Helsinki University of Technology

Faculty of Electronics, Communications and Automation
Department of Electronics
Lighting Unit

Mohammad Shahidul Islam

Replacement of incandescent lamps with energy efficient lamps in developed and developing countries

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Supervisor Professor Liisa Halonen

Instructor D.Sc. Eino Tetri

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Author: Mohammad Shahidul Islam

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All over the world energy inefficient incandescent lamps are used in great numbers. Replacement of these inefficient lamps with energy efficient lamps can save energy and reduce energy bills for the consumers. This work discusses how much energy can be saved by replacing incandescent lamps used for task lighting with energy efficient lamps. This replacement results in cost savings and reduction of CO_2 emission. The purpose of the work is to assess the feasibility of the energy efficient lamps compared to the existing incandescent lamps. The performance of the compact fluorescent lamp (CFL) and light emitting diode (LED) lamps has been measured mainly for task lighting and then compared with that of the incandescent lamps. The performance of 60 W incandescent lamps has been compared with the performance of CFLs of power 11 W to 15 W and LED lamps of power 4 W to 13 W. The performance of these different lamps has been demonstrated through measurements made for both developed and developing countries. The measurements show that it is possible to replace incandescent lamps used for task lighting with energy efficient CFL and LED lamps have shown very promising results and they have a bright future in lighting.

Keywords: AC LED, CFL, CO_2 emissions, energy savings, incandescent lamp, LED

Preface

The study was accomplished at Lighting Unit in the Department of electronics of the faculty of Electronics, Communications and Automation, Helsinki University of Technology. I would like to acknowledge the direct and indirect contribution and involvement of different persons and authority in my work.

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Espoo [20.10.2009] Mohammad Shahidul Islam

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List of symbols and abbreviations

CCT	Correlated color temperature
CDM	Clean Development Mechanism
CER	Certified emission reduction
CFL	Compact fluorescent lamp
CO_2	Carbon dioxide
CRI	Color rendering index
DSM	Demand Side Management
ECCP	European Climate Change Program
EPA	Environmental Protection Agency
EU	European Union
FfE	Die Forschungsstelle für Energiewirtschaft
GHG	Greenhouse gas
GLS	General lighting service
Gtoe	Gigatons of oil equivalent
GWh	Gigawatt hour
HRE	Heat replacement effect
IEA	International Energy Agency
kWh	Kilowatt hour
LED	Light emitting diode
LFL	Linear fluorescent lamp
LIF	Lighting industry federation
LFMF	Luminous flux maintenance factor
LSM	Load Side Management
Mt	Mega tons
NGO	Non-governmental organization
OECD	Organization for economic co-operation and development
pf	Power factor
T & D	Transmission and Distribution
TWh	Terawatt hour
UF	Utilization factor
UN	United Nations
UV	Ultraviolet

Symbols

Φ	Luminous flux
E	Illuminance
I	Luminous intensity
L	Luminance
ω	Solid angle

Unit conversion

1 Plmh = 10^{15} lmh
1 TWh = 10^{12} Wh = 1 billion kWh
1 Giga ton = 10^{9} ton

1 Introduction

Energy is one of the fundamental needs for maintaining the quality of human life and it plays a vital role in both developing and developed countries. Secured energy supply is an important issue since the first real energy crisis in the 1970s. These days, global climate change makes this issue even more important. Thus, in today's world, energy saving and environmental protection against greenhouse gases (GHG) are two very important issues. The growing demand of electricity is putting a larger load on the economies and energy infrastructures all over the world. Two ways to meet this extra demand are either to build new power plants or to save energy. To build power plants is extremely expensive but to save energy by using energy efficient technology is cheap and also effective.

CO_2 is one of the main gases responsible for the greenhouse effect and a cause of climate change and global warming. So, the reduction of CO_2 emissions to protect the environment from the bad effect of GHG is an important issue for both developed and developing countries. In developed countries, the Kyoto Protocol objectives and emerging constraints on energy supply have raised the importance given to energy efficiency policies. Energy efficiency can play a vital role in alleviating the financial burden of fossil fuel imports in developing countries. It can make the best use of existing supply capacities to improve the energy crisis situation in developing countries. Achieving energy efficiency in residential buildings, especially in lighting, can play an important role to get a sustainable energy future and gain socio-economic development. In developing countries, efficient lighting technologies can play an important role in improving the energy supply situation. Energy efficiency in buildings (in lighting) can help to reduce CO_2 emissions and thus to combat climate change and global warming.

Incandescent lamps consume much power and convert only 5 % to 10 % of the input power to light energy (Hong *et al.* 2005). Efficient lighting technologies which are today already available can offer outstanding saving possibilities. Energy efficient lamps provide the same level of services by consuming much less power than that of incandescent lamps. Lighting technologies are getting improved and better day by day. There is the possibility that conventional inefficient incandescent lamps can be replaced with energy saving compact fluorescent lamps (CFL) and light emitting diode (LED) based lamps. This can be helpful to improve the energy consumption situation. This will in turn also reduce energy bills as well as reduce levels of CO_2 emissions.

Assessment has been done through measurements and data collections for both developping and developed countries in terms of illuminance. In this work, performance of the different lamps has been compared through measurements, data analysis and some calculations. Both CFL and LED lamps have been used for the measurements in places where it is possible to compare their performance with that of incandescent lamps.

1.1 Objectives of the study

The aim of the work was to find out whether it was possible to replace incandescent lamps used for task lighting with appropriate CFL and LED lamps. The aim was also to see what were the appropriate power ratings of the CFL and LED lamps for replacement and thus to calculate how much energy and cost as well as emissions of CO_2 could actually be saved.

1.2 Importance of energy conservation

Energy maintains the standard of our living and economy. Lack of electricity is unexpected in today's society. The earlier situation of over capacity has decreased and the balance between supply and demand is becoming narrower day by day, and the reserve capacity of fossil fuel is decreasing. For these reasons, the situation may not remain the same because of the growth of the world population and their growth of demand due to further economic growth and rising living standards. In both developed and developing countries, electricity consumption per capita is increasing. The imbalanced tug-of-war between the population growth and electrification may result in an increase in the number of people without access to electric light (Mills 2002). World-wide energy demand is projected by the World Energy Council to be at least double that of its present level by the year 2050. Most of this growth, and much of the increase in energy consumption, will occur in developing countries. (Europa 2009b)

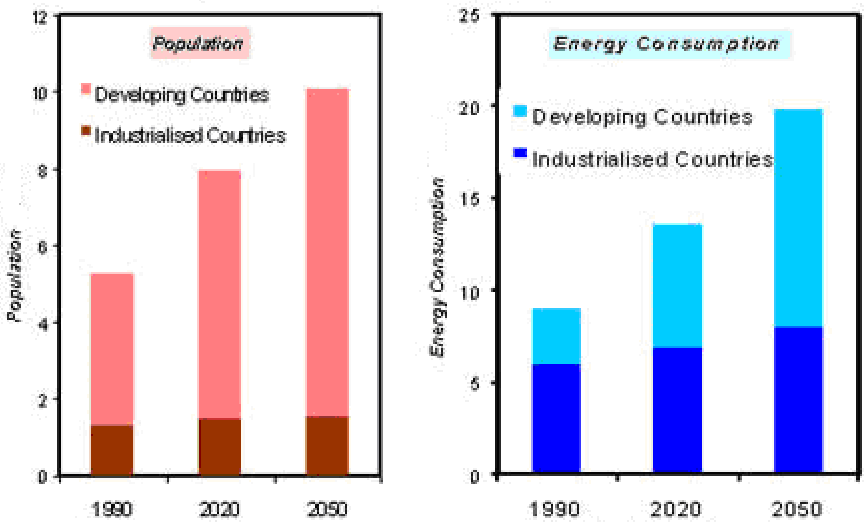

Figure 1-1. *Projected growth in world population (billion) and energy consumtion in Gtoe (Europa 2009b).*

Shortages of electric power and supply normally occur in most developing countries because of an inadequate number of generating facilities and fuel shortage. A huge investment is needed to ensure system adequacy and to improve supply security.

Studies show that about 53 % of the electricity consumed in 29 European countries is generated by using fossil fuels (WEC 2008). The figure could increase to 70 % by 2030. Unfortunately, a significant proportion of these fuels come from outside of the European Union (EU). (EC 2007). This dependence on imported fossil fuels is rising and may increase the vulnerability of the EU countries. Further increases in energy demand will put greater pressure on the finite reserves of fossil fuel. This combination of factors means that there is a risk of a rise in price and supply disruptions of energy.

Improving energy efficiency in electricity consumption in developing countries is very important. It will help to supply more consumers with the same electricity production capacity. It will slow down the high electricity demand growth. So, energy conservation is needed to ensure the essential supply of energy required for boosting both economic development and people's quality of life, as well as protecting the environment. Energy conservation through energy efficiency in homes is essential to reach that goal.

1.3 How to make a home energy efficient

Households account for a large share of global electricity consumption and the related CO_2 emissions into the atmosphere. Residential electricity demand is rapidly growing due to larger homes, new services and additional appliances needed for the growing of population (Europa 2007). Electrical appliances like oven, dryers, toaster etc. used at home work with efficiency of more than 70 %. Electric fans are normally 90 % efficient. (Humphreys 2008). There is not much potential for large energy savings in this area. On the other hand, the efficiency of incandescent lamps is very poor.

Incandescent lamps convert only 5 % to 10 % of the input power to visible light (Hong *et al.* 2005) and 90 to 95 % of its input energy is wasted as heat. So, there is much more potential to save a large amount of energy from lighting based on incandescent lamps than from most other appliances.

1.3.1 Keep them for room heating or replace them with energy efficient lamps

Energy efficiency measures related to heating system and lighting are cost-effective and can offer a better opportunity to increase the security and reliability of energy supply in the future. To some extent, it might be helpful to utilize the heat generated from incandescent for space heating. Effective possibility is to use energy saving lamps in lighting. Replacement of energy inefficient incandescent lamps with efficient lamps can be one of the most effective ways to make buildings energy efficient.

A study led in UK by the lighting industry federation (LIF) showed that substantial savings in energy consumption, operating costs, and emission of CO_2 can be achieved by replacing incandescent lamps with CFLs. This was also true even when the heat replacement effect (HRE) from a typical domestic heating system was considered. It also showed that the savings are dependent on the type of CFLs used. Considering the HRE from heating systems, the annual percentage net savings in all three cases (energy consumption, operating costs and CO_2 emissions) were only a few percentage points less than the claimed gross savings for both *stick* and *look-alike* CFLs. (LIF 2004)

There are some regions (e.g. USA) where heating systems are used in winter and cooling systems (air conditioners, heat pumps etc.) are used during the hot summer. There are also regions (Indian subcontinent, most Middle Eastern or African countries) where no heating systems are required in winter but air conditioners, heat pumps, electric fans etc. are widely used to alleviate the heat of the hot summer. In these cases, the use of incandescent lamps increases the load of cooling systems.

The thermal energy produced by incandescent lamps can significantly amplify the demand for space cooling, as a whole, in those regions and will be a net contributor to the overall increase in energy demand. Thus, lighting loads add an extra load to the space coo-ling systems during peak hours. Of course, the amount will depend on the efficiency of the air cooling systems in operation. If the average system coefficient of performance of value 2 is assumed, then the overall power demand will be 1.5 W when the power demand for lighting is 1 W (IEA 2006). So, heat generating incandescent lamps can increase the lighting related loads in those areas by up to 50 % when the load of cooling systems is considered.

During the time when heating is required, thermal energy gained from the incandescent lamps might help to some extent to offset the need for space heating and hence reduces space-heating energy demand. On the other hand, during periods when cooling is required the thermal energy from lighting adds to the indoor cooling load and increases the cooling energy demand. In practice, space cooling is provided by electricity which is more expensive and cannot be easily stored. On the other hand, space heating is provided by a variety of energy forms which are less expensive and can be readily stored. (IEA 2006)

A thorough analysis of these factors is beyond the scope of this thesis work, but it is likely that, as a whole, the heat produced by lighting makes a net contribution to the overall primary-energy consumption for space conditioning, increases total peak power demand and increases associated CO_2 emissions. (IEA 2006)

2 Background

2.1 Descriptions of different types of lamps used

2.1.1 Incandescent lamp

When current passes through the tungsten filament wire of an incandescent lamp the filament gets heated and causes electromagnetic radiation. This electromagnetic radiation in turns emits visible light and invisible infrared rays. The tungsten filament has a very high melting point (3410^{o}C) and the lowest evaporation rate (Coaton and Marsden 1997). Most of the energy consumed by incandescent lamps is dissipated as heat. Incandescent lamps convert only 5 % to 10 % of the input power to light energy and the rest is wasted as heat. (Hong *et al.* 2005)

Incandescent lamps are also known as general lighting service (GLS) lamps. The efficacy of incandescent lamps is in range of 10 to19 lm/W depending on the type of the lamps (Energysavers 2009). The life time of an incandescent lamp is usually less than 1000 hours at rated voltage (Coaton and Marsden 1997).

Incandescent lamps are very cheap to buy and easy to use. They do not need any auxiliary equipment. They are dimmable, small and they start immediately. They have color rendering index (CRI) of 100 and correlated color temperature (CCT) of normally 2700 K (IESNA 2000). There is no need to use special type of recycling technology after they are burnt out because they do not contain hazardous substances.

A large amount of CO_2 is emitted from power plants that supply the energy needed during the operating periods of incandescent lamps. The amount of mercury emissions from the power plant (mainly coal based) for supplying the energy to incandescent lamps is more than the CFLs can emit from their mercury content (Zukauskas *et al.* 2002)

2.1.2 Compact fluorescent lamp

A compact fluorescent lamp is a latest version of a linear fluorescent lamp. Light is produced predominantly with the help of phosphor activated by ultraviolet (UV) rays generated by the mercury arc inside the lamp. The lamp contains electrodes, mercury vapor at low pressure with a small amount of inert gas for starting. The inner walls are coated with phosphor. When current flows between the electrodes through the mercury vapor, an arc is produced. This discharge generates UV radiation mostly at the 254 nm wavelength. This discharge generates a very small amount of visible radiation. The phosphors are excited by the UV and emit visible light. (IESNA 2000)

At optimal conditions, about 63 % of the consumed energy by a CFL is converted to UV radiation. The rest of the energy is converted to heat. About 40 % of the UV radiation is converted to visible light. Around 3 % of the consumed energy by a CFL is converted to visible light directly. Thus, in the case of a CFL approximately 27 % of input power is converted to visible light, about 36 % to conductive and convective heat and 37 % to IR radiation (Zukauskas *et al.* 2002).

The CFLs have a negative voltage-current characteristic and are normally operated with electronic ballasts which limit the current to the required value for which the lamps are designed. The ballast also provides the required starting and operating voltages. Some

CFLs have integrated ballasts and some have external. Ballasts with poor quality may reduce either the life or light output or both of the CFLs. The starting of a fluorescent lamp occurs in two stages. First, the electrodes must be heated to their emission temperatures. Second, a sufficient voltage must exist across the lamp to ionize the gas in the lamp and develop the arc. (IESNA 2000). The luminous efficacy of CFLs varies typically from 35 to 80 lm/W. The luminous efficacy can rise by 10 to 15 % with electronic ballasts operated at frequencies above 20 kHz. The electronic ballasts have losses of about 11 % (4 W for a 36 W fluorescent lamp). A CFL also produces heat energy. A 12 W CFL converts 3 W into visible light and 9 W into heat. (IEA 2006). They have an average life time of 8,000-15,000 h (LIF 2004b) depending on type. The high luminous efficacy is a great advantage of CFLs, which consume normally 1/4 to 1/5 of the energy to provide the same level of light compared to their incandescent lamp equivalents. The CFLs have a high CRI value (82 to 90) and broad range of CCT. (IEA 2006). Almost all CFLs (look-alike) have a color temperature of 2700 K. On the other hand, pin base CFLs have a CCT of 2700-4000 K. (LIF 2004b)

The CFLs are expensive to buy. Their light output is strongly dependent on the ambient air temperature which influences the pressure of the mercury (Zukauskas *et al.* 2002). Short burning cycles shorten CFL lamp life and light output depreciates with age (Lecture 2008). Most CFLs contain on average 4 mg of mercury (Martikainen 2009). After they are burnt out, they must be recycled with care. The recycling process can cost also money.

2.1.3 Light emitting diode

Solid-state lighting technology has brought the possibility of changing the entire lighting infrastructure. The Light-emitting diode (LED), the primary solid-state lighting technology, has gained attention from scientists and government agencies as the next generation light source in lighting technology. At present, LED based lighting technology is in growing-up state. Changes and improvements are being achieved in LED based lighting technology everyday. Till date, a South Korean company, named Seoul Semiconductor, has demonstrated the brightest AC power driven LED. The efficacy of their AC LED is 80 lm/W (LEDsmagazine 2008). The renowned company Cree has achieved efficacy of 161 lm/W from a DC driven high-power LED (Cree 2008). These results are normally achieved under test condition in the laboratory. Normally, the amount of luminous flux claimed by LED manufacturers is based on an LED junction temperature (T_j) of 25°C. LEDs are tested during manufacturing under conditions which differ from actual operation in a lumenaire or system. Generally, the luminous flux of an LED is measured under instantaneous operation (a 20 millisecond pulse) in open air. (EERE 2009b)

Working principle and performance of a LED

An LED emits light using the process called electroluminescence. In this process electric current is passed through the LED by applying forward voltage across the p-n junction of the LED. Excess holes and electrons are produced by this injection of current. The LED emits light due to the radiative recombination of these excess electron and holes. (Zukauskas *et al.* 2002). Light is extracted with the help of an absorbing medium with a high index (Lecture 2008).

Achieving white light

White light is normally achieved in LEDs by two main ways: a) phosphor conversion, in which a blue or near-ultraviolet (UV) chip is coated with phosphor to get white light and b) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed to get white light. (EERE, 2008a)

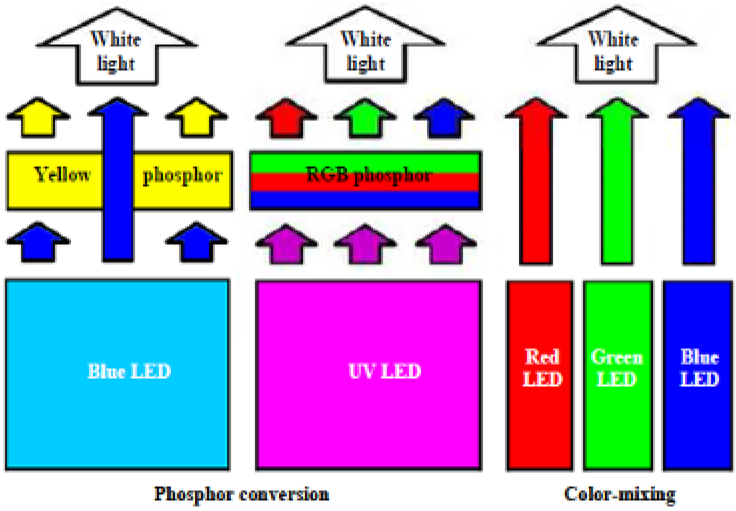

Figure 2-1. *Achieving white light from LEDs (Lecture 2009).*

Important features

LEDs consume (Härle 2007) very low power (0.1W- 15 W). A number of LEDs can be used together to make a powerful light source. LED lamps can convert about 15-25 % of the input power to visible light and 75-85 % to conductive and convective heat. They produce no UV and IR radiation (EERE 2009a). The junction temperature of LEDs will always increase when operated under constant current in an LED lamp. So, the heat must be taken away from the LED with the help of heat sinks, housings, or luminaire frame elements. Any increase in temperature reduces the efficacy of LEDs. Nowadays, LEDs, even in a well-designed lumenaire with adequate heat sinks, will produce 10 %-15 % less light than indicated by the luminous flux rating. LED drivers used for DC LEDs, which have typical efficiency of about 85 %, cause a further reduction of 15 %. (EERE 2009b)

White LEDs (Phosphor-converted) show relatively high CRI values ranging from 70-90+ (EERE 2008b). White LEDs (Hera 2008) have a wide range of CCT values (warm white 2850 K - 3500 K and cool white 5000 K - 7000 K). Typically, LEDs have life of more than 50,000 hours with at least 70 % of lumen output (Cassatatro 2007). LED-based lighting technologies have already begun to be used in many applications (e.g. traffic lamps, automotive, display, and architectural directional-area lighting). LEDs are disadvantaged by very high initial price (cost/ luminous flux). On the other hand, minimal use of resources, no hazardous substances and low power consumption make them very environmentally friendly. They do not harm to insects and do not disturb insect orientation unlike fluorescent lamps do. (Bueno & Michelini 2007). The overall efficiency of a system with LEDs depends on the efficacy of LED, driver efficiency and fixture (luminaire) efficiency etc. Moreover, AC LEDs do not need any control gear. Application of AC LEDs reduces the cost related to LED drivers and there is no extra loss of lumen output with AC LEDs unlike DC LEDs due to LED drivers.

2.2 Reasons behind the replacement of incandescent lamps

The energy efficiency of an incandescent lamp has not been improved much since its invention. In domestic lighting all over the world, the dominant light source is still the incandescent lamp (Halonen 2008). Lighting technology based on energy inefficient incandescent lamps consumes much energy. In 2005, incandescent lamps consumed electricity energy of amount 970 TWh which was around 37 % of total energy consumption for lighting purpose worldwide (2650 TWh) but they produce only 9 % of the electric light (IEA 2006, IEA 2007, Martikainen 2009). Thus, incandescent lamps consumed about 7 % of global total electricity consumption (13950 TWh) and give rise to about 2 % of global energy-related CO_2 emissions (IEA 2006, Waide 2007b).

In the residential sector incandescent lamps consumed 592 TWh which was about 61 % of the amount 970 TWh (energy consumption in all sectors by incandescent lamps). Around 873 TWh of electricity energy was wasted as heat (90 % of 970 TWh) and only 97 TWh was utilized to yield light energy. If the current rate continues they would consume 1610 TWh of electricity annually by 2030. According to the International Energy Agency (IEA) study, the amount of electricity consumed by incandescent lamps was responsible for emission of 560 Mt of CO_2 in 2005. (IEA 2007). The inefficiency of lighting systems based on incandescent lamps and their huge consumption of energy show that there is a huge potential for large energy savings in this field than in any other area. The European Climate Change Programme (ECCP) identified residential lighting as an important area to achieve considerable savings (EnERLIn 2009).

There is a huge potential to save energy and CO_2 emissions as well as money if these energy inefficient incandescent lamps could be replaced with energy efficient lamps. Because of these reasons, the IEA held a meeting in 2007 on energy efficient lighting and recommended to phase out inefficient lighting products used in homes (Anderson 2007). The phasing out regulation has already been in force in the EU from September 1^{st}, 2009 with incandescent lamps of 100 W and over (Halonen & Tetri 2009). This has been done by thinking that the directives and regulations will have a remarkable effect on phasing out incandescent lamps from general use and effect on increasing the share of CFL sales in the market.

2.2.1 Direct energy savings and economical benefits

CFLs consume normally 20 to 25 % of the energy to provide the same level of service in terms of illuminance compared to their incandescent lamp equivalents (IEA 2006). For cost analysis, the energy costs, power consumption, maintenance costs, lamp costs, life time and light output etc. are the needed factors. Among them, the most important part is the cost of operation in terms of energy and energy cost. It contributes a very large proportion of the total costs compared to the other costs for the total cost of lighting. Lamp cost and cost of operation of the lamp have been considered to compare how much energy and cost can be saved by CFLs.

Lamp manufacturers claim that a 20 W CFLs can replace a 100 W incandescent lamp. In that case, the amount of saved power is 80 W. The average electricity price for residential consumers in Finland is 12.44 ¢ per kWh (Energia 2009). Table 2-1 shows how much energy and costs can be saved by replacing 100 W incandescent lamps with 20 W CFLs over an operational period of 10,000 h.

Table 2-1. *Energy and cost savings by using a 20 W CFL.*

Features	Incandescent 100 W lamp	20W CFL
Lamp life	1000 h	10,000 h
No of lamps used	10	1
Electricity usage	1000 kWh	200 kWh
Electricity bill	€ 124.4	€ 24.88
Saved energy	800 kWh	
Saved energy bill	€ 99.52	

According to the German research institute "Die Forschungstelle für Energiewirtschaft" (FfE), the CFLs require approximately five times more energy to produce equivalent incandescent lamps. It has been found that a 20 W OSRAM DULUX EL lamp (life of 15-000 h) needs around 3.9 kWh and a 100 W incandescent lamp needs 0.83 kWh. On the other hand, it requires 15 equivalent incandescent lamps to get the lighting service for 15,000 h instead of only 1 CFL. The amount of energy needed to produce 15 incandescent lamps will be 12.5 kWh. (Martikainen 2009)

LED based Technology

LED lamps are very promising. LED lamps may use 1/12 - 1/10 of the energy of the incandescent lamps (STLD 2007). In the life cycle cost analysis of LED lamps the contribution of production cost due to energy usage is less important. For LED-based lamps over 98 % of the energy consumed during life cycle is used to provide service by generating light. Less than 2 % of energy is needed for production. (Huang 2009).

It is claimed that one 7 W Zetalux LED lamp can replace one 60 W incandescent lamp. The LED lamp Zetalux uses the latest LED from CREE and provides the same level of service that is equivalent to that of a 50-60 W incandescent lamp. A 7 W Zetalux LED lamp has life of 50,000 h. (Earthled 2008). The figures in Table 2-2 in terms of energy saving and cost of energy are calculated for 50,000 h.

Table 2-2. *Energy and energy cost savings by using a 7 W LED lamp.*

Features	Incandescent 60 W lamp	7 W LED lamp
Lamp life	1000 hours	50,000 hours
No of lamps used	50	1
Electricity usage	3000 kWh	350 kWh
Electricity bill	€ 373.2	€ 43.54
Saved energy	2650 kWh	
Saved energy bill	€ 336.41	

For the production of a 60 W incandescent lamp 0.9 kWh (according to Tesco) of energy is needed and for a LED lamp the amount is about 15 to 50 kWh (Matthews *et al.* 2009). Therefore, the amount of energy needed for production of fifty 60 W incandescece-ent lamps is 45 kWh.

The amount of energy and money that could really be saved

If all incandescent lamps were replaced by CFLs, roughly 800 TWh in 2010 rising to 1200 TWh in 2030 would have been saved. Collectively this would have reduced global net lighting costs by € 880 billion ($1300 billion) from 2008 to 2030. (Waide 2007b). It has been claimed that if every American household would have replaced their five most frequently used incandescent lamps with ENERGY STAR qualified CFLs they would have saved close to € 5.42 ($8) billion in energy costs per year. (Gourgue 2008). A study in the EU showed that by replacing only one additional incandescent lamp with one CFL per household a gain of 11 TWh could be achieved annually (EnERLIn 2009). Switching from incandescent lamps to new efficient lighting techniques European customers would save € 5 billion in electricity bills every year (AIE 2009).

Worldwide lighting energy consumption could be decreased by more than 50 % by a transition from existing lamp technologies to LED lamp technology. In that case, lighting would then consume less than one-tenth of all electricity produced. LED lighting can thus reduce at least 10 % in fuel consumption within the next 5–10 years. Even greater reductions can be achieved on a 10–20-year timescale. (Humphreys 2008)

Researchers at the "Rensselaer Polytechnic Institute" claim that if all of the world's light lamps could be replaced with energy-efficient LEDs for a period of 10 years a huge amount of energy, money and CO_2 emission could be saved (Kim and Schubert 2008).

Table 2-3. *Amount of saved energy, money and CO_2 emission (Kim and Schubert 2008).*

Features	Estimated savings
Reduction in total energy consumption	1.892×10^{20} Joule
Reduction in electrical energy consumption	18,310 TWh
Financial savings	1.2413×10^{12} €
Reduction in CO_2 emission	10.68 Giga ton
Reduction of crude-oil consumption	962.4×10^{6} barrels
Number of power plants not needed	280

Table 2-3 shows the benefits that could be achieved if all of the world's lamps could be replaced with energy-efficient LEDs for a period of 10 years.

Accroding to Osram, over 1/3 of the world wide used electricity for light can be saved by using energy efficient lamps. This means savings of 900 TWh of electrical energy per year (Martikainen 2009).

2.2.2 Environmental benefits

CO_2 emissions account for about 85 % of the total of all greenhouse gas emissions (Wang 2007). Thus, CO_2 is one of the main causes of global warming and greenhouse effect. CO_2 emission causes increase in our carbon footprint. The carbon footprint is almost 50 % of humanity's overall ecological footprint. The present ecological footprint is 2.2 global hectares per person. We need the equivalent of 1.3 earths to provide the resources we use and to absorb the waste we produce. Moderate United Nations (UN) scenarios indicate that if the current population growth and consumptions trends continue, by the mid 2030s we will require the equivalent of 2 earths to support us. (GFN 2009, Science 2008). In order to combat climate change, the Kyoto Protocol has set legally binding commitments on CO_2 emissions for industrialized countries. According to the protocol agreeing industrialized countries are to reduce their CO_2 emissions by 5.2 % compared to 1990 levels during the first commitment period 2008-2012 (Wang 2007).

Artificial lighting production accounts for approximately 8 % of world CO_2 emissions (Lefevre & Waide 2006). Unfortunately, it is not widely realized that lighting is one of the main reasons for CO_2 emissions all over the world. The energy consumed to supply the lighting load all over the world causes emissions of 1900 Mt of CO_2 per year. (Humphreys 2008). In 2005, grid based lighting (Waide 2007) emitted about 1528 Mt CO_2 into the air consuming around 2650 TWh of electricity. So, in 2005 the average amount of CO_2 emissions was 577g of CO_2 per kWh of electricity production worldwide. The amount was estimated assuming an energy mix based on the electricity generation values of 40 % from coal, 20 % from natural gas, 16 % from hydropower, 15 % from nuclear, 7 % from oil, and 2 % from renewable energy other than hydro. (Humphreys 2008).

CO_2 emission reduction by replacing incandescent lamps with CFL and LED can be an effective and efficient way for the industrial countries to reach the goal of Kyoto Protocol as well as to combat global warming. The Table 2-4 below shows how much CO_2 emissions could be saved if incandescent lamps were replaced in 2005.

Table 2-4. *Estimation of CO_2 emissions reduction by CFL and LED lamp.*

Features	Amount
Reduction of CO_2 emission with 20 W CFL	
Saved energy over 10,000 hours	800 kWh
Saved energy per 1000 hours	80 kWh
Saved CO_2 emissions per 1000 hours	46.16 kg
Reduction of CO_2 emission with 7 W LED lamp	
Saved energy over 50,000 hours	2650 kWh
Saved energy per 1000 hours	53 kWh
Saved CO_2 emissions per 1000 hours	30.58 kg

The amount of CO_2 emissions that could really be saved

If all incandescent lamps were replaced by CFLs, roughly 470 million tons of CO_2 emissions in 2010 and rising to 700 million tons of CO_2 in 2030 would have been saved. Cumulatively, this would have avoided 6.4 billion tons of global CO_2 emissions from 2008 to 2030 (Waide 2008). A study in the EU concerning energy savings showed that by replacing only one additional incandescent lamp with one CFL per household, a reduction of 1.2 million tons of CO_2 emissions could be achieved annually. (EnERLIn

2009). If every American household would have replaced their five most frequently used incandescent lamps with ENERGY STAR qualified CFLs they would have prevented the emissions of CO_2 equivalent to the emissions from nearly 10 million cars (Gourgue 2008). According to Osram, 450 million tons of CO_2 emission could be saved annually by using energy efficient lamps. (Martikainen 2009)

About mercury content of CFLs

On average, a CFL contains 4 mg of mercury *(*Martikainen 2009). According to the Environmental Protection Agency (EPA), a power plant (e.g coal) emits 0.016 mg of mercury per kWh of electricity production (Ramroth 2008). So, the power plant emits about 16 mg of mercury because of ten 100 W incandescent lamps over 10,000 h whereas the amount of mercury emissions because of a 20 W CFL is 3.2 mg for the same period of time. Although CFLs contain mercury but they can be kept out of the environment if CFLs are disposed of correctly and recycled after they are burnt out. Even if the CFL ends up in a landfill (worst case), the total amount of emission can be 7.2 mg. Unfortunately, mercury emitted by coal power plants to supply incandescent lamps is never recycled. Lamp industry is continuously reducing the mercury content of CFLs. The OSRAM DULUX Long life lamp contains less than 3 mg of mercury. The short-term goal of Osram (lamps producer) is to manufacture CFLs with 1.3 mg of mercury per lamp. (Martikainen 2009)

One of the best policies for reducing emission of CO_2

The widespread adoption of energy efficient lighting technology is one of the easiest, most practical and most cost-effective ways to save energy, to reduce energy bills as well as emissions of CO_2. There is no need for large investments or development work (unlike for biodiesel or new power plants, for example) to implement energy efficient lighting technology. Energy efficient lighting lamps are simple to use and can mostly be used in the existing luminaires of the old technology of incandescent lamps..

A replacement strategy with energy efficient lamps can be one of the quickest, most practical and easiest ways to reduce emissions of CO_2. The policy of replacing incandescent lamps by energy efficient lamps could be one of the best policies. According to the Kyoto Protocol, developing nations like China and India are not obliged to reduce or limit their emissions though they emit about 4500 million tons of CO_2. The United States, the number 1 emitter of CO_2 has not ratified the protocol. Besides reducing CO_2 emissions, industrialized countries have three other options to fulfill their commitment to the protocol. There is the opportunity for them to trade CO_2 emissions credits as required. They will be able to finance projects in other developed countries, or implement new projects in developing countries. (UM 2009). This kind of trading costs again money. But energy, money can be saved and CO_2 emission can be reduced by replacing incandescent lamps with energy efficient lamps by every country.

2.2.3 Benefits for power sector

Replacement of incandescent lamps with energy efficient lamps (CFLs and LED lamps) can increase the Load Side Management (LSM) program efficiency. Saving energy by replacing incandescent lamps with CFL and LED lamps in large numbers will decrease the loads on customer side to some degree. So, this will help power system to decrease transmission and distribution (T & D) losses in developing countries.

It will help much in a power system with high T& D losses. For example, Bangladesh has T & D losses of around 19.3 %. The number of customers in Bangladesh is 10.42 million (Power Cell 2007a). If every customer would replace one 100 W incandescent lamp with one 20 W (as claimed by local assembling companies) CFL, the amount of saved energy would be 834 $\times 10^6$ kWh per 1000 hours. So, the actual amount of saved energy in generation side would be 1033 $\times 10^6$ kWh per 1000 hours. This would save a huge amount of fuel (gas in Bangladesh) that can be used for other purposes. To achieve this kind of benefit, the power supply must have good power quality with power factor correction units and CFL and LED lamps must have a high power factor.

For a typical installation with non-linear loads dependent on a large number of CFLs based on a small transformer, the transformer would have to be de-rated (done because of non-linear harmonic loads) to 88 % of its rated kVA. The power reduction using CFLs instead of normal incandescent lamps is an 80 % reduction of load (e.g. from 100 W incandescent to 20 W CFL). Assuming that high power factor of the CFL and the network has power factor correction units, the saving on the transformer would be 0.88 x 0.80 = 0.704 per unit, or a 70.4 % reduction in load. The transformer would be able to supply 3.3 times more CFLs light points than normal incandescent light points, which in turn would save transformer installation cost for the utility. (Halonen & Tetri 2009)

2.3 Scope of replacements of incandescent lamps

In 2005, it was estimated that grid connected lighting provided 133.3 petalumen–hours (Plmh) of artificial light worldwide (IEA 2006). To get this amount of light 2650 TWh of electricity was consumed, which was about 19 % of global electricity consumption, equivalent to the electricity production of all 1265 gas-fired power plants (Waide 2007). In the residential sector the amount of lighting was about 19.2 Plmh which was about 14.4 % of the total amount. The commercial and public-building sector consumed around 59.5 Plmh (44.6 % of the total). In 2005, about 11.0 % (14.7 Plmh) of the total amount was contributed by incandescent light sources (incandescent, reflector and halogen lamps). Most of the incandescent lamps are used in these two sectors. In domestic lighting, the dominant light source is the incandescent lamp. (IEA 2006).

In 2005, the amount of electric light produced only by incandescent lamps was 12.4 Plmh in the residential and commercial sectors. The amount of electrical energy needed for this amount of light was 1033 TWh. (Halonen & Tetri 2009). It is clear from Table 2-5 that incandescent lamps use more energy compared to the amount of light they produce than the linear fluorescent lamps (LFLs). The number of global installed incandescent base is approximately 15 billions and the global annual incandescent lamp demand is approximately 12.5 billions.

So far, the largest part of the energy consumption comes from incandescent lamps of power range 60W to 100W. (Denneman 2008).

Table 2-5. *Worldwide light production and associated energy consumption in residential and commercial sectors in 2005 (Halonen & Tetri 2009).*

Lamp type	Amount of light (Plmh)	Lamp efficacy (lm/W)	Amount of energy (TWh)
Residential sector			
Incandescent	8.5	12.0	708
LFL	8.2	66.0	124
Commercial sector			
Incandescent	3.9	12.0	325
LFL	44.1	66.0	668

Thus, around 70 % of total global lighting market share are still made up of inefficient incandescent lamps. Therefore, there is a large opportunity and scope for saving a huge amount of energy in these sectors.

2.3.1 Situation in developed countries

In developed countries the amount of energy consumption for lighting in terms of percentage of the total electrical energy consumption may be small but the amount is still large. In the industrialized countries, electrical energy consumption for lighting ranges from 5 % (Belgium and Luxembourg) to 15% (Denmark, Japan, and the Netherlands) of total electricity consumption (Mills 2002). Lighting (Martikainen 2009) consumes 16 % of all electricity consumption within the EU and more than 20 % in North America. It is important to mention that lighting represents 20 % of the residential electricity consumption in the 12 new member states of the EU and a significant amount of electricity, accounting for around 18.3 TWh/year (Bertoldi & Atanasiu 2007). About 238 TWh of electricity was consumed in the USA for residential lighting in 2005. Member countries of Organization for Economic Co-operation and Development (OECD) consumed 372 TWh. Table 2-7 shows the number of lamps per household in some OECD countries. The number varies from 10.4 (Greece) to 43 (USA). (Waide 2007)

Table 2-6. *Lighting electricity consumption in household and number of lamps per household in some OECD member countries (Waide 2007).*

Country	Lighting electricity consumption per household kWh/year	Lamps per household	Installed light power density W/m^2	Household floor area m^2
UK	720	20.1	14.7	84
Sweden	760	40.4	14.0	110
Germany	775	30.3	15.6	83
Denmark	426	23.7	5.7	134
Greece	381	10.4	7.8	113
Italy	375	14.0	10.6	108
France	465	18.5	16.1	81
USA	1946	43.0	21.5	132
Japan	939	17.0	8.1	94

According to the report by Navigant consultancy (Navigant 2002), incandescent lamps constituted 63 % of the 7 billion lamps in the United States but they contributed the least amount of light to the national annual light demand. Although incandescent sources are responsible for only 12 % of all light generated in the United States, they are responsible for about 42 % of all lighting energy consumed (Hong *et al.* 2005).

Around 32 % of energy consumption in the commercial sector was for incandescent lighting but only 8 % of the commercial light was generated by this source (Navigant 2002). Incandescent lamps of different variety were 86 % of 4.6 billion lamps used in the United States residential buildings in 2001. Although the incandescent lamps accounted for 90 % of the total lighting electricity consumption, their share for the total generated lumen was only 69 % whereas fluorescent lamps provided 30 % of the generated lumens, consuming only 10 % of the lighting energy. Australian and New Zealand households have the similar trend of the dominance of incandescent lamps. (Halonen & Tetri 2009)

The large amount of estimated 372 TWh of electricity used for domestic lighting in 2005 in IEA countries was consumed by incandescent lamps. The average number of lamps per household in these countries was 27.5, of which 19.9 were incandescent lamps. (Halonen & Tetri 2009). In the EU-27, the average lighting points in 2007 were 19.5 (Bertoldi 2007). Around 85 % of the lamps used in European homes are energy inefficient lamps (ELCF 2008). In 2004, the number of sold incandescent lamps in the EU-25 was 1225 million (68 % of the total market lamp sale) and consumed 74 of TWh electrical energy. The amount of light spots for incandescent lamps was around 37 % and they consumed about 25 % of all the electricity used for lighting but they produced only 4 % of the light produced in the EU-25 area (Halonen & Tetri). In 2006, the amount of sold incandescent lamps (GLS and GLS-R) in the EU-27 was 1350 millions and most of the sold lamps were 60 W (Tichelen *et al.* 2008). These figures show that there is a huge scope and possibilities to save lighting energy in the EU by replacing the incandescent lamps with energy efficient lamps. An estimated amount of 39 TWh of energy can be saved in the EU until 2020 with energy saving technology alone in home lighting (Martikainen 2009). With more efficient and acceptable policies to further increase the CFL penetration (Bertoldi & Atanasiu 2007) in the market and use at homes, savings can be achieved in a relatively short time.

Situation in Finland

The electricity supply in Finland was about 87 TWh in 2008 (Energia 2009b). The peak load demand was reached with the average hourly demand of 13,770 MW in the winter season 2007/2008. Data from the year 1997 showed that in Finland, about 10 % of the total electrical energy was consumed for lighting purposes (Tetri 1997). The situation has not changed much. The reason for thinking of energy efficiency of lighting in the residential sector is the high percentage of electricity consumption for lighting in homes. Lighting consumes the largest amount of electrical energy in homes in Finland. In 2006, around 2427 GWh of electrical energy was consumed for lighting at homes, which was approximately 22 % of the total energy consumption (10,992 GWh) in homes. (Martikainen 2009).

Around 80 % of the electricity consumed for lighting by Finnish households is consumed by incandescent lamps. If these lamps could be replaced with energy savings lamps, it would save around 900 GWh of electricity, which is equal to the annual electricity consumption of 50,000 households (the calculation was based on the estimated energy consumption for 2010).

For total Finnish households this would mean savings of € 80-100 million per year. Up to 200,000 tons of CO_2 emissions could be saved by the replacement. (HS 2007)

In 2007 the number of households in Finland was 2.3 millions (Bertoldi 2007). Table 2-8 shows lighting energy consumption and number of light points in the residential sector in Finland in 2007.

Table 2-7. *Lighting energy consumption and number of light points in the residential sector in Finland (Bertoldi 2007).*

Features	Amount
Residential electricity consumption [TWh]	12.2
Lighting energy consumption [TWh]	1.7
Avg lighting energy consumption/HH [kWh]	739
Number of HH with CFLs [%]	50
CFLs/HH (including HH without CFLs)	1
Lighting points/HH	23.5

If one additional CFL per household were installed, then 2.3 million pieces of CFLs were added and then the amount of saved energy would have been 62.12 GWh per year. If 25 % of the lighting points per household in Finland were installed with CFLs, then the amount of saved energy could be 285.43 GWh per year. (Bertoldi 2007). At present, the sales of CFLs (only about 15 %) in Finland are very low compared to incandescent lamps though CFLs have been available from 1985. (Martikainen 2009).

2.3.2 Situation in developing countries

Over 100 years ago, Thomas Alva Edison (inventor of the incandescent lamp) made a statement –"We will make electricity so cheap that only the rich will burn candles". But his dream of cheap electricity has not come true for more than 1.6 billion (in 2005) people around the globe, who do not have access to electricity. (Halonen 2008). Many of them live in south Asia. Over 400 millions of them live alone in India (The Economic Times 2009).

The present state of electrical energy availability in many developing countries is far from an adequate level to supply the needs of all of the population. Only about 24 % of the people living in sub-Saharan Africa had access to electricity in 2000. Electrical networks in these countries are connected mainly to the urban areas. In the rural areas of these countries, only 2 % - 5 % of the population have access to electricity. In countries such as Brazil, Bangladesh, India, Morocco, and South Africa 20 % - 30 % of the rural population have access to electrical networks with some higher grid connection. The rest of the people (without access to the electricity) use liquid fuels (kerosene) for lighting.(Halonen 2008)

It is good news that the electrification rate in the developing countries has been continuously increasing during the past few decades. The situation is improving day by day. In most developing countries people consume electricity mainly for lighting purposes. So, lighting consumes the largest amount of total electrical energy in these countries. The amount can be as high as 86 % (Tanzania) of the total electricity production (Mills 2002). On the other hand, the dominant light source in domestic lighting is inefficient incandescent lamp. This indicates that there is a large saving potential in these countries if these lamps can be replaced with energy efficient lamps.

Although the electrification rate is increasing in the developing countries, the number of households without electricity is also increasing due to growth of the population. Around 18 million people in sub-Saharan Africa were newly supplied with electricity in time period between 1970 and 1990, but the total population growth at the same time was 118 million. This population growth resulted in an additional 100 million people who did not have access to electricity. Also in South Asia, the number of people without electricity grew by more than 100 million during the same time period. (Halonen 2008)

Situation in Bangladesh

The present state of energy availability in Bangladesh is far from an adequate level to supply the needs of all of its population. The power generation capacity of Bangladesh is 5269 MW. With this capacity about 43 % of the population (150 millions) in Bangladesh has access to electricity. (Power cell 2007a). The electrical network covers 82 % of urban households and 18 % of rural households (Hussain *et al.* 2009). Energy efficiency is, therefore, a prerequisite for future development. Lighting consumes a major part of electrical energy demand in households in Bangladesh.

Peak supply reaches about 4100 MW (some generating units are kept out of the operation due to some maintenance reasons) while peak demand exceeds 5000 MW making a substantial gap of about 900 MW between demand and supply. About 43 % of the total connected load is consumed by households, mostly for lighting purposes. According to studies, the *light load* accounted for about 80 % of peak demand in Bangladesh. (Hussain *et al.* 2009)

Lighting consumes about 30 % of total electrical energy consumption in Bangladesh. Incandescent lamps are the cheapest and most commonly used lamps. There are also other types of lamps including fluorescent lamps. Fluorescent lamps are mainly used for commercial buildings. A study done by Philips Bangladesh in 1993 showed that there were about 6.5 million light points for incandescent lamps and approximately 1 million light points for fluorescent lamps at that time. After 10 years, a study in 2003 showed that there were about 9.6 million incandescent lamps and about 1.5 million fluorescent lamps in use. In year 2002-03, it was estimated that 41 % and 5 % of total electricity was consumed by commercial and domestic consumers, and industrial consumers respectively for lighting purposes. (Khan 2006)

The comparison between the numbers of light points over this 10 years time period shows that the number of light points for incandescent lamps is increasing significantly day by day. Nowadays, compact fluorescent lamps are available in Bangladesh but the numbers of CFLs is insignificant compared to that of incandescent lamps. This scenario in Bangladesh suggests that there is a scope of a huge energy savings in the lighting sector by replacing these inefficient incandescent lamps with energy efficient lamps. Efficient lighting can provide an easy solution to the present energy crisis prevailing in the country by decreasing the demand for electricity.

3 Methods

In our everyday life, there are some tasks for which we need light only on a small and specific area. The cooker in the kitchen, reading tables or service tables in restaurants are some examples of these kinds of areas. Lighting systems which can provide the needed downward light for these kinds of areas can be considered as *task lighting*. Lighting systems over the cooker in kitchens or study lamps or luminaires which provide light on the tables in restaurants are some examples of task lighting systems. These kinds of systems were considered for the thesis work to make an evaluation of the performances of different types of light sources (incandescent lamps, CFLs and LED lamps).

3.1 CFLs and LED lamps as replacements for incandescent lamps

Incandescent lamps are omni-directional lighting sources. That is why most of their light output is wasted and the utilization factor is very low for this kind of task lighting purposes. Only 40 % (Archenhold 2007) of the total lumen output reaches onto the working plane for these kinds of tasks. Incandescent lamps with an efficacy of 12 lm/W results in a final efficacy of only around 5 lm/W. CFLs are also omni-directional lighting source but their utilization factor (UF) for task lighting is higher than that of incandescent lamps. The UF for CFLs is about 58 % (Mondoarc 2008). They use up to 75- 80 % less energy than incandescent lamps providing the same level of services (IEA 2006).

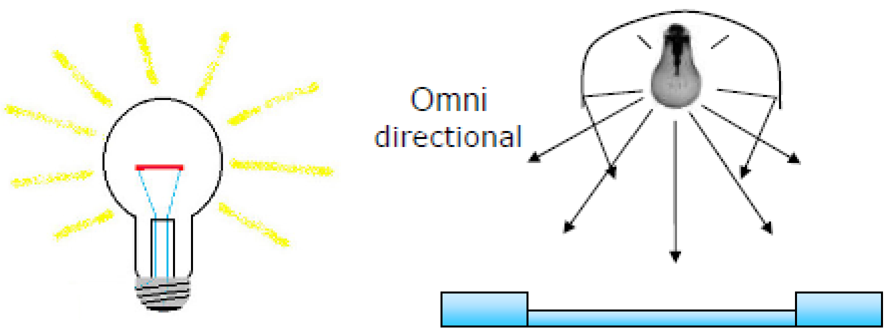

Figure 3-1. *Omni-directional light and 0.40 UF of incandescent lamps for downward task lighting (Archenhold 2007).*

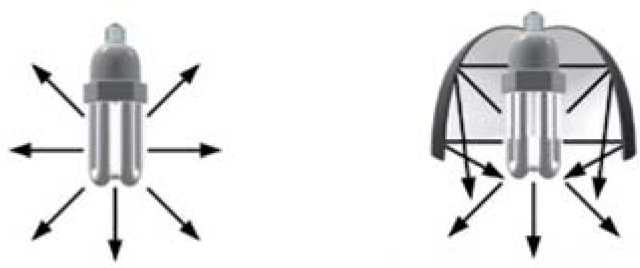

Figure 3-2. *Omni-directional light and 0.58 UF of CFL for downward task lighting (Mondoarc 2008).*

On the other hand, LEDs provide directional light. The new lighting technology with LEDs has the highest utilization factor because LEDs provide light on the specific and small area and most of the light is confined to the small area. Around 80 % (Archenhold 2007) of their light output can be utilized for down lighting (task lighting). LED P4 of Seoul Semiconductor with an efficacy of 100 lm/W thus results in a final efficacy of 80 lm/W.

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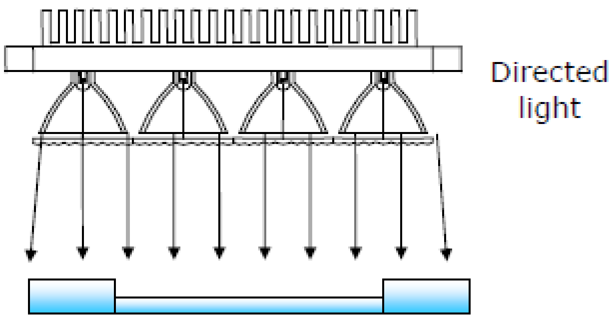

Figure 3-3. *Directed light and 0.80 UF of LED for downward task lighting (Archenhold 2007).*

That is why LEDs lamps do not need to have the same amount of lumens as the incandescent lamps to perform the task when down lighting is important. They may use much less power than that of incandescent lamps used for the same purposes.

3.2 Methodology for measurements

Replacement in the context of this work means to set an energy efficient lamp in the same light point where an incandescent lamp exists, without changing anything associated with the luminaire. After replacing the existing lamp with energy efficient one, the performance of the energy efficient lamp has been compared by measuring the illuminance level on the working plane.

Some measurement points on the working planes have been chosen and the illuminance has been measured with a lux meter for the existing lamp. Then for the same working plane and same measurement points, readings have been taken with the energy efficient lamps. After that the illuminance levels of the existing and energy efficient lamps have been compared. The basic concept was whether the energy efficient lamps can reach the same illuminance level or better. In some cases, it was also considered whether energy efficient lamps yielded an illuminance level that fulfilled the CIE or European standards or the local standards. So, one method of comparison was whether the energy efficient lamps could perform better than existing lamps or at least perform as equally well as the existing lamps. The other method was to see whether the readings with the energy efficient lamps are fulfilling the CIE or European standards or the local standards when the illuminance level of the energy efficient lamps was less than that of the incandescent lamps.

3.2.1 Comparison of CFLs and incandescent lamps

Normally, CFLs produce light that is more diffuse than incandescent lamps and they are very good for area lighting (Hussain *et al.* 2009). Most lamp manufacturers advise users to calculate the power of the CFL for the replacement of incandescent lamp by dividing the power of the previously used incandescent lamp by 5. It has been seen that there is a difference between the claimed and measured luminous flux. It is also seen that for CFLs of power less or equal to 12W, the luminous flux (claimed or measured) is less than that of a 60W incandescent lamps. Users who follow the advice of the manufacturers may not be satisfied with the amount of light they get from the lamp. So, it is preferable to divide the power of incandescent lamps to be replaced by 4 (instead of 5) to calculate the power of the equivalent CFLs. (Roisin *et al.* 2007). A look-alike CFL and a spiral type CFL should have at least same luminous flux (in lumen) as the previously used incandescent lamp or more than that of the incandescent lamps. It is better to have more luminous flux than the incandescent lamps because this extra luminous flux can bring some advantages. Firstly, it will be able to compensate the differences in the luminous flux maintenance factor (LFMF) between the two types of lamps. Incandescent lamps have an LFMF of 0.93 whereas CFLs have an LFMF of 0.85. So, to get the same luminous flux after a short period of time a CFL with a higher luminous flux than an incandescent lamp should be installed. The luminous flux of the CFL must be higher than that of an incandescent lamp by a factor of about 10 % ($1- 0.93/0.85 \approx 10$ %). The other advantage is that it will be able to compensate the warm-up time of the CFL. For example, a CFL 15 W yields luminous flux of about 800 lm and a 60 W incandescent lamp yields luminous flux of 700 lm. For the CFL, the 700 lm luminous flux is reached when about 88 % of the full luminous flux is reached. So, the light output of the CFL is equivalent to the light output of the incandescent lamp within about 2 minutes. If a CFL with luminous flux of 700 lm or less is used instead of CFL with luminous flux of 800 lm, CFL with 700 lm would take more than 10 minutes to reach the same level of light output (700 lm). (Roisin *et al.* 2007). Table 3-1 shows how a user can choose a CFL to save energy by replacing the corresponding incandescent lamps. A good comparison is to use a 15W CFL to replace a 60W incandescent lamp. The lower wattage means less energy consumption and less heat output. (Hussain *et al.* 2009)

Table 3-1. *Wattage rating comparison of incandescent lamps and CFLs for same amount of light output (SMUD 2008).*

Incandescent lamps	Light output in lumen	Equivalent CFL
40 W	450	9-13 W
60 W	800	13-15 W
75 W	1,100	18-25 W
100 W	1,600	23-30 W
150 W	2,600	30-52 W

It should be considered that for a tubular CFL the situation is different from the look-alike and spiral CFLs. A 14W northLIGHT has 2 tubes of length 16 cm each. The total unfolded length of the CFL will be 32 cm and the diameter of the tube is 1 cm. So, the projected area on the plane will be 0.32 x 0.01= 0.0032 m^2. In that case luminance of the lamp, $L= I/ A_{projected}$. Now, $I_{max}= \Phi/(\pi)^2= 800/9.86= 81$ candela. Then the value of luminance, $L= 81/0.0032= 25312$ cd/m^2. The illuminance at a point just under the lamp of height 1.8 m is 25 lux ($E= I/d^2$). When a tubular CFL is placed horizontally or vertically, the value of luminous intensity I to the projected area is changed because the area from which light emits is different in both cases. In that case,

Luminous intensity in horizontal case, $I_H = L x A_{proj\ (horizontal)}$
Luminous intensity in vertical case, $I_V = L x A_{proj\ (vertical)}$

When the lamp is placed vertically then, the projected area is 0.05 x 0.01= 0.0005 m^2. I_V = 13 candela. The illuminance at a point just under the lamp of height 1.8 m is 4 lux. The actual value of illuminance, however, will be larger than 4 lux when the lamp is set vertically because of the reflection of light from the white part of the base of the CFL as well as from the other tubes. Part of light will come through the gap between the two tubes (red box in Figure 3-4). This light can be reflected part of light from the tubes, the white base and some part of the light can come directly from the tubes.

The projected area is larger when the tubular lamp is set horizontally to the working plane than the projected area when the lamp is set vertically. The lumenance, L is constant for a lamp. So, the CFL yields more illuminance on the working plane when it is placed horizontally to the working plane.

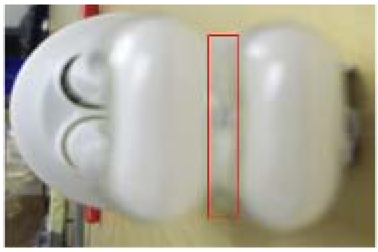

Figure 3-4. *Gap between two tubes of a tubular CFL.*

3.2.2 Comparison of LED lamps and incandescent lamps

There is a misunderstanding that the LED lamp must have the same amount of lumen output to replace the incandescent lamp but for task lighting (down light in the kitchen, for study lamp etc.) LED lamps do not need to have the same amount of lumen output. It is shown mathematically below.

For 60 W incandescent lamp

Luminous flux Φ =710 lumen, luminous intensity $I= \Phi/ (4\pi) = 57$ candela
The illuminance beneath the lamp is $E= I/d^2 = 18$ lux where d is the height of the lamp from the working plane and the value of d is assumed to be 1.8 m.

For a 4W AC LED lamp with an external lens of viewing angle of 70 degree

Solid angle $\omega= 2\pi (1-\cos\theta)$ where θ=35 degree, so $\omega = 1.14$ sr
Luminous flux (claimed) Φ_c= 230 lumen. Because of the use of optics about 10 % of the luminous flux will be lost (claimed). So, the actual amount of luminous flux will be Φ= 207 lumen.

Luminous intensity $I= \Phi/ \omega =181$ candela.
The illuminance level beneath the lamp is $E= I/d^2 = 56$ lux where d is the height of the lamp from the working plane and the value of d is assumed to be 1.8 m.

The area on which the light will mainly fall is $A= \pi R^2$, where $R=1.8 \, x \, \tan 35^o= 1.26$ m. So, the area = $3.14 \, x \, (1.26)^2 = 5 \text{ m}^2$. More light will be concentrated on a small area and in developing country like Bangladesh people do not have large kitchens. They need light only on the small area for performing chores in the kitchen.

It shows that there is a possibility that incandescent lamps used for task lighting to get downward light could be replaced with LED lamps. This is compared only according to the illuminance level. But actual replacement is more than the illuminance level. There are also important factors like CRI, CCT, and uniformity of light, which should also be considered.

4 Measurements and results

4.1 Case study Finland

For taking measurements in Finland, the scenarios considered are: a ceiling luminaire in a dormitory kitchen and a hanging luminaire over a service table in a restaurant. The ceiling luminaire had 60W incandescent lamps whereas the luminaire over the table in the restaurant had a 40 W incandescent lamp. Other luminaires considered are those used for under cabinet lighting, a luminaire over the cooker in the kitchen of the student dormitory as well as a study lamp. In this case, the readings have been taken to observe the performance of the LED lamps to compare with that of the existing lamps.

4.1.1 Readings for ceiling luminaire in dormitory kitchen

Measurements have been taken to compare the performance of CFLs with that of the existing 60W incandescent lamps. The height of the luminaire with a glass cover was 2.43 m. The measurements have been taken at the same measuring points with a 60 W incandescent lamp and with 11W Osram Dulux, 11 W northLIGHT, 14 W northLIGHT and 15 W Airam CFLs. A point of measurement just under the luminaire of height 1.98 m, two points on two sides the basin of height 1.52 m from the luminaire (not distance of the point from the luminaire), two points on the two sides of the cooker also of height 1.52 m were considered. A point on the dining table and two points (one in lower and one in upper position) inside of a cupboard were also considered. Measurements with CFLs have been taken after 20 minutes of burning. During the measurements inside of the cupboard, the door of the cupboard was kept totally open. The lamps were set horizontally inside of the luminaire. The readings are shown in Table 4-1.

Figure 4-1. *Overview of the kitchen and the reading point (lux meter) on the table.*

Figure 4-2. *Readings points P8 and P7 respectively (lux meter) inside the cupboard.*

Table 4-1. *Comparison of illuminance level (in lux) of different types of lamps used in the ceiling luminaire in the dormitory kitchen.*

Name of the lamp	Point just under the luminaire	Point on the table	Points on two sides of basin		Points on two sides of cooker		Points on two parts of cupboard	
	P1	**P2**	left **P3**	right **P4**	left **P5**	right **P6**	lower **P7**	upper **P8**
Incandescent lamp 60 W	45	49	49	49	55	60	43	57
Osram Dulux 11 W	49	50	57	59	64	64	54	72
northLIGHT 14W	50	52	59	61	66	66	50	74
Airam 15 W	61	63	72	75	81	82	67	91

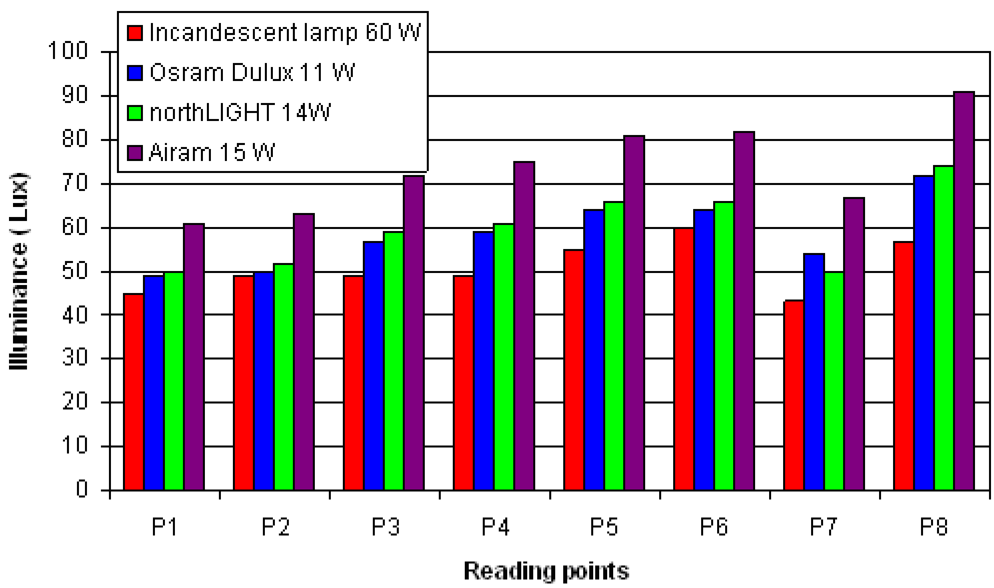

Figure 4-3. *Comparison of illuminance level of different types of lamps.*

Measurements with 11 W northLIGHT CFL (look-alike) were taken two times. Once without the glass cover (northLIGHT 11 W CFL does not yield that much glare) and once with the glass cover. The glass cover was used all the time for incandescent lamps to reduce the glare. The result is shown in Table 4-2.

Figure 4-4. *Performance of 11 W northLIGHT CFL without glass cover.*

Table 4-2. *Comparison of illuminance (in lux) of 11 W northLIGHT CFL and 60 W incandescent lamp.*

Name of the lamp	Point just under the luminaire	Point on the table	Points on two sides of basin		Points on two sides of cooker		Points on two parts of cupboard	
	P1	**P2**	left **P3**	right **P4**	left **P5**	left **P3**	right **P4**	left **P5**
Incandescent lamp 60 W	45	49	49	49	55	60	43	57
11W CFL (no cover)	38	44	43	43	48	51	38	50
11W CFL (glass cover)	27	28	32	32	35	36	30	39

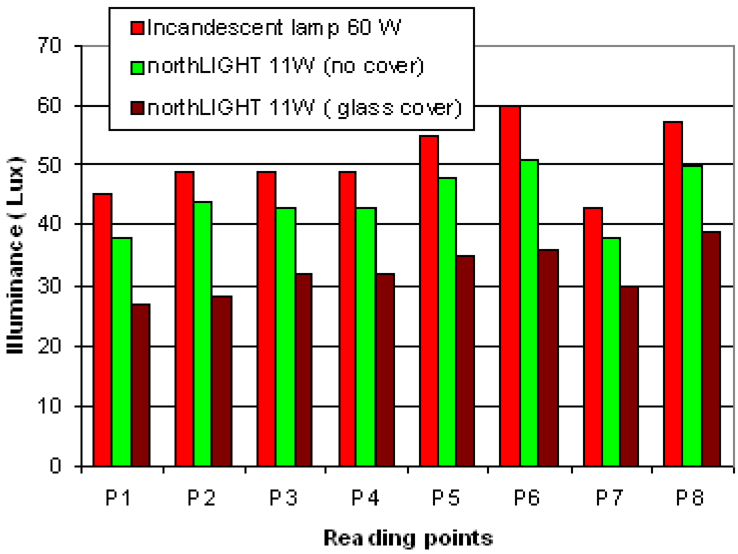

Figure 4-5. *Comparison of illuminance level of 60 W incandescent and 11W northLIGHT lamp*

Findings

Table 4-1 shows that 11 W Osram Dulux, 14 W northLIGHT and 15 W Airam CFLs have shown better performance in terms of illuminance than the 60 W incandescent lamp. So, it is possible to replace the incandescent lamps for this kind of down lighting application. For replacement not only illuminance values but also CRI, CCT and power factor values of these lamps should also be taken into consideration.

Table 4-3. *Measured values of CRI, CCT, luminous flux and power factors of different lamps.*

Lamps	Luminous flux (lm)	CCT (K)	CRI	Power factor
Incandescent lamp 60W	714	2730	99	1.0
Osram Dulux 11 W	690	2750	82	0.63
northLIGHT 14 W	785	2850	82	0.60
Airam 15 W	954	4170	83	0.60
Megaman 11 W	567	2730	83	0.69
northLIGHT 11 W	541	2720	83	0.61
Biltema 11 W	370	3040	80	0.61

The 11 W northLIGHT (look-alike) provides less illuminance than 60 W incandescent lamp. The main reason was that the measured luminous flux of this lamp was 541 lm whereas the 60 W incandescent lamp had 714 lm. For the same reason 11 W Biltema and 11 W Megaman will show a poorer result than incandescent lamp.

4.1.2 Readings for luminaire over the cooker in dormitory kitchen

The wattage rating of the lamp used in the luminaire was 11 W (Osram Dulux S). Its rated CRI value was 80 and CCT was 2700 K with luminous flux of 900 lm. The height of the luminaire from the working plane was 65 cm. It was installed 23 cm in front of the wall. The dimensions of the luminaire were 22.5 cm X 6.5 cm. The actual dimensions of the cooker were 60 cm X 51 cm. During measurement, an extra width of 20 cm to left and right side of the cooker was considered. Points for measurements were chosen as shown in the picture below.

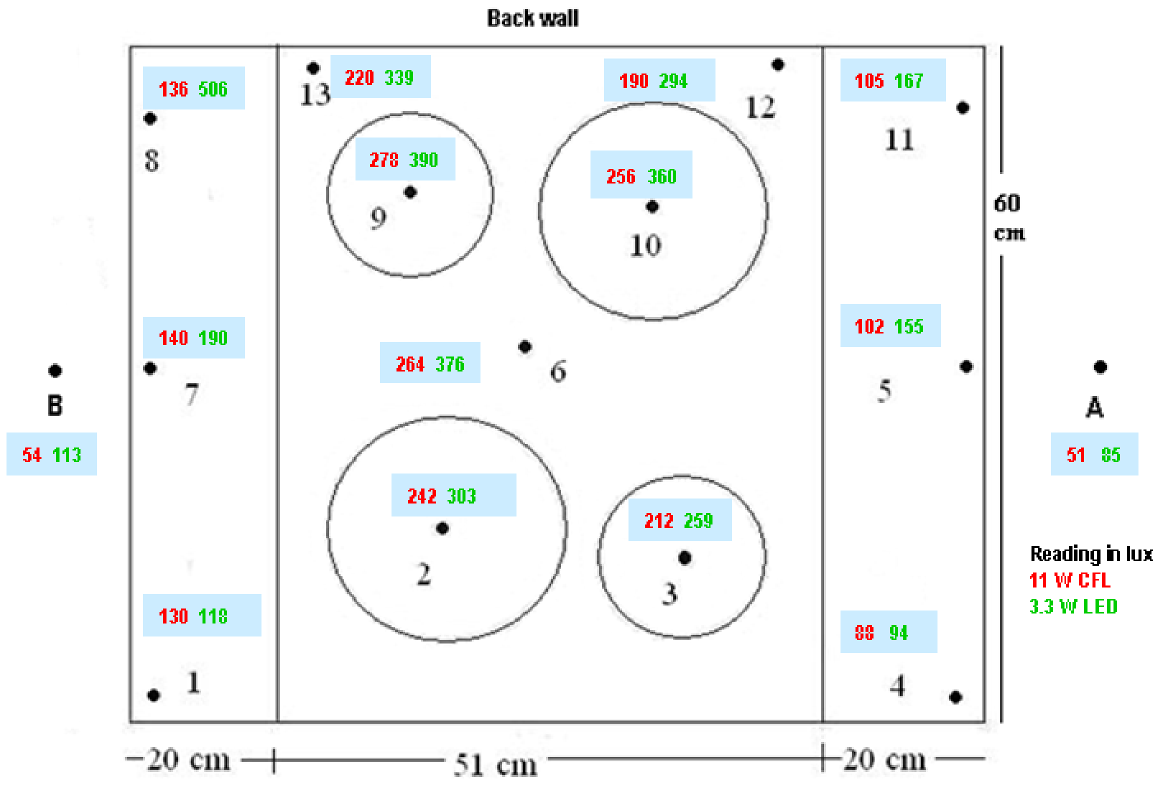

Figure 4-6. *Measurement points and readings on the working plane of the cooker.*

Point 1: 57 cm from back wall and 18 cm from left side of the cooker
Point 2: 16 cm from the front of the cooker and 14.5 cm from left side of the cooker
Point 3: 14.5 cm from the front of the cooker and 19 cm from right side of the cooker
Point 4: 57 cm from wall and 18 cm from right side of the cooker
Point 5: 30 cm from back wall and 18 cm from right side of the cooker
Point 6: 29 cm from front side of cooker and 21.5 cm from left side of the cooker
Point 7: 30 cm from back wall and 18 cm from left side of the cooker
Point 8: 10 cm from back wall and 18 cm from left side of the cooker
Point 9: 19 cm from back wall and 13 cm from left side of the cooker
Point 10: 14.5 cm from back wall and 20.5 cm from right side of the cooker
Point 11: 10 cm from back wall and 18 cm from right side of the cooker
Point 12: 5 cm from back wall and 6.5 cm from right side of the cooker
Point 13: 5 cm from back wall and 6.5 cm from left side of the cooker

Readings for the existing lamp have been taken in such a way that the height of the working plane remains the same during measurements with the LED lamp. One book of height 2 cm was used to place the lux meter over it to make the height of the lamp to be 63 cm during measurement with the existing lamp. It is because when the LED lamp was set up at the same place, the height of the lamp was 63 cm instead of 65 cm. The length of the LED lamp was 29.5 cm and width was 2.8 cm. The LED lamp was set at the same place under the glass used for the existing lamp. The power of the LED lamp was 3.3 W excluding the driver. The width of the LED package was 1 cm. There were 52 LEDs on the LED stripe. External lenses with a viewing angle of 60^{o} have been used.

Table 4-4. *Readings (in lux) with the existing 11 W CFL and 3.3 W LED lamp.*

Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8	Point 9	Point 10	Point 11	Point 12	Point 13
Reading for the existing 11 W CFL												
130	242	212	88	102	264	140	136	278	256	105	190	220
Reading for the 3.3 W LED lamp												
118	303	259	94	155	376	190	205	390	360	167	294	339

Two points outside of the working plane were also considered. Point A was considered 30 cm away from back wall and 40 cm from right side of the cooker and Point B was considered 30 cm away from back wall and 30.5 cm from left side of the cooker.

Table 4-5. *Readings (in lux) with the existing 11 W CFL and 3.3 W LED lamp in two points.*

	Point A	Point B
11 W CFL	51	54
3.3 W LED	85	113

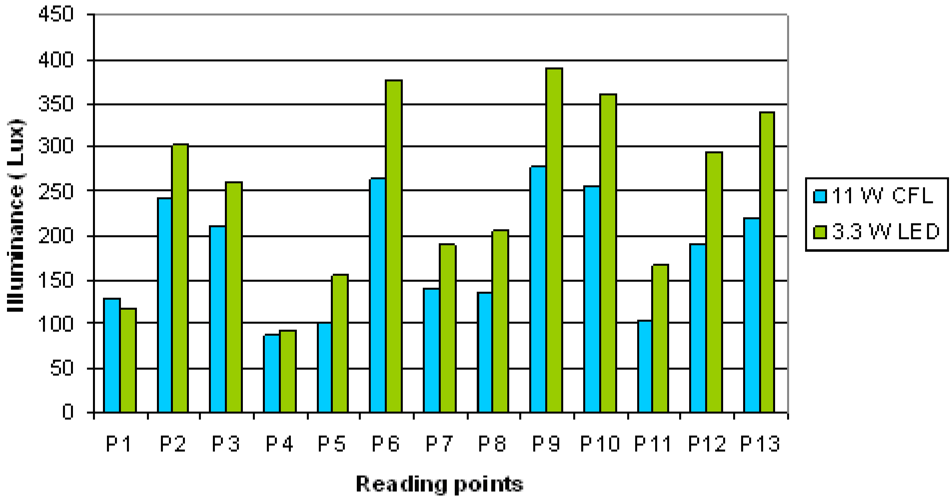

Figure 4-7. *Comparison of illuminance level of 11 W CFL and 3.3 W LED lamp.*

Findings

The LED lamp is promising in giving a better illuminance level but its CRI value is 72 and CCT is 5190 K. Also, the power factor including the driver is very low (0.46).

4.1.3 Readings for luminaire under the cupboard in dormitory kitchen

Power of the lamp used in the luminaire was 18 W (GE F18W/29). F18W/29 had rated CCT value of 2950 K and CRI value of 51. Its rated lamp life was 9000 h with lumen output of 1150 lm. (Geciasia 2006). The height of the luminaire from the working plane was 46 cm. The distance of the luminaire from back wall was 15 cm and from the left side of the working plane was 11 cm. The dimensions of the luminaire were 63 cm X 5.5 cm. The actual dimensions of the working plane were 90.5 cm X 59.5 cm. During the measurement, some points on the working plane were considered. Points were chosen with the distance from the left and right side of the working plane on the same line (10 cm from the back wall). At every point, measurements for different distances in front of the back wall were taken.

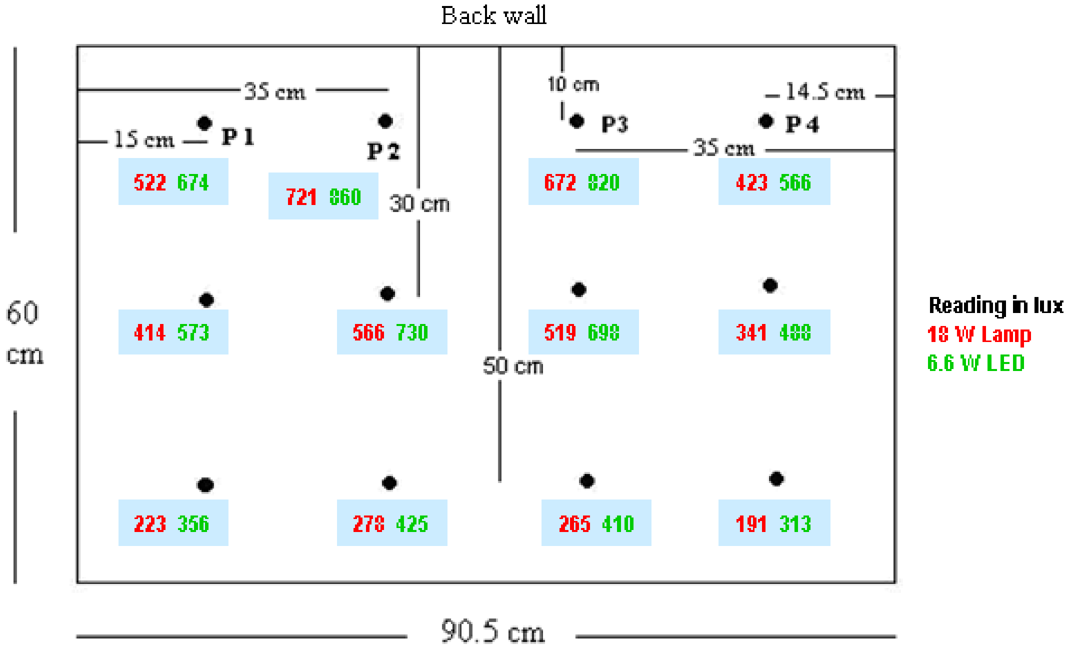

Figure 4-8. *Different measuring points on the working plane under the cupboard.*

Point 1, **P1**: 15 cm from the left side of the working plane
Point 2, **P2**: 35 cm from the left side of the working plane
Point 3, **P3**: 35 cm from the right side of the working plane
Point 4, **P4**: 14.5 cm from the right side of the working plane

All the readings were taken by placing the lux meter at a height of 45 cm because LED lamp was set on the same place but 1 cm below the existing luminaire. It made the height of 45 cm for the LED lamp from the working plane. Measurements were taken after 20 minutes of burning for both the existing lamp and the LED lamp. Readings have been taken in such a way that no extra light has come into the working plane.

The power of the LED lamp was 6.6 W. The height of the luminaire from the working plane was 45 cm. It was placed under the cupboard on the same place of the existing lamp. The distance of the luminaire from the back wall was 14.5 cm. The dimensions of the luminaire were 63 cm X 3.5 cm. The width of one LED package was 1 cm, which had 104 LEDs. The readings were taken after 20 minutes of burning and on the same points where the readings for the existing luminaire were taken.

Table 4-6. *Readings (in lux) with the existing luminaire (fluorescent lamp).*

Distance from the back of the table	Illuminance at point 1 **P1** (lux)	Illuminance at point 2 **P2**(lux)	Illuminance at point 3 **P3**(lux)	Illuminance at point 4 **P4**(lux)
Readings with the existing luminaire (fluorescent lamp)				
10 cm	522	721	672	423
30 cm	414	566	519	341
50 cm	223	278	265	191
Reading with the LED lamp.				
10 cm	674	860	820	566
30 cm	573	730	698	488
50 cm	356	425	410	313

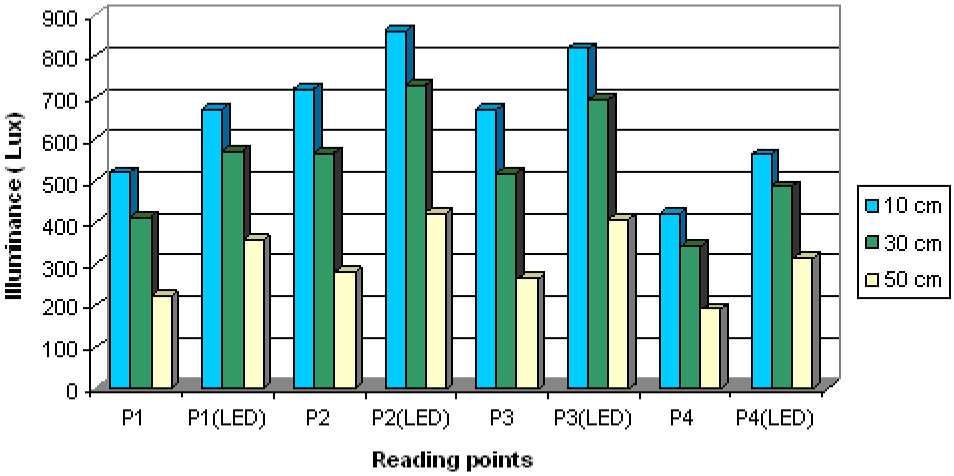

Figure 4-9. *Comparison of illuminance level of 18 W fluorescent lamp and 6.6 W LED lamp.*

Findings

The LED lamp is promising in giving a better illuminance level but its CRI value is 72 and CCT is 5190 K. Also the power factor including the driver is low (0.48).

4.1.4 Readings for luminaire over service table in the restaurant

The name of the restaurant where measurements were taken is Zetor. The address is Mannerheimentie 3-5, Kaivopiha, 00100 Helsinki, Finland. It has 26 bucket-like luminaires which are mainly used to focus light on a specific area including service tables.

Figure 4-10. *Different types of luminaires used in the Restaurant Zetor.*

Measurements were taken on a service table over which one bucket-like luminaire was used to focus light on the table. The dimensions of the table were 115.5 cm x 70.5 cm. The luminaire used one 40 W (Philips) incandescent lamp. The height of the lumenaire (from lower part) was 67 cm from the table and the height of the lamp (inside the luminaire) was 82 cm. The lower diameter of the luminaire was 32.5 cm. The point just under the lamp was found out on the table, whose distance was 41 cm from the back of the table and 62 cm from the left side of the table. During measurement, some points were chosen on the table. Points were chosen with the distance from the left side of the table on the same line (9 cm from the back of the table). At every point, measurements were taken for different distances from the back side of the table (9 cm, 34 cm and 60 cm).

The 40 W incandescent lamp was replaced with an 8 W CFL (northLIGHT) and a 4 W AC LED lamp. The LED lamp was assembled with the 4 W AC LED manufactured by Seoul Semiconductor.

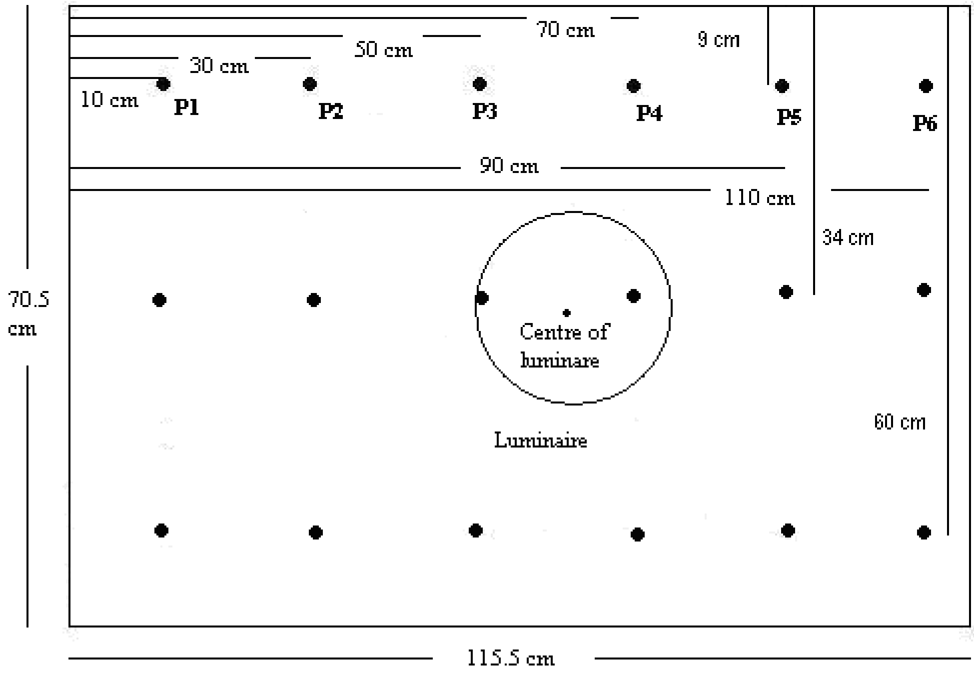

Figure 4-11. *Different measuring points on the service table.*

Point 1, **P1**: 10 cm from the left side of the table
Point 2, **P2**: 30 cm from the left side of the table
Point 3, **P3**: 50 cm from the left side of the table
Point 4, **P4**: 70 cm from the left side of the table
Point 5, **P5**: 90 cm from the left side of the table
Point 6, **P6**: 110 cm from the left side of the table

Table 4-7. *Readings with one 40 W incandescent lamp, 8 W CFL and 4 W AC LED lamp.*

Distance from the back of the table	Illuminance at point 1 **P1** (lux)	Illuminance at point 2 **P2**(lux)	Illuminance at point 3 **P3**(lux)	Illuminance at point 4 **P4**(lux)	Illuminance at point 5 **P5**(lux)	Illuminance at point 6 **P6**(lux)
Readings with one 40 W incandescent lamp						
9 cm	26	33	41	41	36	26
34 cm	29	40	53	54	44	31
60 cm	26	37	47	49	41	30
Readings with one 8 W CFL						
9 cm	40	53	66	66	57	48
34 cm	44	59	70	73	66	53
60 cm	39	51	59	62	56	45
Readings with one 4 W AC LED lamp						
9 cm	42	55	73	79	70	54
34 cm	48	71	96	106	87	62
60 cm	45	66	88	98	81	59

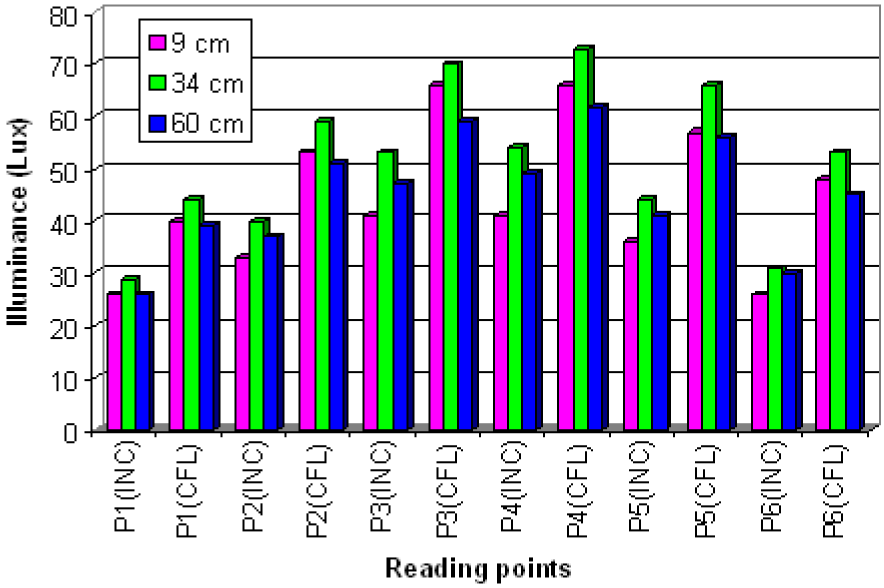

Figure 4-12. *Comparison of illuminance level of 40 W incandescent lamp and 8 W CFL on the service table.*

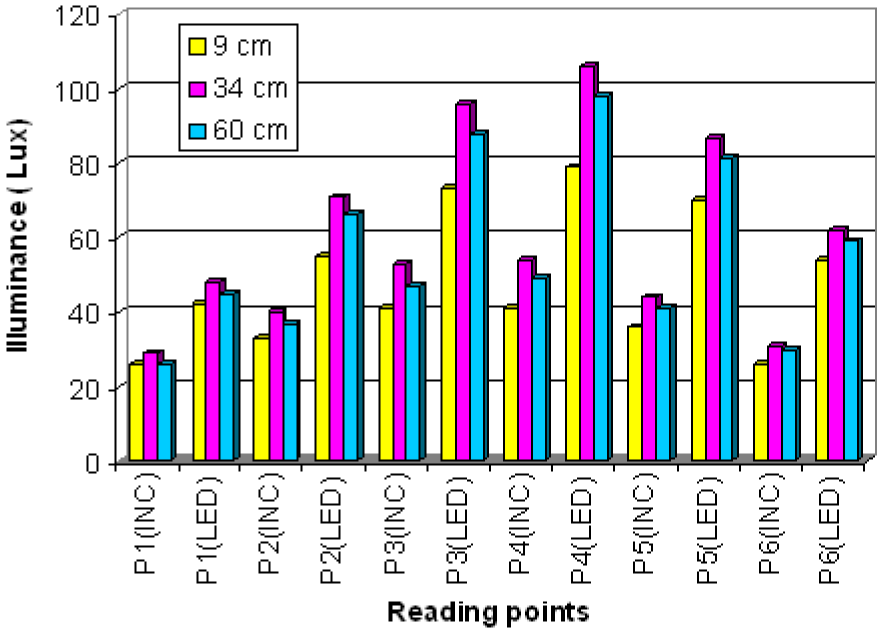

Figure 4-13. *Comparison of illuminance level of 40 W incandescent lamp and 4 W AC LED lamp on the service table.*

a) b) c)

Figure 4-14. *View of the service table with light from a) 40 W incandescent lamp b) 8 W CFL and c) 4 W AC LED lamp.*

Findings

The CFL and LED lamps are better in term of illuminance level (Table 4-7) than the incandescent lamp. The CFL had CRI value of 84, CCT of 2780 K but low power factor of 0.61. On the other hand, the 4 W AC LED lamp has very high power factor (0.93) but a CRI value of 66 and CCT of 5860 K (cool white).

One small survey was made with the CFL and LED lamps to examine whether people like the environment with the CFL and LED lamps. The purpose was also to see whether energy savings and environmental protection against global warming are important factors. A CFL and an LED lamp were set over different service tables beside which there was an incandescent lamp so that people could compare easily. The opinions of the most of the people who have participated in the survey have expressed that the overall performance of CFLs is better than incandescent lamps.

Opinions about LED lamp express that the performance of LED lamp in terms of illuminance is promising. The customers did not have any problem to see the food. Two out of three customers expressed that the color of the food was different when they were asked the question "Is the colour of the food different with this light?". When they were asked "Is the light from LED too bright compared to incandescent lamp, causing discomfort for seeing?" all customers replied with "Difficult to say". Again, when they were asked "Do you like the new environment lighted by the LED lamp?", two out of three customers replied "Difficult to say". These answers indicate that maybe, the customers are not confident to say "Yes" or "No" about the new lighting technology. It can be also possible that the customers are not yet ready to accept the new environment with this new lighting technology. Some customers expressed to the manager of the restaurant that this kind of lighting gave them a cold feeling. These opinions indicate that the overall performance of LED lighting should be improved.

More details about survey on the CFL and LED lamps can be found in Appendix (Survey and Questionnaire).

Explanatory about the LED lamp performance

The color rendering index (CRI) of a light source expresses how well the light source can render the color of the things lit by that light source. The AC LED has a CRI value of 66 which is not good enough to render the color of the food well whereas incandesceent lamps have a CRI value of 100 (100 is the maximum value). Another important factor of white light source is the correlated color temperature (CCT) which is responsible for color appearance (warm, cool or neutral white) of the light emitted from the light source. The AC LED has CCT of 5860 K which gives a cool white appearance of light emitted from the LED lamp.

People are confused with new technology and very conservative to accept new technology cordially. People are habituated with the warm colour appearance of incandescent lamps for over 130 years. So, it is really difficult to change their habit in a short time.

4.1.5 Readings at the entrance of a service room in the restaurant

Measurements were taken also at the entrance to a room decorated with service tables. In that area there were two 40 W incandescent lamps (Philips). The distance between the lamps was 130 cm. The height of the first luminaire, L1 (close to the entrance door) was 219 cm and the height of the other luminaire, L2 was 233 cm. The first luminaire was mainly used to provide light on the floor close to the door and the second luminiare was providing light on the floor as well as on two nearby service tables. Some random points were chosen on the floors (including two points just under the lamps, **P1**, **P4**) and on the nearby two tables. During all the measurements for the incandescent lamps, the CFL (8W northLIGHT) and the 4 W AC LED lamp, all other luminaires nearby remained switched on. It did not make any problem to the measurements because the illuminance level of incandescent lamps, CFL and LED lamps were taken at the same points keeping other factors constant (illuminace level from other lamps was always constant).

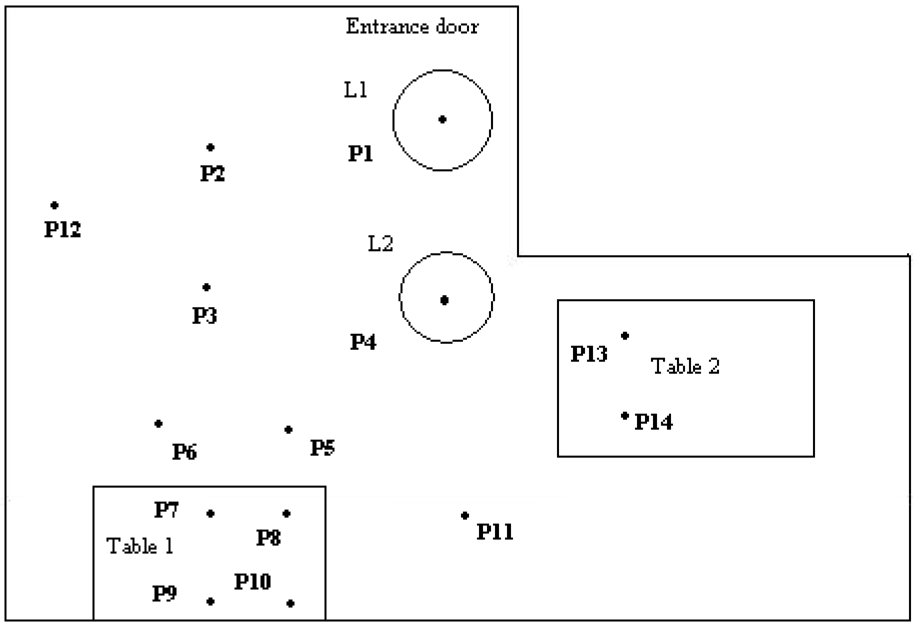

Figure 4-15. *Different measuring points on the floor and service tables.*

Point 1, **P1**: Just under the lamp of luminaire L1 on the floor
Point 2, **P2**: On the floor near to the luminaire L1
Point 3, **P3**: On the floor near to the luminaire L2
Point 4, **P4**: Just under the lamp luminaire L2 on the floor
Point 5, **P5**: On the floor near to the luminaire L2
Point 6, **P6**: On the floor near to point P5
Point 7, **P7**: On the right side of Table 1 under the influence of luminaire L2
Point 8, **P8**: On the right edge of Table 1 under the influence of luminaire L2
Point 9, **P9**: On the right side of Table 1 under the influence of luminaire L2
Point 10, **P10**: On the right edge of Table 1 under the influence of luminaire L2
Point 11, **P11**: On the floor between two tables
Point 12, **P12**: On the floor away from the luminaires
Point 13, **P13**: On the left side of Table 2 under the influence of luminaire L2 (close)
Point 14, **P14**: On the left side of Table 2 under the influence of luminaire L2 (away)

Table 4-8. *Readings with two 40 W incandescent lamps and two 8 W CFLs.*

Reading points	Illuminance with 2 incandescent lamps (lux)	Illuminance with 2 CFLs (lux)
Point 1, **P1**	15	17
Point 2, **P2**	17	21
Point 3, **P3**	15	19
Point 4, **P4**	13	15
Point 5, **P5**	11	14
Point 6, **P6**	10	12
Point 7, **P7**	10	17
Point 8, **P8**	11	17
Point 9, **P9**	9	14
Point 10, **P10**	9	14
Point 11, **P11**	9	12
Point 12, **P12**	10	17
Point 13, **P13**	10	17
Point 14, **P14**	9	16

Figure 4-16. *Effect of lighting with two 40 W incandescent lamps and two 8 W CFLs at the entrance of the room.*

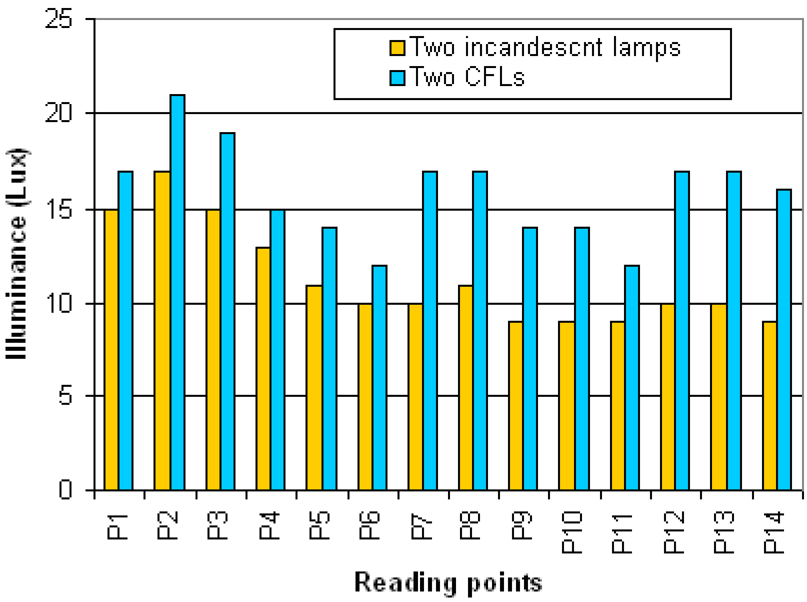

Figure 4-17. *Comparison of illuminance level of two 40 W incandescent lamps and two 8 W CFLs at the entrance of a room.*

Table 4-9. *Readings with one 40 W incandescent lamp and one 4 W AC LED lamp (luminiare L2 only).*

Reading points	Illuminance with incandescent lamp (lux)	Illuminance with AC LED lamp(lux)
Point 1, **P1**	10	13
Point 2, **P2**	13	16
Point 3, **P3**	11	15
Point 4, **P4**	8	13
Point 5, **P5**	8	12
Point 6, **P6**	8	15
Point 7, **P7**	10	16
Point 8, **P8**	10	15
Point 9, **P9**	9	12
Point 10, **P10**	9	13
Point 11, **P11**	7	12
Point 12, **P12**	10	13
Point 13, **P13**	8	12
Point 14, **P14**	8	12

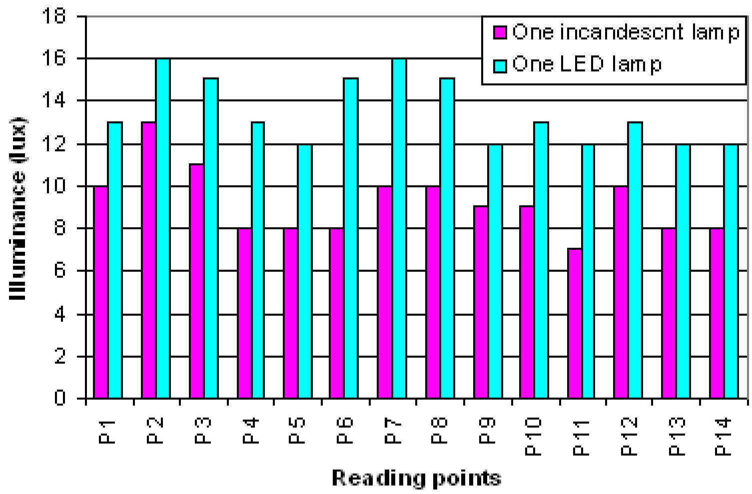

Figure 4-18. *Comparison of illuminance level (in lux) of one 40 W incandescent lamp and one 4 W AC LED lamp at the entrance of a room.*

4.1.6 Readings for study lamp

The wattage rating of the lamp (Osram Dulux S) used in the table lamp was 11 W. The dimensions of the luminaire were 29 cm X 6.5 cm. The actual dimensions of the working plane for the luminaire were 90.5 cm X 60 cm. The height of the lamp from the working plane was considered 50 cm during measurement. The luminaire of the study lamp was placed in such a way that the head of the luminare was 35.5 cm away from the right side of the table and tail of the luminaire was 26 cm away from the left side. The distance of the luminaire from the front of the table was 4.5 cm at its tail and 6.5 cm at its head. During measurement, some points on the working plane were considered. Points were chosen with the distance from the left side of the working plane on the same line. At every point, measurements were taken for different distances in front of the back wall. The back wall was covered by black plastic paper so that there was no reflection from the wall.

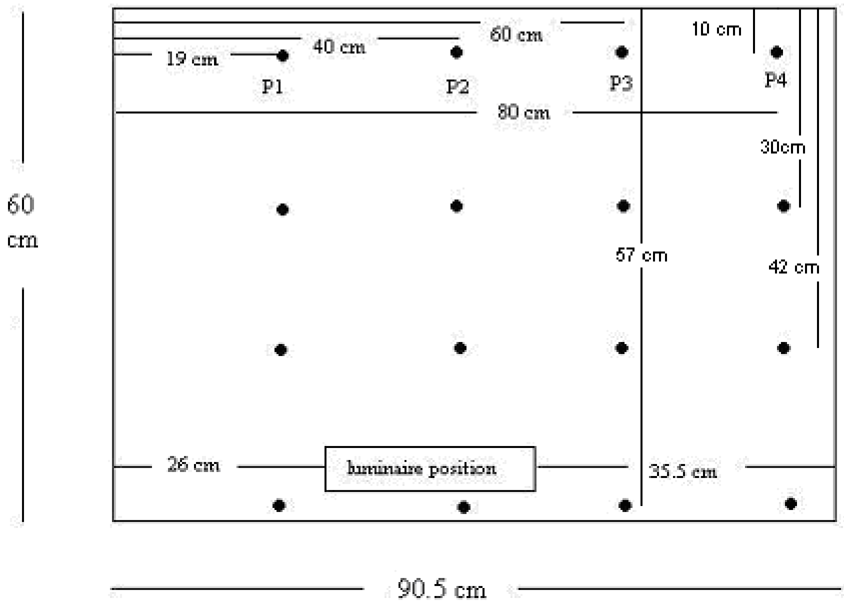

Figure 4-19. *Different measuring points on the working plane.*

Point 1, P1: 19 cm from the left side of the working plane
Point 2, P2: 40 cm from the left side of the working plane
Point 3, P3: 60 cm from the left side of the working plane
Point 4, P4: 80 cm from the left side of the working plane

The same LED lamp was used, which has been described in Section 4.1.2. The LED lamp was set on the same place as the existing 11 W CFL but outside of the structure, not inside where the CFL was installed. So, the lamp was set in such a way that the height was again 50 cm from the working plane. The LED lamp was set just in the middle of the existing structure of the study lamp. The study lamp was set in such a way that it was placed like the same way as before. Measurements were taken after 20 minutes of burning for both existing lamp and LED lamp.

Table 4-10. *Readings with 11 W CFL and 3.3 W LED lamp at different points on the working plane.*

Type of lamp	Illuminance at 10 cm (lux)	Illuminance at 30 cm (lux)	Illuminance at 42 cm (lux)	Illuminance at 57 cm (lux)
Readings in downward direction for point 1: **P1**				
CFL 11W	140	215	238	233
LED lamp 3.3 W	133	320	331	338
Readings in downward direction for point 2: **P2**				
CFL 11W	186	310	356	358
LED lamp 3.3 W	174	442	480	460
Readings in downward direction for point 3: **P3**				
CFL 11W	160	257	297	301
LED lamp 3.3 W	157	362	394	352
Readings in downward direction for point 4: **P4**				
CFL 11W	101	140	154	159
LED lamp 3.3 W	107	193	205	173

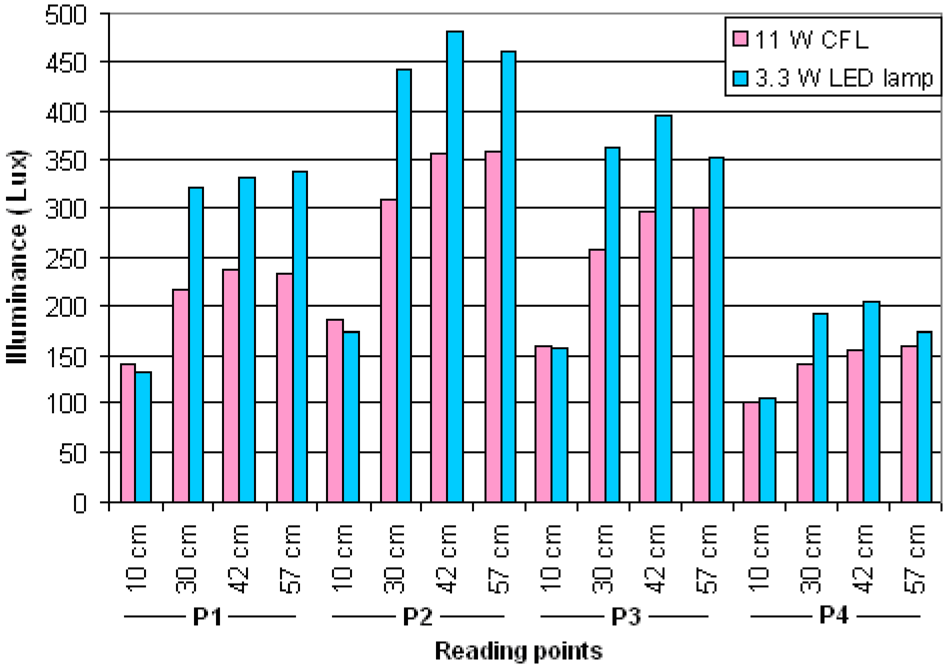

Figure 4-20. *Comparison among readings with 11 W CFL and 3.3 W LED lamp at different points on the working plane.*

Findings

The LED lamp is promising in giving a better illuminance level but its CRI value is 72 and CCT is 5190 K. Also, the power factor including the driver is low (0.46).

4.2 Case study Bangladesh

In the case of taking measurements for Bangladesh, a study lamp and a bare hanging lamp in a kitchen like room were considered. In both cases, 60 W incandescent lamps are used in Bangladesh (in general).

4.2.1 Readings for the kitchen

A room with an area of 4 m^2 (2m x 2m) has been constructed, where the measurements were taken to compare the performance of different kinds of lamps. Black walls have been used in the room so that no light is reflected. The lamp holder was put in such a position so that readings could be taken in all directions on the working plane. The distance between the working plane and the lamp was 1.8 m. This height is typical for the lamp in the kitchen of households in Bangladesh. During the measurements the height of the lamp was always adjusted according to the size of the lamp.

The measuring directions have been shown in Figure 4-21. For measurements, the longest radius was taken to be 1.00 m (the working plane area was then 3.14 m^2). In every direction, measurements have been taken with a different distance from the center point (r = 0.5 m, r = 0.7m, r = 0.85m, r = 1.00 m). The point on the working plane just under the lamp was considered to be the center point.

For cooking purpose, people do not need a large working area. It is assumed that an area of about 3 m^2 is generally used in Bangladesh. In that case, the radius is 0.977m.

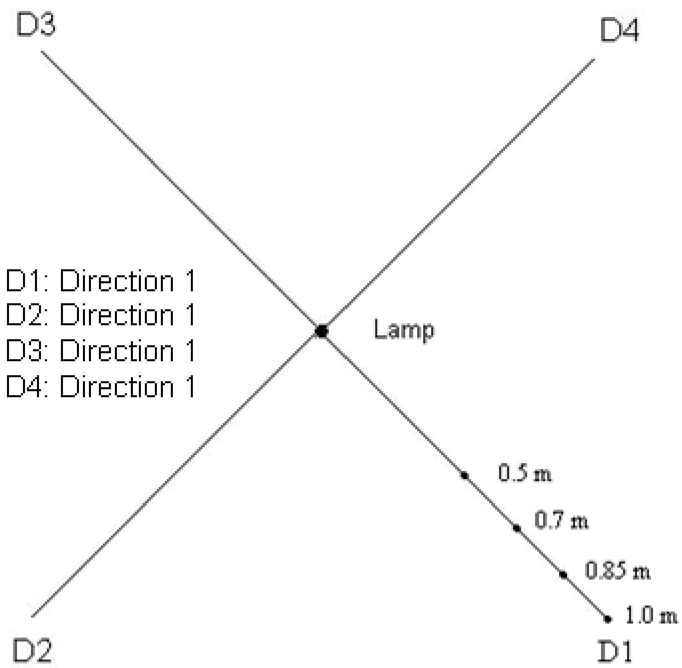

Figure 4-21. *Different directions of taking measurement.*

Table 4-11. *Readings with different lamps at the point just under the lamp on the working plane.*

Type of lamp	Illuminance under the lamp (lux)
Incandescent lamp 60W	23
Osram Dulux 11 W	24
Biltema 11 W	7
Megaman classic 11 W	12
northLIGHT (look-alike) 11W	16
Osram dulux superstar 12 W	13
northLIGHT (tubular) 14 W	9
Airam (tubular) 15 W	16
GE (look-alike) 15 W	27
Philips (spiral) 15 W	38
AC LED lamp 4W	19
AC LED lamp (reflector) 4W	61
Evolux LED lamp 13 W	72
Topco LED lamp 13 W	70
Quasar JDR LED lamp 6 W	46

Table 4-12. *Readings with incandescent and different CFLs (14 to 15 W) in different directions on the working plane.*

Type of lamp	Illuminance at r= 0.5m (lux)	Illuminance at r= 0.7 m (lux)	Illuminance at r=0.85 m (lux)	Illuminance at r= 1.00 m (lux)
Readings in direction 1: D1				
Incandescent lamp 60W	21	19	18	16
northLIGHT (tubular) 14 W	11	11	11	11
Airam (tubular) 15 W	17	17	17	17
GE (look-alike) 15 W	25	22	21	19
Philips (spiral) 15 W	36	34	32	30
Readings in direction 2: D2				
Incandescent lamp 60W	21	19	17	16
northLIGHT (tubular) 14 W	11	11	11	11
Airam (tubular) 15 W	18	18	18	18
GE (look-alike) 15 W	24	22	20	19
Philips (spiral) 15 W	38	35	33	31
Readings in direction 3: D3				
Incandescent lamp 60W	21	19	18	17
northLIGHT (tubular) 14 W	10	11	12	12
Airam (tubular) 15 W	18	18	18	18
GE (look-alike) 15 W	24	23	21	20
Philips (spiral) 15 W	38	35	33	30
Readings in direction 4: D4				
Incandescent lamp 60W	21	20	18	17
northLIGHT (tubular) 14 W	10	11	11	12
Airam (tubular) 15 W	18	18	18	19
GE (look-alike) 15 W	25	23	22	19
Philips (spiral) 15 W	37	34	34	32

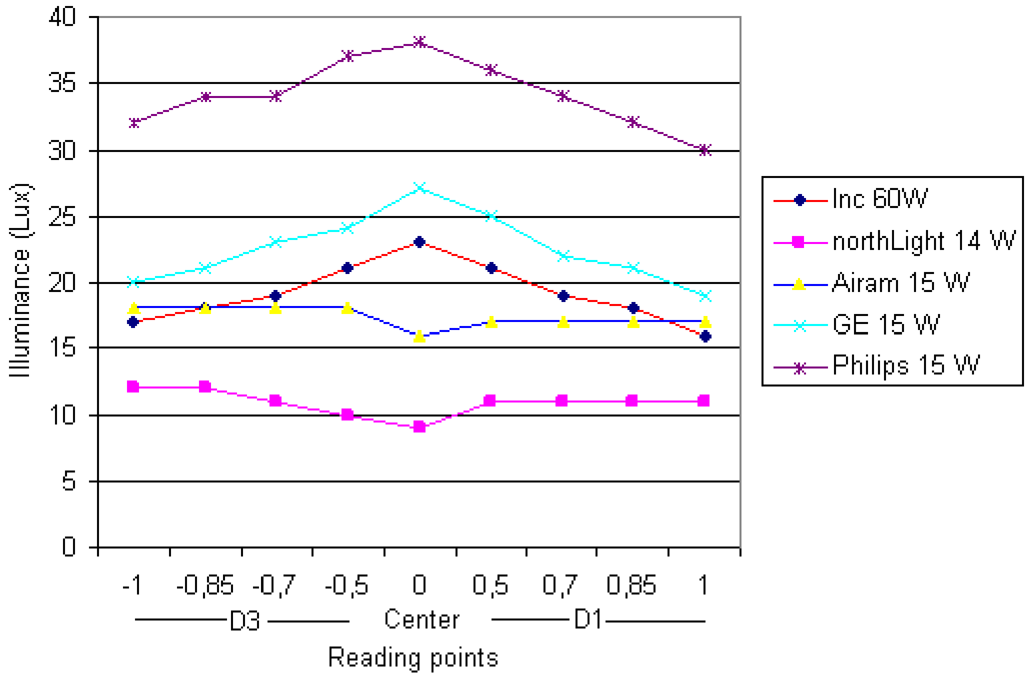

Figure 4-22. *Comparison among readings with incandescent lamps and different CFLs (at point under lamps and at different points in directions D1 and D3).*

Direction D1 and D3 (opposite to each other) were considered for drawing the graph because readings were almost the same between D1 & D2, and between D3 & D4. The readings had the same pattern in all directions.

Table 4-13. *Readings with incandescent lamp and different CFLs (11 to 12 W) in different directions on the working plane.*

Type of lamp	Illuminance at r= 0.5m (lux)	Illuminance at r= 0.7 m (lux)	Illuminance at r=0.85 m (lux)	Illuminance at r= 1.00 m (lux)
Readings in direction 1: D1				
Incandescent lamp 60W	21	19	18	16
Osram Dulux 11 W	22	20	19	17
Biltema 11 W	7	6	6	5
Megaman classic 11 W	12	11	10	9
northLIGHT (look-alike) 11W	15	14	13	12
Osram dulux superstar 12 W	13	13	12	12
Readings in direction 2: D2				
Incandescent lamp 60W	21	19	17	16
Osram Dulux 11 W	22	20	19	17
Biltema 11 W	6	6	6	5
Megaman classic 11 W	12	11	10	10
northLIGHT (look-alike) 11W	15	14	13	12
Osram dulux superstar 12 W	14	14	14	13
Readings in direction 3: D3				
Incandescent lamp 60W	21	19	18	17
Osram Dulux 11 W	23	21	19	18
Biltema 11 W	6	6	5	4
Megaman classic 11 W	12	11	10	9
northLIGHT (look-alike) 11W	15	14	13	12
Osram dulux superstar 12 W	15	15	15	14
Readings in direction 4: D4				
Incandescent lamp 60W	21	20	18	17
Osram Dulux 11 W	22	21	19	18
Biltema 11 W	6	6	5	5
Megaman classic 11 W	12	11	11	9
northLIGHT (look-alike) 11W	15	14	13	13
Osram dulux superstar 12 W	13	13	13	13

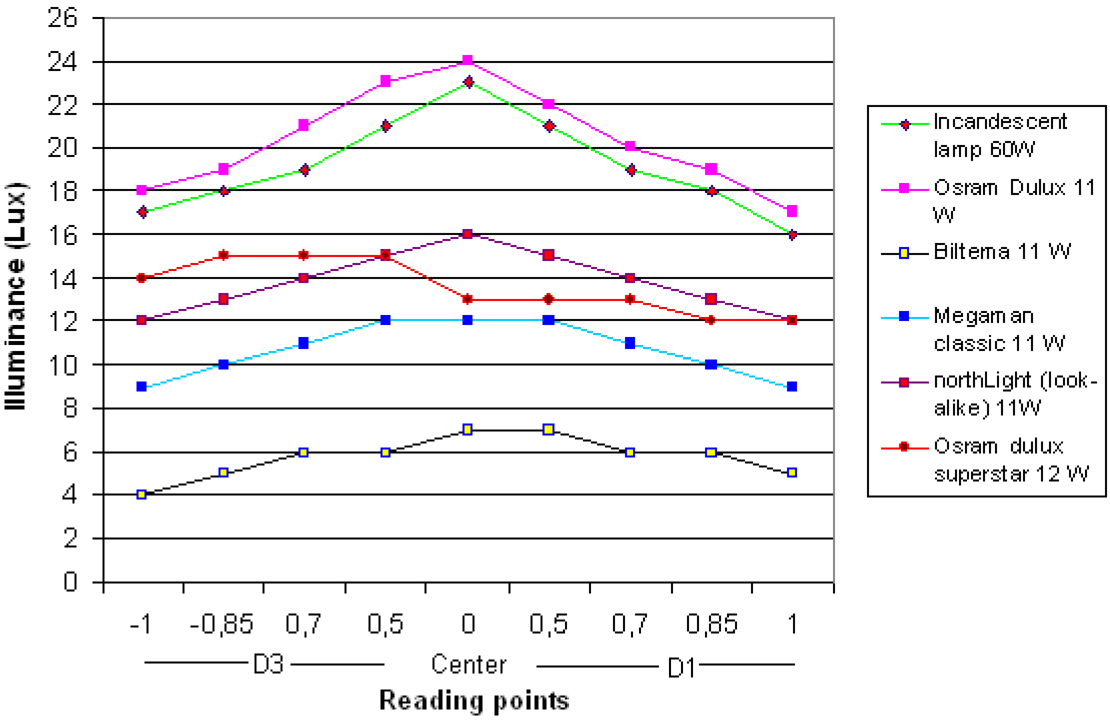

Figure 4-23. *Comparison among readings with incandescent lamp and different CFLs (at point under lamps and at different points in directions D1 and D3).*

Table 4-14. *Readings with incandescent lamp and different LED lamps (4 to 13 W) in different directions on the working plane.*

Type of lamp	Illuminance at r= 0.5m (lux)	Illuminance at r= 0.7 m (lux)	Illuminance at r=0.85 m (lux)	Illuminance at r= 1.00 m (lux)
Readings in direction 1: D1				
Incandescent lamp 60W	21	19	18	16
4W AC LED lamp	16	14	13	11
4W AC LED lamp (reflector)	47	36	28	21
13 W Evolux LED lamp	57	45	38	32
13 W Topco LED lamp	60	49	41	34
6 W Quasar JDR LED lamp	39	33	29	25
Readings in direction 2: D2				
Incandescent lamp 60W	21	19	17	16
4W AC LED lamp	15	13	12	10
4W AC LED lamp (reflector)	47	35	26	19
13 W Evolux LED lamp	60	49	41	35
13 W Topco LED lamp	59	48	40	34
6 W Quasar JDR LED lamp	38	32	28	24
Readings in direction 3: D3				
Incandescent lamp 60W	21	19	18	17
4W AC LED lamp	16	14	13	12
4W AC LED lamp (reflector)	45	33	25	19
13 W Evolux LED lamp	57	46	38	33
13 W Topco LED lamp	58	47	40	34
6 W Quasar JDR LED lamp	39	34	30	26
Readings in direction 4: D4				
Incandescent lamp 60W	21	20	18	17
4W AC LED lamp	17	15	13	12
4W AC LED lamp (reflector)	47	34	27	20
13 W Evolux LED lamp	56	44	36	31
13 W Topco LED lamp	59	47	40	34
6 W Quasar JDR LED lamp	39	34	30	27

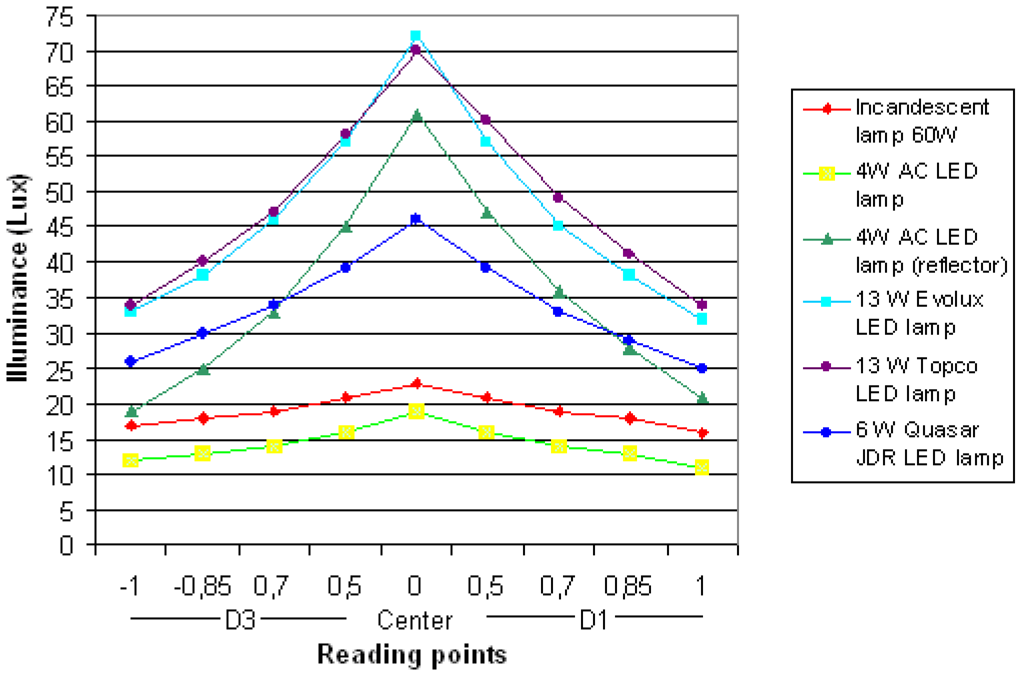

Figure 4-24. *Comparison among readings with incandescent lamps and different LED lamps (at point under lamps and at different points in directions D1 and D3).*

Findings

The 15 W CFL (GE look-alike, Philips spiral), the 11 W Osram Dulux and all LED lamps (except the 4 W AC LED lamp without reflector) have yielded better illuminance level (Table 4-11 to 4-14 and related figures) than the 60W incandescent lamp. Other CFLs: 11 W Megaman (look-alike), 11 W northLIGHT (look-alike), 11 W Biltema (look-alike), 12 W Osram (tubular), 14 W northLIGHT (tubular) and 15 W Airam (tubular) have failed to yield the same illuminance level as the 60 W incandescent lamp on the working plane. To get the same or better illuminance level on the working plane (in case of down lighting like this) it is better to use 15 W CFLs (look-alike or Spiral). All CFLs (except Airam 15 W) have a warm color temperature whereas all LED lamps have a cool color temperature. All CFLs and LED lamps (except the AC LED) have a low power factor. Table 4-15 shows the CRI, CCT and power factor (pf) values of different lamps.

Table 4-15. *Measured CRI, CCT and power factor (pf) values of different lamps.*

Lamps	CRI	CCT	PF
Incandescent lamp 60W	100	2730	1.0
Airam 15W	84	4070	0.63
northLIGHT 11 W	83	2720	0.61
Osram Dulux 11 W	82	2750	0.63
Megaman 11 W	83	2730	0.69
Biltema 11 W	80	3040	0.61
northLIGHT 14 W	82	2840	0.60
Philips 15W	83	2790	0.59
GE 15 W	83	2800	0.62
Quasar JDR 6 W	76	6053	0.61
Evolux 13 W	77	7250	0.49
Topco 13 W	78	7050	0.55
AC LED 4 W	66	5860	0.93

It has been also experienced that performance of the CFL is position sensitive. The same CFL yields different illuminance level on the working plane depending on how it is set. Tubular CFLs yield better illuminance level when they are placed horizontally than when they are placed vertically to the working plane.


Figure 4-25. *The same CFL is fitted vertically and horizontally to check the position sensitiveness of the lamp.*

Table 4-16. *Readings with the same CFLs in different position (horizontal and vertical).*

Type of lamp	Illuminance under the lamp (lx)	
	V	H
northLIGHT(tubular) 14 W	9	24
Airam (tubular) 15 W	16	25
Philips (spiral) 15 W	38	29

H: Readings in horizontal position
V: Readings in vertical position

Table 4-17. *Readings with the same CFLs in different position (horizontal and vertical).*

Type of lamp	Illuminance at r= 0.5m (lx)		Illuminance at r= 0.7 m (lx)		Illuminance at r=0.85 m (lx)		Illuminance at r= 1.00 m (lx)	
	V	H	V	H	V	H	V	H
Readings in direction 1: D1								
northLIGHT (tubular) 14 W	11	25	11	24	11	22	11	21
Airam (tubular) 15 W	17	30	17	28	17	26	17	24
Philips (spiral) 15 W	36	28	34	26	32	25	30	24
Readings in direction 2: D2								
northLIGHT (tubular) 14 W	11	26	11	24	11	22	11	20
Airam (tubular) 15 W	18	30	18	29	18	27	18	24
Philips (spiral) 15 W	38	28	35	26	33	24	31	23
Readings in direction 3: D3								
northLIGHT (tubular) 14 W	10	25	11	24	12	22	12	20
Airam (tubular) 15 W	18	26	18	24	18	23	18	21
Philips (spiral) 15 W	38	23	35	21	33	19	30	17
Readings in direction 4: D4								
northLIGHT (tubular) 14 W	10	25	11	24	11	22	12	21
Airam (tubular) 15 W	18	28	18	26	18	24	19	21
Philips (spiral) 15 W	37	23	34	20	34	18	32	17

H: Readings in horizontal position
V: Readings in vertical position

4.2.2 Measurements for study lamp

Study lamps are used to get spot light on some particular area and are normally used to read books and study related documents on the reading table. In Bangladesh, people usually use 60 W incandescent lamps for this purpose. The readings have been taken with the different CFLs and LED lamps to compare their performance with that of a 60 W incandescent lamp. The dimensions of the table were 100 cm x 75 cm. The height of the lamp from the working plane was set 45 cm (from the bottom point of the lamp). The lower diameter of the luminaire was 19 cm. The luminaire was set in such a way that the point just under the lamp was 45 cm from the right side of the table and 43 cm from the back of the table. During the measurement, some points were chosen on the working plane. Measurement points for the study lamp are shown in Figure 5-26. Points were chosen with the distance from the right side of the table on the same line (10 cm from the back of the table). At every point, measurements were taken for different distances from the back side of the table.

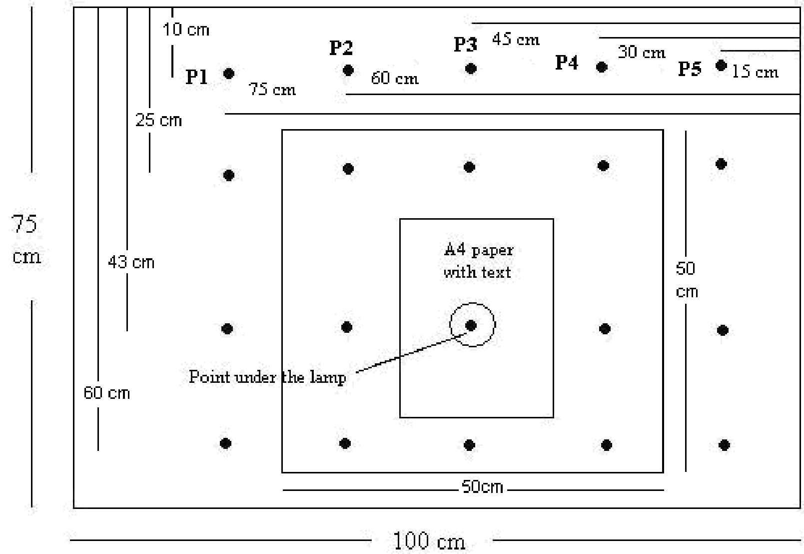

Figure 4-26. *Different measuring points on the working plane.*

Point 1, **P1**: 75 cm from the right side of the working plane
Point 2, **P2**: 60 cm from the right side of the working plane
Point 3, **P3**: 45 cm from the right side of the working plane
Point 4, **P4**: 30 cm from the right side of the working plane
Point 5, **P5**: 15 cm from the right side of the working plane

Table 4-18. *Readings on the table with the 60 W incandescent lamp and different CFLs.*

Type of lamp	Illuminance at 10 cm (lux)	Illuminance at 25 cm (lux)	Illuminance at 43 cm (lux)	Illuminance at 60 cm (lux)
Readings in downward direction for point 1: **P1**				
Incandescent lamp 60W	234	340	414	350
northLIGHT (tubular) 14 W	210	295	347	285
Airam (tubular) 15 W	251	385	433	348
GE (look-alike) 15 W	294	418	505	425
Philips (spiral) 15 W	419	598	670	539
Readings in downward direction for point 2: **P2**				
Incandescent lamp 60W	335	560	740	570
northLIGHT (tubular) 14 W	287	406	512	438
Airam (tubular) 15 W	344	538	668	550
GE (look-alike) 15 W	404	638	842	641
Philips (spiral) 15 W	601	944	1136	834
Readings in downward direction for point 3: **P3**				
Incandescent lamp 60W	387	721	1028	706
northLIGHT (tubular) 14 W	329	491	638	506
Airam (tubular) 15 W	429	645	805	661
GE (look-alike) 15 W	456	747	1006	740
Philips (spiral) 15 W	694	1146	1412	1022
Readings in downward direction for point 4: **P4**				
Incandescent lamp 60W	350	593	807	586
northLIGHT (tubular) 14 W	293	423	575	440
Airam (tubular) 15 W	385	565	726	551
GE (look-alike) 15 W	380	607	781	602
Philips (spiral) 15 W	595	935	1178	850
Readings in downward direction for point 5: **P5**				
Incandescent lamp 60W	245	366	447	285
northLIGHT (tubular) 14 W	214	302	375	322
Airam (tubular) 15 W	283	282	481	394
GE (look-alike) 15 W	277	390	472	389
Philips (spiral) 15 W	421	584	689	550

When the figure was drawn reading points at 10 cm from the back of the table were not considered because they lay almost on the edge of the table.

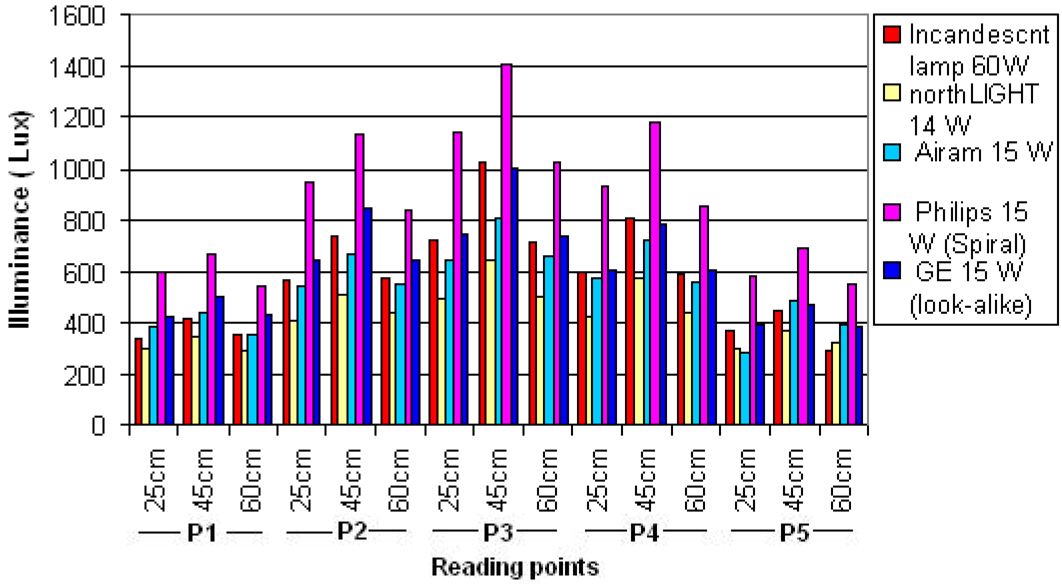

Figure 4-27. *Comparison among readings with incandescent lamp and different CFLs (at different points in downward direction on the working plane).*

Table 4-19. *Readings on the table with the 60 W incandescent lamp and different CFLs.*

Type of lamp	Illuminance at 10 cm (lux)	Illuminance at 25 cm (lux)	Illuminance at 43 cm (lux)	Illuminance at 60 cm (lux)
Readings in downward direction for point 1: **P1**				
Incandescent lamp 60W	234	340	414	350
Osram Dulux 11 W	234	334	410	340
Megaman classic 11 W	142	206	231	187
northLIGHT (look-alike) 11W	174	257	313	265
Osram dulux superstar 12 W	199	287	327	267
Readings in downward direction for point 2: **P2**				
Incandescent lamp 60W	335	560	740	570
Osram Dulux 11 W	323	526	699	535
Megaman classic 11 W	201	321	379	280
northLIGHT (look-alike) 11W	243	394	534	413
Osram dulux superstar 12 W	281	435	515	397
Readings in downward direction for point 3: **P3**				
Incandescent lamp 60W	387	721	1028	706
Osram Dulux 11 W	363	624	851	640
Megaman classic 11 W	237	399	481	320
northLIGHT (look-alike) 11W	282	480	683	490
Osram dulux superstar 12 W	316	517	640	451
Readings in downward direction for point 4: **P4**				
Incandescent lamp 60W	350	593	807	586
Osram Dulux 11 W	313	506	672	527
Megaman classic 11 W	218	322	385	275
northLIGHT (look-alike) 11W	250	398	535	407
Osram dulux superstar 12 W	286	432	518	396
Readings in downward direction for point 5: **P5**				
Incandescent lamp 60W	245	366	447	285
Osram Dulux 11 W	224	319	391	332
Megaman classic 11 W	154	205	232	181
northLIGHT (look-alike) 11W	179	258	313	365
Osram dulux superstar 12 W	209	287	331	270

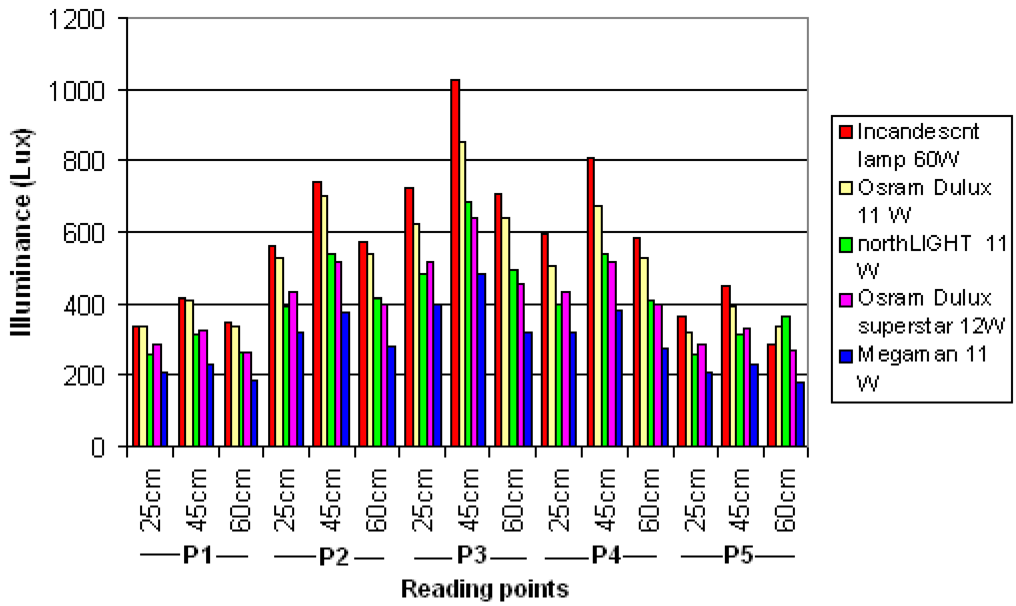

Figure 4-28. *Comparison among readings with incandescent lamp and different CFLs (at different points in downward direction on the working plane).*

Table 4-20. *Readings on the table with the 60 W incandescent lamp and different DC LED lamps.*

Type of lamp	Illuminance at 10 cm (lx)	Illuminance at 25 cm (lx)	Illuminance at 43 cm (lx)	Illuminance at 60 cm (lx)
Readings in downward direction for point 1: **P1**				
Incandescent lamp 60W	234	340	414	350
13 W Evolux LED lamp	252	368	423	335
13 W Topco LED lamp	275	393	429	339
6 W Quasar JDR LED lamp	167	283	363	288
Readings in downward direction for point 2: **P2**				
Incandescent lamp 60W	335	560	740	570
13 W Evolux LED lamp	351	615	831	514
13 W Topco LED lamp	379	682	799	509
6 W Quasar JDR LED lamp	250	459	631	472
Readings in downward direction for point 3: **P3**				
Incandescent lamp 60W	387	721	1028	706
13 W Evolux LED lamp	387	769	1034	604
13 W Topco LED lamp	418	829	1026	577
6 W Quasar JDR LED lamp	268	525	768	539
Readings in downward direction for point 4: **P4**				
Incandescent lamp 60W	350	593	807	586
13 W Evolux LED lamp	309	518	684	449
13 W Topco LED lamp	335	575	687	451
6 W Quasar JDR LED lamp	209	376	533	389
Readings in downward direction for point 5: **P5**				
Incandescent lamp 60W	245	366	447	285
13 W Evolux LED lamp	205	295	344	277
13 W Topco LED lamp	224	311	353	281
6 W Quasar JDR LED lamp	110	191	259	200

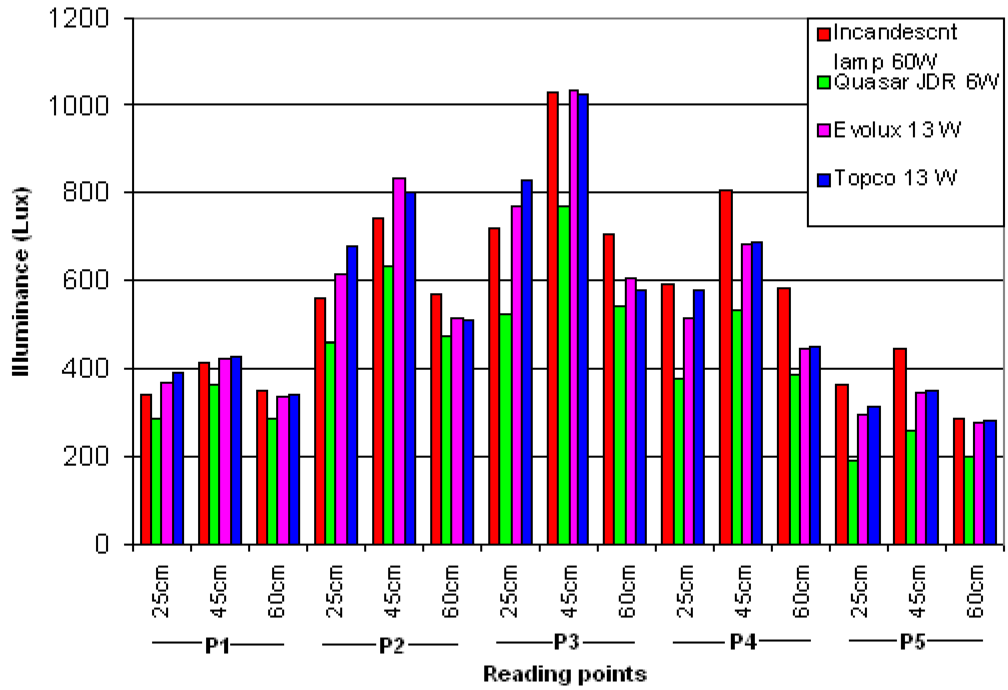

Figure 4-29. *Comparison among readings with incandescent lamp and DC LED lamps (at different points in downward direction on the working plane).*

Table 4-21. *Readings on the table with the 60 W incandescent lamp and 4 W AC LED lamp (with and without reflector).*

Type of lamp	Illuminance at 10 cm (lx)	Illuminance at 25 cm (lx)	Illuminance at 43 cm (lx)	Illuminance at 60 cm (lx)
Readings in downward direction for point 1: **P1**				
Incandescent lamp 60W	234	340	414	350
4W AC LED lamp	95	135	161	139
4W AC LED lamp (reflector)	46	116	172	104
Readings in downward direction for point 2: **P2**				
Incandescent lamp 60W	335	560	740	570
4W AC LED lamp	132	231	269	213
4W AC LED lamp (reflector)	117	375	644	321
Readings in downward direction for point 3: **P3**				
Incandescent lamp 60W	387	721	1028	706
4W AC LED lamp	154	263	347	257
4W AC LED lamp (reflector)	180	628	1070	521
Readings in downward direction for point 4: **P4**				
Incandescent lamp 60W	350	593	807	586
4W AC LED lamp	137	223	290	226
4W AC LED lamp (reflector)	131	408	714	363
Readings in downward direction for point 5: **P5**				
Incandescent lamp 60W	245	366	447	285
4W AC LED lamp	96	146	178	147
4W AC LED lamp (reflector)	51	138	209	124

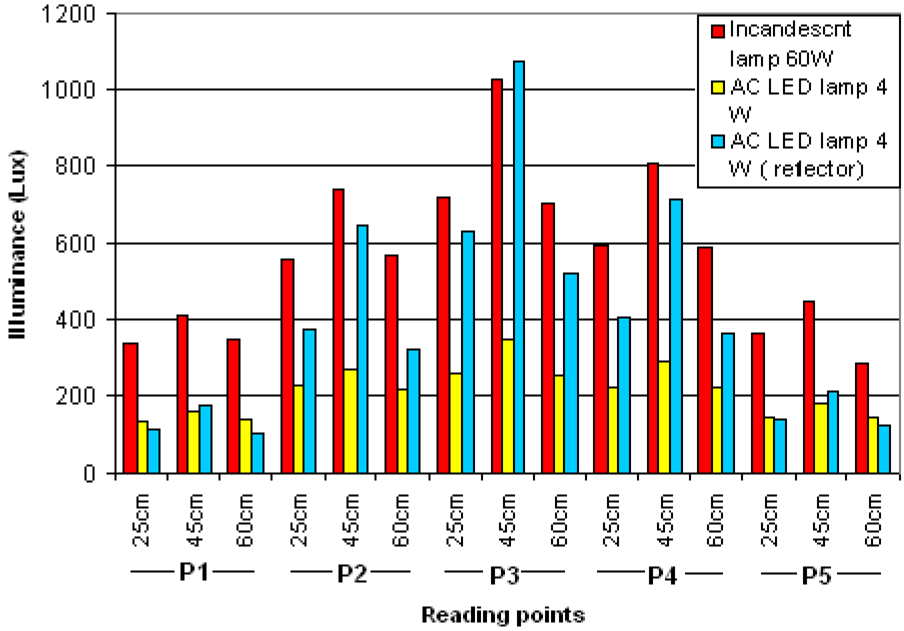

Figure 4-30. *Comparison among readings with incandescent lamp and AC LED lamp (at different points in downward direction on the working plane).*

Special case for 4 W AC LED and 6 W Quasar JDR LED lamp

One piece of paper of size A4 with text was placed in such a way that the point just under the lamp on the working plane was the middle point of the paper. The dimensions of the paper were 29.7 x 21 cm. On the paper, measurements were taken to see the uniformity of the light on the paper. On the paper, some points were considered in the same way like on the table. Measurements were taken at every point for different distances from the upper side of the paper.

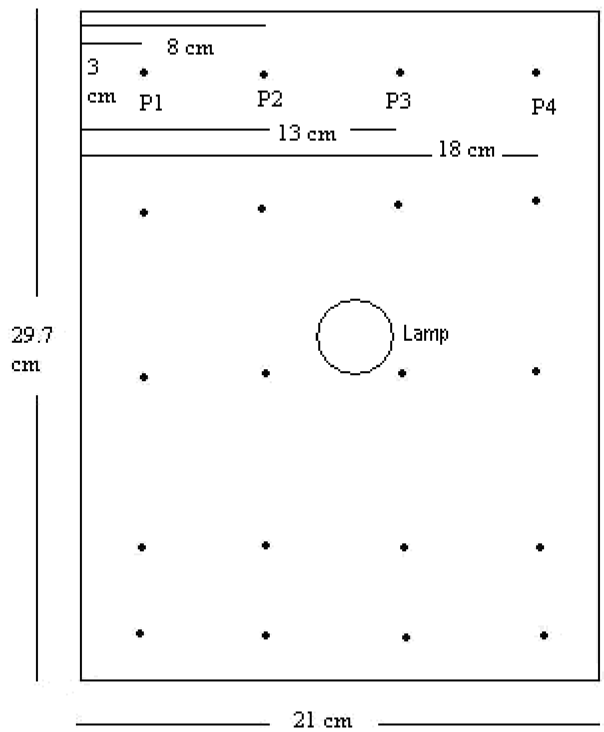

Figure 4-31. *Different measuring points on the paper (A4 Size).*

Point 1, **P1**: 3 cm from the right side of the paper
Point 2, **P2**: 8 cm from the right side of the paper
Point 3, **P3**: 13 cm from the right side of the paper
Point 4, **P4**: 18 cm from the right side of the paper

Table 4-22. *Readings on the paper (A4) with the 60 W incandescent lamp and 4 W AC LED lamp (with reflector).*

Type of lamp	Illuminance at 3.2 cm (lux)	Illuminance at 10 cm (lux)	Illuminance at 17 cm (lux)	Illuminance at 24 cm (lux)	Illuminance at 28 cm (lux)
Readings in downward direction for point 1: **P1**					
Incandescent lamp 60W	795	892	902	822	760
4 W AC (Reflector)	768	913	930	933	593
6 W Quasar JDR	640	725	740	674	598
Readings in downward direction for point 2: **P2**					
Incandescent lamp 60W	848	972	985	875	806
4 W AC (Reflector)	878	1032	1035	844	676
6 W Quasar JDR	663	754	770	699	612
Readings in downward direction for point 3: **P3**					
Incandescent lamp 60W	860	996	1019	883	812
4 W AC (Reflector)	895	1047	1053	868	695
6 W Quasar JDR	643	730	735	675	590
Readings in downward direction for point 4: **P4**					
Incandescent lamp 60W	828	961	965	848	769
4 W AC (Reflector)	821	974	987	805	641
6 W Quasar JDR	583	656	673	614	543

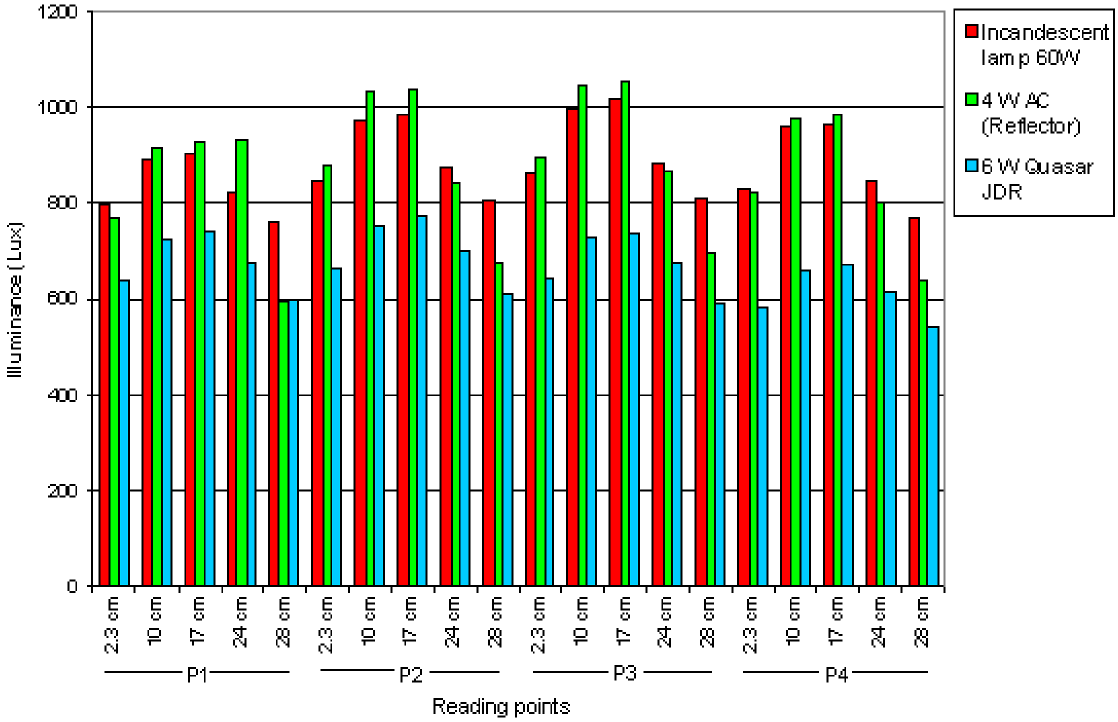

Figure 4-32. *Comparison among readings with incandescent lamp and 4 W AC (reflector) and 6 W DC LED lamp (at different points in downward direction on the paper).*

Findings

For study purposes, people do not need the same amount of light or the same level of illuminance on the whole table. But for visual comfort, it is better to have uniformity of the lighting. For uniformity, some ambient lighting is important. For the measurements, the ambient lighting has not been considered because the performance of individual light sources was being compared.

In Finland, the recommended average illuminance level for reading (CIE & ISO 2005) is 500 lux. In Bangladesh the recommended value is also 500-1000 lux (Khan 2006). But the recommendation does not mention anything about the height of the study lamp and the area to be illuminated with this illuminance level. Normally, when people read a book and study material with the study lamp, they read books using a small area of the table instead of using the whole table. It is assumed that a 50 cm x 50 cm (Figure 4-26) area is good enough to study. There should, however, be uniformity of light. The calculation has been done based on that assumption. The area was taken in such a way that the points **P2**, **P3** and **P4** were inside of the area and the readings for these points at different distances (from 25 cm to 60 cm from the back of the table) were included. The calculated average illuminence levels and uniformity for this area have been shown in the second and third columns of Table 4-23.

The recommended uniformity for reading on the reading area is 0.70 (CIE & ISO 2005). The study lamp was considered when measurements were taken without any ambient light from other luminaires. Normally, when people study on a table they get some ambient light that comes from the other luminaires in the room. Fourth and fifth columns of Table 4-23 show the average illuminance level when the area of 90 cm x 75 cm was considered.

Table 4-23. *Average illuminance ($\bar{E}$) levels for a study lamp with different lamps.*

Lamp types	Average $\bar{E}$ on area of 50 cm x 50 cm (lux)	Uniformity only for 50 cm x 50 cm	Average $\bar{E}$ on area of 90 cm x 75 cm (lux)	Uniformity for whole area
Incandescent lamp 60W	701	0.80	503	0.46
Osram Dulux 11 W	620	0.82	458	0.49
Megaman classic 11 W	351	0.78	267	0.53
northLight (look-alike) 11W	481	0.82	361	0.48
Osram dulux superstar 12 W	462	0.93	368	0.54
northLight (tubular) 14 W	492	0.82	384	0.55
Airam (tubular) 15 W	634	0.85	486	0.52
GE (look-alike) 15 W	733	0.82	551	0.50
Philips (spiral) 15 W	1050	0.79	791	0.53
AC LED lamp 4W	258	0.83	192	0.49
AC LED lamp (reflector) 4W	560	0.57	322	0.14
Evolux LED lamp 13 W	668	0.67	478	0.43
Topco LED lamp 13 W	682	0.66	494	0.45
Quasar JDR LED lamp 6 W	521	0.72	364	0.30

Osram Dulux 11 W CFL, Airam (tubular) 15 W CFL, GE (look-alike) 15 W CFL and Quasar JDR 6 W LED lamp meet the recommended illuminance level and uniformity value for the area 50 cm x 50 cm. For the same area, Philips (spiral) 15 W CFL shows a very high illuminance level with a value of 1050 which is out of the highest range value. Evolux 13 W LED lamp, Topco 13 W LED lamp meet the requirement in terms of illuminance level but their uniformity values are less than 0.70. In the case of the 4 W

AC LED (with reflector), the illuminance level meets the requirement but its value of uniformity is lower than 0.70. Also, its CRI value is low (66). More information about the reflector can be found in Appendix (Reflector).

When the area 90 cm x 75 cm was considered, then only GE (look-alike) 15 W CFL, Philips (spiral) 15 W CFL have shown a better illuminance level than that of 60 W incandescent lamp meeting the recommended requirement. 13 W LED lamps Evolux and Topco showed illuminance level (478 lux and 482 lux respectively) quite close to the recommended value. In every case, the uniformity is much lower than the recommended value. In that case, uniformity will depend on ambient light coming from other luminaires in the room and the value of ambient illuminance should be high.

It has been also experienced that the CFLs have performed differently when it was set in the existing lamp holder of the study lamp and when it was fitted in such a way that the lamp was totally inside of the structure of the luminaire. When the lamp was set in the existing lamp holder of the study lamp small part of the lamp was outside of the luminaire.

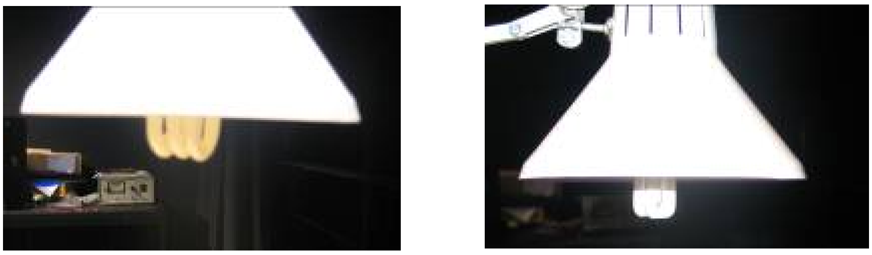

Figure 4-33. *Small part of the tubular CFLs is outside of the structure when they are set in the existing holder of the table lamps.*

Table 4-24. *Perfomance of CFLs in existing and modified holder of the table lamp.*

Reading points	Illuminance at 10 cm (lux)		Illuminance at 25 cm (lux)		Illuminance at 43 cm (lux)		Illuminance at 60cm (lux)	
	EL	ML	EL	ML	EL	ML	EL	ML
Readings for northLIGHT (tubular) 14 W								
For point 1: **P1**	210	304	295	420	347	473	285	388
For point 2: **P2**	287	426	406	656	512	776	438	590
For point 3: **P3**	329	457	491	764	638	997	506	667
For point 4: **P4**	293	384	423	613	575	730	440	566
For point 5: **P5**	214	281	302	384	375	440	322	347
Readings for Airam (tubular) 15 W								
For point 1: **P1**	251	357	385	503	433	547	348	457
For point 2: **P2**	344	459	538	744	668	890	550	693
For point 3: **P3**	429	513	645	895	805	1112	661	770
For point 4: **P4**	385	496	565	757	726	900	551	679
For point 5: **P5**	283	367	282	466	481	522	394	441
Readings for GE (look-alike) 15 W								
For point 1: **P1**	294	310	418	443	505	516	425	419
For point 2: **P2**	404	437	638	711	842	906	641	687
For point 3: **P3**	456	505	747	876	1006	1152	740	832
For point 4: **P4**	380	451	607	748	781	936	602	710
For point 5: **P5**	277	324	390	475	472	571	389	460

EL: With existing lamp holder
ML: With modified lamp holder

Later, the holder of the study lamp was set in such a way that whole lamp was fitted inside of the luminiare structure. In that case the performance was better giving higher illuminance at every reading point than before. The reason was the reflection of the light from inside wall of the luminaire. When the lamp was set inside of the luminaire structure more light was reflected. So, if the size of the CFLs were as small as 60 W incandescent lamps, the same lamps would have performed better.

It can be concluded that the 60 W incandescent lamps can be replaced with 15 W CFLs. One should, however, be careful to make the right choice during purchase. Spiral and look-alike type CFLs perform better than the tubular CFL in this kind of lighting.

Performance of LED lamps is promising. The technology for LEDs is improving day by day. It is expected that their overall performance will get improved and much better in the near future than today.

Limitations of readings

A lux meter was used to take measurements, which may show some error with the readings because of the different spectral power distribution of the incandescent lamps, CFLs and LED lamps. When measurements were taken on different days with different clothes of different colors, they may have a little influence on the readings because of the reflection, but careful attention was given to that fact. Measurements were read from a safe distance so that reflection from the clothes does not affect the readings with lux meter. It was not possible to take measurements in real situations (on sites) for the section of the study work related to Bangladesh unlike in the Finnish case.

5 Analysis of the results

5.1 Measurements with CFLs

60 W incandescent lamps are replaceable for task lighting with CFLs. The manufacturers claim that a 11 W CFL can replace a 60 W incandescent lamp but the finding of this study work is that one should use one 15 W CFL to get same or better level of performance in term of lumen output and illuminance level on the working plane. All 11 W and 12 W CFLs except 11 W Osram Dulux have shown poorer illuminance level than 60 W incandescent lamps in all cases (except study lamp) of the measurements.

It has been found that CFLs are very position sensitive. The same CFL can yield a different illuminance level (Table 4-16 and Table 4-17) on the working plane depending on the position of the CFL i.e how the CFL is installed (horizontal or vertical to the plane). The pf values (Table 4-15) of the most CFLs are low (around 0.60) compared to that of the incandescent lamps. In this case, the amount of saved energy is 75 %. In the case of focus lighting in the restaurant, 8 W CFLs have shown better performance than 40 W incandescent lamps. In this case, amount of saved energy is 80 %.

5.2 Measurements with LED lamps

LED lamps based on DC LEDs have shown a good result. Their performance in terms of illuminance level is better than 60 W incandescent lamps in the case of down light in the kitchen for Bangladesh (Figure 4-24). But their CRI, CCT and pf values should be improved to achieve better overall performance. AC LEDs are promising with a very high power factor (0.93), though they are only at the very initial stage of their development process. The AC LED based lamp has shown better performance than a 40 W incandescent lamp (Figure 4-13 and Figure 4-18) for focus lighting in the restaurant. In the measurement for the kitchen in Bangladesh, it has shown better performance (Figure 4-24) than a 60 W incandescent lamp after using a reflector with a viewing angle of 68^o. The amount of saved energy would be 90 % for the 6 W Quasar LED lamp, 78 % for the 13 W Evolux LED lamp and 93 % for the 4 W AC LED lamp when they would replace a 60 W incandescent lamp.

In the case of focus lighting in the restaurant the amount of energy saving would be 90 % when the 4 W AC LED would replace a 40 W incandescent lamp. Improvement in efficacy, CRI and CCT values should be achieved to get better overall performance.

5.3 Cost analysis

5.3.1 Cost analysis in Finland

Cost analysis for 15 W CFLs

Total cost has been analyzed considering only purchase cost and cost of operation of the lamps. The price of a packet with two 60 W incandescent lamps is 1.35 € and the price of a 15 W Airam CFL is 5.90 € (Prisma). Total cost has been calculated for 15 W (Airam) CFL over 12,000 hours because a 15 W Airam has a life of 12,000 hours. The average electricity price for the residential customers in Finland is 12.44 ¢ per kWh (Energia 2009). Table 5-1 shows the amount of saved energy and saved cost. The amount of saved energy in percentage is 75 %.

Table 5-1. *Energy and cost savings by using a 15 W Airam CFL in the kitchen (ceiling luminaire) over 12,000 hours.*

Features	Incandescent 60 W lamp	15W CFL (Airam)
Lamp life	1000 hours	12,000 hours
No of lamps used	12	1
Cost of lamps	€ 8.1	€ 5.90
Electricity Usage	720 kWh	180 kWh
Electricity bill	€ 89.57	€ 22.39
Total cost	€ 97.67	€ 28.29
Saved energy	540 kWh	
Saved money	€ 69.38	

The payback time has been calculated in term of hours. The payback period for a 15 W Airam CFL is 1021 hours. It is feasible to buy one 15 W Airam CFL for the ceiling lumenaire in the kitchen to get down light even if it lasts only 1021 hours instead of 12,000 h.

Cost analysis for 8 W CFL

Total cost has been analyzed considering only purchase cost and cost of operation of the lamps. The price of a packet with two 40 W incandescent lamps is 1.20 € (Prisma) and the price of one 8 W northLIGHT CFL 3.90 € (Clas ohlson). The total cost has been calculated for one 8 W northLIGHT CFL over 8,000 hours because one 8 W northLIG-HT CFL has a life of 8,000 hours. The electricity price for domestic sector in Finland is 12.44 ¢ per kWh (Energia 2009). Table 5-2 shows the amount of saved energy and saved cost. The amount of saved energy in percentage is 80 %.

Table 5-2. *Energy and cost savings by using one 8 W northLIGHT CFL in the restaurant over 8,000 hours.*

Features	Incandescent lamp 40 W	CFL 8W
Lamp life	1000 hours	8000 hours
No of lamps used	8	1
Cost of lamps	€ 4.8	€ 3.90
Electricity Usage	320 kWh	64 kWh
Electricity bill	€ 39.81	€ 7. 96
Total cost	€ 44.61	€ 11.86
Saved energy	256 kWh	
Saved money	€ 32.75	

The payback period for 8 W northLIGHT CFL in terms of hours is 953 hours. So, it is feasible to buy one 8 W northLIGHT CFL even if it lasts only 953 hours instead of 8,000 hours.

Payback time period

The payback period in terms of months or years is dependent on the usage time of the lamp per day. The longer the usage time per day the shorter is the payback time. Payback time is dependent on the price of the lamp and the length of the life of the lamp. The payback time states that it is feasible to use the CFL even if the CFL lasts till just the end of the payback period.

Table 5-3. *Purchase prices, life time, total cost saved and payback period of different lamps.*

	Purchase cost €	Life time (hours)	Cost/1000 h €	Total cost saved €	Pay back time (hours)
60 W incandescent	0.675	1000	0.675	n/a	n/a
15W GE	6.95	6000	1.16	30.98	1346
15W Philips	8.95	8000	1.12	41.23	1737
14 W northLIGHT	5.90	8000	0.75	45.28	1043
15 W Airam	5.90	12000	0.49	69.38	1021
40 W incandescent	0.60	1000	0.60	n/a	n/a
8 W northLIGHT	3.9	8000	0.49	32.75	936

Table 5-3 shows payback periods, purchase cost, cost /1000h, total cost saved over their life time for different types of CFLs.

5.3.2 Cost analysis in Bangladesh

Total cost has been analyzed considering only purchase cost and cost of operation of the lamps. The average price of a 60 W incandescent lamp in Bangladesh is about 0.35 €. The total cost has been calculated for 10,000 hours because assembling companies in Bangladesh claim that their CFLs have a life of 10,000 hours. The average electricity price for the residential sector in Bangladesh is 3.6 ¢ per kWh (Power cell 2007b).

Table 5-4. *Energy and cost savings by using a 15 W CFL in the kitchen over 10,000 hours.*

Features	Incandescent lamp 60 W	CFL 15W
Life span	1000 hours	10000 hours
No of lamps used	10	1
Cost of lamps	€ 3.50	€ 2.50
Electricity Usage	600 kWh	150 kWh
Electricity bill	€ 21.6	€ 5. 40
Total cost	€ 25.10	€ 7.9
Saved energy	450 kWh	
Saved money	€ 17.20	

(100 BDT = 1 Euro)

Payback period for a 15 W CFL in terms of hours is 1453 hours. The reason for the longer payback period in Bangladesh compared to Finland is that the price ratio of the lamp and the electricity price (70 times) is higher than that in Finland.

5.4 Analysis of CO_2 emissions

When the amount of CO_2 emissions was calculated, it was considered that the customers are reducing their individual carbon foot print by using CFLs while they are reducing their electricity bill. This means, when a consumer uses a 60 W incandescent lamp, it contributes to his carbon foot print for consuming 60 W and when he uses a 15 W CFL, it saves his carbon foot print by 45 W. This is how they save 75 % of their carbon foot print. So, the consumers reduce the emissions of CO_2 at the same rate they save energy.

5.4.1 Analysis of CO_2 emissions in Finland

In Finland, the rate of emissions of CO_2 in 2008 was 168 g/kWh of energy (Energia 2009). This amount may vary from year to year.

Table 5-5. *Amount of saved CO_2 emissions in Finland for 15W Airam CFL.*

Features	Amount
Saved energy over 12000 hours	540 kWh
Saved energy per 1000 hours	45 kWh
Saved CO_2 emissions per 1000 hours	7.56 kg

Table 5-6. *Amount of saved CO_2 emissions in Finland for 8 W CFL.*

Features	Amount
Saved energy over 8000 hours	256 kWh
Saved energy per 1000 hours	32 kWh
Saved CO_2 emissions per 1000 hours	5.38 kg

5.4.2 Analysis of CO_2 emissions in Bangladesh

In Bangladesh, the rate of the emissions of CO_2 in 2003 was 900 g/kWh (SSN 2003). This amount may vary from year to year.

Table 5-7. *Amount of saved CO_2 emissions in Bangladesh for 15W CFL.*

Features	Amount
Saved energy over 10000 hours	450 kWh
Saved energy per 1000 hours	45 kWh
Saved CO_2 emissions per 1000 hours	40.5 kg

5.5 Impact of the replacement

A substantial amount of energy can be saved by applying this replacement approach in both developing and developed countries. This in turn will help to save money by reducing the energy bills for the end-users. Reduction in energy consumption will also reduce the amount of emission of greenhouse gases including CO_2 emissions into the air.

5.5.1 Benefits in Finland

CFLs have higher purchase cost than incandescent lamps but their purchase costs are not that high compared to incandescent lamps in terms of cost /1000h (The fourth column of Table 5-3). CFLs are cost effective in the long run as they save much money in their life time and their payback time is short. A 15W CFL can reduce energy consumption by 75 % when it replaces a 60W incandescent lamp.

In Finland, energy generation and consumption are the source of 80 % of all emissions of CO_2. Reduction in emissions of CO_2 with rational and economical use of electrical energy in households can help combat climate change. The target and obligation of energy savings as well as the reduction of emissions of CO_2 in Finland is based on the EU directives and Kyoto Protocol. The purpose of Finnish energy and climate strategy is to ensure that Finland will achieve the targets set for the reduction of the emissions of CO_2 in accordance with the Kyoto Protocol. (Motiva 2009)

Every household in Finland can reduce energy consumption as well as household cost and contribute to reduction of emission of CO_2 by reducing their individual carbon foot print. This kind of approach will thus play an important role and accelerate the progress in achieving the target here in Finland.

Recently, the Finnish government has made an agreement (under the CDM) with a Chinese environmental company to buy 1.4 million tons of CO_2 emissions right from the company for € 14.5 million by 2018. According to the agreement, Finland will buy Certified Emission Reductions (CER) for both the Kyoto period 2009-2012 as well as for the post-Kyoto period 2013-2018. (CE 2009). If it is possible to save CO_2 emissions here in Finland by replacing incandescent lamps with CFLs, then the Government could apparently save €14.5 millions.

5.5.2 Benefits in Bangladesh

The electricity bill for customers will be reduced by about 75 %. The payback time for the CFL is about 1453 hours in Bangladesh and after that time the customers will pay only a very small energy bill.

The government of Bangladesh subsidizes electricity for residential customers 2 BDT per kWh (Haider 2008). So, during the life time of a 15 W CFL, the government can save 900 BDT per lamp. If every customer (10.2 Million in Bangladesh) would replace one 60 W incandescent lamp with one good quality 15 W CFL, the amount of saved energy would be 469×10^6 kWh per 1000h. This saved energy could be used to solve the load shedding problems or could also help to supply more consumers with the same electricity production capacity reducing the number of people without access to electricity. This will in turn help to reduce CO_2 emissions.

When rural people would be able to install small solar panels along with CFL or LED lamps instead of existing lighting systems, it will decrease CO_2 emissions for the reason of simply not using kerosene oil for lighting in homes. The government would also save the money used to subsidize kerosene oil.

Some non-governmental organizations (NGOs), not profitable organisations or even a utility company can make an agreement for some projects with some organizations from developed countries to do carbon trading under (UNFCCC 2009) the Clean Developme-nt Mechanism (CDM). The projects will be related to the reduction of CO_2 emissions by using CFLs in Bangladesh. The CFLs can be financed with the money from the project. In that case the customers will get them for free or at vastly reduced price. This will certainly drive adoption of energy efficient lamps for domestic lighting in Bangladesh significantly.

To achieve this kind of benefit, the power supply must have good power quality and energy efficient lamps should be of good quality.

6 Discussion and recommendations

The research work has been carried out mainly with lamp application for task lighting. Both CFL and LED lamps have been used to compare their performance with that of the incandescent lamps. CFLs of 11 to 15 W and LED lamps of 4 to 13 W have been used for this purpose. In the case of LED lamps, an AC LED based 4 W lamp has been used. The readings have been taken as case studies of both developed (Finland) and developing (Bangladesh) countries. In both cases, task lighting has been considered for experiment.

According to the results, it is possible to replace the 60W incandescent lamps with 15 W CFLs for task lighting. Though the lamp manufactures claim that 11 W CFLs are able to replace the 60 W incandescent lamps, in most cases they fail to yield the same level of illuminance as the 60 W incandescent lamps. In the case of study lamp, however, when standard recommendation for illuminance level is compared then only a few of them have fulfilled the requirement though they fail to reach the same illuminance level as the 60 W incandescent lamps. So, it can be stated that if the recommendation standard (CIE, ASE-NA) is used to compare the performance in every situation of using lamps the outcome can be different. In that case further assessment is needed.

CFLs are now available with a wide range of color temperatures and with the different shapes (Look-alike, spiral, tubular). The same CFL can give different illuminance level on the working plane depending on the position of the CFL i.e how the CFL is installed (either horizontal or vertical to the plane).

Figure 6-1. *Different types of CFLs available in the market as substitutes for the incandescent lamps.*

One thing should be considered about CFLs while replacing incandescent lamps that the performance of CFLs is position sensitive. The tubular CFLs perform better when they are placed horizontally than when they are placed vertically. On the other hand, look-alike or spiral type CFLs perform better when they are placed vertically than when they are placed horizontally (Table 4-16 and Table 4-17).

The size of CFLs can also be an important factor for replacement, which has been experienced in case of the study lamp. The CFLs (longer than the incandescent lamp) show lower illuminance when they were set in the existing lamp holder than when they were set fully inside of the study lamp structure (Table 4-24).

The result shows that it is possible to save 75 to 80 % energy consumption for task lighting with CFLs depending on the type of application. The payback period is dependent on the price, life time of the lamp and also on the ratio between the lamp price and electricity price. If this ratio is small then the payback period is short.

In the case of LEDs, the amount of saved energy would vary from 78 % to 93 % depending on the type of LEDs and type of application if they would replace incandescent lamps. They perform better than incandescent lamps in terms of illuminance level but their overall performance is not sufficiently great that it would be a good idea to replace the incandescent lamps with them.

AC LEDs can play an important role for replacing incandescent lamps, especially in developing countries where most of the electrical load is lighting load. The reason is that AC LED based lamps do not need control gear (source of harmonic current) and their power factor is very high unlike DC LED based lamp. So, lamps with AC LED could be manufactured more cheaply than DC LED based lamps as they do not need control gear. The size of the lamps will be also smaller than DC LED lamps. There are also no losses related to LED drivers. The technology is getting better and improving everyday. So, it would be better to wait until the technology reaches to a more developped state.

Limitations of CFLs

There are a few limitations of CFLs. Their life time is sensitive to frequent on/off switching. Their rated life time is reduced if the lamp is switched on and off very often. Not all CFLs can be used on dimmer switches and the CFLs with dimmer are very expensive at the moment. CFLs contain a small amount of mercury for which they should be recycled after they are burnt out. Collecting burnt out CFLs and recycling costs money. In Finland, retailers take them back for free after they are burnt out (but not in every country). As CFLs use electronic control gear (electronic ballast) and their power factor is not high, they can create some harmonic distortion in the power system network. The power system network with good power quality will not have much bad effect from this.

Marketing of CFLs

Though they have been available on the world market for long time, CFLs still do not have a high market share, despite their benefits of potential energy savings, long life and cost savings over the lamp life. High initial price, lack of knowledge and awareness of the users, lack of information about energy saving features, some bad experiences with claimed life of CFLs are the majors contributors to the reluctance of the customer to buy CFLs. There are several types of CFLs from different manufacturers available in the market. The cost varies significantly from one brand to another. It can be a difficult task for the customs to decide which lamps they should buy. Customers just look at initial price not at total ownership cost. This kind of thinking should be changed by some initiatives. On the packet, payback period, cost/1000h, total cost saving etc. can be given so that customers get the real information easily. If this kind information (Table 5-3) can be put on the packet of the lamp, then the customers can compare the price with that of incandescent lamps. They will be able to see the amount of saved cost, payback period of CFLs.

Information can be given in a small paper inside of the packet about the disposal of CFL i.e. what they should do after the lamp is burnt out or even what they should do if the lamp is broken after or before it burnt out. Informative demand side management (DSM) programs can be initiated using advertising through newspaper, radio and TV programmes, and energy audits to provide customers with reasons to encourage and to save energy. The government of Bangladesh can subsidize CFL (with the saved money for not giving subsidy to the energy used by incandescent lamps) for the first time through the utility company. In Bangladesh, 30 % of the total load is for lighting. So, if 100 % lighting load is replaced by CFL with bad quality, it could result in a problem for the power system because of harmonics and low power factor. So, the utility company in Bangladesh should be very careful about CFL quality by making some kind of standards to limit harmonics and improve power factors.

Future of LED based lighting technology

The future of the LED is very promising. It has many advantages with main disadvantage of a very high initial cost. The technology is experiencing new advances every day. Challenges like high initial cost and thermal management are being overcome rapidly. Higher CRI and a variety of CCT are being achieved. Efficiency of the control gear is also improving. The newly introduced 6W Pharox60 LED lamp has a CRI of 86, CCT of 3000 K and produces 336 lm (LEDs Magazine 2009a). The LED producing company, Cree has claimed that their latest cool-white LEDs with an output of up to 367 lm when driven at 1A, and an efficacy of up to 132 lm/W at 350 mA, will be commercially available soon (LEDs Magazine 2009b). An AC LED producing company, Seoul Semiconductor has already announced that they have achieved an efficacy of 75 lm/W with CCT of 3000 K and CRI of 85 (LEDs Magazine 2009c).

Figure 6-1 shows how the LED technology is following Haitz's law. Haitz's law is equivalent of Moore's Law (for computers) in LED technology. It states the relationship between the increasing light outputs with the decreasing cost of LED. (Archenhold 2007)

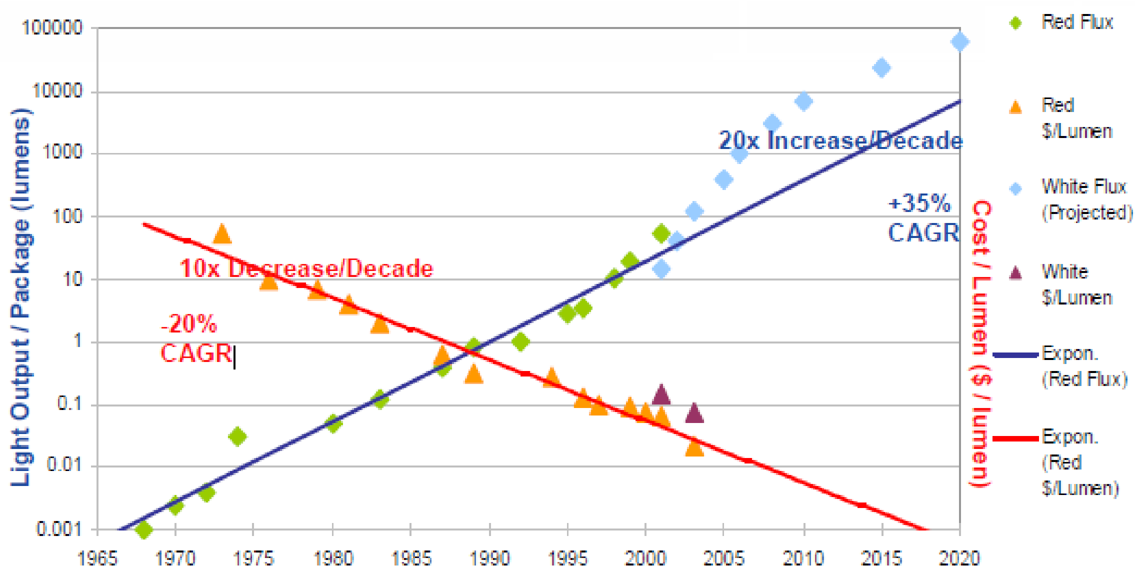

Figure 6-1. *Haitz's law in LED technology (Archenhold 2007).*

It can be expected that the price for LEDs will be reasonable soon. LED technology is in a rapidly developing state and its market for general lighting is in very initial state. So, lamps based on LEDs technology should be given very careful attention so that the same mistake like CFLs marketing does not repeat again. When first marketed in the early 1980s, CFLs were about 20 to 30 times more expensive to produce than their incandescent equivalents (Lefèvre & Waide 2006). This made the manufacturers put a very high initial purchase cost compared to incandescent lamps and the high initial cost made the customers reluctant to buying CFLs.

As the efficiency of LEDs is increasing and the price is decreasing in accordance with Haitz's law, performance of LEDs in general lighting should be realistic and factual, and costs should be reasonable before it enters the general lighting market.

Some LED lamps are cheaper than incandescent lamps in terms of cost/1000h. A 6 W JDR LED lamp costs € 26 ($ 38) with a claimed life time of 50,000 hours. It is cheaper (only € 0.52) than a 60W incandescent lamp (€ 0.68) in terms of cost/1000h. But it should not be recommended to be marketed in large volume because the technology is in developing state and the price is decreasing day by day, and 26 € is very high initial price.

When a customer will buy an LED lamp, it may last about 34 years (4h/day usage). The customer will think about changing the lamp for a luminaire after 30 years. So, the manufacturers should start to put them in the general lighting market carefully with high quality when the technology will be stable if manufacturers want to put them in large volume. Good quality LEDs lamps for general lighting can then gain the market share in the lighting market.

By the time, the CFLs are fully accepted by the customers more efficient and environmentally friendly LED based lighting systems will be on the market at a reduced price and with a high efficacy as well as better CRI and CCT values. LEDs do not need to be recycled in a special way unlike CFLs.

Further studies

This study was mainly done for task lighting and further studies can be done for all kinds of lighting applications for indoor lighting. In the study, the performances of different lamps were compared in terms of illuminance level. Further studies can include also the lumen distribution of different types of lamps to compare their performance for general lighting. Studies can be done with demo installations with CFLs for indoor lighting to calculate the real amount of saving of energy and related costs. The study was carried with mainly CFLs and available LED lamps. Further assessment and research experiment can be done for all kind of possible lighting applications with new improved technology based LED lamps. In the near future, the LED based lamps will be more efficient and cheaper than today and further studies and demo installations can be done with LED based lamps also.

7 Conclusions

Lighting consumes a major portion of the total energy consumed in the residential sector all over the world, especially in developing countries. One of the reasons for that is the usage of more than a century old and energy inefficient incandescent lamps. The energy efficient lamp technologies are available now, which can be applied to save energy and energy-related cost and GHG emissions. The main purpose of the research was to find out whether the available lamp technologies are able to replace the existing technology mainly based on incandescent lamps. The main area of the research was task lighting. The results of the research show that it is possible to replace 60 W incandesce-ent lamps used for task lighting with CFLs. CFLs can save 75 to 80 % of energy depen-ding on the application type. This can save thus energy, reduce energy bills for the customers as well as reduce their carbon footprint. Though the initial price of the CFLs is high but the cost /1000h is not high compared to that of equivalent incandescent lamps. The payback period in terms of hours is short compared to life time of the CFLs. The payback period can be longer in a developing country (Bangladesh) because the ratio between the price of the lamp and price of electricity is higher than that of a developed country (Finland).

It was experienced during the measurement that CFLs are position sensitive. The tubul-ar CFLs perform better in a horizontal position and look-alike and spiral CFLs perform better when they are placed in a vertical position to the working plane. The incorrect choice of lamp may result in bad performance. CFLs may result in some harmonic current because of the power electronic components and may have a lower power factor than incandescent lamps. This is not a problem if good quality CFLs are used and the power networks have power factor correction units in the network. Energy efficient lighting based on CFLs can be one of the easiest, most practical and most cost-effective ways for every country to save energy, especially for developing countries. To save energy means to ensure sustainability of the future energy supply for the growing population and to protect the climate change and combat global warming.

If it is possible to replace all incandescent lamps in a developing country, it would help to mitigate its power shortage problems and help to provide electricity to more custom-ers with the same power generation capacity. It would thus reduce the number of people without electricity even without building any new power plants. Thus the strategy can pave the way for possibility of providing electricity to them if the local government and utility company go ahead with proper plans and programs. In that case, the utility companies in developing countries should have power factor correction units and they should allow only CFLs with good quality in the markets by making standards that limit the harmonics.

The available lamps based on LEDs have shown very positive results. Their performa-nce is better in providing higher illuminance level than their equivalent incandescent lamps. At the moment, it could be possible to save from 78 to 93 % of energy by replacing incandescent lamps depending on the type of LEDs and type of application. But the technology is in growing-up state and the technology is improving everyday. An AC LED based lamp has shown better results when a reflector has been used and their pf is very high (0.93) but their CRI and CCT values are in an improving state. New advances are being achieved everyday. Though the initial cost of the LED lamps at the moment is very high, the price is decreasing and the light output is increasing according to Haitz's law (Figure 6-1). The LED-based lamp technology has a very bright future.

Further assessment and research experiment can be done for lighting with new improved technology based LED lamps.

New technologies are always like big challenges. The energy efficient lamp technology needs the widespread of acceptance of users. Users can be informed with important information regarding the financial and environmental benefits of the new energy efficient lamps through different kinds of initiative programs. These kinds of programs can be initiated by manufacturers, local governments and utility companies. Further experiment and assessment can be done with demo installations of energy efficient lamps in homes to calculate the actual amount of energy savings and cost savings. Surveys about energy efficient lamps and the acceptance of the technology by end-users can be done to get an idea of the end-users expectation and behavior toward new technology.

The replacement strategy of energy inefficient incandescent lamps with energy efficient lamps can pave the way for the possibility of huge energy saving potential in both developed and developing countries. This can in turn result in energy-related cost savings for the customers and reduce emission of CO_2 to combat global climate change, something that benefits the whole of humanity.

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Appendices

List of Appendices

Appendix 1

Performance of LEDs

The performance of the of LED is characterized by its radiant efficiency which is expressed as $\eta_e = \eta_{ext}\,\eta_f$, where η_{ext} is the external quantum efficiency and η_f is the feeding efficiency. The luminous efficiency of an LED is dependent on radiant efficiency via luminous efficacy. The external quantum efficiency is defined as the ratio of the number of photons emitted and the number of electrons passed through the LED. The external quantum efficiency is dependent on radiative efficiency, injection efficiency and optical efficiency and is calculated from the following equation

$\eta_{ext} = \eta_{rad} \times \eta_{inj} \times \eta_{opt}$

where

η_{rad} is radiative efficiency

η_{inj} is injection efficiency

η_{opt} is optical efficiency

Injection efficiency: Is the fraction of the electrons which are passed through the LED that are injected into the active region where radiative recombination takes place.
Radiative efficiency: Is the number of electron-hole pairs that recombined radiatively per the total number of pairs that recombined in the active region.
Optical efficiency: Is the fraction of the photons generated that come out of the LED.

Feeding efficiency is the ratio of the amount of the mean energy of the photons which are emitted to the energy that an electron-hole pairs gains from the power source when passing through the LED. The value of feeding efficiency can vary from 0.75 to 0.97. The luminous efficiency of a LED is dependent on radiant efficiency via luminous efficacy. The luminous efficacy can be achieved from the equation $K=\Phi_v/\Phi_e$, where Φ_v is luminous flux and Φ_e is radiant flux. Radiant efficiency shows the ability of the light source to convert the consumed power P into the radiant flux and is express as $\eta_e = \Phi_e/P$. It may vary from 0 to 1. Luminous efficiency is the ability of the source of converting the consumed power P into visual light. It is expressed as $\eta_v = \Phi_v/P \equiv \eta_e \times K$. (Zukauskas *et al.* 2002)

The figure below shows how usable light technique works in a real application of an LED. Efficacy of the LED decays with the increase of the drive current.

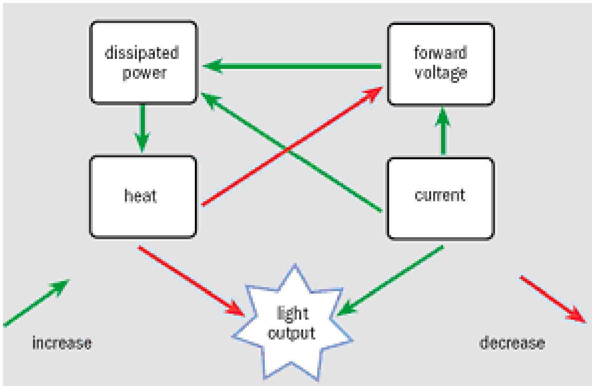

Figure 1. *Working technique of the usable light in a LED (*Whitaker *2007).*

AC LEDs

The working principle of AC LEDs is based on chip-level approach (anti-parallel connection of two strings of LEDs (Figure 2). In this case, light emitting diodes work in both cycles of alternating current of the AC mains. Some diodes work during the positive cycle and some work during the negative cycle of the supply current. This technique eliminates intermediate and inefficient driving stages between the AC mains and LEDs. They have some benefits over DC LEDs. As they do no need any drivers, it will help to reduce the price and size of the AC LED based lamp. They will increase the reliability as they do not need any drivers whereas drivers for DC LEDs have losses (20 %).
(Pinho 2009)

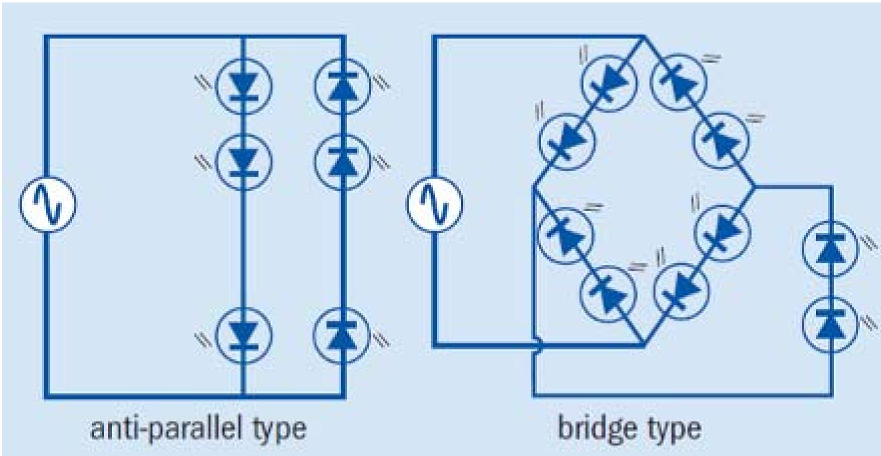

Figure 2. *Working principle of AC LEDs (Pinho 2009).*

They have higher power factor and higher systems level efficiency and they decrease EMI (Electro magnetic interference).

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Appendix 2

Survey and Questionnaire

Questionnaire for CFLs:

Question # 1: Is the amount of light sufficient to see and to eat the food?
Answer: A) Yes B) No C) Other (own opinion):

Question # 2: Is the colour of the food different with this light?
Answer: A) Yes B) No C) Not so good D) Difficult to say
E) Other (own opinion):

Question # 3: Is the light from CFL too bright compared to incandescent lamp, causing discomfort for seeing?
Answer: A) Yes B) No C) Difficult to say
D) Other (own opinion):

Question # 4: Do you like the new environment lighted by the CFL?
Answer: A) Yes B) No C) Difficult to say
D) Other (own opinion):

Question # 5: Do you prefer yellowish colour from the incandescent lamps to colour of the CFL?
Answer: A) Yes B) No C) Difficult to say D) It is not important to me
D) Other (own opinion):

Question # 6: Is energy saving and environment protection from emission of CO_2 important to you?
Answer: A) Very important B) No C) Difficult to say D) It is not important to me E) Other (own opinion):

Findings of the Survey:

There were total 14 replies. The opinions of the people are provided bellow.

Question # 1: Is the amount of light sufficient to see and to eat the food?
13 persons answer "Yes"
1 person answers "No"

Question # 2: Is the colour of the food different with this light?
7 persons answer "No"
5 persons answer "Difficult to say"
1 person answers "Yes"
1 person answers "Not so good"
Question # 3: Is the light from CFL too bright compared to incandescent lamp, causing discomfort for seeing?
12 persons answer "No"
1 person answers "Difficult to say"
1 person answers "Yes"

Question # 4: Do you like the new environment lighted by the CFL?
6 persons answer “Difficult to say”
5 persons answer “Yes”
3 persons answer “No”

Question # 5: Do you prefer yellowish colour from the incandescent lamps to colour of the CFL?
5 persons answer “Yes”
3 persons answer “No”
4 persons answer “It is not important to me”
2 persons answer “Difficult to say”

Question # 6: Is energy saving and environment protection from emission of CO_2 important to you?
11 persons answer “Yes” (important to very important)
2 persons answer “No”
1 person answers “Difficult to say”

From these 14 persons two persons have written their own opinion
One person has written “This lamp CFL saves less energy but it costs more money to recycle”.

One other person has written “Energy consumption and CO_2 emission are reduced but if the creation or recycling needs more energy than for incandescent lamp, I still prefer to use it if it is less polluting in the global result”.

Survey with AC LED lamp

Question # 1: Is the amount of light sufficient to see and to eat the food?
Answer: A) Yes B) No C) Other (own opinion):

Question # 2: Is the colour of the food different with this light?
Answer: A) Yes B) No C) Not so good D) Difficult to say
E) Other (own opinion):

Question # 3: Is the light from LED lamp too bright compared to incandescent lamp, causing discomfort for seeing?
Answer: A) Yes B) No C) Difficult to say
D) Other (own opinion):

Question # 4: Do you like the new environment lighted by the LED lamp?
Answer: A) Yes B) No C) Difficult to say
D) Other (own opinion):

Question # 5: Do you prefer yellowish colour from the incandescent lamps to colour of the LED lamp?
Answer: A) Yes B) No C) Difficult to say D) It is not important to me D) other (own opinion):

Question # 6: Is energy saving and environment protection from emission of CO_2 important to you?
Answer: A) Very important B) No C) Difficult to say D) It is not important to me E) Other (own opinion):

Findings with AC LED lamp

I kept the LED lamp on for 24 hours continuously in a same supply along with two other incandescent lamps without any problems before using it in the restaurant. The restaurant had some technical problems for which the LED lamp had to be taken out of the luminaire. So, there were only 3 replies before taking out of the luminaire.

Question # 1: Is the amount of light sufficient to see and to eat the food?
3 persons answer “Yes”

Question # 2: Is the colour of the food different with this light?
2 persons answer “Yes”
1 person answers “Difficult to say”

Question # 3: Is the light from LED too bright compared to incandescent lamp, causing discomfort for seeing?
3 persons answer “Difficult to say”

Question # 4: Do you like the new environment lighted by the LED lamp?
2 persons answer “Difficult to say”
1 person answers “Yes”

Question # 5: Do you prefer yellowish colour from the incandescent lamps to colour of the LED lamp?
1 person answers “No”
2 persons answer “It is not important to me”

Question # 6: Is energy saving and environment protection from emission of CO_2 important to you?
3 persons answer “Yes” (important to very important)

Some customers expressed that this kind of lighting gives them cold feeling (It can be defined as psychological effect because of the cool white colour temperature of the LED lamp). They think it is bad to have this kind of feeling while eating. It could be better if the survey could have been done without mentioning that what kind of lamp have been used (CFL or LED lamp) in the luminiare. The participants would have given more natural opinions in that case.

Appendix 3

Important terms

Lumious flux maintenance factor (LFMF): It is defined as the ratio of the luminous flux emitted by the lamp at a given time in its life to the initial (100 hour) luminous flux)

Lamp warm-up time: It is defined as the time needed for the lamp after start-up to emit a defined proportion of its stabilized luminous flux.

Luminous flux, Φ: Luminous flux is a physical quantity that expresses the calculated capability of radiant flux to create a stimulus for light perception. The unit is lumen (lm).

Luminous intensity, I: It is the amount of luminous flux emitted in a particular direction per solid angle. Unit is Candela.

Luminance, L: Luminance is defined as the amount of light, per unit of apparent surface, that is emitted by or reflected by a particular area within a given solid angle (unit: cd/m2);

Illuminance , E: It is defined as the ratio between the total amount of luminous flux and the onto which the luminous flux is falling. The unit is lux.

Uniformity: This is the ratio between the average illuminace and the minimum illuminace in a given working plane.

Haitz's law

This law is about the steady improvement of LEDs over the years. As a still-emerging technology, LED lighting technology is a moving target that is continually getting better, as well as cheaper. This fact is described by Haitz's Law. It describes that the light output per LED package increases 20-fold while the price decreases by a factor of 10 in every 10 years. This corresponds to a cost decrease of about 20 percent per year. (Brodrick 2009)

This law is similar to Moore's Law for transistor integration in ICs. From the late 1960s to the end of the 1990s, the lumen output levels from packaged LEDs have roughly doubled every two years, based on observations and projections by Roland Haitz. However, for the last 10 years, the rate of doubling has increased from every 24 months to about 18 months. (Lineback 2006)

References

LINEBACK, R., 2006. *Solid-state lighting set to boost LED growth.* Available from: http://ledsmagazine.com/features/3/5/6/1 [Accessed 15 October 2009]

BRODRICK, J., 2009. *The Cost Factor.* Available from: http://www.ies.org/LDA/HotTopics/LED/2.cfm [Accessed 15 October 2009]

Carbon footprint

The carbon Footprint is 50 % of humanity's overall Ecological Footprint. The carbon Footprint is the most rapidly-growing component of Ecological Footprint. Reduction of humanity's carbon Footprint is the most essential step to be taken to end overshoot and live within the means of the planet. (GFN 2009a)

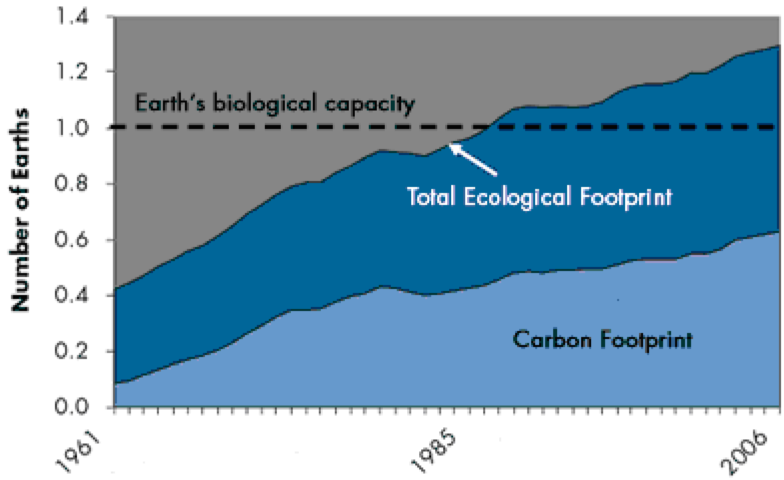


Figure 1. *Humanity's Ecological Footprint (GFN 2009a).*

The term "carbon footprint" is usually used as shorthand for the amount of CO_2 (measured in units of CO_2, usually in kg) emitted by an activity or organization. The carbon footprint is thus a representation of the effect human activities have on the climate in terms of the total amount of greenhouse gases produced. The carbon component of the Ecological Footprint takes a slightly differing approach, converting the amount of CO_2 into the amount of productive land and sea area required to sequester CO_2 emissions. Today we need the equivalent of 1.3 planets to provide the resources we use and to absorb the waste we produce. This means that it takes the Earth one year and four months to regenerate what we use in a year. Moderate UN scenarios indicate that if the current population growth and consumption trends continue, by the mid 2030s we will need the equivalent of two planets to support us. The reason is that turning resources into waste faster than waste can be recycled back into resources puts us in a global ecological overshoot, depleting the resources on which human life and biodiversity depend. (GFN 2009a, GFN 2009b)

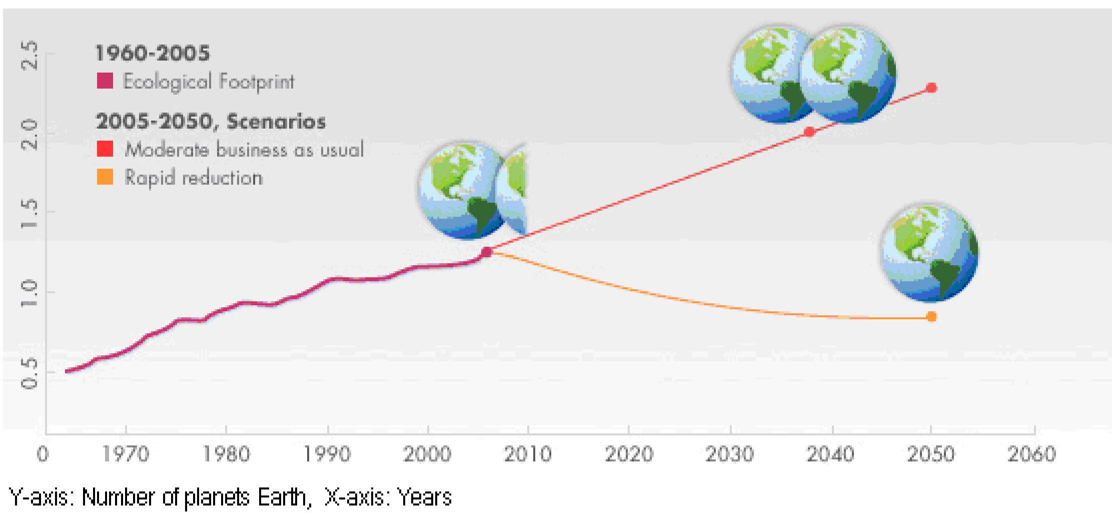


Figure 2. *Effect of carbon Footprint on the Earth (GFN 2009b).*

The Ecological Footprint is defined as the amount of biologically productive land and water that is required to supply resources and absorb wastes. Ecological Footprints are generally expressed in units of global hectares. Global hectares are thus the units which measure our demands on the earth (ecological footprint) and the ability of the Earth to supply our demands (bio-capacity). A global hectare is defined as one hectare of land or water with world-average productivity. Measurements in global hectares are normally adjusted according to the productivity of land or water in a given year. It depends on the type of the land and a land with high productivity (eg. cropland) will have more global hectares than less productive land (eg. pasture) of an equivalent size. (Science, 2008)

Savings of emissions of CO_2 can help us protect our earth and thus our future well-being.

References

GFN (Global Footprint Network), 2009a. *Carbon Footprint.* Available from: http://www.footprintnetwork.org/en/index.php/GFN/page/carbon_footprint/ [Accessed 15 August 2009]

GFN (Global Footprint Network), 2009b. *World Footprint: Do we fit on the planet?* Available from: http://www.footprintnetwork.org/en/index.php/GFN/page/world_footprint/ [Accessed 15 August 2009]

SCIENCE, 2008. Glossary | Making our mark – ecological footprints. Available from: http://www.science.org.au/nova/107/107glo.htm [Accessed 15 August 2009]

Appendix 4

Reflector

For AC LED lamp a reflector was used. The reflector was used to get concentrated light on the task area by decreasing the viewing angle of the AC LEDs. The viewing angle of the AC LEDs was 110^o. The reflector is called BOOM reflector and is made especially for Acriche AX3221 & P7 LEDs from Seoul semiconductor. The efficiency of the reflector was 90 %. (Ledil 2009)

Figure 1. *Boom reflector for Acriche AX3221 and P7 LEDs (Ledil 2009).*

The angle of the reflector Boom -W was 68^o (Mäki 2009). Relative intensity of the reflector BOOM-W is shown in Figure 2.

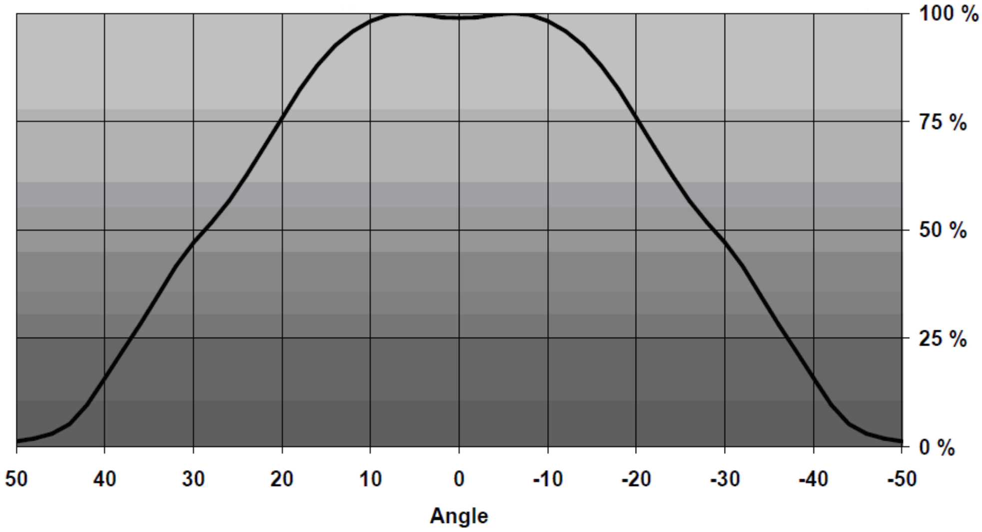


Figure 2. *Relative Intensity of BOOM-W (Ledil 2009).*

LEDIL, 2009. *BOOM reflector for Acriche AX3221 & P7 LEDs.* Availabe from: http://www.ledil.fi/datasheets/DataSheet_BOOM.pdf [Accessed 16 June 2009]

MÄKI, J., 15 June 2009. VS: VS: I would like to buy. Reflectors [Online]. Available from: joni.maki@ledil.com [Accessed 16 June 2009].

Appendix 5

Pictures of the lamps used


15W Airam


14W northLIGHT


15W GE


15W Philips


8W northLIGHT


11W Megaman


12W Osram Superstar

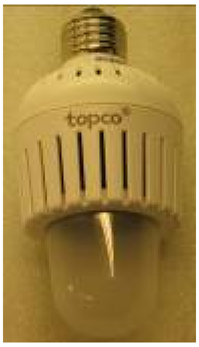

11W Biltema


11W northLIGHT


11 W Osram Dulux


60W incandescent lamp


4W AC LED lamp

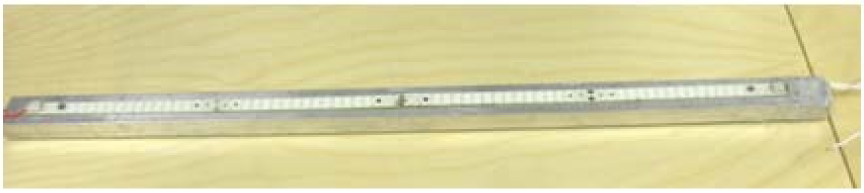


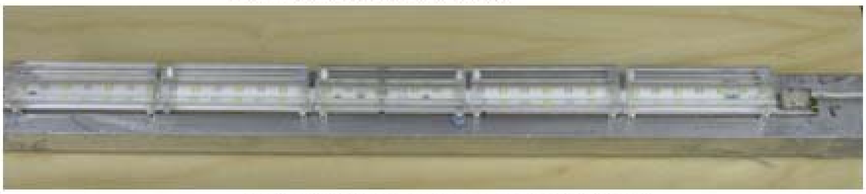
13W Topco LED lamp


6W Quasar JDR LED lamp


13W Evolux LED lamp


40 W incandescent lamp


6.6 W DC LED lamp (63 cm)


3.3 W DC LED lamp with lens (29.5 cm)