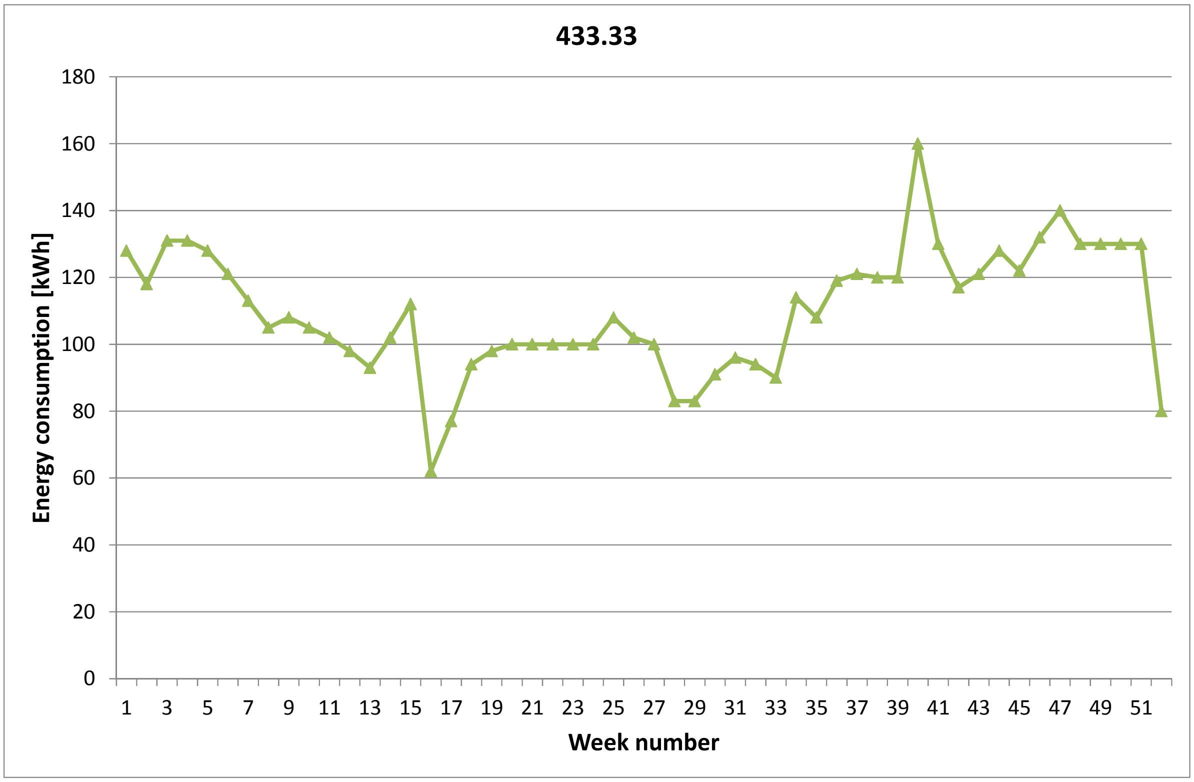

Figure 18: Energy usage in 2011 recorded by meter 33.

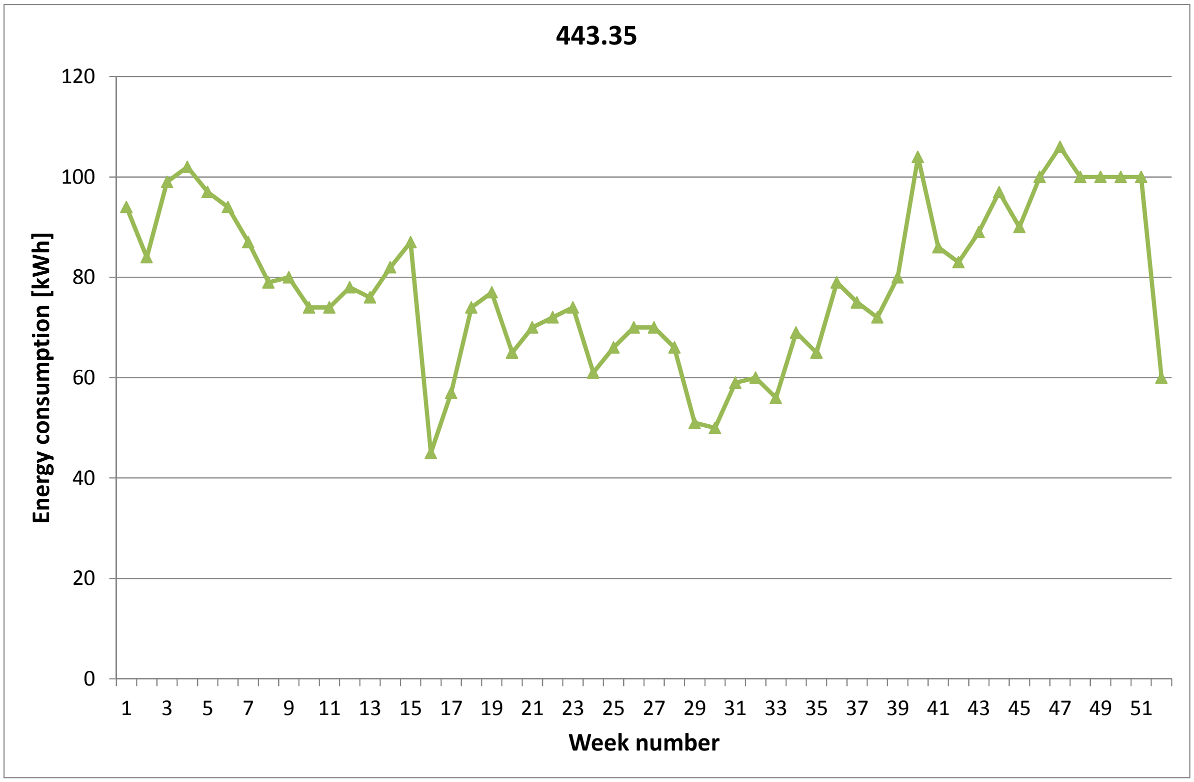

Figure 19: Energy usage in 2011 recorded by meter 35.

13.4 Lighting calculations

Detailed lighting calculations of the two areas considered have been carried out by the company Glamox. The software tool OptiWin has been used as a tool for calculating LENI numbers (Lighting Energy Numeric Indicator) for the various spaces in the building. The calculations are based on EN 15193. This means that it is assumed that the space is used for 3120 hours per year.

The working hours are assumed to be 2500 hours during daytime and 620 hours during nighttime. The "absence factor" is assumed to be 40% at the individual workplaces.

For the calculations it was assumed that private offices were used according to the drawings. However, in actual fact there are no private offices in these areas but rater a large office landscape.

The estimated reduction due to daylight dimming is approximately 55% in the perimeter zones of the building.

For the perimeter areas were daylight dimming and occupancy sensors are used the calculated energy use is from 7.5 to 9.9 kWh/m^2 per year.

For the corridor areas the calculated energy use is from 22 to 29 kWh/m^2 per year.

For the areas further away from the window walls marked as team offices on the drawings, the calculated energy use is typically from 16 to 23 kWh/m^2 per year.

The total average energy use is calculated to 17.3 kWh/m^2 per year and 15.8 kWh/m^2 per year respectively for the two areas. For the area covered by meter 33 this 21% is higher than the measured consumption. For the area covered by meter 35 the calculated consumption is 3% lower than the measured consumption.

13.5 Conclusions from Miljøbygget

The measured lighting energy usage in the studied areas is 14.3 kWh/m^2 per year and 16.2 kWh/m^2 per year respectively. This corresponds quite well with the energy usage predicted from calculations.

The fact that the there are no private offices in these areas but rater a large office landscape influences the energy consumption in several ways. On the negative side the occupancy detector might be triggered by people at nearby workplaces or people walking in the corridors. On the positive side the lighting from nearby workplaces or from the corridor areas might contribute to larger savings for the luminaires with daylight dimming.

Possible means to reduce the energy consumption for lighting in the area studied could include:

- A smaller field of view for the occupancy detector in order to avoid undesired triggering.
- A shorter delay time for the occupancy detectors.
- Daylight redirection systems in the upper window areas that redirect sunlight towards the ceiling.
    - Sensors that detect illuminance levels on the ceiling and dim the upward electric lighting accordingly.
    - Daylight dimming for the electric lighting also in the corridor areas.

14 Conclusions

For the reference building used in the LECO project an annual lighting energy consumption of 47 kWh/m^2 is assumed. This high energy consumption can result from a non-efficient lighting installation such as the one described in chapter 11. Several measures can be used in order to reduce the energy consumption for lighting. The results from each of these measures can be combined in order to achieve significant energy savings. The combination of more efficient lighting equipment, occupancy scheduling, daylight harvesting, improved lighting maintenance and the application of a non-uniform electric lighting scheme could provide lighting energy savings of up to 90% compared to the reference situation (47 kWh/m^2).

From the results it can be derived that the annual energy consumption for lighting in a Norwegian office building could become as low as 5 kWh/m^2 (factor 10) by combining technologies and solutions that are available today. Furthermore, in the near future, solid state lighting (LED and OLED) can be utilized in order to provide opportunities for even lower energy consumption.

It should be emphasized that the potential savings given in Table 5 depend on a large number of assumptions, and the numbers given are only intended as rough estimates. The actual savings that can be obtained for a given building can only be verified by a more detailed investigation.

Furthermore, the indirect savings resulting from reduced needs for cooling can be substantial but these energy savings are not discussed in this report. In order to take full benefit of energy efficient lighting, the operation of advanced lighting solutions should preferably be integrated with other building systems, including solar shading and HVAC. Efficient integration of the different technologies is an area for further research.

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