A Facility Lighting Comparison Based on Energy Savings and Efficiency, Pollution Prevention and Life Cycle Assessment

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Received: July 30, 2016 Accepted: August 17, 2016

doi:10.5296/emsd.v5i2.9801 URL: http://dx.doi.org/10.5296/emsd.v5i2.9801

Abstract

The objective of this study is to compare the energy efficiency, potential energy savings and the environmental impact among different lighting types-incandescent lamps, CFL (compact fluorescent light) lamps and LED (light-emitting diode) lamps in a manufacturing facility. Three different tools were applied: Energy Assessment Spreadsheet (EAS), Pollution Prevention (P2) tool and GaBi 6. EAS was used to calculate the energy savings, P2 tool was used for carbon footprint analysis, and GaBi was used for the life cycle assessment (LCA) in lightings' use phase. The results indicated a saving of over $21,000 and a reduction of 151 MT CO_2e (metric tons of CO_2 equivalents) greenhouse gases (GHGs) using CFL in comparison to incandescent lamps. Approximately, $24,000 could be saved and 170 MTCO_2e of GHGs could be reduced by using LED lamps instead of incandescent lamps every year for the operation phase of the facility. The environmental impact categories identified from the LCA in lighting use phase indicated that using incandescent lamps for the facility was much more harmful for the environment than using CFL and LED lamps. Additionally, the environmental impact from the use of LED lamps for the facility was less than that of CFL lamps.

Keywords: Lighting energy and efficiency, CFL/LED lamps, Pollution prevention, Life cycle assessment

1. Introduction

In the past few decades, the role of policies to promote the adoption of energy efficient technologies has increased considerably. Such technologies are of great importance due to the shortage of energy supply and numerous benefits such as reduction in the energy costs of buildings and the environmental impact as a result of using lesser energy. Currently, the global energy use contributed by buildings is about 40% of the total contribution (U.S. DOE, 2011), and the research by Ullah (1996) indicates that lighting systems consumed around 30%–40% of the total electricity used in commercial buildings. The U.S. Energy Information Administration (EIA) estimated that in the United States about 404 billion kilowatt hours (kWh) of electricity were used for lighting by the residential and the commercial sectors in 2015. This accounts for about 10% of total US electricity consumption (U.S. DOE, 2016). The International Energy Agency has estimated that emissions of approximately 1900 MT CO_2 is due to lighting consumptions per year, of which 80% are associated with electricity generation (Waide and Tanishima, 2006). Mahmood (2012) suggested that reducing the electricity consumption and improving end-use efficiency can reduce GHG emissions. Furthermore, U.S. DOE (2013) predicted that the total electricity demand will increase by 24% in household sector because of increase in total households by 2040.

Incandescent, CFL and LED lamps are most commonly used lighting fixtures for both residential and commercial purposes. Energy efficiency of a lighting fixture is based on emitted light (lumens) divided by power it draws (watts). Incandescent lamps convert only 1% to 5% of the electricity consumed into usable light (the maximum efficiency for a near white light is 408 lm/W). Fluorescents, and especially compact fluorescent lamps are actively promoted and their conversion efficiencies are much higher than that of incandescent lamps but are unlikely to grow much above 100 lm/W. LED has similar or better efficiency than CFL, and it is still far from reaching theoretical limits that have already constrained future improvements in incandescent and fluorescent lamps (Azevedo et al., 2009). Smil (2003) argued that the provision of illumination is one of the most promising areas for future improvement in energy efficiency. According to the articles, Unlocking the Power of Energy Efficiency in Buildings from Natural Resources Defense Council (2008) and California Long Term Energy Efficiency Strategic Plan adopted by the CPCU (2008), governments and electricity providers created subsidies for appliances that are proven to save energy. Nearly 80% of all energy efficiency subsidies have gone to CFLs accounting for more than 20 billion dollars in investment since 1970, thus, replacing inefficient lightings such as incandescent lamps (NRDC, 2008 and CPCU, 2008). Lim et al. (2012) suggested that LEDs, an emerging and unsubsidized technology, have the potential to save more energy than CFLs. LEDs produce better light and are less damaging to the environment. The energy cost of each lighting fixtures used in the facility was estimated using Energy Assessment Spreadsheet (EAS).

Pollution Prevention (P2) is any practice that reduces, eliminates, or prevents pollution at its source, has been the declared policy of the US since the passage of the Pollution Prevention Act of 1990 and it is gaining more and more importance at the international level within governments and industries (U.S. EPA, 2016a). According to Spivak et al. (2013), P2 has been practiced and studied over the last 25 years and the Pollution Prevention Act states that pollution should be prevented or reduced at the source. Pollution prevention assessments for facilities with and without Energy Star Certification studied by Velagapudi et al. in 2014 showed that lightings with energy star certification are more energy efficient and environmentally friendly. P2 tool developed by U.S. EPA was used in this project.

LCA is emerging as one of the most functional techniques to estimate the energy use and GHG emissions during the life cycle of a product or project which includes life stages such as raw materials extraction, manufacture, product or project use and end of life of products (Finnveden et. al., 2009). This study used GaBi 6 for the LCA analysis.

From the literature it is clear that during the lighting use phase, the CFL/LED lamps consumes lesser electricity than the traditional incandescent bulbs and produces lesser GHGs, as incandescent lamps have lower ratio between the luminous flux (in lumens) of light output to the input electric power (in watts). However, a study that focuses specifically on comparison among incandescent, CFL and LED lamps in a facility does not exist in published literature. This paper intends to compare the energy efficiency, potential energy savings and environmental impact for an industrial facility using different lighting fixtures (incandescent, CFL and LED lamps) in the state of Ohio in US.

2. Methodology

2.1 Assessment Tools

Three assessment tools (EAS, P2 tool, and GaBi) were used to perform the analysis. They are described in the following sections.

2.1.1 Energy Assessment Spreadsheet v1.0 (EAS)

The Energy Assessment Spreadsheet (EAS) tool is a simple platform for compiling input data and carrying out needed mathematical operations, which is an imminent part of the energy assessment project. The EAS (UT, 2016) developed by The University of Toledo Air Pollution Research Group (APRG) has three sections: lighting, motors, and HVAC systems that account for the majority of industrial energy consumption. The lighting section is further divided into three subsections: input data, lighting cost, and lighting cost reductions. Inserting the wattage, quantity, and annual operating hours for each category of fixtures, along with the unit cost of energy automatically generates information about annual energy consumption and operational cost of all individual fixture types and their corresponding totals. The EAS tool was designed by the APRG at The University of Toledo, which can be conveniently used by industries to calculate the annual energy consumption of lightings, motors and HVAC systems.

2.1.2 U.S. EPA's P2 Tool

According to FY 2014-2018 Strategic Plan of the U.S. EPA, four P2 program outcomes should be measured in an assessment. They are: reductions in hazardous releases and hazardous inputs (pounds), reductions in GHG releases (metric tons of CO_2: $MTCO_2e$), reduced water consumption (gallons), cost savings associated with reducing hazardous pounds, $MTCO_2e$, and water consumption. P2 tool is designed by the U.S. EPA in the EXCEL spreadsheet format to measure the environmental and economic performance resulting from pollution prevention activities. It includes three spreadsheets: P2 Cost Savings Calculator, Gallons to Pounds Converter and P2 GHG calculator, of which P2 Cost Savings Calculator and P2 GHG Calculator are used for the purpose of measurement in this study. They demonstrate a unique multimedia perspective in reducing GHG emissions and producing associated cost savings. The P2 Cost Savings Calculator assesses cost savings associated with a variety of factors such as: reduced costs for hazardous inputs, handling hazardous waste, reductions in air permitting fees, reduced charges for water usage, and electricity. P2 GHG Calculator calculates GHG emission reductions from electricity conservation, green energy, fuel and chemical substitutions, water conservation, and improved materials management. (U.S. EPA, 2016b)

2.1.3 Life Cycle Assessment

The LCA process is governed under ISO 14000, the series of international standards addressing environmental management. The LCA model in this paper was constructed using GaBi 6 software. The goal of this LCA study is to compare different lighting types (incandescent, CFL and LED lamps) in their impact on the environment due to the electricity consumption in their use phase in the facility, The functional unit is overall lighting service of all the lamps in the facility with yearly operation time of 2750 hours, which is the yearly electricity consumed using incandescent, CFL and LED lamps respectively, all three types of lamps provide with same lumens in different wattages in all the areas of the facility as it is illustrated on the background of the facility, and in this study only the use phase of incandescent, CFL and LED lamps is included, the production, disposal and distribution stages of the lamps are not included. The total yearly electricity consumed for each lighting technology (incandescent, CFL and LED lamps) is used as the input data (the energy consumption during use stage) for GaBi LCA analysis, which is obtained from the calculation assuming all the areas in the facility using three different lighting types respectively, and the lighting fixtures quantities and wattages required were collected through the audit in the facility. The life cycle impact assessment method for this analysis is CML method developed at the Leiden University, and the following environmental impact categories chosen in this study from the GaBi software database are: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Air (ODP), Photochemical Ozone Creation Potential (POCP) and Human Toxicity Potential (HTP).

2.2 Background of the Facility

The industrial facility considered for this study has grown to become one of the largest producer of bronze bearings in northwest, Ohio, US. It has been used as an example facility to compare the differences among incandescent, CFL and LED lamps in terms of energy efficiency and environmental impact. An energy assessment was conducted for this facility. The audit included a walk through survey where the number of lighting fixtures and wattage required in different areas were collected. The data on the wattage and quantity of bulbs are shown in Table 1. The EAS was used to calculate the cost of all the lighting fixtures yearly, on the assumption that machine shop and warehouse operating hours are 8.5, office areas operating hours are 11, the number of facility operation days per year is 250 and the cost of energy is $0.1/kWh for different lighting fixtures. Assuming that CFL and LED lamps used in the facility produce the same amount of lighting output as that of incandescent lamps in all areas of the facility. The lighting data of the incandescent lamps are presented in Table 1. The data for CFL and LED lamps can be obtained through equivalent wattages and light output of incandescent lamps shown in Table 2. The CFL and LED bulbs data are presented in Tables 3 and 4. Table 2 shows the equivalent wattages and light output of incandescent, CFL and LED bulbs for wattage conversion in this study. These data have been obtained from a business website called Eartheasy and it displays solutions for sustainable living (Eartheasy, 2014). The 80-watt CFL lamps in Table 2 and the 42-watt LED lamps is converted from the 400-watt incandescent lamps in Table 1 assuming that they produce the same lumens. The cost of electricity for the incandescent, CFL and LED lamps were estimated using EAS. The P2 GHG Calculator and P2 Cost Calculator were used to determine the GHG reduction and money savings respectively. LCA for use phase of incandescent, CFL and LED lamps were carried out using the GaBi 6 software.

Table 1. Incandescent lamps data for the facility

Fixture Type	Fixture Details	Wattage	Quantity(number of bulbs)	Operating Hours per Year
A	Incandescent lamps Machine Shop	400	155	2125
B	Incandescent lamps Warehouse	400	66	2125
C	Incandescent lamps Office 1	40	168	2750
D	Incandescent lamps Office 2	150	101	2750
E	Incandescent lamps Office 3	100	93	2750

Environmental Management and Sustainable Development
ISSN 2164-7682
2016, Vol. 5, No. 2

Incandescent lightings were assumed to be used in the facility.

Table 2. Equivalent wattages and light output of Incandescent, CFL and LED bulbs (Eartheasy, 2014)

Light output	Incandescent	CFL	LED
Lumens	Watts	Watts	Watts
450	40	8-12	4-5
750-900	60	13-18	6-8
1100-1300	75-100	18-22	9-13
1600-1800	100	23-30	16-20
2600-2800	150	30-55	25-28

Table 3. CFL lamps data for the facility

Fixture Type	Fixture Details	Wattage	Quantity(number of the bulbs)	Operating Hours per Year
A	Compact Fluorescent Lights (CFL) Machine Shop	80	155	2125
B	Compact Fluorescent Lights (CFL) Warehouse	80	66	2125
C	Compact Fluorescent Lights (CFL) Office 1	10	168	2750
D	Compact Fluorescent Lights (CFL) Office 2	42.5	101	2750
E	Compact Fluorescent Lights (CFL) Office 3	26.5	93	2750

CFL lamps were assumed to be used in the facility.

Table 4. LED lamps data for the facility

Fixture Type	Fixture Details	Wattage	Quantity	Operating Hours per Year
A	LED Machine Shop	42	155	2125
B	LED Warehouse	42	66	2125
C	LED Office 1	4.5	168	2750
D	LED Office 2	26.5	101	2750
E	LED Office 3	18	93	2750

LED lamps were assumed to be used in the facility.

3. Results

3.1 Energy Assessment Results

The facility has 583 lighting fixtures as it is shown in Table 1. Table 5 shows that the electricity usage in all areas of the facility is 273568 kWh assuming that all the lighting fixtures are incandescent lamps. If CFL and LED lamps are assumed to be applied in all the areas, the electricity usage would be 60772kWh and 33767 kWh respectively, which is shown in Table 6 and Table 7. These data are generated by performing comparative assessments with incandescent lamps in the facility. The total yearly cost savings for CFL and LED lamps are $21,280 and $23,980 in the facility respectively. The percentage cost reduction is 77.8% for CFL lamps and 87.7% for LED lamps, which is calculated by annual cost reduction divided by annual total cost for the facility assuming to use incandescent lamps. Also, a cost comparison of CFL with LED lamps at the facility shows that the total yearly cost saving can be around $3377 with a 44.4% cost reduction rate, which can be calculated from Fig. 1.

Table 5. Total cost per year for the facility using Incandescent lamps

Lighting Cost					
Enter Cost of Energy per kWh = $ 0.10/kWh					
Fixture Type	A	B	C	D	E
Wattage	400	400	40	150	100
Quantity	155	66	168	101	93
Total Wattage	62000	26400	6720	15150	9300
Total Hours / Year	2125	2125	2750	2750	2750
kWh / Year	131750	56100	18480	41663	25575
Cost / Year	13175	5610	1848	4166.25	2558
Total kWh / Year =	273568				
Total Cost / Year =	$ 27357				

The annual energy consumption for all lightings, operational cost of all individual fixture types and their corresponding totals were estimated assuming that the facility uses incandescent lamps.

Table 6. Total cost per year for the facility using CFL lamps

Lighting Cost					
Enter Cost of Energy per kWh = $ 0.10/kWh					
Fixture Type	A	B	C	D	E
Wattage	80	80	10	43	27
Quantity	155	66	168	101	93
Total Wattage	12400	5280	1680	4293	2465
Total Hours / Year	2125	2125	2750	2750	2750
kWh / Year	26350	11220	4620	11804	6777
Cost / Year	2635	1122	462.00	1180	678
Total kWh / Year =	60772				
Total Cost / Year =	$ 6077				

The annual energy consumption for all lightings, operational cost of all individual fixture types and their corresponding totals were estimated assuming that the facility uses CFL lamps.

Table 7. Total cost per year for the facility using LED lamps

Lighting Cost					
Enter Cost of Energy per kWh = $ 0.10/kWh					
Fixture Type	A	B	C	D	E
Wattage	42	42	5	27	18
Quantity	155	66	168	101	93
Total Wattage	6510	2772	756	2677	1674
Total Hours / Year	2125	2125	2750	2750	2750
kWh / Year	13834	5891	2079	7360	4604
Cost / Year	1383	589	208	736	460
Total kWh / Year =	33767				
Total Cost / Year =	$3377				

The annual energy consumption for all lightings, operational cost of all individual fixture types and their corresponding totals were estimated assuming that the facility uses LED lamps.

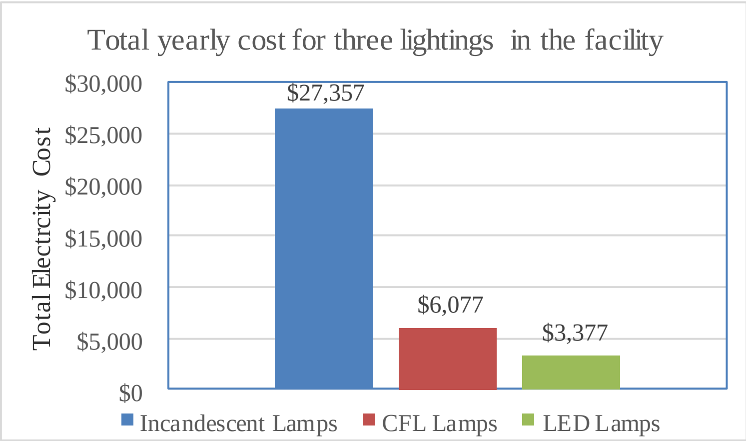

Figure 1. Total yearly cost of different lighting types applied in the facility

3.2 P2 Calculations

As shown in Table 8 and Table 9, the P2 GHG Calculator and P2 Cost Calculator calculated the gas emission reduction and dollar savings using CFL and LED lamps instead of incandescent lamps respectively. The reduction of GHGs is 151 $MTCO_2e$, with a savings of $21,280 by using CFL lamps. The reduction of GHGs is 170 $MTCO_2e$, with dollar savings of $23,980 by using LED lamps. The total GHG produced from the use of incandescent lamps from the P2 calculation is 194 $MTCO_2e$. Also 27,005 kWh of electricity is conserved and $2,701 is saved when the LEDs are used compared with CFLs.

Table 8. P2 GHG Calculator output

Light fixture	State or US (select)	Electricity conserved	Unit reported	GHG reduction ($MTCO_2e$)
CFL	U.S.	212,80	kwh	150.80
LED	U.S.	239,80	kwh	169.93

Table 9. P2 Cost Calculator output

Light fixture	State or US (select)	Electricity conserved	Unit reported	Unit cost($/unit)	Dollar savings
CFL	U.S.	212,80	kWh	$0.10	$21,279.60
LED	U.S.	239,80	kWh	$0.10	$23,980.10

3.3 Results from GaBi

The LCA of the GHG emissions related to use phase of incandescent, CFL and LED lamps were identified using criteria under the method of CML 2001 in GaBi 6. In the LCA of lightings, only the use phase of the lightings in the facility were presented, as most of the environmental impact is related to the use stage due to the electric energy consumption during the life cycle of lamps. In fact, a study (Elijošiutė et al., 2012) showed that for incandescent lamps, over 99% of CO_2e emission comes from the generation of the electricity required to power the lamp at the users' sites and the rest comes from production and end of life phases, and for CFL lamps, over 91% of the CO_2-equiv. emissions are generated during the use phase and the remaining comes from production and end of life phases. For LED lamps, less than 2% of the primary energy demand over the complete life cycle is required for manufacturing and 0.1% for end of life (Principi and Fioretti, 2014). The total yearly electricity consumed using incandescent, CFL and LED lamps is 273568 kWh, 60772 kWh and 33767 kWh respectively for the facility, which is used as the input for GaBi software. The six environmental impact categories chosen in this study from the GaBi output related to the lighting electricity consumption are GWP, AP, EP, ODP, POCP and HTP. They are also illustrated in the handbook of LCA by Guinée (2002). Figures 2 through 5 show the numerical values for each impact categories for incandescent, CFL and LED lighting fixtures obtained from GaBi analysis.

The Global Warming Potential (GWP) is an index to measure the contribution to global warming of a substance that is released into the atmosphere. It was calculated for a time frame of 100 years, and it is expressed by CO_2e. As we can see from the Fig. 2, the GWP of the GHG emissions in terms of CO_2e using incandescent lamps is 182 metric tons, which is 141.5 metric tons greater than that produced by using CFL lamps and 158.5 metric tons more than that produced by using LED lamps. The GWP of the GHGs produced from the use of LED lamps are18 metric tons lower than that of CFLs for the facility. These are close to the results obtained through P2 calculators.

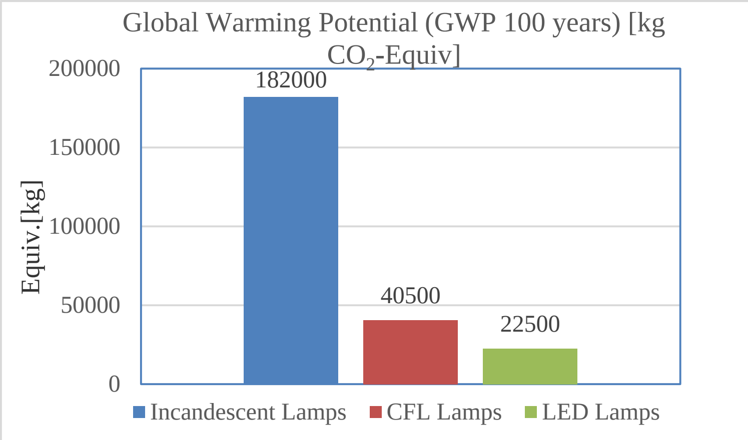

Figure 2. The characterization of the functional unit according to the environmental impact category of Global Warming Potential during LCA use phase

The Acidification Potential (AP) calculates the loss of the nutrient base (calcium, magnesium, potassium) in an ecosystem, and its replacement by acidic elements caused by atmospheric pollution. The AP here is dominated by nitrogen (NO_2) and sulfur dioxide (SO_2) emissions and is expressed by SO_2e, as it is shown in Fig. 3. The emission of SO_2e using incandescent lamps is 427 kg, which is 305 kg greater than that of the emissions from CFLs and 359.3 kg higher than that using LED lamps in the facility. The LED lamps show lower AP values for than CFL by a mass of 54.3 kg.

The Human Toxicity Potential (HTP) assessment aims to estimate the negative impact of humans' processes. It is a calculated index that reflects the potential harm of a unit of chemical released into the environment, is based on both the inherent toxicity of a compound and its potential dose. It is expressed by DCB-Equivalents. As shown in Fig. 3, the emission of DCB-Equivalents using incandescent lamps is 8420 kg, which is 6020 kg more than that using CFLs and 7080 kg more than that using LED lamps for the facility. The LED lamps show lower HTP values than CFL by a mass of 1060 kg.

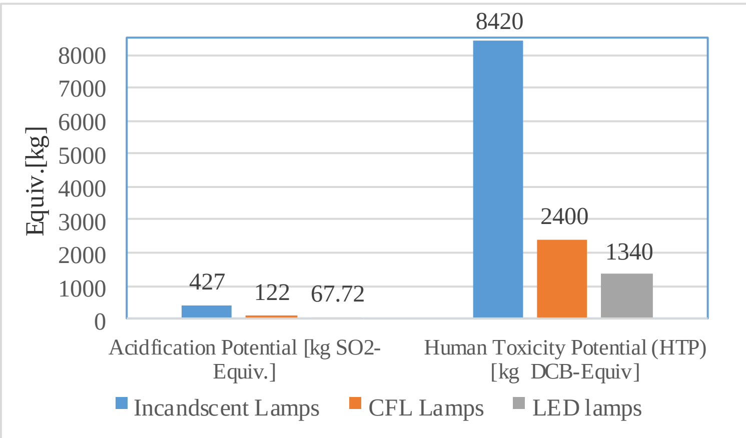

Figure 3. The characterization of the functional unit according to the environmental

impact category of Acidification Potential and Human Toxicity Potential during LCA use phase

The Eutrophication potential (EP) is caused mainly by nitrogen oxide (NOx) emissions, followed by chemical oxygen demand and ammonia. It is expressed by phosphate (PO_4^{3-}) equivalents. As shown in Fig. 4, the emission of PO_4^{3-}e using incandescent lamps is 26.3 kg, which is 18.8 kg higher than that of CFL and 22.1kg more than that of LEDs for the facility. The LED lamps show 3.3 kg lower eutrophication potential than CFL.

Photochemical ozone production (POCP) in the troposphere, also known as summer smog, is suspected to damage vegetation and material on the ground level. High concentrations of ozone are toxic to humans; it is expressed by ethylene equivalents. As it is shown in Fig. 4, the emission of Ethylene Equivalents using incandescent lamps is 26.9 kg, which is 19.2 kg higher than that using CFLs and 22.6 kg more than that using LEDs for the facility. The LED lamps show 3.4 kg lower POCP values than CFL lamps.

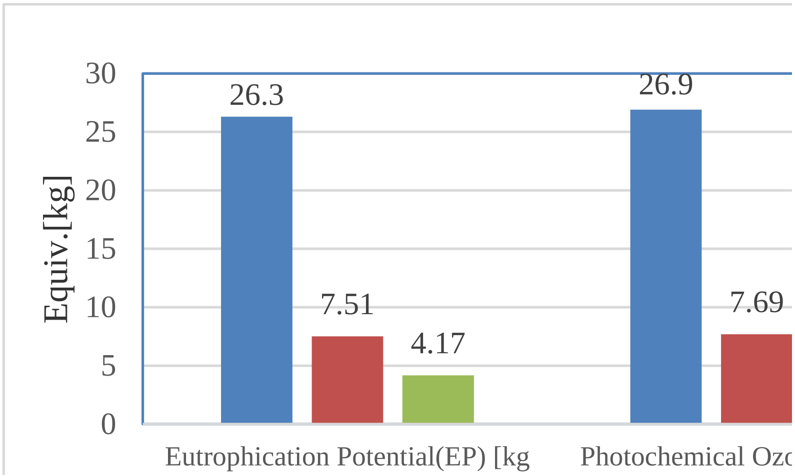

Figure 4. The characterization of the functional unit according to the environmental impact category of EP and POCP during LCA use phase

Ozone Depletion Potential (ODP) is a global measure of Ozone degradation in the stratosphere, such as Chloro-fluoro-carbons (CFCs). It is expressed by CFC 11e or R-11e. As shown in Fig. 5, the emission is significantly low and almost close to zero, while the emission using incandescent lamps is 52.2 mg, which is much higher than that of CFLs and LEDs for the facility. The LED lamps show lower ozone depletion potential than CFLs.

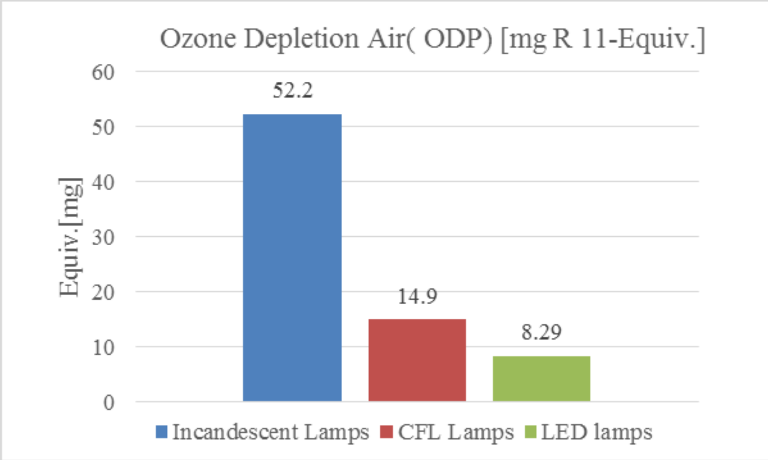

Figure 5. The characterization of the functional unit according to the environmental impact category of Ozone Depletion Potential during LCA use phase

4. Discussion

By running the hypothetical scenarios for the facility using incandescent, CFL and LED lamps in a machine shop, one warehouse and three offices, the EAS assessment showed that the LED lamps has the lowest yearly cost and best energy efficiency. The use of LEDs reduced the electricity consumption and cost reduction by 87.7% in comparison with incandescent lamps in the facility. The use of CFLs reduced the electricity and dollar consumption by 77.8% in contrast to incandescent lamps. The P2 assessment showed that LED lamps produced the lowest yearly $MTCO_2e$ emissions, and reduced GHG emissions by 87.7% when compared with incandescent lamps. The CFL lamps reduced GHG emission by 77.8% in contrast to incandescent lamps. The outputs obtained from the GaBi software for average yearly operations in the facility is expressed in terms of six different environmental impact categories. The environmental impact for each category from the use of CFL and LED lamps at the facility are much lower than that obtained from using incandescent lamps. The resulting emissions from using LED lamps is lower than that of using CFL lamps. During the lighting use phase in the facility, the LED lamps would produce 87.6% less CO_2e (GWP) and around 84.1% less SO_2e (AP), Phosphate-Equiv. (EP), R11e. (ODP), Ethane-equiv. (POCP) and DCB-equiv. (HTP) than that generated by using incandescent lamps, and the LED lamps would produce around 44.4% less emissions of the six impact categories than that of CFL in the facility. The CO2e for GWP obtained from the LCA analysis is very close to the results gained from P2 assessment. The CO2e for GWP and the equivalent HTP emissions are much larger than emissions from the other impact categories, especially than ODP emissions, which is close to zero.

The results from P2 assessment and GaBi analyses showed that LED and CFL lamps use in the facility could cause much lower environmental impacts than that of incandescent lamps, and LED lamps cause a lower environmental impact than the CFL lamps, mainly as a result of different electricity wattage consumption during the facility's lighting operation. The luminous efficiency of the lamps is the factor that affects the results most in reducing electricity cost and impact on the environment during lighting function stage.

The assessment carried out in this study has many limitations. The equivalent wattages and light output of incandescent, CFL and LED bulbs shown in Table 2 was in reference to a business website. Such values may not be the actual values for the fixtures being used in the facility. The results of the LCA study were obtained for the use-phase of the lightings. This assumption was based on previous studies that showed the lighting use-phase dominates the entire life cycle of all the three lamps. However, the lifespan of the lightings and the cost of maintenance and installation should be investigated in future before upgrading the lighting services. Real-time emissions and the environmental impact potentials could vary in real life depending on the source of electricity production and may impact the conclusions due to uncertainty of the input data in GaBi. Also, every software goes through updates with time to improve the results. Therefore, the users are advised to use current version.

6. Conclusions

The analysis conducted in this study shows that using CFL and LED lamps in the facility could be economically and environmentally beneficial in the lighting operation phase compared to incandescent. Additionally, the analyses show that LED lamps have better energy efficiency that reduces the electricity consumption, GHG emission and other hazardous emissions in the lighting use phase when a comparison is run between LED and CFL. During the study it was found that it is necessary for any facility to choose lightings with higher luminous efficacy (energy efficiency) in order to reduce electricity consumption and environmental impact from lighting electricity consumption.

Acknowledgement

The assessment was part of the Pollution Prevention Incentives for States (PPIS) Grant Program funded by the US Environmental Protection Agency (EPA). The opinions expressed in the paper are those of the authors. References in the papers to any specific commercial service or process, by trade name, trademark, manufacturer, or otherwise, do not necessarily imply their endorsement or recommendation by the U.S. EPA or the authors.

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