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A Case Study for Developing Eco-efficient Street Lighting System in Saudi Arabia

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It is now well-known phenomenon that energy efficiency has highest short-term pay out period to decrease overall energy consumption. The replacement of conventional lighting technology with innovative lighting solutions can save up to 40 % of lighting energy. The ecological evaluation of street light provision system in King Abdulaziz University (KAU), Jeddah is carried out using Sustainable Process Index (SPI) methodology. This study is carried out selecting three commonly used street illuminating devices i.e. High Pressure Sodium (HPS) lamps, Compact Fluorescent (CF) lamp and Light Emitting Diode (LED). The results show that energy consumption can be decreased by a factor of 1 to 4 by replacing HPS lamp with high efficiency LED lamp. Similarly, environmental assessment results reveal that ecological footprint as well as carbon footprint caused by lighting service can also be lowered by replacing HPS and CF lamps with LED lamps.

1. Introduction

The Saudi Energy Efficiency Centre (SEEC, 2013) has reported that buildings in the Kingdom of Saudi Arabia (KSA) are consuming about 80 % of overall electricity production for air conditioning, lighting and other electrical and electronic devices. Air conditioning is the main user with 50 % electricity consumption. The electricity demand for lighting comes at number 2 and in some cases it can reach up to 30 %. The literature shows that on average lighting consumes about 19 % of world's energy (Waide et al., 2006). The replacement of conventional lighting technology with innovative lighting solutions can save up to 40 % of lighting energy (Noortek, 2015). It is very important to find out the hotspots in the energy networks and minimize the network losses and consumption at the end use point. The electricity consumption for lighting can be significantly reduced by installing efficient lighting system in accordance to the local needs. The redundancy in the use of incandescent lamp and shift to Metal halides, CF and LED based lighting devices is a step forward towards attaining energy efficiency in lighting systems (Shahzad et al., 2015). In the past few years, light quality and efficiency has greatly improved with the development of related technologies. The outdoor electric illumination was started with the use of old fashioned inefficient incandescent lamps. In the recent times, variety of energy efficient alternatives are available, including HPS, CF, Metal halides and LED lamps, to be used for outdoor lighting. The ever increasing population and economic growth is leading to the amplification of urbanization. The gradual development of public infrastructure is accompanied by increased electricity demand for lighting in the public areas. The use of eco-efficient lights in the public areas can save significant amount of energy and can have positive impact on the economics as well as environment (Abdul Hadi et al., 2013). This study focuses on the comparison of HPS, CF and LED luminaires used for street lighting, to find out eco-efficient solution for the street lighting system in King Abdulaziz University (KAU), Jeddah, Saudi Arabia.

1.1 Life Cycle Assessment with Sustainable Process Index

Sustainable Process Index (SPI) is a Life Cycle Assessment (LCA) based footprint methodology, developed by Krotscheck and Narodoslawsky (1996). It follows the basic normative behind the development of ecological footprint. It means that anthropogenic resource consumption should be restricted to available natural capital and ecosystem services, i.e. “ecological budget”. The solitary natural income for our planet to support sustainable economy are solar radiations reaching to the earth surface (Shahzad et al., 2013). The crucial source required to convert this natural income into exploitable material (biomass) or energy is area. It can be done by direct use – conversion of solar radiations into electricity or as thermal energy and by the indirect use via biomass production and its use as energy products (Shahzad et al., 2015).

SPI is used for process design, development (Kettl et al., 2011) and optimization by spotting ecological hotspots in the sub-processes as well as overall process (Kettl et al., 2012). This methodology is in accordance to the norms of ISO and has been successfully used for making comparative analysis of alternate technologies, renewable based technologies and evaluation of bio refineries (Titz et al., 2012) for biofuels and PHA production along with other. In this study SPIonWeb (an online tool available at: spionweb.tugraz.at) has been used to measure environmental pressure.

1.2 Goal and Scope of the Study

This study deals with the evaluation of different light emitting devices used for street lighting in King Abdulaziz University (KAU). The estimated street light requirements for KAU are 94,806 Mlm·h/y (Million Lumen hours/year) considering average 4,000 h/y lighting operation time. The life cycle assessment considering CF and LED luminaires as alternates of HPS (business as usual), has been performed using SPI methodology. The luminaire normally consists of housing, power supply and bulb. The LED luminaire has LED array instead of bulbs. The luminaires considered in this study are of different powers, having 400 W for HPS, 98 W (49 X 2) for CF and 180 W for LED with luminous efficacy of 72.6, 82.7 and 97.3 lm/W for HPS, CF and LED respectively. The analysis is carried out using 100,000 hour light requirement which is equivalent to 25 years life span of the infrastructure. The inventory data for ecological impact assessment is used from literature (Tähkämö and Halonen, 2015; Tähkämö, 2013; Eco-invent data base), however SPIonWeb is used for investigation. The detailed features of selected luminaires under study to fulfil lighting requirement are shown in Table 1.

Table 1: Selected features of luminaires under study

Characteristics	HPS	CF	LED	Unit
Power of luminaire	400	98	180	W
Power consumption	440	104	180	W
Luminous efficacy	72.58	82.69	97.26	lm/W
Light flux	31,935.2	8,600	17,508	lm
Lamp life time	20,000	20,000	50,000	h
Life time light flux	638.7	172	875.38	Mlm·h
Impact scalar	1.37	5.09	1	
Light requirement for 100,000 lighting h		2,370,151		Mlm·h
No. of lamps required	3,711	27,560	2,708	Units
Life time energy consumption	8,800	2,080	9,000	KWh
Energy consumption during 100,000 lighting h	32,655.70	28,662.29	24,367.98	MWh

The selected parameters include power of the luminaire (W), actual power consumption per luminaire (W), luminous efficacy i.e. lumen/ watt (lm/W), light flux or light output/unit luminaire (lm), lamp life time (h), and impact scalar based on LED luminaire as reference. The system boundary for this study includes material and energy intake for luminaire manufacturing, transportation and electricity consumption during its use phase. The energy used during manufacturing phase was considered as “Net electricity mix EU27, medium voltage” while during use phase “Net electricity medium voltage, KSA” i.e. from local electricity network has been used. The energy and material consumption during packing has been considered, however disposal and recycling of the material is out of scope of this study. Functional unit selected is the light requirement at KAU for 100,000 lighting hours, and is 2,370,151 Mlm·h. It is assumed that street lighting infrastructure have 25 years life time, while HPS and CF lamps will be replaced after every 20,000 light h while LED luminaire will be replaced after 50,000 light h i-e their respective life times.

2. Results and Discussion

2.1 LCA for High Pressure Sodium Luminaire

The sodium lamps contain xenon gas and metallic amalgam of sodium and mercury. The xenon and metallic amalgam are enclosed in the aluminium oxide arc under high vacuum. When electricity is supplied to the arc it turns blue due to the vaporization of xenon. Mercury vaporises after xenon and arc turns into dark blue colour. At temperature of about 240 °C sodium vaporises and produces yellowish colour. The impurities xenon and mercury are deliberately added to the sodium to produce which light (MFE, 2009).
In this study HPS of 400 W with luminous flux of about 32,000 lm·h, luminous efficacy of about 72.6 % and life time of 20,000 h has been considered. The overview based on its ecological pressure contribution during LCA and SPI footprint distribution in the related material and energy provision and emission dissipation categories are shown in Figure 1.

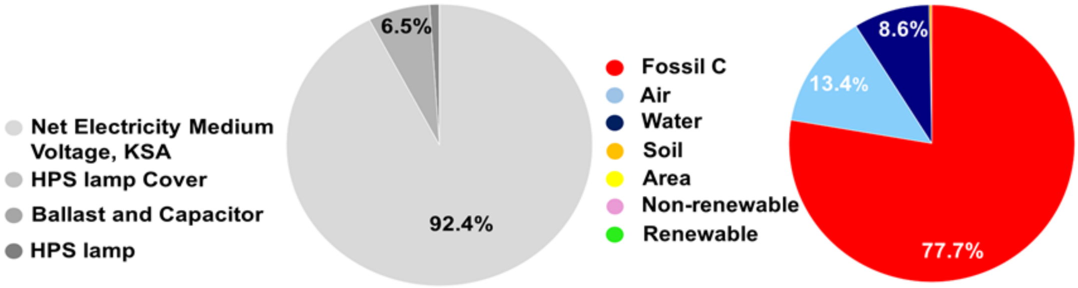

Figure 1: Ecological pressure contribution of material and energy inputs (left), and SPI footprint distribution among defined footprint categories for HPS luminaire (right)

From Figure 1 it can be seen that electricity demand in the use phase accounts for more than 92 % of the overall environmental impact while luminaire cover production contributes about 6.5 % of the overall impact. The SPI footprint has the highest contribution from fossil based C resources causing almost 78 % of the total footprint. The footprint contribution from emission dissipation into air and water compartments are two other main contributors having 13 % and 9 % shares respectively. Remaining footprint categories, such as emissions in soil, area required to provide installation and area related to non-renewable and renewable consumptions contribute to less than 1 %. The total SPI footprint value for HPS luminaire is 1.62 km^2·y.

2.2 LCA for Compact Fluorescent Luminaire

The compact fluorescent (CF) lamps are significantly more efficient than incandescent lamps. In CF lamps the light is produced by energizing mercury vapours filled in the glass tube. The energized mercury vapours emit ultraviolet (UV) light. The glass tubes are coated with special type of phosphor which absorbs UV light emitted by mercury vapours and emits visible light to the environment (VDDME, 2012).
In the current study CF luminaire containing two lamps of 49 W consuming cumulative power of 104 W has been considered. The luminaire has 20,000 h life time, 8,600 lm·h luminous flux and lumen efficacy of 82.7%. The ecological pressure contribution during LCA and related SPI footprint distribution in the corresponding categories are shown in Figure 2.

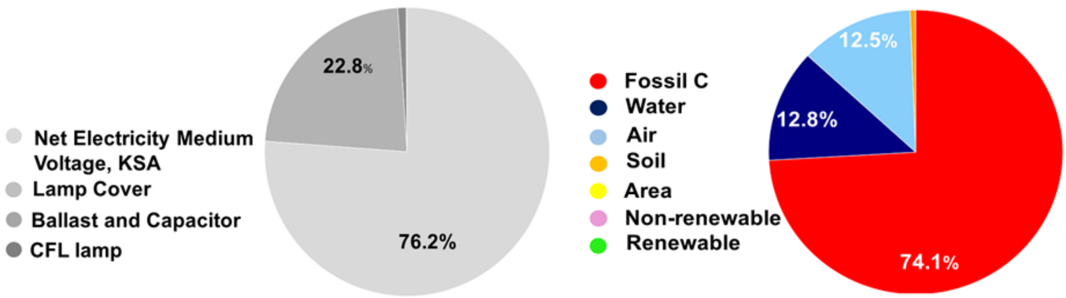

Figure 2: Ecological pressure contribution of inputs (left) and SPI footprint distribution among defined footprint categories for CF luminaire (right)

For CF luminaire production, the inventory data show that net electricity consumption in the use phase contributes the most to the environmental impact (76 %). The luminaire cover production contributes about 23 % of the remaining 24 % share. The total SPI footprint for CF luminaire is 0.41 km^2·y. This per unit footprint value is almost one fourth of HPS luminaire production unit. The major share of overall footprint (about 74 %) is caused by material and energy flows consisting of fossil C origin. The other two main contributors to the overall footprint are areas required for sustainable dissipation of emissions to water and air compartments. The emissions to water and air have quite similar footprint contributions, 12.8 % and 12.5 % of overall footprint.

2.3 LCA for LED Luminaire

The LED basically consists of three components. The first one is the die which is the key part and emits light. It consists of the semi-conductor material. The second part is the lead frame which is used to place the die and the third one is known as capsule which protects the die (Yeh and Chung, 2009). Currently, LED is considered as one of the most environmentally friendly lighting choice because of its high energy efficiency, long life time and most importantly mercury free material composition. The luminous efficacy of LEDs has been reported in the range of 142 lm/W to 231 lm/W at lab scale depending on the semiconductor material and design selection during fabrication process (Tan et al., 2012), while at the commercial scale luminous efficacy of LEDs is smaller (De Almeida et al., 2014), see also Table 1.

In this study a luminaire of 180 W having LED array consisting of 132 LEDs with luminous flux of around 17,500 lm·h and luminous efficacy of 97 % is considered. The contributions to ecological pressure during LCA, and SPI footprint distribution among different categories are shown in Figure 3.

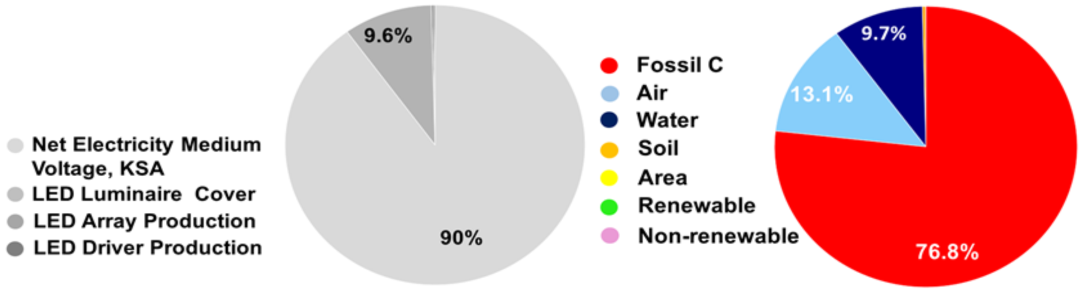

Figure 3: Ecological pressure contribution of inputs (left) and SPI footprint distribution among defined footprint categories for LED luminaire (right)

It can be seen from Figure 3 that electricity consumption during use phase has the highest environmental pressure of inputs with a share of 90 %, while material and energy input for luminaire production have 9.6 % share. LED array and driver production have negligible material input contributions to the inventory. The distribution graph of SPI footprint into corresponding categories reveals that material and energy input based on fossil C have highest contribution of almost 77 %. The footprint contributions from air and water dissipation areas are significant, having about 13 % and 10 % contributing shares respectively. The material and energy flow from renewable and non-renewable resources, emissions to soil and direct use of area have negligible contributions to the overall footprint. The SPI footprint value for LED luminaire is 1.7 $km^2 \cdot y$. This unit footprint value is greater than unit footprint value of HPS luminaire while almost 4 times the unit footprint value of CF luminaire.

The SPI footprint ($m^2 \cdot y$) and C footprint (t $CO_{2,\ equivalent}$) for production of one luminaire and for annual light output (4,000 h of light per y) is given in Table 2. The C footprint is estimated from area for fossil C category. Carbon footprint (kg CO_2 equivalent) = value of area required for fossil C category multiplied by 3.667/500. This equation is based on sea bed area required for C sequestration. The reported C sedimentation rate per m^2 of sea bed is 0.002 kg/y (Bolin and Cook, 1983).

Table 2: SPI and carbon footprint comparison for HPS, CF and LED luminaires

Categories	HPS	CF	LED	Unit
SPI footprint / Unit luminaire	1.62	0.41	1.7	$km^2 \cdot y$
C footprint / Unit luminaire	9.24	2.53	9.59	t $CO_{2,eq}$
SPI footprint / 100,000 h light	5,649.1	5,028.23	4,381.25	$km^2 \cdot y$
C footprint / 100,000 h light	32,763	29,708	25,077	t $CO_{2,eq}$

The life cycle footprint results for one luminaire reveals that LED luminaire has the highest environmental pressure with footprint value of 1.7 $km^2 \cdot y$. This footprint value is more than four times higher than for CF luminaire, while 5 % higher than for HPS luminaire. These values include material and energy input flow over the life time of the unit luminaires (HPS, CF and LED) including manufacturing, packing, transportation and use phase. The estimated 100,000 h light requirement for street lighting in KAU campus is 2,370,151 Mlm·h. The comparison of SPI footprint for 100,000 h light for street lighting in KAU is presented in Figure 4.

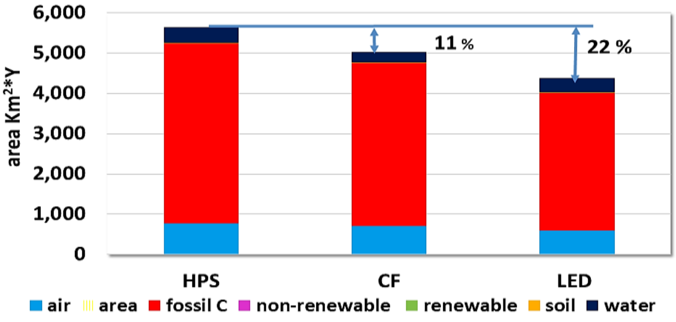

Figure 4: Comparison of SPI footprint for 100,000 h street light provision in KAU

It is clear from Figure 4 that the use of HPS luminaire has highest footprint, while its replacement with CF and LED luminaires reduces the footprint by 11 % and 22 %, respectively. LED luminaire has the smallest impact on the environment and produces the lowest footprint. LED luminaire footprint is even 13 % lower than CF luminaire. The comparative analysis of C footprint for 100,000 h street lighting in KAU is shown in Figure 5.

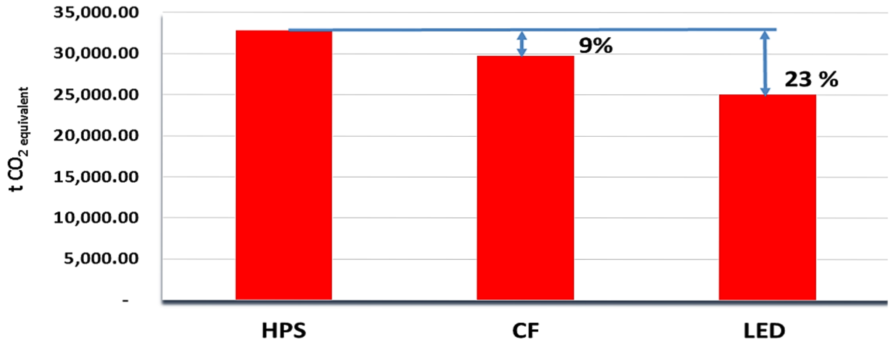

Figure 5: Comparative C footprint analysis for 100,000 h street light in KAU

It is evident from the obtained results that HPS has maximum C footprint value. Its value is 9 % and 23 % higher than installation of CF and LED luminaires, respectively.
The results reveal that the most important parameters the selection of suitable lighting devices for a specific place are user phase energy consumption and light flux efficacy. These results are in accordance to literature findings that 87 % and 96 % environmental impacts of LED and HPS luminaire are caused during use phase (Tähkämö and Halonen, 2015). Overall, it can be seen that the environmental impact of lighting system can be decreased by one fourth by replacing HPS with LED luminaires. This decrease in environmental pressure could be achieved with the selection of more efficient lighting system. Another factor which is very important in making lighting system more eco-efficient is switching from fossil based energy system to alternative and renewable energy systems.

3. Conclusions and Future Work

The analysis clearly shows that luminaire with high luminous efficacy as well as longer life period are suitable options to fulfil light demand with lower environmental impacts. The results reveal that ecological impact caused by electricity consumption in the use phase is the overriding factor for all luminaires. It means that low efficacy of the luminaire results in higher consumption of electricity as well as environmental pressure to provide similar service. As obtained from the inventory data, electricity consumption increases footprint the most for all three luminaires. It highlights the necessity to focus on the energy production from the alternative renewable resources along with the development of more sophisticated and highly efficient end use technologies to attain sustainability.
The future work will include analyses of i) impacts of predicted increased lamp efficacy in the future, and ii) effects due to change of energy provision resources (water, wind, solar, geothermal, coal, natural gas, crude oil). Furthermore, variations in footprint depending on geographic location will be studied. Economic analysis

of luminaire replacement including carbon credits and CO_2 emissions will be performed. Finally the annual equivalent amounts of oil and gas savings, and GHG emission savings and carbon crediting will be calculated.

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