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Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies

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ABSTRACT

A life cycle assessment compared the environmental impacts of two typical road lighting technologies: high-pressure sodium (HPS) and light-emitting diode (LED) luminaires. The environmental impacts of manufacturing, use and end-of-life of the luminaires were studied with a special regard to the functional unit. The results confirmed that the use caused the majority of the environmental impacts: 96% in HPS and 87% in LED luminaire over 30 years of operation, while manufacturing accounted for 4% and 13%, and end-of-life less than 1%, respectively. In the comparison per luminaire or per lumenhour, the LED luminaire caused 26% or 17% lower average environmental impacts than the HPS luminaire, respectively. However, a luminaire or an amount of lumenhours does not describe the actual function of the luminaire. When the luminaires were compared on the basis of a kilometre of lit road, the difference between the LED and HPS technologies was only 3% on average. This illustrates the importance of the functional unit. In addition, the development of the LED technology will decrease its environmental impacts and make it clearly environmentally favourable: with the estimated luminous efficacy development in 2020, the environmental impacts of the LED luminaire per kilometre of lit road were estimated to be 41% lower compared to the HPS technology.

1. Introduction

Lighting is one of the basic needs in modern-day society. In outdoor environments; such as roads, streets, car parks, pedestrian ways and parks; lighting enables the detection of people, vehicles and other objects after dark. Outdoor lighting contributes to the feeling of safety and comfort of the road users. Road lighting has been found to have the potential to decrease the amount of accidents (Wanvik, 2009; Commission Internationale de l'Eclairage, 1992). In addition to its positive effects on road safety and the potential for improving the appearance of the urban environment, road lighting consumes a notable amount of energy: in Europe, road lighting consumed approximately 35 TWh (1.3%) of electricity in 2005 (VITO, 2009).

Road lighting in the European Union (EU) is facing a major challenge due to the Ecodesign Directive. The Directive forces the outdoor lighting sector to replace the most inefficient light source technologies with more energy efficient alternatives. The replacement is expected to reduce the energy consumption and the life cycle costs of the installations. The energy consumption of lighting can be further reduced by control systems, but dimming and continuously switching on and off suits poorly with the fluorescent and high-intensity discharge (HID) technologies traditionally used in road lighting. In contrast, lighting controls work well with light-emitting diode (LED) technology and enable dimming and controlling according to several parameters, such as presence, time schedule, and availability of daylight. In contrast to the discharge technologies, the controlling of the LED system is not limited by restrictions in starting time or minimum level of dimming.

In the EU, the most common outdoor lighting technology was the high-pressure sodium (HPS) lamp (47%), whereas the high-pressure mercury (HPM) lamps accounted for 32%, low-pressure sodium lamps 9%, fluorescent lamps 8%, and metal halide (MH) lamps 3% in 2006 (VITO, 2009). The amount of LED light sources was estimated to be 6% in 2011 and 9% in 2012 in outdoor lighting (McKinsey&Company, 2012). The amount of HPM lamps in the EU is expected to radically decrease, since the Ecodesign Regulation on fluorescent and HID lamps, ballasts and luminaires (European Commission, 2009) sets lamp efficacy requirements, which the HPM technology cannot fulfil. As a result, the HPM lamps are

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banned from the EU market in April 2015. The most evident alternatives for near-future outdoor lighting solutions are the HPS and LED technologies, since the HPS technology is currently the most frequently used technology in the EU (VITO, 2009), the share of the LED technology is rapidly increasing, and both technologies are able to fulfil the requirements of the Ecodesign Regulation. Thus, it is valid to evaluate and compare the environmental performance of HPS and LED technologies in the life cycle assessment (LCA) of road lighting.

The HPS technology was developed in the 1960's. The operation of an HPS lamp is based on an electric arc created between two electrodes in the discharge tube. The discharge tube is made of alumina and contains sodium vapour. The HPS luminaire typically contains the lamp, an ignitor, a compensating capacitor and a ballast to limit the current. Currently, the HPS luminaire is frequently used in outdoor applications on roads, streets, sports areas, and industrial premises. The luminous efficacy of the HPS luminaire is typically between 50 and 150 lm/W but its colour rendering properties are poor, as it produces a yellow-orange light. The HPS technology is mature and its efficacy is not predicted to significantly increase.

The use of the LED technology has evolved from the signal lights to general lighting over the last decade. The physical phenomena in the semiconducting material was found already in the 1900's but its application in general lighting was possible in a large scale only after the development of the white LED in 1990's. The operation of the LED technology is based on a semiconductor junction emitting light when electric field is applied to the material. It is technically possible to manufacture LED components that produce various colours. White light can be provided either by combining several LED components of different colours (colour mixing) or by converting the light from a coloured LED component with a phosphor (phosphor conversion). The LED products can be designed as separate LED luminaires or as LED lamps or modules that are able to replace another lamp technology in an existing luminaire. The luminous efficacy of an LED luminaire ranges around 100 lm/W currently on the market, while the efficacy of an LED chip is said to be developed as high as 303 lm/W in laboratory conditions (Cree et al., 2014). The LED luminaires are currently used in a wide range of applications from decorative lighting and residential lighting to high-power outdoor applications. LED luminaires of various colours are available on the market with a wide range of colour rendering properties. Unfortunately, the quality of the LED products on the market is not uniform and poor-quality products may hamper the rocketing market. The LED technology is being developed and its luminous efficacy is predicted to improve, and development is also expected in other properties, such as colour rendering, reliability and life.

Only two LCAs were found in the literature that analyse the light source technologies used in road lighting. Abdul Hadi et al. (2013) compared ceramic metal halide (CMH) and LED street light luminaires in a hybrid LCA using previous data provided by Navigant Consulting Europe Ltd (2009), Hartley et al. (2009), OSRAM (2009) and Energy works (2014), which do not represent outdoor lighting luminaires. Dale et al. (2011) analysed the environmental performance of HPS, MH, LED and induction luminaires used in street lighting. Their analysis stated using original inventory data on LED and HPS luminaires, but the actual data was not provided. However, the same group authored the report by Hartley et al. (2009) providing preliminary inventory data of LED and HPS luminaire housings. Dale et al. (2011) compared the luminaires on the basis of 100 000 h of use but they excluded the ballasts. In contrast to the previous publications, the LCA presented in this paper offers data on the materials and components of the luminaires including the light sources, control gears and luminaire covers.

2. Method

The LCA in this article compared two technologies used in road lighting: HPS and LED luminaires. The luminaires are illustrated in Fig. 1 with measurements. The assessment was conducted according to the international standards (ISO 14040, 2006; ISO 14044, 2006). The goal was to study the environmental performance of the road lighting luminaires and to illustrate the importance of the functional unit in this application.

The LCA analysed the manufacturing, use and end-of-life (EoL) of the luminaires consisting of a light source (lamp or array), control gear (ballast or driver) and luminaire cover. Manufacturing included the raw material acquisition, manufacturing processes of materials and parts, transport of the materials and parts, and packaging, both interim and final product. Use accounted only for the electricity consumption during operation. End-of-life was modelled including the transport and disposal of the materials.

The parameters of the HPS and LED luminaires are collected in Table 1, and the life cycle inventory (LCI) data is collected in Table 2 for the HPS and in Table 3 for the LED luminaire. The HPS luminaire with a 150 W lamp consumed 176 W and produced a luminous flux of 12 775 lm according to the luminaire manufacturer. The LED luminaire containing 98 pieces of 1 W LEDs (diodes) consumed 117 W and provided 11 380 lm according to the luminaire manufacturer. The life of the HPS lamp (long life) was 32 000 h according to the lamp manufacturer. Given their robust structure, the lives of the HPS luminaire cover and the magnetic ballast were estimated to be very long, lasting over 30 years of operation, 4000 h per year. The HPS lamp requires a compensating capacitor and an ignitor to operate properly. The compensating capacitor was estimated to last 10 years regardless of use (VITO, 2009). The life of the ignitor was estimated to be the same as that of the luminaire and the ballast (VITO, 2009) and it was considered as a part of the ballast. The life

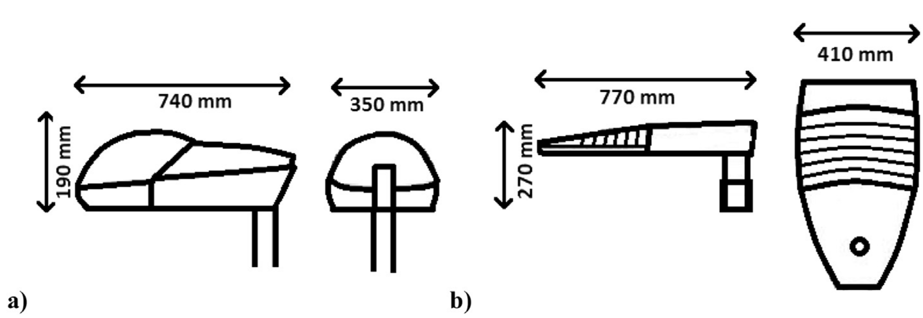

Fig. 1. Graph of the a) HPS and b) LED luminaire with dimensions.

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