ARTICLE IN PRESS

Renewable and Sustainable Energy Reviews xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of Light Emitting Diodes technology for general lighting: A critical review

Andrei Nardelli, Eduardo Deuschle, Leticia Dalpaz de Azevedo, João Lorenço Novaes Pessoa, Enedir Ghisi*

Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópolis, SC 88040-900, Brazil

A R T I C L E I N F O

Keywords:
Light Emitting Diode
LED
Lighting
Energy efficiency
Buildings
Environmental sustainability

A B S T R A C T

Lighting consumes about 19% of the electricity used around the world, and since inefficient lighting sources are still in use worldwide, there is great potential for electricity savings. Even fluorescent lamps, with better luminous efficiency than incandescent and halogen lamps, have some limitations. This article presents the results of an evaluation of the potential of Light Emitting Diodes (LEDs) as a light source for use in buildings, under several aspects, and compares them to more consolidated sources. It includes a review of scientific articles, governmental reports and product catalogues for lighting sources from seven manufacturing companies. Results showed that LEDs have a long lifespan, a wide range of correlated colour temperature, good luminous efficiency, colour rendering index and many other characteristics similar to those of fluorescent lamps. However, the acquisition costs are still higher than those of other lighting systems and the market still offers too many low-quality LEDs. Furthermore, LEDs with inefficient heat dissipation may have high lumen depreciation and, therefore, a shorter lifespan. Despite these limitations, however, LED technology is evolving rapidly and, unlike other light sources, has great potential for improvement and may be the best alternative for lighting in the next few years.

1. Introduction

Lighting accounts for 19% of the world's electricity consumption [1]. The lighting source most commonly used in buildings worldwide is still the incandescent bulb [2]. This light source has low luminous efficiency and a short lifespan and thus a major environmental impact. In order to fill the growing demand for energy, more efficient lighting sources must replace inefficient ones. High-intensity discharge lamps and tubular and compact fluorescent lamps already predominate in many countries since they are consolidated technologies and have a longer lifespan and better luminous efficiency than incandescent bulbs [1–3].

However, fluorescent lamps also have deficiencies such as relatively high lumen depreciation and mercury in their structure. Therefore, it is necessary to keep developing new alternatives. One such alternative, Light Emitting Diode (LED) technology, has been developed and continues to be studied as it has great potential to replace less efficient light sources. Its versatility allows for wide use when reliability, lifespan, colour and visibility are essential, such as for traffic lights, automotive lighting and electronic device screens. Recently it has also been employed in public and decorative lighting [3–5].

LEDs are made of semiconductor diodes which emit energy in the form of photons when crossed by an electric current. The wavelength and colour of the light emitted depend on the chemical composition of the semiconductor material used. The main advantages of LEDs are: long lifespan (over 50,000 h); high-speed response time (micro-second level on-off switching); reduced dimensions; better thermal management than conventional lighting sources; near absence of mercury in their structure; no emission of infrared rays and so they are less harmful to health; a wide range of operating temperatures and a broad array of controllable colour temperatures [4–8]. Moreover, they have a wide range of luminous flux and very efficient colour emission with a single output wavelength, and they are dimmable without loss of efficiency [8]. For all these advantages, LEDs are described as a technology capable of reducing energy consumption and therefore of reducing the emission of greenhouse gases [9].

However, the literature has not yet reached a consensus regarding the superiority of LEDs to other technologies when all of the main characteristics of a lighting system are considered. While laboratories linked to the US Department of Energy (DOE) claim LED technology is capable of replacing other lighting systems, other research has shown that it still has disadvantages such as poorer total harmonic distortion and low colour rendering index, and so, it may not yet be suitable for general lighting in buildings [6,10–12].

* Corresponding author.

http://dx.doi.org/10.1016/j.rser.2016.11.002
Received 17 July 2015; Received in revised form 31 October 2016; Accepted 1 November 2016
Available online xxxx
1364-0321/

2. Objectives

The main objective of this article is to describe LED technology used in lighting, considering general and thermal characteristics, correlated colour temperature, colour rendering index, luminous efficiency, power factor and total harmonic distortion, lifespan, environmental impact, life cycle and economic feasibility. Then LEDs are compared to conventional lighting systems such as incandescent, halogen and fluorescent lamps now available on the market with reference to the same characteristics. Based on these comparisons, the main advantages and disadvantages are presented in order to put to rest the current controversy about the suitability of LEDs for general lighting.

3. Method

This study was a literature-based review of scientific articles related to the use of LEDs as a light source. Theoretical and practical results obtained by implementing LEDs in lighting systems, as well as reports from government and non-governmental institutions and catalogues from large-scale manufacturers were also reviewed. As for data acquisition, preference was given to the most recent studies on the subject, preferably those published between 2008 and 2016.

For a detailed comparison between LEDs and the main types of lamps used in general lighting, 395 lamps available on the North American, European and Brazilian markets were surveyed, studying characteristics of luminous flux, power output, lifespan, power factor, correlated colour temperature and colour rendering index. Information about them was found on the internet in the catalogues of seven manufacturing companies: Philips, Osram, Elko, Cree, TCP, Samsung and LG [13–19].

4. Results

After its launching in the 1960s, LED technology was first used in calculators, digital watches and testing equipment. Decades later, ever since the early 1990s,, LEDs have become very popular because of advances in their technology. With the development of green, red and blue LEDs, significant applications for semiconductors now exist. The combination of primary colours allows for the production of large-area displays, automotive and aerospace lighting and traffic signals. With nanoscale production, LEDs can now be inserted into sensors, printers, scanners and optical communication. In the coming decades, given their potential to reduce energy consumption, the use of LEDs in lighting systems is expected to increase [7].

An LED chip is composed of two electrical contacts (lead), either anode or cathode, from which the electric current that is applied flows through the chip by wire bonds. The chip also contains a heat sink slug that has good thermal conductivity, usually made of aluminium or copper; a case which serves as protection, a mounting and manufacturing guide; a lens to direct the beam of light; and an encapsulator [20].

Light sources such as tungsten filament lamps or fluorescent lamps depend on incandescence or discharge gases to produce illumination. However, in both processes, huge energy losses result. The semiconductor offers an effective way of generating light and has a potential for electricity conversion close to 100% [1,21].

The basic LED is composed of a p-n junction and a single semiconductor that generates a transition interface. Under forward bias conditions, the p-type region receives electrons and holes are injected into the n-type region. The recombination of these minority carriers with majority carriers at the p-n junction leads to light generation. Since this type of LED has some disadvantages, it is no longer used. As the entire structure has the same composition, self-absorption of the generated light is high, reducing its efficiency [21].

In order to improve the luminous performance of LEDs, different epitaxial structures are used in a single emitting diode. As the semiconductors have distinct chemical compositions, they are called heterostructures. A different type of semiconductor composes each region, p and n, of the diode. Thus, the photon absorption in the n region is minimized, resulting in up to twice the efficiency of the homojunction [21].

Another characteristic of LEDs is that, at room temperature, they reach the maximum luminous flux immediately when they are switched on, unlike fluorescent lamps. Moreover, even when they are still warm, they can be switched on again with no impact on their lifespan [22].

Efficiency can be further enhanced through the production of small structures. The use of a small-size semiconductor decreases transmission problems from one interface to another, reducing possible irregularities [21].

In order to produce white light lamps, RGB (Red, Green and Blue) systems or multiple phosphorus techniques can be used. Most commercial LEDs use phosphorus layers because they are still less expensive and have higher luminous efficiency [6]. Additionally, RGB systems have a high complexity of electrical control of photon diffusion [3].

4.1. Colour temperature and colour rendering index

A single LED diode emits light in a narrow interval of wavelengths, between 500 and 700 nm giving the appearance of a monochromatic source. LED lamps can put together several components so that the combination appears as white light to the human eye. However, of the lamps available on the market, a large number effect a conversion with phosphor, mainly with InGaN, ZnSe or blue SiC to emit white light [1,3,23].

In theory, LED lamps that combine different monochromatic sources have greater efficiency. However, the existence of intrinsic deficiencies in the process of phosphor conversion means that, in practice, LEDs can have poorer colour consistency. Therefore, they require a more sophisticated optical system in order to ensure adequate mixing which makes them more complex and expensive [23].

Colour temperature is an important characteristic of a light source and is defined as the absolute temperature in Kelvin at which a black body radiator must be operated to have a chromaticity equal to that of the light source. The colours with higher temperatures are usually designated as cold and those with lower temperatures, as hot [23–25]. An incandescent bulb is very close to an ideal black-body radiator, so its colour temperature is the temperature of the filament. As for other light sources, this characteristic is represented by a correlated colour temperature and not the true colour temperature [25].

Correlated colour temperature index is the one most used to classify colour temperature; however, it has limitations since it uses a single number to represent a complex spectral distribution. For example, two sources with the same correlated colour temperature may appear different to the human eye. The current LED lamp can produce white light in the range of correlated colour temperatures used for lighting between 2700 and 6500 K. Light sources with colour temperatures above 5000 K emit bluish-white light while light sources with temperatures below 4000 K emit yellowish light similar to that of incandescent lamps. There is no ideal colour temperature but different appropriate temperatures for different functions. The predominant use of low colour temperatures in the residential sector is influenced by centuries of use of other light sources with low colour temperatures [24].

The colour rendering index attempts to quantify how different a set of test colours of a light source appears when compared to a standard source with the same correlated colour temperature. It is measured on a scale of 0–100, where 100 is the illumination of a reference source. Typical reference sources are daylight and incandescent bulbs. The measurement is made by human observers and is, therefore, subjective. Low index values of colour reproduction may mean that the colours are somewhat saturated (with pale aspect) or too saturated (with vivid