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Comparative Life Cycle Analysis of Different Lighting Devices

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In the modern era, tremendous technological and sustainable development has forced the societies to adopt modern energy efficient lighting devices instead of old fashioned less efficient incandescent lamps. The examples of such new lamps compact fluorescent lamps (CFLs) and Light Emitting Diode (LED) lamps. These devices can provide similar light output at the expense of only 20 % electricity consumption in comparison to incandescent lamps due to less energy lost as heat during luminance phenomenon. CFLs convert about 45 % energy into visible light, while incandescent lamp converts only 10 % (Tosenstock, 2007). The ecological footprint evaluation for street lighting network in Veszprem County, Hungary has been carried out utilising Sustainable Process Index (SPI) methodology (Narodoslawsky and Krotscheck, 1995). The analysis was carried out considering three different light bulbs i.e. conventional or old fashioned less energy efficient incandescent lamps and high tech more energy efficient CFLs and LED lamps. The analysis results reveal that there is a potential to decrease environmental impacts by 2 to 4 times by changing lamps from conventional incandescent to CFL and LEDs. These results are in coherence with the ecological assessment study conducted by the Department of Energy (DOE, 2012) for replacement of incandescent lamps with more efficient CFLs and LED lamps.

1. Introduction

In the current era with the development and availability of modern lighting devices, like compact fluorescent lamps (CFLs) and Light Emitting Diode (LED) lamps, peoples are replacing old fashioned, high energy consuming and less durable incandescent lamps. These modern devices can provide similar light output by consuming about 20 % electricity in comparison to incandescent lamp. The consumption of electricity for lighting purposes in EU-15 countries is about 12 %, while in new member states of Eastern Europe consumption of electricity for lighting is much higher reaching in the range of 21 % to 30 % of the overall residential electricity consumption (Methews et al., 2009).
During the past decade or so, a general trend of incandescent lamps replacement with CFLs has been observed due to its better energy efficiency during usage. This is because of less energy loss as heat during luminance phenomenon. CFLs convert about 45 % energy into visible light while incandescent lamp converts only 10 % (Tosenstock 2007). CFLs have high light production efficiency, as they utilize the advantage of both passive and semi conducting electronic components. The manufacturing of these components involve complex material flows inducing high energy demand (Balciukevičiūtė et al., 2012). Similarly, literature review reveals that lighting device based on LEDs showed enormous potential to outstrip many conventional lighting technologies in terms of colour quality, versatility, life time and energy efficiency. The LED lamps have slightly better environmental impacts than CFLs, while they are considerably lower in case of incandescent lamps. It has been estimated that all environmental indicators have 3 to 10 times reduction in their values when incandescent lamps are replaced with more efficient CFLs or LED lamps (DOE, 2012).

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1.1 Life Cycle Impact Assessment with the Sustainable Process Index (SPI)

In this study, SPI methodology was used as preferred LCIA method. It is an aggregate method resulting in an ecological footprint (m^2.y), calculating the area required to embed the whole life cycle in an ecosphere to sustainably provide products or service. The sustainable Process Index (SPI) follows the concept of natural income and assumes that the only income to our planet is solar energy. The key resource required to transform this natural income into utilizable material (biomass) (Gwehenberger and Narodoslawsky, 2008) or energy is area e.g. using direct conversion of solar energy into electricity using photovoltaic, thermal solar energy and indirect use of solar energy via conversion of biomass into energy products (Schnitzer et al., 2007).

The productive land, water and air are the key resources in a sustainable economy; all emissions to these three compartments (air, water, soil) have been considered for the ecological footprint calculations. The SPI value is a sum of seven sub-areas namely area for; area, non-renewable material, renewable material, fossil carbon source and emissions to three compartments (air, water, soil). The cumulative sum of all areas for the provision of raw material, energy and absorption of emissions or wastes is known as ecological footprint of the specific service or product under study. SPI helps to design, develop (Kettl et al., 2011) and optimize the ecological process by detecting ecological hotspots in the overall process as well as sub-processes (Kettl et al., 2012). SPI methodology follow ISO 14040 norms and proved its worth in comparing alternative technologies (Narodoslawsky and Krotscheck, 2000) assessing renewable based technologies (Niederl-Schmidinger and Narodowsky, 2008) and evaluating integrated bio-refinery (Shahzad et al, 2013) for PHA and biodiesel production along others.

1.2 Goal and Scope of the Study

In the current study, SPI methodology is used to evaluate the effect of use of light devices in the street lighting system of Veszprem. According to the data received from County administration, lighting system in Veszprem operates for about 4,000 h/y. The estimated overall light requirement for the city is 251,507 Mlm h/y. The effect of replacement of incandescent lamps with compact fluorescent lamps (CPLs) and light emitting diode (LED) lamps has been evaluated using life cycle assessment (LCA) approach. Moreover, these lamps are of different powers. In the current study, incandescent lamp (60 W), CPLs (15 W) and LED lamp (12.5 W) were considered to fulfil street light requirements. For ecological assessment inventory data for lamp production was utilized from (DOE, 2012 and eco-invent data base), while the analysis was performed utilizing web-based free ware tool known as SPIonWeb (SPI, 2015). The performance parameters for selected lamps to fulfil street light requirements are given in Table 1.

Table 1: Performance parameters for lamps considered in this Analysis

Characteristics	Incandescent	CFL	LED Lamp
Power consumption (W)	60	15	12.5
Light flux (lm)	900	825	812
Lamp life time (h)	1,500	8,000	25,000
Life time light flux (Mlm h)	1.35	6.6	20.3
Impact scalar	15.04	3.08	1
Total light requirement for Veszprem street lights			251,507 Mlm h
No. of Lamps required	186,302	38,107	12,390

The performance parameters include power consumption, light flux (lumen), device life time, life time light flux, no. of lamps required and impact factor using LED lamp as reference. The LCA analysis includes material and energy consumption for lamp manufacturing and its energy consumption for usage. The manufacturing energy was considered as “Electricity mix from China” while usage electricity provision is “Net electricity, lower voltage HU”. The Packing of the lamps was included while recycling of the material and disposal has not been considered for this specific study.

2. Results and Discussion

2.1 LCA for Incandescent Lamp-60 W

For benchmarking the ecological assessment of the electric lamps, one of the lamps selected for analysis was incandescent lamp, which is the most familiar light source in the world. The inventory data included material and energy flow during manufacturing and assembly processes for an ordinary 60 W incandescent lamp with luminous intensity of 900 lm and a life time of 1,500 h (DOE, 2012). The inventory input graph as well as distribution of ecological footprint into seven SPI categories for 60 W incandescent lamp LCA analysis is shown in Figure 1.

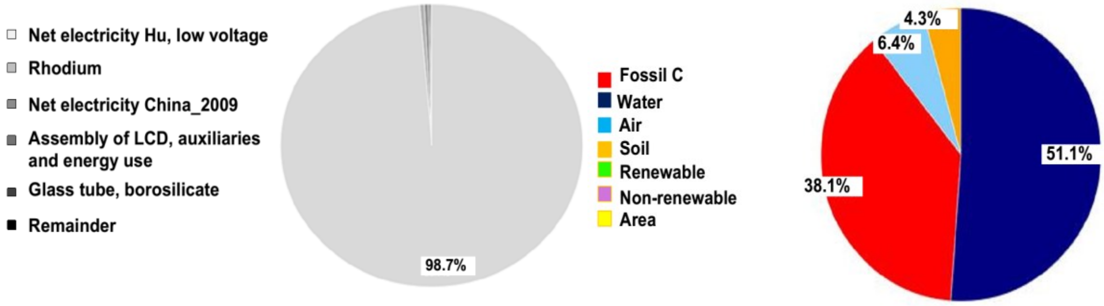

Figure 1: Graphical presentation of inventory input shares as well as SPI footprint distribution for 60 W incandescent lamps.

The inventory input graph shows that electricity consumption during usage phase is the main contributor, sharing almost 99 % of the total material and energy input. The footprint distribution graph reveals that emissions to water having 51 % share and fossil carbon with 38 % share are the main contributor. The other two prominent emission categories are air and soil having 6 % and 4 % shares. The ecological footprint for per unit incandescent lamp is 32,048 m^2.y.

2.2 LCA for Compact Fluorescent Lamps 15 W

The other lamp selected for comparative environmental analysis is one of the most common energy-efficient light sources known as Compact Fluorescent Lamp (CFL). The large linear tube fluorescent system commonly used in commercial office buildings were scaled down to make CFL. The linear tube has been bent and twisted to reduce the size by factor. It has ballast in the base of the lamp instead of a separate component wired to the sockets. The LCA analysis for CFLs was calculated for 15 W compact lamp having 825 lm light output intensity and a life time of 8,000 h (DOE, 2012). The graphical presentation of the inventory input for CFLs life cycle analysis as well as ecological footprint distribution among seven different categories is presented in Figure 2.

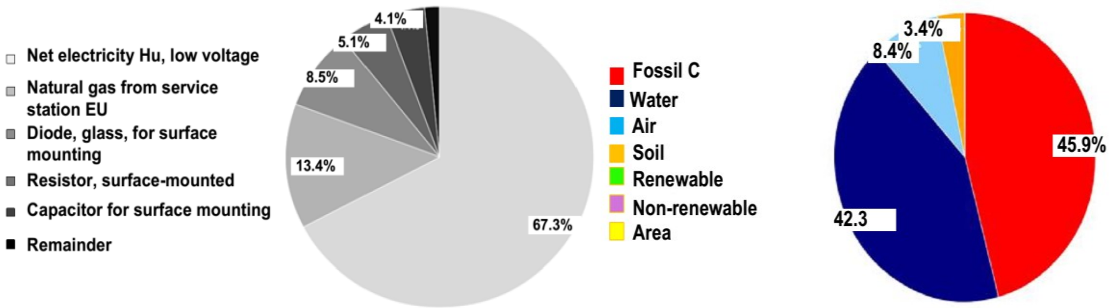

Figure 2: Graphical presentation of inventory input shares as well as SPI footprint distribution for 15 W compact florescent lamp

The inventory input graph reveals that net electricity consumption for usage phase has maximum 67% contribution, while natural gas, diode glass, resister and capacitors are the main contributors. The ecological footprint for unit CFL is 627.06 m^2 y. The emission contributions from fossil fuel category are little higher than emissions to water having 46 and 42 % shares. Other noticeable categories are air and soil having 8 % and 3 % contributions.

2.3 LCA for LED Lamp 12.5 W

The third lamp selected for comparative life cycle assessment for lighting devices was 12.5 W LED lamp, which is representative of most energy efficient lamps at the moment. The ecological foot print for LED lamps was calculated for 12.5 W lamp having 812 lm light output intensity and a life time of 25,000 h (DOE, 2012). The contribution of different energy and material flows for LED lamp manufacturing and distribution of footprint among different SPI categories has been shown in Figure 3.

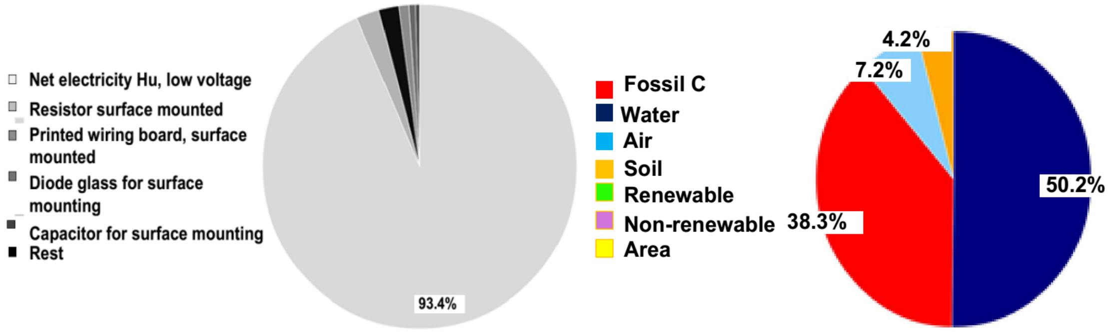

Figure 3: Graphical presentation of inventory input shares along with footprint distribution into different categories for 12.5 W LED lamp

The inventory input graph represents that electricity provision during usability phase has highest contribution of about 93 %, while manufacturing and material consumption constitutes the rest 7 %. The ecological footprint for 12.5 W LED lamp is 117,606 m^2 y. It shows that fossil C category has highest contribution of about 65 %, while water and air are second and third main contributors. The calculation of SPI footprint (m^2.y) as well as C footprint (t) (calculated from fossil C category using CO_2 equivalent (kg) = Value of fossil C category * 3.667/500) for three different scenarios namely unit lamp production, 20 Mlm h light output and total light requirement for Veszprem street lights, for all three types of lamps has been given in Table 2.

Table 2: SPI and C footprint for different scenarios

Categories	Incandescent lamp	CPL	Led Lamp
SPI footprint / lamp (m^2.y)	32,048.32	62,706.09	117,606.5
C footprint / lamp (t)	0.09	0.21	0.33
SPI footprint / 20 M lm.h	482,006.7	193,134.8	117,606.5
C footprint / 20 Mlm.h (t)	1.35	0.65	0.33
SPI footprint /Total light requirement **251,507 Mlm h**	**16,691,178**	**8,037,533**	**4,096,090**
C footprint / total light requirement (t) **251,507 Mlm h**	**16,691**	**8,038**	**4,096**

The results obtained for unit lamp production shows that incandescent lamp have 76 % lower life cycle footprint than LED lamp, while its footprint is about 60 % lower than CFLs. These values include whole life cycle of the unit lamps but energy input, life time and total life time light output values are different. So in order to bring harmony in the analysis, it is conducted for 20 Mlm. H, which is normal life time light output for 12.5 WLED lamp. This light output is equivalent to 3.08 CFLs and 15.04 incandescent lamps life time light output as described in Table 1. Similarly total light input required for street lighting in Veszprem is 251,507 Mlm h. The comparison of SPI footprint (m^2.y) for street lighting in Veszprem is shown in Figure 4.

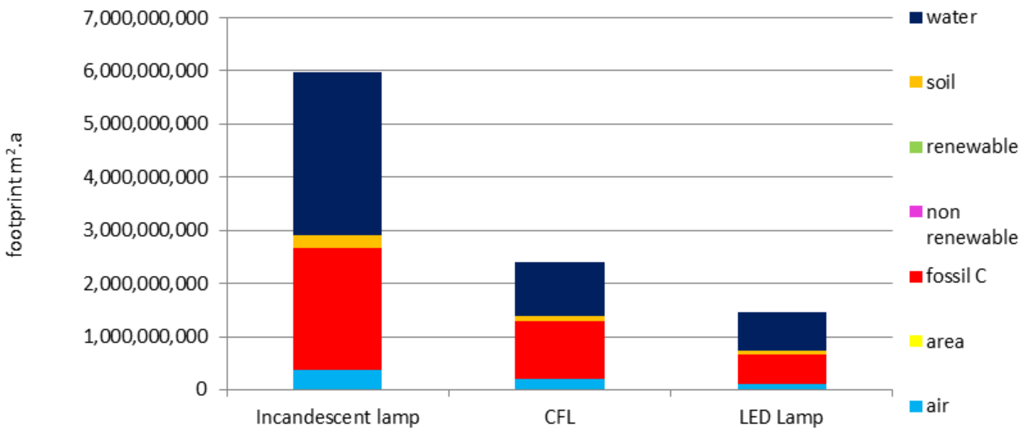

Figure 4: Comparison for SPI footprint for street lighting in Veszprem using different light bulbs

It denotes that utilization of Incandescent lamps have highest footprint, while use of CFL and LED lamps, results in 60 % and 76 % reduction in footprint correspondingly. Similarly use of LED lamps has lowest footprint value, which is about 39 % lower than use of CFLs. The comparison of C footprint for street lighting in Veszprem is given in Figure 5.

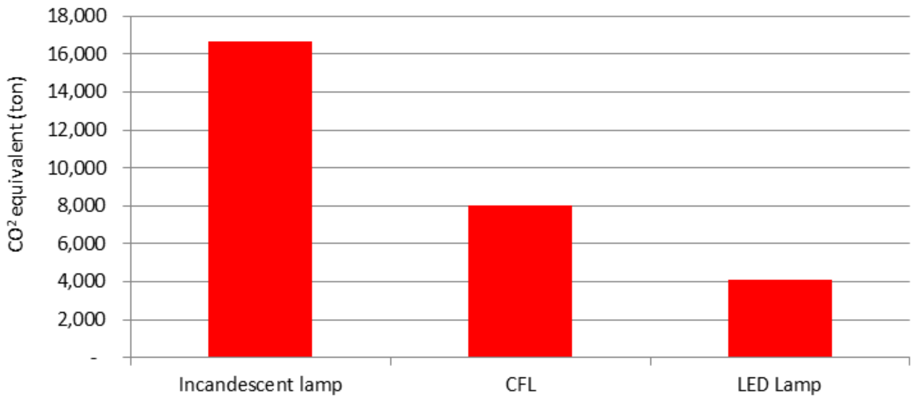

Figure 5: Comparison of C footprint for street lighting in Veszprem using different light bulbs.

It shows that use of incandescent lamps have highest C footprint value, which is 52 % higher than CFL and 75 % higher for LED lamp. Moreover, replacement of the light producing devices has positive impact on the environment. According to the inventory input charts, highest contribution is coming from electricity provision during usage phase. In case of compact fluorescent lamp, electricity consumption share is about 25 to 30 % less than LED and incandescent lamp, but there is an additional 13 % share coming from natural gas consumption during production phase. All in all, it can be said that there is a potential to decrease environmental impact by 2 to 4 times by changing lamps from conventional incandescent to CFL and LEDs.

3. Conclusion

Overall this study confirms that energy consumption in the use phase is the dominant impact for all three lamps, although 15 W CFL and 12.5 W LED lamps perform better than 60 W incandescent lamp. In other words higher consumption of electrical energy per unit of light output results in substantially higher environmental impacts. LED lamps having lowest energy input per unit light output are most environment friendly among the three lamps. Considering highest contribution of the electricity consumption for all three lamps, it is evident that along with technology development for manufacturing of light emitting devices, there is need to focus on energy production utilising renewable and environment friendly technologies. The results reveal that environmental impact of street lighting as well as residential lighting can be reduced by replacing old fashioned and low efficiency lamps with the modern and highly efficient lighting devices.

4. Future Outlook

As electricity input during use phase is the main contributor for environmental emissions, the effect of change of electricity provision from different resources and technologies (coal, natural gas, biomass, hydro power, wind energy) will be interesting to look at. It will also be very interesting to analyse impact of geographical context and energy provision on the ecological impacts.

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