Evaluation of Effectiveness of LED Lighting in Buildings

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Abstract

Solid-State Lighting (SSL) technologies including Light-Emitting Diodes (LEDs) have gained substantial attention because of their lower energy consumption over conventional lighting technologies. However, energy savings is only one aspect of effectiveness of LEDs. The quantity and quality of illumination together with the economic feasibility are also important in the determination of overall effectiveness. This study was carried out to evaluate all aspects of an installation of SSL, including energy savings, illumination quality, cost-effectiveness, human performance and waste disposal. The study focused on a design that replaces fluorescent lamps (most commonly "T8" linear lamps) with LED products in a commercial building. The lighting level of the working plane at 0° degree of vertical angle was measured to be 370 lux $\pm$ 12 for LED lamps and 144 lux $\pm$ 44 for fluorescent lamps. The lighting level of the 30° degree and 60° degree vertical angle were indicated as 365 lux for LED lamp and 100 lux for fluorescent lamp. This shows the lighting level of the LED is meeting with required standard (IESNA) which has given the range, 250-450 lux for a study area and an office environment. However, the fluorescent lighting was below the required level. The range of detected correlated colour temperature was 6000K – 6500K for both the lamps.

In the associated survey among users of the space, more than 65% of the sample population provided a positive feedback on LED lighting system in relation to the human performance factors such as visibility, mood effect, visual health, colour appearance and work performance.

Considering the above factors, LED lamps can be recommended as efficient and eco-friendly lighting systems for illumination of domestic and commercial buildings.

Introduction

With the technological and industrial development, global energy consumption would considerably increase, from 12 billion toe (tone of oil equivalent - toe) in 2009 to 18 billion toe in 2035 [1]. Therefore, it is vital to promote sustainable consumption of energy and to enhance the energy efficiency of all devices, to ensure long term sustainability of global energy supply.

Sri Lanka is an island, situated in the Indian Ocean, southwest of the bay of Bengal, between latitudes 5° and 10° N, and longitudes 79° and 82° E. Consisting of a total land area of 65,610 square kilometers, Sri Lanka is home to a population of 20 million people.

Sri Lanka's energy mix consists primarily of biomass, hydro-electricity and petroleum that contribute 47%, 8% and 45% of total energy, respectively. In the power sector, the installed capacity for electricity generation from hydro, thermal and wind power presently stands at 3500 MW by 2016, compared with 1,409 MW in 1999. All households now enjoy grid connected electricity. The demand for electricity is estimated to rise at an annual pace of 5% to 7%. Annual per capita consumption of electricity meanwhile was 394 kWh per person in 2006 and has since risen to about 600 kWh/person in 2016.

Hydropower sources have now been exploited to their maximum capacity. In this situation, Sri Lanka has to depend on imported fossil fuels for power generation to serve the growing demand. In the next 15 years, options for thermal power generation for base-load operation are imported coal and imported natural gas.

Sri Lanka, even with its relatively high share of renewable energy sources in the electricity generation mix, has recognized the difficulties in meeting the demand for power, especially with the rapid growth in the commercial sector.

The increasing demand for petroleum products for electricity generation, transportation, industrial production and domestic needs has

made the Sri Lankan economy more vulnerable to oil price shocks.

The cost of producing and delivering electricity exceeds 18 LKR/kWh (0.12\$/kWh) (CEB statistical digest 2016). The average price of electricity is presently about 17 LKR/kWh (0.11\$/kWh), which is inadequate to cover the costs of power generation, transmission and delivery to customers. At such selling prices, there will be no return on investment, or funds to invest on new assets to meet the growing demand.

For lighting, the incandescent lamp was invented by Edison in 1882, and artificial lighting has progressed through three phases; incandescent lamp, neon light, and discharge lamp, and progressed towards the fourth phase to semiconductor lighting, especially white LEDs. White LEDs are already being used in numerous applications such as traffic signals, electronic & electrical appliances, mobile phones and full-color video displays. White LEDs are the stunning “green lighting source of the 21st century” and show wide usages and considerable potential market [2, 3].

LEDs introduce new opportunities for modifying the color of light, and compared with conventional light sources, they are small in size, giving freedom in luminaire design.

About 20% electricity generated is used for lighting [4]. In Sri Lanka, an estimated 30% of the total electricity sold is used for lighting. Public and private sector organizations use lighting during daytime, too. Therefore, maximizing the energy efficiency of lighting is a timely necessity.

Several different approaches have been suggested to define lighting quality [5, 6, 7]. The lighting requirement may be based on 50% factual and 50% psychological factors [8]. Modern thinking is that lighting quality is much more than simply providing an appropriate quantity of light. Other possible factors contributing to lighting quality include illuminance uniformity, luminance distribution, light color characteristics and glare [7]. There are many physical and physiological factors that can influence the perception of lighting quality. Lighting quality cannot be expressed simply in terms of photometric measures nor can there be a single universally applicable technique for good quality lighting [8, 9].

The quality, quantity and concentration of light around us expressively affect our visual appreciation of outer environment. It is important for us to understand the relationship between light and color, what we see and how we see it. The special persistence of lighting installations is to allow people to satisfactorily fulfill physical or visual tasks. The effectiveness of performing these tasks correlates to the quantity and the quality of the environment.

In the real world, lighting should be considered primarily for the comfort of the occupants. The energy efficiency and aesthetic value of lighting installations are secondary considerations. However, the importance of energy efficiency is greatly increased with issues such as climate change and energy pricing, which all impact our community. Thus, more efficient lighting offers potentially large savings in energy, and is closely related to the performance of its control electronics.

According to Narendran et al (2007), effects of fluorescent light on the ocular health of persons with pre-existing eye pathologies, have indicated that cellular activity of the human retina could be damaged with cool white fluorescent tube when more time is spent under such lighting conditions [11]. Another study has proven that people are affected with reading difficulties and academic achievement related to fluorescent lighting. In fact, they have estimated that 12 -14 percent of the world's population can be affected by fluorescent lighting which may trigger physical and emotional symptoms and stress [12] [13].

In this study, it is attempted to provide a basic understanding of the effects of lighting conditions on performance, comfort and safety, and explore the potential of LEDs to provide new approaches to specific applications. The performance of a visual task almost always involves visual, cognitive and psychomotor components [14]. Different tasks have different combinations of these components. Further, how these components fit into the overall task structure and the extent to which they interact will vary from task to task. Such complexity makes it difficult to predict the performance in one task from measurements on another, which complicate studies of this nature [15].

This study is aimed at determining the power consumption, human performance under LEDs and the existing lighting system, and whether

LED technology could successfully replace the existing lighting system.

Materials and Methods

Location of the Study

University of Vocational Technology (UNIVOTEC) was selected to represent the commercial building.

Installation of LEDs

A manageable area was selected for the experiments, considering the time frame and the initial investment. Currently the UNIVOTEC has five building blocks given in Table 1. Two rooms were selected; one in the study area, and the other one, a classroom.

Table 1 - Available Indoor Spaces of UNIVOTEC Premises

Building No	Number of Spaces/ Rooms			
	Office/ Rooms	Lab	Class Rooms	Study Area
Build. - A	22	13	06	
Build. - B	54	07	13	02
Build. - C	07		02	
Build. - D	30			
Build. - E	30			
Build. - F	07			
Build. - G	Under construction			

Measurements of the selected areas, including length, width, height, height of the work plane, height of room cavity and height of ceiling cavity, were taken. Then, the lumen method formula was used to determine the average illuminance in selected areas.

Figure 1 - Vertical line Diagram of Study Area, with Fixtures

Figure 2 - Vertical Line Diagram of the Classroom, with Fixtures

Determination of Power Consumption

The power consumption of existing luminaires with T8 fluorescent bulbs was first measured in both areas. A digital power meter (Everfine-PF9802) was used to measure power consumption. The power consumption was measured for lamp + ballast.

Although the study room four rows of luminaires, the first two rows (each row consisting of fifteen lamps) were selected for measurement. The power of each fixture was measured with the power meter at 9.00am and 4.00pm, continuously for two weeks.

Thirty (30) sampling points were selected in the study area to measure illuminance levels, as shown in Figure 3. Twenty (20) sampling points were selected in the classroom. A lux meter (YF-172) was used to measure illumination levels.

Figure 3 - Points of Measuring Lighting Levels in Study Area

Determination of the Human Performance under LED and T8 Fluorescent Lighting Systems

Performance of individuals is influenced by three routes: through the visual system,

through the circadian system and through the perceptual system [9]. A questionnaire prepared based on these principles was distributed among randomly selected 30 students and university staff members.

Results and Discussion

Power Consumption of the Study Area

Table 2 shows the power consumption for T8 LED lamps and fluorescent lamp within one unit area of the building space. A reduction of 40% was observed when LED lighting was used.

Table 2- Power Consumption with different Luminaires in a Study Area

Power	T8 Fluorescent lamp	T8 LED Lamp
Total	2000W (20W X 100)	1200W (12W X 100)
per unit area	6.0W/m ² (2000W/335.2m ²)	3.6W/m ² (1200W/335.2m ²)

As a result of installation of the T8 linear LED lighting system, the power consumption per unit area was reduced up to 60%. It shows that LED lighting contributed to save 40% of energy compared with fluorescent.

According to the manufacturer specifications, the power factor was 0.52 for fluorescent and 0.54 for LED.

Table 3 - Lighting Level (lux) of Fluorescent and LED Lamps under 0°, 30° and 60° angles (Study Area)

Point	4			6			8			12			18		
Angle	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°
LED (lux)	344	338	336	338	338	329	341	338	323	338	338	333	340	338	325
FL (lux)	124	122	103	130	120	102	134	118	102	125	121	102	128	118	102

Determination of Lighting Levels of LED and Fluorescent Lamps in the Study Area

Table 3 illustrates the lighting levels of fluorescent and LED lamps under zero angle of the working plane. As per the following data, the lighting level of LED is approximately two times that of the fluorescent lamps. The lighting levels of 30° degree angle for both types of lamps did not show a significant variation

among them. The 60°-degree angle of fluorescent lamps recorded the lowest lighting levels compared with other two angles as illustrated in Table 3. All measurements indicated a value close to 100 lux in fluorescent lamps.

Measurements of Lighting Levels of LED and Fluorescent Lamps in Classroom

Table 4 shows the average lighting levels measured for three different angles in the classroom. At the zero angle 380 lux level for

LED lamp and 180 lux for fluorescent lamp were recorded. At the 60° of angle LED lamp and fluorescent lamp were recorded 357 lux and 99 lux respectively.

Table 4 - Lighting Level of Fluorescent and LED Lamps under 0°, 30° and 60° angles (class room)

Point	1			2			5			7			8		
Angle	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°
LED (lux)	380	368	355	385	371	364	379	367	360	376	376	359	381	371	351
FL (lux)	180	152	101	181	154	89	182	154	104	179	151	101	180	151	101

In the study area, the average lux levels were recorded the range of 328lux – 340lux for LED lamps in a working plane. In the classroom, it disperses with 358 lux – 382 lux for LED lamps and 93 lux – 181 lux for fluorescent lamp. Illuminance levels were not significantly different between the two areas. In the classroom, the working plane is higher than the study area, and ceiling mounted troffer fixtures were not present. Therefore, some factors can affect the lighting level. The standard (recommended) lighting level of the study area

and office environment is in the range of 250 lux to 450 lux [10].

Comparison of Mood Effects

Most of the respondents rated the mood effect under the LED as excellent. The rest of the sample responded as either very good or good. Nobody has rated it to be poor or very poor. Under the fluorescent lamp, 72.7% rated the mood effect as good.

Table 5 - Observed Responses about Human Performance under Fluorescent & LED Lamps

Response	Visibility		Mood Effect		Visual Comfort		Color Appearance		Work Performance		Feeling Preference to Stay	
	FL	LED	FL	LED	FL	LED	FL	LED	FL	LED	FL	LED
Very Poor	2	0	2	0	6	0	3	0	3	0	0	0
Not bad	25	0	20	0	23	0	25	0	25	0	16	0
Good	47	5	53	8	50	7	51	3	47	3	58	8
Very Good	5	15	4	21	1	20	1	24	2	25	6	28
Excellent	1	60	1	51	0	53	0	53	3	52	0	44
Total	80	80	80	80	80	80	80	80	80	80	80	80

Comparison of Visual Comfort

Majority of the respondents rated the visual health condition of LED lamps as very good and excellent. However, for fluorescent lamps, none has responded visual health to be excellent.

Determination of the Human Performance under LED and Fluorescent Lighting Systems

Eighty responses of the sample population were observed with six variables of the human performance. Table 5 shows that a majority (75%) of the population considered level for visibility of LED lamps as excellent.

Meanwhile, according to Table 8, a majority (66%) of the population rated the fluorescent lamps in the good visibility category and only 2.5% rated it as very poor.

Color Appearance

With regard to color appearance of people and furnishings under the LED lamps, majority recorded it as excellent. None has rated it to be poor or bad condition, and more than 50% of the respondents rated color appearance of fluorescent lamps as good with only 1 person responding as very good.

Work Performance

About 65% considered work performance as excellent under LED lamps. In comparison

with 58% of those responded rated work performance as very good, and 38% rated negatively under fluorescent lamps.

Feeling Preference to Stay/work under the Lighting

All those responded (100%) showed positive preference to work under LED lighting in comparison to fluorescent lights. Whereas 20% and 72% preferred fluorescent lights as not bad and good, respectively.

Feeling Sleepiness

In addition to the above parameters, the sleepiness feeling was measured and around 95% of the population mentioned no sleepiness mood working under the LED lighting condition.

LED Technology can Successfully Replace the Existing Lighting System

Considering the cost of electricity during a 60 month period, LED lamp recorded the lowest cost amounting to LKR 1,532.16 (\$ 12.76). Two replacements of fluorescent lamps will be required during this period, but LED lamps do not need replacements due to their durability. Therefore, the total cost is lower in the case of LED lamps. LED lamps, when compared with fluorescent lamps reduced CO₂ emissions by 30% as well as maintenance cost and replacement cost could not be applied to LED lamps during the five-year period as prescribed in Table 6.

Fluorescent lamps, when discarded, have more potential to emit toxic gases to the environment, but solid state LED lamps have not given harmful or toxic substances to the ecosystem. Further, fluorescent lamps need to be replaced twice within a five-year period due to burnout, unlike LED lamps. In addition to that during production and disposal of fluorescent lamps there is a potential risk affecting the environmental and the human health due to the presence of mercury [16].

Table 6 - Cost Analysis for 60-month period

	Incand.	T8 FL	T8 LED
No. of lamps	01	01	01
Lamp wattage (W)	60	18	12
Average life (h)	1,000	8,000	35,000

Burning time (hours per year)	2,688	2,688	2,688
Re-lamping cost (Rs)	80	1,100	4,500
Replacement cost (Rs)	200	200	200
Electricity cost (Rs/kWh)	9.50	9.50	9.50
CO ₂ emission factor (CO ₂ /kWh)	0.5	0.5	0.5
Connected load with ballast (kW)	0.06	0.020	0.012
Hrs of operation over 60 months	13,440	13,440	13,440
No. of lamps required over 60 months	14	1.68	NA
Lamp replacement & re-lamping cost (Rs)	3920	2600	NA
Power consumption over 60 months (kWh)	806.4	268.8	161.28
Electricity cost after 60 months (LKR)	7660.80	2253.60	1532.16
Total cost over 60 months (LKR)	11580.80	4853.60	1532.16
CO ₂ emission over 60 months (kgCO ₂)	403.20	134.40	80.64

Conclusions

The key benefit of LED technology for general lighting application is the reduced maintenance cost due to the long-life.

More than 65% of the respondents have given a positive feedback with regard to human performance factors like visibility, mood effect, visual comfort, colour appearance, work performance, and feeling preference to stay under T8 LED lighting conditions.

Although the initial investment is higher than the fluorescent lamps, the shelf life is longer than any other artificial lighting sources. Life cycle assessment of LED lights indicated less environmental hazards compared with fluorescent and other illumination sources. It has been reported that most of the fluorescent

lamps contained up to 40mg of mercury which contribute to pollution of the environment and pose chronic health risk to the human by causing neuropsychological damages [16].

The main effect of lighting conditions on task performance is through the changes it makes to the stimuli presented to the visual system and hence the information that can be extracted from the environment.

Finally, considering the above risks and adverse health factors of the fluorescent lighting, LED lighting can be considered as eco-friendly. Even though initial investment on the LED lamp is higher than the fluorescent lamps, there is little or no maintenance cost and the lower power consumption is an added advantage.

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