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**Article**

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Research paper

# Efficiency, quality, and environmental impacts: A comparative study of residential artificial lighting

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ABSTRACT

The recent ban on conventional incandescent lamps for residential use led Brazilian consumers to choose from three main lighting technologies: incandescent halogen, CFL (Compact Fluorescent Lamp), and LED (Light Emitting Diode). Despite the fact that their electrical performances are well known, there are still some technical features to be discussed and compared. Therefore, this paper tends to show a comparative study of three low-cost lighting technologies. Laboratorial apparatus were used to measure electricity quality, electrical performance and photometric indicators. With the aid of the lumen method, the number of lamps needed to light a hypothetical apartment was evaluated. The consequent costs and environmental impacts were evaluated as well. This study finds out that LED lamps are clearly the best lighting option, considering the overall comparisons of the variables mentioned above. However, the tested LED lamp present some disadvantages as compared with the others, such as power factor, harmonic introduction and environmental impacts in manufacturing phase. Also, it was noted that there are some inconsistencies between measured lighting data and information given by manufacturers. Among the evaluated technologies, the incandescent lamp shows more measured values that are approximately the same as the values indicated by the manufacturer.


## 1. Introduction

In the beginning of the 1990's, governments, non-governmental organizations, and multilateral organizations and agencies from various countries have invested in energy efficiency programs in order to address these issues. One of the objectives of these programs was to promote the replacement of incandescent light bulbs by CFL (Compact Fluorescent Lamp), which have better efficiency ratings (Martinot and Borg, 1998).

In Brazil, where energy use trends resembled those observed worldwide, the residential electricity consumption doubled in the 1970's, continued to grow rapidly in the 1980's. It also increased by 6% per year between 1990 and 1996, with an annual average increase of about 4.2% (EPE — Empresa de Pesquisa Energética, 2014). Projections for 2014–2024 predict increases in consumption of around 4.3% per year (EPE - Empresa de Pesquisa Energética, 2014). In 1985, the Brazilian Federal Government created the Electric Energy Conservation Program (PROCEL) with the objective to "rationalize the use of electric energy and to provide the same product or service with less consumption" (Geller et al., 2000). In 2001, despite this program, the energy supply was not sufficient to meet the growth in electricity demand in Brazil; this resulted in an electricity supply crisis that led to a 13% decrease in residential electricity demand in 2001 (Achão and Schaeffer, 2009). The energy crisis revealed the importance of energy efficiency in various consumption sectors, especially when encouraged by effective normative instruments (Hunt et al., 2018).

Before 2001, approximately 95% of the lamps used were incandescent (Braga et al., 2014). However, due to their low energy efficiency and the energy crisis, the replacement of incandescent bulbs with CFLs was encouraged by the government. A federal decree was issued in 2010 and the replacement of these lamps was signed into law. A 6-year period was proposed for the complete replacement of conventional low-performance incandescent lamps. Thereafter, the importation and production of these lamps were prohibited (Brazil, 2010). Thus, CFL played an important role in the significant reduction of energy consumption for an extended period. Sequel to the advancement in lighting technology, Light Emitting Diode (LED) lamps were released into the

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market. These lamps are likely to dominate the market in the near future because they are affordable and more efficient than CFL (De Almeida et al., 2014).

Despite their efficiency, CFL and LED lamp technologies have disadvantages with regard to the quality of electrical energy (Molina and Sainz, 2014). Firstly, they produce electrical effects on the network, such as harmonic distortions and flicker effects. These electrical effects can have negative consequences on other equipment connected to the same network (Monteiro et al., 2014; Lobão et al., 2015). Another disadvantage is related to the quality of illumination. The quality of illumination can be literally observed through the ability of these lamps to imitate the typical colors of sunlight, to which human eyes are adapted. CFL and LED lamps do not have the ability to reproduce these colors as well as incandescent lamps. In addition, CFLs are disadvantaged by environmental impacts throughout their lifetime. Although these lamps are more efficient and therefore impose lower environmental impact during operation, the presence of toxic materials associated with their usage seems to be counterbalancing the gains in efficiency. This dilemma may be crucial in countries whose electric matrix has a small share of fossil fuels, such as Brazil.

In the Brazilian market, it is possible to find incandescent halogen, CFL, and LED technologies for residential use. There is a restriction on the use of Incandescent lamps. Bulbs less than 45 mm in diameter and with power equal to or less than 40 W are allowed. They are permitted in commercial places based on special application. Incandescent lamps are used for greenhouses, such as painting and drying, hospital equipment, and other applications. They are also used as reflecting/deflecting or mirror incandescent lamps, which are characterized by their redirection of luminous flares. Incandescent lamps are used in traffic signs and traffic lights. Similarly, halogen incandescent and infrared lamps are used for specific heating via emission of infrared radiation. Finally, incandescent lamps are used in automobiles (Brazil, 2010).

With the ban on marketing conventional incandescent bulbs for residential use, three major technologies are available to consumers to satisfy their demand for lighting. These include incandescent halogen, CFL, and LED. Regardless of their noticeably lower electricity consumption, LEDs are inferior to CFLs and incandescent bulbs in terms of energy quality parameters and environmental impacts.

This article tends to compare these three lighting technologies with the regards to technical performance, economic viability and environmental impact. All dimensions are explored using these three technologies to light a typical apartment. Comparing variables include energy performance, impact on the quality of electricity, lifetime cost and environmental impacts.

## 2. Efficiency and quality in the use of electrical energy

In order to be utilized in various human activities, energy undergoes various forms of transformations through a chain of processes. In the case of electric energy, natural energy sources (primary energy) are transformed into electricity (final energy). The final energy provides the consumer with an energy service, such as cooking, lighting, food cooling, appliance operation and more (Ghisi et al., 2007).

In general, energy efficiency is defined as the consumption of less energy in the process of guaranteeing the same energy service. Rational use can be achieved at any stage of the energy process between primary energy transformation and final energy consumption.

In the case of a residence, the final use of energy (electrical or thermal) depends mainly on the demand of the residents in terms of activities that require energy, such as cooking, lighting, and air conditioning. Demand is composed of several factors such as local climate, cultural factors, family income, type of housing, and age group (Schipper et al., 1992).

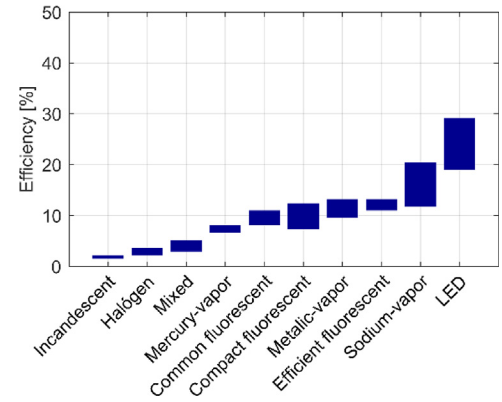


**Fig. 1.** Lamp technology efficiencies (DiLaura and Houser, 2011).

In Brazil, the consumption of electricity by lighting represents approximately 17% of total consumption (EPE - Empresa de Pesquisa Energética, 2014). The importance of the energy gains achieved with more efficient electric lamps is clearly expressed through lighting maintenance costs to the residents, the environment luminosity factor per area unit and the demand for active power. Saving energy through rational actions also reduces environmental impacts and frees space in electrical networks for other loads.

Fig. 1 shows the energy efficiencies of selected major lamp technologies. Incandescent lamps have efficiencies ranging between 1.5% and 2.2%, while LEDs are much more efficient, with efficiencies varying between 19% and 29.2%. These differences in efficiency are related to the conversion efficiency of electricity into luminous flux in each technology, based on the different physical principles used. From Fig. 1, the conversion efficiency is close to 30% for LED technology. This value is low when compared with other electrical applications such as electric motors, where the conversion of electrical energy into mechanical energy can exceed 90%.

The use of specialized electronic devices called drivers, is necessary in most of the recently developed illumination technologies. These devices are coupled with the lamp to provide the various voltages and current waveforms needed by a given technology, which often differ from the classic sinusoidal waveform. The rise in the use of such electronic components in electrical equipment can lead to various types of electrical disturbances and this can affect energy quality (Ryckaert et al., 2012).

Considering these interferences, energy quality became one of the most important objectives of the energy industry and end users in the 1980's. Energy quality involves various types of disturbances in electric power systems due to increased use of electronic components in electrical equipment. The definitions of energy quality vary with the criteria used, which range from system reliability to the power supply capacity needed for given equipment to function correctly. Generally, energy quality is understood to be a consumer-oriented issue and it also has an economic impact. This is because any disturbance that manifests in the current, voltage, or frequency of the system can cause malfunctions or failures in the end user's equipment (Aman et al., 2013).

The quality of electrical energy resulting from the use of lamps has become as important as the quality of the lighting,

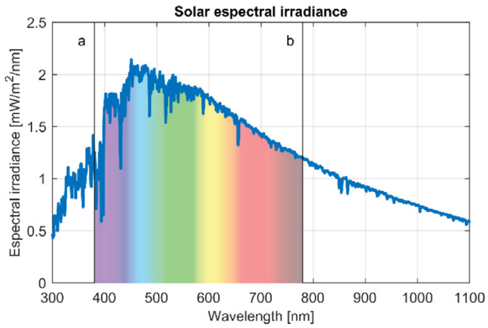


**Fig. 2.** Sunlight spectral energy emission curve with a color temperature of 6500 K; sun at midday (Tawfik et al., 2018).

which depends fundamentally on the chosen technology. Residential lighting systems consisting of more efficient bulbs, such as CFL and LED have a relevant contribution to the lowering of the power factor and may introduce grid harmonic distortion and light flicker effects. Among other consequences, motor and lighting system malfunctions can be caused by intense harmonic distortion in residences, which are connected to the same energy distribution network (Nassif and Xu, 2009).

## 3. Lamps and color reproduction

The colors of objects illuminated by artificial light depend on a number of factors. These factors include the spectral distribution, which is a characteristic of the light source and reflected by the object in question. The human eye is sensitive to wavelengths from 380 nm to 780 nm (nm = nanometers = $10^{-9}$ m). Sunlight is composed of several wavelengths, each correspond to a color. When sunlight hits a surface that does not absorb a certain wavelength, that wavelength is reflected by the object and observed as color (Dai et al., 2018).

The chromatic representation of a luminous source is expressed by its spectral curve that relates the wavelengths emitted by the source to the potency of each band. The reference spectral curve is that of the sun, which is shown in Fig. 2.

The sun, which is considered to be a "perfect" light source, emits light throughout the visible spectrum, representing all of the possible colors from 380 nm (ultraviolet) through 780 nm (infrared), which are highlighted in Fig. 2 between the lines "a" and "b". Artificial luminous sources (lamps) can be qualified in terms of color reproduction according to how well they reproduce the spectrum of the sun. This qualification is called Color Reproduction Index (CRI) and is expressed in percentage. Table 1 shows the CRI classification of lamps for each type of use.

## 4. Lamps and correlated color temperatures

Artificial lighting sources are characterized according to their spectral curves along with their color temperature, expressed in kelvin (K). The color temperature of a luminous source is the color of the energy emitted, represented by the heating of a black body. When the body in question is heated between 2000 K and 3000 K, a red hue known as "hot" is emitted. When heating the same body between 3000 K and 4000 K, the emission becomes yellowish. However, between 4000 K and 5500 K, the emission is characterized as white or neutral, while above 5500 K, the emission is considered bluish (Judd, 1936).

In 1960, the International Commission on Illumination (CIE) recommended the representation of color temperature based on the use of chromaticity coordinates. The Plank curve expresses

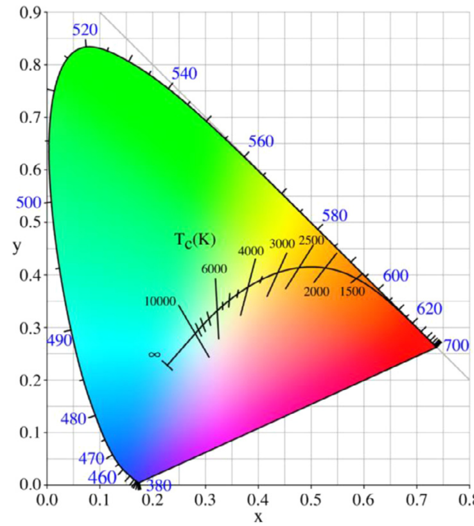


**Fig. 3.** Chromaticity diagram (Schanda and International Commission on Illumination, 2007).

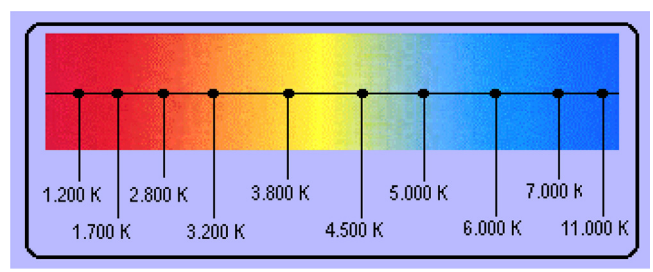


**Fig. 4.** Correlated color temperature in Kelvin (Schanda and International Commission on Illumination, 2007).

the color temperature of a black body and the secant lines correspond to the correlated color temperature, which is also known as the shade of the light source and its varies from 1515 K to ∞ (Golasi et al., 2019), as shown in Fig. 3.

Raising the corresponding color temperature renders the tonality of the source more clearly. Decreasing the correlated color temperature renders a redder source color. Thus, the source is considered to be "hot" or "cold" due to the shade of the light radiated into the environment, not because of the physical temperature resulting from the use of the equipment.

In order to properly illuminate an environment, it is important to know the function of the environment. This is because sources with softer tones make the environment more comfortable and relaxing. In contrast, when the source is clear, the environment is considered more "stimulating" (Golasi et al., 2019). Fig. 4 shows the tonality of the correlated color temperature.

Sunlight presents color temperature variation during the day. In the early stages of sunrise and when the sun sets, the color temperature is low due to some factors. These factors include the variation in the angle of incidence of the sun's rays in the Earth's atmosphere, the scattering of light by atmospheric particles and the composition of the molecules in these particles. The color temperature of the sun during these times reaches approximately 1800 K. When the sun is high at midday, the color temperature can reach 9000 K (Judd et al., 1964).

**Table 1**
Color reproduction index classification (DiLaura and Houser, 2011).

| Classification | Level | RA | Applications |
|---|---|---|---|
| Excellent | 1 | 90 to 100 | Color tests, floriculture, offices, residences, shops |
| Very good | 1 | 80 to 89 | Color tests, floriculture, offices, residences, shops |
| Good | 2 | 70 to 79 | Circulation areas, stairs, workshops, sports gyms |
| Reasonable | 2 | 60 to 69 | Circulation areas, stairs, workshops, sports gyms |
| Regular | 3 | 40 to 59 | Deposits, gas stations, industrial assembly yard |
| Insufficient | 4 | 20 to 39 | Traffic lanes, construction sites, parking lots |

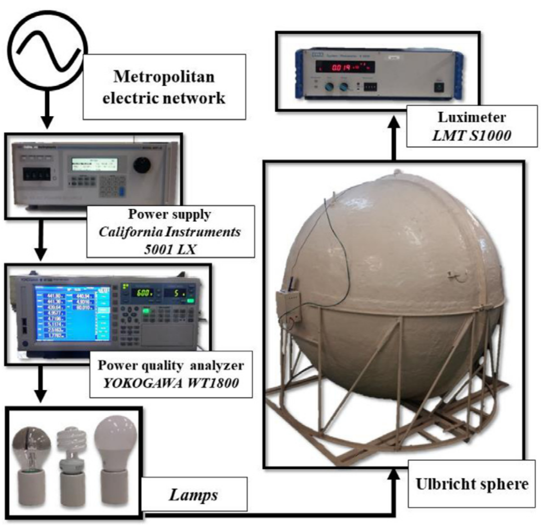


**Fig. 5.** Measurement scheme for electrical quantities and luminous flux.

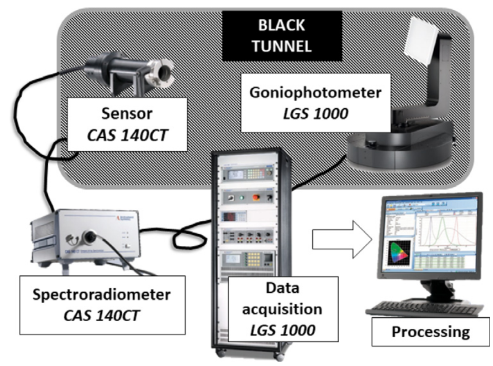


**Fig. 6.** Measurement scheme in the spectroradiometer.

## 5. Materials and methods

A Yokogawa WT1800 analyzer was used for electrical energy quality measurements and energy quality verification. The analyzer used a 5 kVA California Instruments 5001 LX source to guarantee the voltage level, frequency, and nominal waveform during performance testing. An Ulbricht integrating sphere was used with an auxiliary lamp to correct the deformation of the flow due to the presence of the test body and bulkheads inside the sphere. The illuminance was recorded with a S100 Luximeter and the sensor was placed inside the ball. The experimental assembly can be seen in Fig. 5.

After the luminous flux measurement, the corresponding color temperature and color reproduction index were measured for each lamp using a CAS 140CT spectroradiometer. It is necessary to perform this measurement inside a tunnel with all black faces, so that absorption of the illumination by the wall is maximized and reflectance is minimized. No other lighting source is used within the tunnel as shown in Fig. 6.

In this work three lamps were used for internal lighting. A declared halogen incandescent technology bulb of 630 lumens, a lamp with CFL (Compact Fluorescent Lamp) technology of declared 750 lumens and a LED light bulb of declared 830 lumens technology. All bulbs were manufactured in 2016.

The tests were carried out respecting the technical and environmental conditions of the current regulations. The nominal test voltage of the lamps was in accordance with nominal values with a variation of less than 0.2%, a frequency of 60 Hz with a maximum variation of 0.2%, a total harmonic distortion of less than 1%, temperature controlled at 25 °C, of 2 °C, relative humidity less than or equal to 65%.

## 6. Lumen method

Traditionally, lighting is evaluated by means of the lumen method as proposed by the CIE (French acronym for International Commission on Illumination). Regardless of the technological advancement that enabled environmental modeling of the luminous effects of lamps and luminaires, the simplicity of the lumen method ensures its continued use by many interior lighting designers (International Commission on Illumination, 1982).

The lumen method estimates the total light flux required for a given environment based on the type of activity performed at the site, the age of the occupying persons and the reflectance of the environmental surfaces. Other parameters include the type of luminaire used and the total flux emitted by the lamp.

The lumen method can be used for rectangular environments with well-defined work surfaces and planes under an assumption of uniform luminous flux distribution. This ideal situation does not always exist, but the method, when performed correctly, slightly overestimates the intensity. Hence, this ensures that the illuminance in the work plane is at least as specified at the design stage at all points until the lamp is aged (i.e., when the luminous flux reaches 75% of its nominal value) (International Commission on Illumination, 1996).

The first step in the lumen method calculation is the determination of the dimensions of the environment. With the dimensions, the K factor (otherwise called place index) can be calculated as shown by Eq. (1):

$$K = \frac{C \times L}{(C + L) \times H_M} \tag{1}$$

where: C is the place length, L is the width of the place, $H_M$ is the distance between the lamp and the working plane. Fig. 7 illustrates the variables used to calculate the place index for each given environment.

The Fig. 8 shows the representative apartment used for the lighting project. Said apartment measures 97.80 m$^2$ and is typically used by a family of four.

Using Eq. (1), it is possible to calculate the place index for each enclosure according to Table 2, assuming that the right foot of the

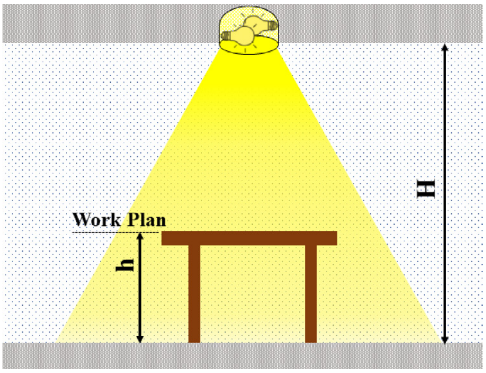


**Fig. 7.** Detail of the height of the working plane (h) and height of the right foot (H).

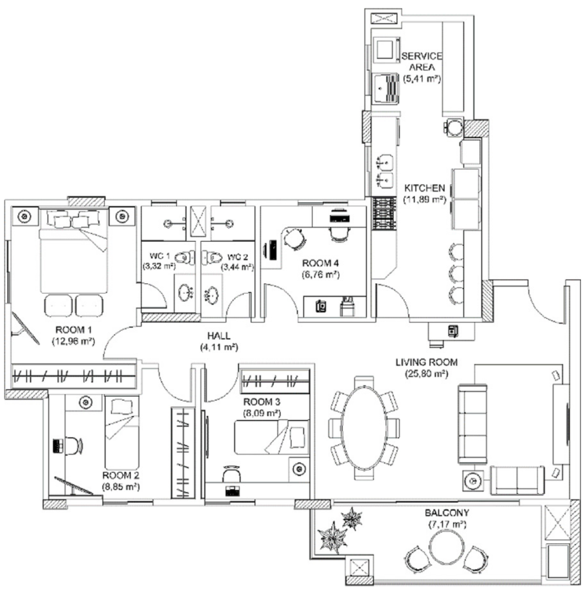


**Fig. 8.** The ground floor of a representative apartment.

**Table 2**
Dimensions of the apartment.

| Environment | Length (m) | Width (m) | Area ($m^2$) | Place index |
|---|---|---|---|---|
| Living room | 6.10 | 4.23 | 25.80 | 1.00 |
| Hall | 4.15 | 0.99 | 4.11 | 0.32 |
| Room 1 | 4.38 | 2.96 | 12.96 | 0.71 |
| Room 2 | 3.53 | 2.51 | 8.85 | 0.59 |
| Room 3 | 3.10 | 2.61 | 8.09 | 0.57 |
| Room 4 | 2.54 | 2.66 | 6.76 | 0.52 |
| WC 1 | 2.55 | 1.30 | 3.32 | 0.34 |
| WC 2 | 2.66 | 1.30 | 3.44 | 0.35 |
| Kitchen | 4.51 | 2.64 | 11.89 | 0.67 |
| Service area | 2.52 | 2.15 | 5.41 | 0.46 |
| Balcony | 4.02 | 1.78 | 7.17 | 0.49 |

building is 3.2 m and the working plane is 0.7 m from the finished floor.

In the next stage of a lighting project, the designer must take into account a number of factors in order to choose an appropriate lighting technology (i.e., incandescent halogen, CFL or LED). These factors include the type of building, energy efficiency and the quality of the desired illumination combined with the type of task to be performed in each environment. The luminaire used must be chosen by analyzing the same variables cited for lamps; not excluding the compatibility between the two devices

**Fig. 9.** Luminaire used.

**Table 3**
Environmental reflectivity (International Commission on Illumination, 1982).

| Index | Reflectivity | Meaning |
|---|---|---|
| 1 | 10% | Dark surface |
| 3 | 30% | Average surface area |
| 5 | 50% | Clear surface |
| 7 | 60% | White surface |

**Table 4**
Utilization factor of the luminaire used.

| Location index (k) | Reflectivity | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **751** | 731 | 711 | 551 | 531 | 511 | 331 | 311 | 000 |
| 0.6 | **0.61** | 0.27 | 0.24 | 0.31 | 0.27 | 0.24 | 0.27 | 0.24 | 0.22 |
| 0.8 | **0.65** | 0.34 | 0.30 | 0.38 | 0.33 | 0.30 | 0.33 | 0.30 | 0.28 |
| **1** | ***0.68*** | **0.39** | **0.36** | **0.43** | **0.30** | **0.35** | **0.38** | **0.35** | **0.34** |
| 1.25 | **0.71** | 0.44 | 0.41 | 0.47 | 0.44 | 0.40 | 0.43 | 0.40 | 0.39 |
| 1.5 | **0.75** | 0.48 | 0.45 | 0.51 | 0.47 | 0.44 | 0.47 | 0.44 | 0.42 |
| 2 | **0.80** | 0.54 | 0.52 | 0.56 | 0.53 | 0.50 | 0.52 | 0.50 | 0.48 |
| 2.5 | **0.82** | 0.57 | 0.55 | 0.59 | 0.56 | 0.54 | 0.55 | 0.54 | 0.52 |
| 3 | **0.85** | 0.60 | 0.58 | 0.61 | 0.59 | 0.57 | 0.58 | 0.56 | 0.55 |
| 4 | **0.88** | 0.63 | 0.61 | 0.63 | 0.62 | 0.60 | 0.61 | 0.59 | 0.58 |
| 5 | **0.89** | 0.65 | 0.63 | 0.65 | 0.63 | 0.62 | 0.62 | 0.61 | 0.59 |

is requisite. The cost of the luminaire/lamp assembly must be accounted over its life cycle, which is one of the stated objectives of this work.

Maintenance flexibility is a key aspect in residential use. However, so many designers to date have chosen to maintain the use of the E27 sockets. The replacement of these sockets is easier because they incorporate drivers and adapters into the lamps. The calculations shown in Fig. 9 are performed for this luminaire. The photometric characteristics of the luminous flux distribution are fundamental in determining the suitable luminaire.

The next step in lighting design is the determination of the utilization factor. This is calculated based on the data provided by the lighting apparatus manufacturer and it accounts for the geometry and reflectivity of the environment. Environment reflectance should always be determined in the following sequence: ceiling, walls, and floors, according to Table 3.

Considering the previously determined location reflectivity, calculated place index and data provided by the lighting apparatus manufacturer, it is possible to determinate the utilization factor for each desired environment (Table 4). This depends on the type of material used in the construction of the said luminaire.

The next step is to determine the maintenance coefficient of the lighting system (i.e the depreciation factor). The reduction of the luminous flux occurs due to the aging of the lamp (e.g., the loss of gas in a discharge lamp, the accumulation of tungsten in a filament lamp, and the aging of the LED). Dirt on the luminaire and lamp also causes depreciation, so it is necessary to determine the light loss through Table 5.

**Table 5**
Depreciation factors (International Commission on Illumination, 1982).

| Type of Environment | Maintenance period (hours) | | |
|---|---|---|---|
| | **2.500** | 5.000 | 7.500 |
| **Clean** | ***0.95*** | **0.91** | **0.88** |
| Normal | **0.91** | 0.85 | 0.80 |
| Dirty | **0.80** | 0.66 | 0.57 |

**Table 6**
Light flow required per enclosure.

| Environment | Required illumination (lux) | Luminous flux (lm) |
|---|---|---|
| Living room | 200 | 7988.54 |
| Hall | 100 | 508.790 |
| Room 1 | 200 | 4199.13 |
| Room 2 | 200 | 3053.58 |
| Room 3 | 200 | 2792.41 |
| Room 4 | 300 | 3497.70 |
| WC 1 | 200 | 1144.09 |
| WC 2 | 200 | 1188.85 |
| Kitchen | 300 | 6156.21 |
| Service area | 300 | 2799.27 |
| Balcony | 200 | 2474.97 |

**Table 7**
Measured luminous flux.

| Technology | Measured luminous flux (lm) |
|---|---|
| Incandescent halogen | 630.05 |
| CFL | 759.27 |
| LED | 727.25 |

With the data mentioned previously, it is possible to calculate the required luminous flux in each environment according to Eq. (2). The illuminance in the working plane must satisfy ISO 8995-1, which establishes references for visual comfort (The International Commission on Illumination (CIE), 2002).

$$\Phi = \frac{E \times S}{\mu \times d} \tag{2}$$

where: $\Phi$ is the total luminous flux (lm), E is the illuminance (lux), S is the area (m$^2$), $\mu$ is the coefficient of use and d is the depreciation factor or coefficient.

Thus, the luminous flux values required for each environment can be obtained according to Table 6 in order to maintain the desired luminous intensity in the working plane.

By calculating the number of lamps required in each environment to meet the total flow, the values of luminous flux measured indirectly through the Ulbricht Sphere shall be used according to Table 7.

It is clear that the incandescent lamp produces the lowest luminous flux, while the fluxes of the LED (Light Emitting Diode) and CFL (Compact Fluorescent Lamp) lamps differ by only 4%. To calculate the number of lamps needed for the environment, we use Eq. (3).

$$n = \frac{\Phi}{\phi} \tag{3}$$

where: $n$ is the number of lamps, $\Phi$ is the luminous flux needed to light the environment (lm), and $\phi$ is the luminous flux produced by each lamp (lm). The data in Table 8 can be obtained using this method.

As expected, a larger number of incandescent lamps is needed due to the lower luminous flux recorded for the incandescent lamps. Equal numbers of CFL and LED lamps would be necessary to illuminate a typical house, because these lamps are similar in luminous flux.

**Table 8**
Number of lamps required.

| Environment | Halogen incandescent | CFL lamp | LED |
|---|---|---|---|
| Living room | 13 | 11 | 11 |
| Hall | 1 | 1 | 1 |
| Room 1 | 7 | 6 | 6 |
| Room 2 | 5 | 4 | 4 |
| Room 3 | 4 | 4 | 4 |
| Room 4 | 6 | 5 | 5 |
| WC 1 | 2 | 2 | 2 |
| WC 2 | 2 | 2 | 2 |
| Kitchen | 10 | 8 | 8 |
| Service area | 4 | 4 | 4 |
| Balcony | 4 | 3 | 3 |

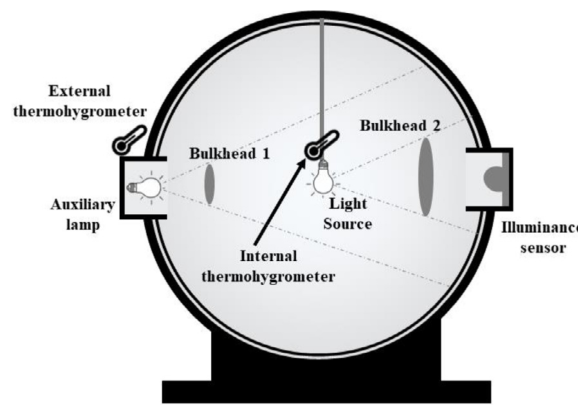


**Fig. 10.** Schematic of an integrating sphere of Ulbricht.

## 7. Measurement of light flow

One of the most common methods for the measurement of luminous flux is through the Integrating Sphere of Ulbricht. This equipment, as the name implies, is a hollow sphere with an internal reflectance of around 90%. It is, therefore, considered to have a Lambertian internal surface. On one of the walls of the sphere, a photocell measures the illuminance (lux). A bulkhead is placed in front of the luminous intensity orifice in order to block the incidence of direct radiation from the light source onto the Photocell. The placement of bulkhead is necessary because only indirect radiation must be measured in the Ulbricht sphere experiments (Rastello et al., 1996).

The auxiliary lamp is located in an orifice opposite the photoelectric cell with a bulkhead in front of it as shown in Fig. 10. The measurement in the sensor is carried out with the sphere completely closed, the auxiliary lamp off and the power supply of the light source in perfect nominal condition. Temperature and humidity are verified throughout the experiment using two thermo-hygrometers placed inside and outside of the sphere.

Considering the spherical geometry, all of the infinitesimal internal points are reflexive for the other points. However, the bulkheads, the lamp base and the lamp geometry itself may cause deviations in the final measurement. An auxiliary lamp is then used to correct this distortion. The auxiliary lamp is energized with the lamp to be tested inside the sphere. The illuminance arriving at the photo sensor must be recorded as the measurement is changed by the geometry of the lamp. For this reason, this procedure should be performed for each source tested.

The luminous flux of the standard lamp is known and generally referenced in inter-laboratory measurements (Rastello et al., 1996), in order to guarantee the accuracy of the measurements. Thus, the illuminance is measured according to Eq. (4).

$$F_{Source} = F_{Standard} \times \left(\frac{E_{Source}}{E_{Standard}}\right) \times \left(\frac{E_{aux(Standard)}}{E_{aux(Source)}}\right) \tag{4}$$

**Table 9**
Measurement results.

| | Reference lamp | Incandescent | CFL | LED |
|---|---|---|---|---|
| Illuminance (lux) | 303.10 | 175.20 | 210.60 | 210.40 |
| Auxiliary lamp (lux) | 27.72 | 27.72 | 27.65 | 28.84 |
| Declared luminous flux (lm) | 1090.00 | 630 | 750 | 830 |
| Measured luminous flux (lm) | 1090.00 | 630.05 | 759.27 | 727.25 |

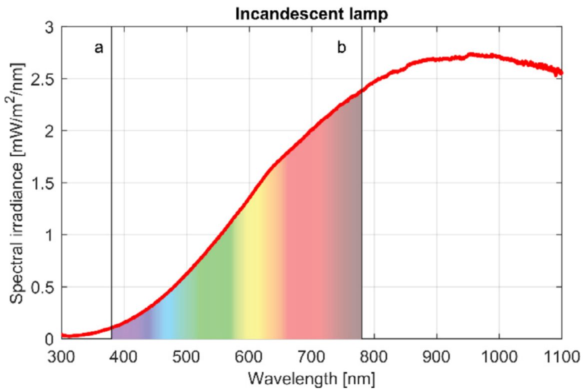


**Fig. 11.** Halogen incandescent lamp spectrum.

where:

- $F_{Source}$ is the luminous flux of the light source under test (lm).
- $F_{Standard}$ is the luminous flux of the reference lamp (lm).
- $E_{Source}$ is the source illumination under test (lux).
- $E_{Standard}$ is the reference source illumination (lux).
- $E_{aux(Standard)}$ is the illuminance of the auxiliary lamp with the reference lamp inside the sphere (lux).
- $E_{aux(Source)}$ is the illuminance of the auxiliary lamp with the source under test inside the sphere (lux).

## 8. Experimental results

### 8.1. Photometric

For each light source, the luminous flux was calculated according to Eq. (4) using measurement data. The results are presented in Table 9.

From table, the luminous flux of the halogen incandescent lamp is consistent with its datasheet. This lamp was tested according to (ABNT NBR 14671, 2001). The CFL lamp was tested according to (ABNT NBR 14539, 2000) and its luminous flux was 1.22% higher than expected. The LED lamp luminous flux was also tested according to (IESNA, 2008) and it was 12.38% lower than the value reported by the manufacturer.

#### 8.1.1. The halogen incandescent lamp

Halogen incandescent lamps have an emission spectrum with all visible light components and some beyond the bounds of visible light in the ultraviolet (380 nm) and infrared (780 nm) spectrums. Among lighting source types, typically, the halogen incandescent lamps most closely resemble the natural daylight.

Fig. 11. shows the emission spectrum of the halogen incandescent lamp measured with the CAS 140CT Array Spectrometer. Fig. 12 shows the chromaticity coordinates of its color temperature. Table 10 shows a comparison between the datasheet and measured values.

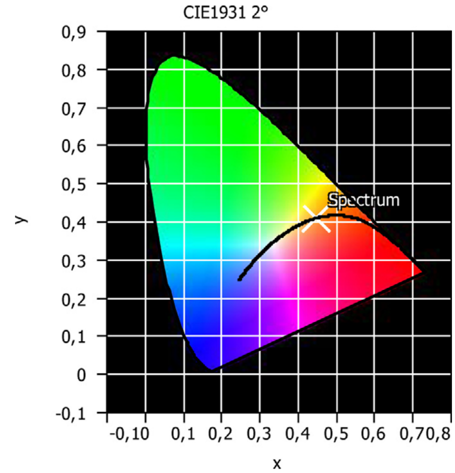


**Fig. 12.** Chromaticity coordinates for the halogen incandescent lamp.

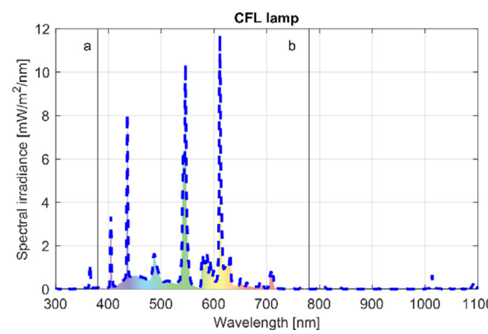


**Fig. 13.** CFL lamp spectrum.

#### 8.1.2. The CFL lamp

CFL lamps produce emission spectrum corresponding to the gas used. In general, they are composed of mercury vapor with a CFL powder on the walls of tube that is usually comprised of argon. The quality of these lamps depends on the gas pressure and type of gas used. Fluorescent are known to have good spectral emission, with high power peaks in certain colors including yellow (611 nm), green (546 nm) and purple (435 nm), as shown in the measurements data in Fig. 13.

The correlated color temperature can be modulated between 3000 K and more than 6500 K by doping the semiconductor material. Table 10 presents a comparison between the datasheet and measured values (see Fig. 14).

#### 8.1.3. The LED lamp

This type of light bulb incorporates solid-state electronic technology, is spreading in global markets, and has a promising outlook in coming years. The principle of LED operation is the reverse of that of the photovoltaic cell. The electric current flows through the semiconductor element which is encapsulated in crystal resin, inducing photon emission at the junction of the light emitting diode.

LED lamps are known to have good spectral emissions with high power peaks at certain colors including green (550 nm) and blue (450 nm), as shown in Fig. 15. The correlated color temperature is generally above 5000 K; the chromaticity coordinates can be seen in Fig. 16. Table 10 shows a comparison between the datasheet and measured values.

Fig. 17 presents spectral irradiation graphs for three lamps. It is clear that the analyzed CFL lamp has high power spectral

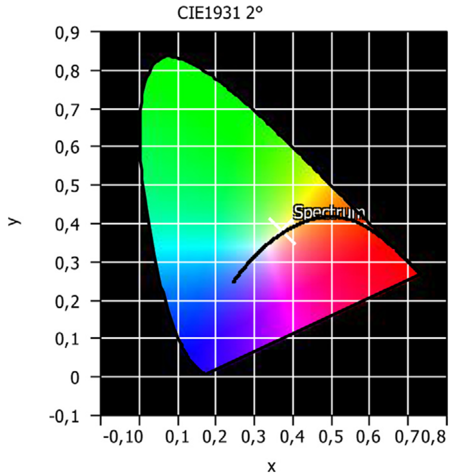


**Fig. 14.** Chromaticity coordinates for the CFL lamp.

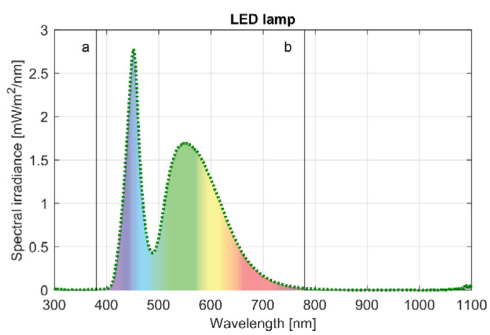


**Fig. 15.** LED lamp spectrum.

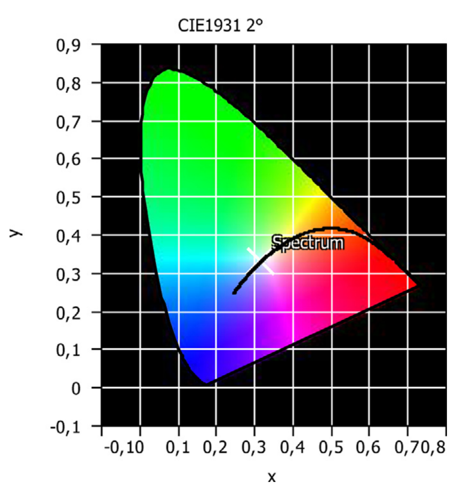


**Fig. 16.** Chromaticity coordinates for the LED lamp.

emission peaks at certain wavelengths. The LED lamp has significantly lower spectral emission power than the CFL lamp; it has two emission peaks, and almost null emission above 700 nm. The incandescent lamp emits throughout the visible spectrum and emits greater power closer to the infrared region and lower power at wavelengths near the ultraviolet region.

The halogen incandescent lamp spectrum features an emission maximum after the visible spectrum in the infrared region. Thus, most of its energy is converted to heat.

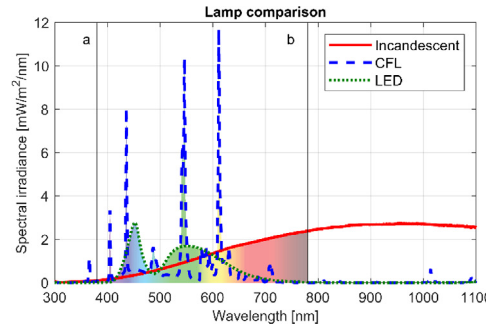


**Fig. 17.** Comparison between the lamp spectra.

It is emphasize in Table 10 that manufacturers do not provide all of the photometric characteristics of the lamps. When carrying out spectrometer measurements using values reported by manufacturers, it was observed that the reported data correspond closely to the measured data. The measurements were made with calibrated equipment.

The LED lamp is the only device that shows similar figures measured CRI values and the values reported by the manufacturer. However, according to Table 10, this index is 7.875% lower than reported value. The CFL lamp has a good CRI (above 80) and the halogen incandescent lamp shows excellent performance due to its glow.

As manufacturer information tends to overvalue technical lamp features, the next test would be to verify the life cycle information given by the manufacturers. In a previous study (Li et al., 2011), lumen degradation was observed in 4 or 5 months of utilization, which is much lower than the lifetime usually attributed to LED technologies.

The halogen incandescent lamp is the only device for which the correlated color temperature does not match that reported by manufacturer. Its measured value is low, which is typical of lamps with incandescence technology. Filament lamps are suitable for use in resting places.

Light bulbs with highly correlated color temperature, such as LED lamps, are recommended for use in places with intense activities. It is important to note that it is possible to control color temperature in LED lamps by semiconductor crystal doping (Chen et al., 2015).

### 8.2. Electrical

#### 8.2.1. Energy quality

One of main parameters in electric power quality is the distortion of voltage waves and electric current from purely idealized sinusoidal forms. This is expressed as the Total Harmonic Distortion (THD) of the voltage and current indexes. THD is the deviation of the measured distorted wave considering the harmonic components of the fundamental wave (IEEE, 2014).

Eq. (5) can be used to calculate the current THD.

$$THD_I = \sqrt{\sum_{h=2}^{\infty} \left(\frac{I_h}{I_1}\right)^2} \tag{5}$$

where:

- $THD_I$ is the total harmonic distortion of current.
- $h$ is the harmonic order.
- $I_h$ is the effective value of $h$ harmonic current.
- $I_1$ is the effective value of fundamental current.

The harmonic limits for lamp input current are shown in Table 11.

**Table 10**
Reported and measured photometric values.

| Technology | Correlated color temperature [K] | | CRI | | Chromaticity coordinates |
|---|---|---|---|---|---|
| | Reported | Measured | Reported | Measured | |
| Halogen incandescent | – | 2.842 | – | 99.7 | x: 0.44826<br>y: 0.40710 |
| CFL | 4000 | 4.225 | – | 82.4 | x: 0.31469<br>y: 0.33162 |
| LED | 6.500 | 6.383 | 80 | 73.7 | x: 0.37332<br>y: 0.38070 |

– Not reported by manufacturer.

**Table 11**
Harmonic limits for lamps (IEEE, 2014).

| Harmonic order h | Limit on fundamental [%] |
|---|---|
| 2 | 2 |
| 3 | $30 \cdot PF$ |
| 5 | 10 |
| 7 | 7 |
| 9 | 5 |
| $11 \leq h \leq 39$ | 3 |

**Table 12**
Nominal and experimental data for the halogen incandescent lamp.

| | Nominal | Experimental |
|---|---|---|
| Power [W] | 42 | 42.17 |
| Luminous flux [lm] | 630 | 630.05 |
| Lifetime [h] | 1000 | – |
| Voltage [V] | 127 | 127.69 |
| Color temperature [K] | N/A | 2842 |
| CRI [%] | N/A | 99.7 |
| Light efficiency [lm/W] | 15 | 14.94 |
| Power factor | N/A | 0.99 capacitive |
| THD [%] | N/A | 0.85 |

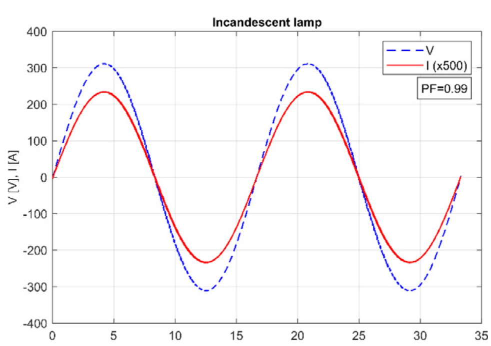


**Fig. 18.** Voltage and current waveforms for the halogen incandescent lamp.

### 8.2.2. The halogen incandescent lamp

Fig. 18 shows the voltage and current waveforms of the supply source for the halogen incandescent lamp. It is possible to observe the sinusoidal behavior of both waves, which indicates practically null harmonic content. It is seen that these waves are in phase, revealing a power factor that tends toward unity.

The harmonic content of the CFL input current can be seen in Fig. 19, where low values of harmonic components are verified in relation to the fundamental component, justifying the waveform shown in fig. and the THD value shown in Table 12. In addition, it was observed that the individual values of the measured harmonics are within the limits shown in Table 12 as recommended by IEC 61000-3-2 (IEC, 1998).

Table 12 shows nominal and experimental data for the halogen incandescent lamp. It is possible to verify that the power factor is almost the same and that the current THD is 0.85%.

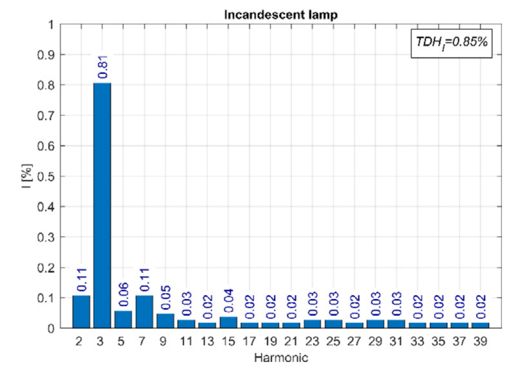


**Fig. 19.** Harmonic content of the halogen incandescent lamp.

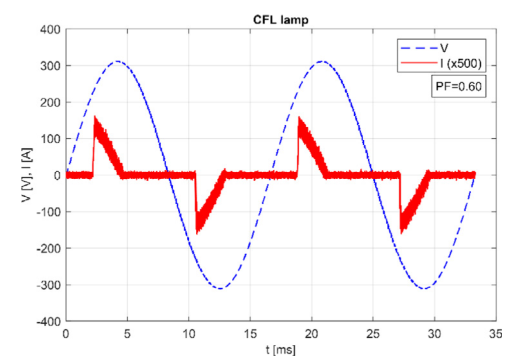


**Fig. 20.** Voltage and current waveforms for the CFL lamp.

### 8.2.3. The CLF lamp

The analysis was repeated for the CFL lamp, the voltage and current waveforms are shown in Fig. 20. We verify that the current displays non-sinusoidal behavior, indicating the presence of a significant harmonic content, for which analysis is presented in Fig. 21.

Fig. 21 shows that odd-order harmonics have representative values, with the third harmonic being the most important having more than 80% of the fundamental values. Nevertheless, it was confirmed that only the second order harmonic is within the limit established by IEC 61000-3-2 (IEC, 1998).

Nominal and experimental data for the CFL lamp are shown in Table 13; the measured power factor is 0.60 capacitive and the THD is 112.85%.

### 8.2.4. The LED lamp

Fig. 22 shows voltage and current waveforms for the LED lamp. It was verified herein that the current displays non-sinusoidal behavior, indicating the presence of significant harmonic content.

Similar to what was observed in the CFL lamp, the harmonic content of the LED lamp input current is as shown in Fig. 23. Only the second order harmonic is within the limit established by IEC 61000-3-2 (IEC, 1998).

**Table 13**
Nominal and experimental data for the CFL lamp.

| | Nominal | Experimental |
|---|---|---|
| Power [W] | 13 | 11.23 |
| Luminous flux [lm] | 750 | 759.27 |
| Lifetime [h] | 8000 | – |
| Voltage [V] | 220–240 | 219.7 |
| Color temperature [K] | 4000 | 4225 |
| CRI [%] | N/A | 82.4 |
| Light efficiency [lm/W] | 63 | 67.61 |
| Power factor | N/A | 0.60 capacitive |
| THD [%] | N/A | 112.85 |

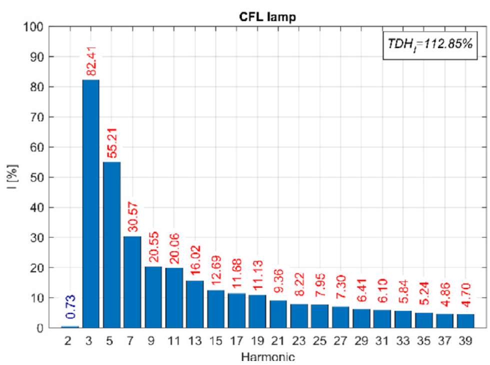


**Fig. 21.** Harmonic content for the halogen CFL lamp.

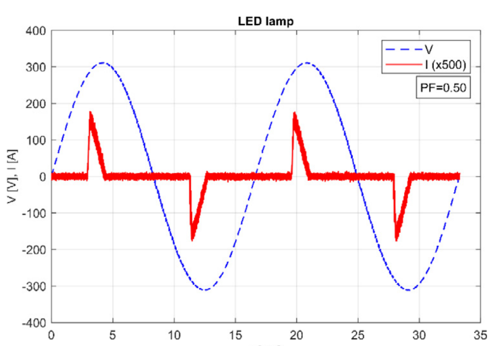


**Fig. 22.** Voltage and current waveforms for the LED lamp.

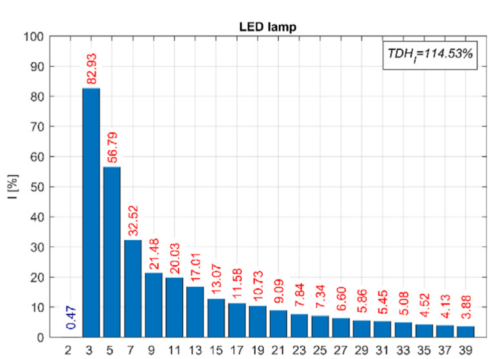


**Fig. 23.** Harmonic content for the LED lamp.

Nominal and experimental data for the LED lamp are as shown in Table 14; the measured power factor is 0.50 capacitive and the THD is 115.53%.

The halogen lamp presented a power factor close to the unit value (0.99). The CFL and LED technologies presented a capacitive power factor of 0.6 and 0.5 respectively. Being these, values significantly below the allowed minimum of 0.92 (capacitive or inductive).

In Brazil, Normative Resolution No. 414 establishes the general conditions for the supply of electricity and determines that the facilities have a power factor below 0.92 with fines. By doing so, users are forced to install devices (capacitors or reactors) responsible for bringing the power factor to the minimum allowed 24 h a day. It would thus be a good point if the lamps were already manufactured with the power factor correction components coupled in the internal converter circuits (Schlischting et al., 2016).

**Table 14**
Nominal and experimental data for the LED lamp.

| | Nominal | Experimental |
|---|---|---|
| Power [W] | 9 | 8.39 |
| Luminous flux [lm] | 830 | 727.25 |
| Lifetime [h] | 15,000 | – |
| Voltage [V] | 110–240 | 219.8 |
| Color temperature [K] | 6500 | 6383 |
| CRI [%] | 80 | 73.7 |
| Light efficiency [lm/W] | 92.2 | 86.68 |
| Power factor | N/A | 0.50 capacitive |
| THD [%] | N/A | 114.53 |

**Table 15**
Assumptions adopted in the economic analysis.

| | Halogen incandescent | CFL | LED |
|---|---|---|---|
| Power [W] | 42.17 | 11.23 | 8.39 |
| Lifetime [h] | 1000 | 8000 | 15,000 |
| Unit price [US$] | 1.48 | 2.78 | 5.16 |
| Daily use [h/day] | 5 | 5 | 5 |
| Tariff [R$/kWh] | 0.1555 | 0.1555 | 0.1555 |
| Annual discount rate | 12% | 12% | 12% |
| Analysis period [year] | 10 | 10 | 10 |

## 9. Economic analysis

The economic analysis performed is based on the annualized lifetime cost. The assumptions for these calculations shown in Table 15 were used with the measured experimental data.

It is assumed herein that the apartment is located in São Paulo (SP), Brazil, under the service area of the local electricity company. As this evaluation comprise residential consumption, the electricity tariff chosen is the conventional tariff modality, subgroup B1, residential class, and already includes taxes. The annualized lifetime cost can be obtained using Eqs. (6)–(10), and (11) (Mankiw, 2007).

$$LCC = AC + EC + RC - CR \tag{6}$$

$$CE = \frac{PEV}{CRF} \tag{7}$$

$$CR = \frac{LC}{CRF_{effective}} \tag{8}$$

$$CR = \frac{VR}{(1+i)^n} \tag{9}$$

$$ALCC = LCC \cdot CFR \tag{10}$$

$$CFR = \frac{(1+i)^n \cdot i}{(1+i)^n - i} \tag{11}$$

where:
LCC = Life Cycle Cost and AC = Acquisition Cost.
EC = Energy Cost and RC = Residual Cost.
CR = Cost of Replacement and PEV = Present Electricity Value.
CRF = Capital Recovery Factor and LC = Lamp Cost.
$CRF_{effective}$ = Effective Capital Recovery Factor.
$i$ = annual discount rate and $n$ = analysis period.

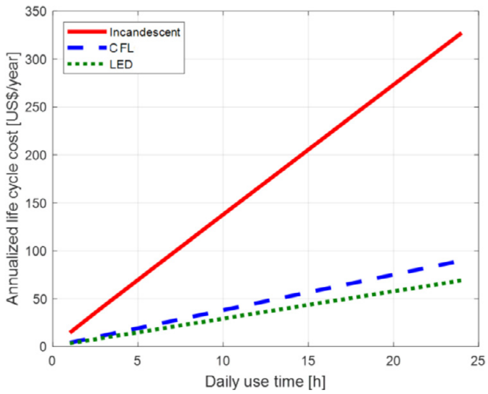


**Fig. 24.** Annualized lifetime cost for each lamp type.

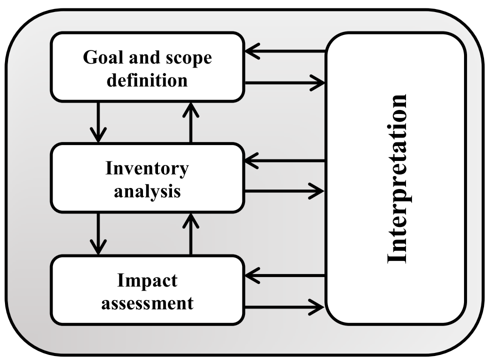


**Fig. 25.** LCA framework schematic based on ISO standards.
*Source:* Adapted from ISO 14040 (2006).

ALCC = Annualized Life Cycle Cost

The results show that for 5 h of daily use, the annualized life cycle costs are US$ 69.71, US$ 19.15, and US$ 14.73 for halogen incandescent, CFL and LED lamps respectively.

It is important to note that each room has a different number of lamps and operating time. Therefore, the study accounts for the period of usage that range from 0 to 24 h for each unit of the three lamp types, as shown in Fig. 24.

## 10. Environmental analysis

### *10.1. Life cycle assessment (LCA)*

Life cycle assessments (LCAs) are generally used for the evaluation of the environmental impact of goods (Aman et al., 2013). In an LCA, the flows of matter and energy, which are each related to certain environmental impacts are totaled over the life cycle of the object. Several studies address this type of evaluation for lamps (Osram, 2009; U.S. Department of Energy, 2012; Principi and Fioretti, 2014).

The most commonly used methodological framework for an LCA is described by ISO 14040 (Life cycle assessment – Principles and framework) and ISO 14044 (Life cycle assessment – Requirements and guidelines), which are both included in the ISO standard family concerning environmental management. According to ISO 14040, the LCA involves four phases which include goal, scope definition, inventory analysis, impact assessment and interpretation. The interactions of these four phases are shown in Fig. 25 (ISO 14040, 2006; ISO 14044, 2006).

During goal and scope definition, the objective of the assessment is defined and the aspects that will or will not be included in the analysis are determined. One must define the system and its function in this context (that is, the context of the purpose of the product). Another important variable is the system functional unit, which is defined as a unit of the system function used as reference according to which all the inputs and outputs are normalized.

The system boundaries are defined from two perspectives. One of them include the physical boundaries of the production system, which encompasses the steps of the life cycle. The other one is related to the regression level of the energy flows to be considered (the extension of the energy flows to be accounted within each boundary). The regression levels according to the author (CAPAZ, 2009), can include:

- Level 1, which considers only the direct energy inputs applied during the process, generally in terms of electricity and heat.
- Level 2, this considers the energy input from indirect inputs.
- Level 3, which includes the energy used in the production of processing equipment.
- Level 4, this includes the energy used to obtain raw materials for the production of equipment, supplies, etc.

In the inventory analysis phase, all flows of matter and energy related to the defined functional unit are identified and quantified (Elijošiute et al., 2012). In this phase, the inputs and outputs of matter and energy are recorded in the various stages of the product life cycle within the boundary defined in the previous phase.

In the third phase, the impact assessment aims at understanding the environmental relevance of the flows identified in the previous phase (Archer et al., 2018). For this, as stated in a previous work (Mendes et al., 2015), the impacts categories that are of relevance for the LCA studied were defined. These impacts include human health impacts, environmental impacts and resource depletion. Then, for each impact category, the units of the flows are multiplied by equivalence factors that refer to a certain category; for instance, for global warming, the flows are converted to kg of $CO_2$ equivalent.

### *10.2. Goal and scope definition*

The LCA conducted in this work aims to compare the environmental impacts of three lamp technologies: incandescent halogen, CFL, and LED. The LCA covers life cycle stages from obtaining the raw materials used for the manufacture of the lamps to final disposal.

The second regression level was taken into account. This involved the consideration of the energy embedded in the materials needed to manufacture the lamps, such as aluminum, glass, and metallic conductors.

The total luminous flux needed to illuminate the hypothetical apartment is equal to 34,804 lm, which results in a functional unit of 537,053,100 lmh, considering 15,000 h of an LED lamp. Considering the different lifetime and luminous flux of each lighting technology, it would be necessary to use 852 incandescent lamps, 88 CFLs, or 49 LED lamps to satisfy this functional unit.

Two transport trajectories were considered, one from the port of Shanghai to the port of Santos and another from Santos to the consumer center in São Paulo. It was assumed herein that all non-functioning lamps are sent to a sanitary landfill. The cost of transportation to the Sao Paulo city landfill was not considered. Fig. 26 presents the phases considered in the LCA conducted in this study.

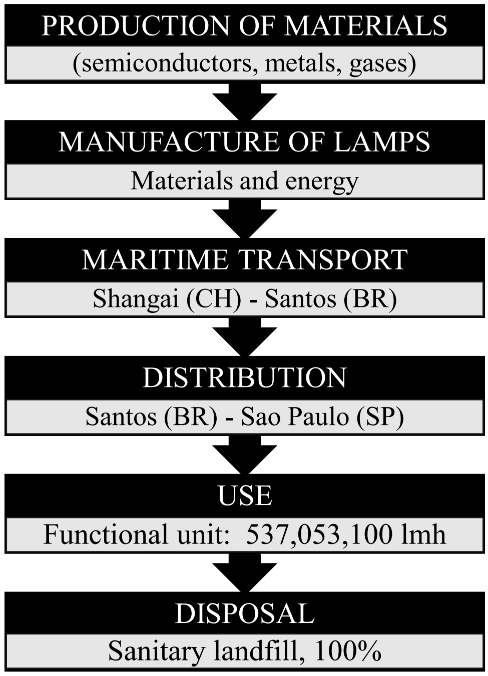


**Fig. 26.** Phases investigated in the lamp LCA. *Source:* Adapted from Osram (2009), Welz et al. (2011).

## 10.3. Inventory analysis

The inventory began with the evaluation of the material composition of each type of technology according to Figs. 27–29.

The energy used during lamp assembly follows a range of values (Sangwan et al., 2014). 1.33 MJ was considered for halogen incandescent lamps, 45.52 MJ for CFL and 1575.15 MJ for LED lamps. Beyond power, CFL assembly requires 10.7 kg of natural gas in factory metal working operations (Osram, 2009). All the assembly operations were carried out in China; therefore, the Chinese energy matrix took the responsibility.

For the transportation from Shanghai to Santos, a low-speed transoceanic freight ship, traveling the shortest route between the two ports, which covers a total distance of 20,476 km was engaged. A total distance of 84 km is driven between Santos and the consumer's center in São Paulo. It is assumed that a diesel freight truck is used (Mendes et al., 2015).

The energy consumption from the Brazilian grid was considered at low voltage. The use time is equivalent to the lifetime of the three technologies analyzed. This include 1000 h for incandescent halogen lamps, 8000 h for CFL and 15,000 h for LED lamps. The hourly energies consumed are consistent with the values already obtained, which include 42.17 Wh for the halogen incandescent lamp, 11.23 Wh for the CFL and 8.39 Wh for the LED lamp.

Some raw materials with high value such as nickel, copper and gold were noted. Furthermore, toxic materials such as mercury and lead can also be used. Responsibility for the proper disposal of such waste is delegated to manufacturers, importers, distributors and traders through an instrument called reverse logistics. Brazil has a legal instrument in place since 2010 that establishes reverse logistics with the objective of enabling the collection and restitution of solid waste to the business sector for reuse. These collections are either used in other production cycles or appropriately disposed (Fernandes Mourão et al., 2012).

This law lists six products for which manufacturers and distributors must implement reverse logistics systems, including

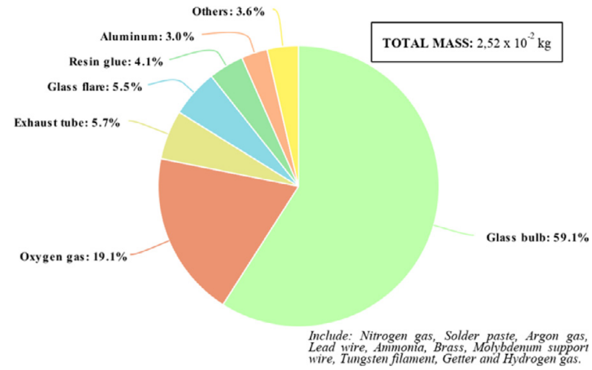


**Fig. 27.** Halogen incandescent lamp assembly: material input. Based on U.S. Department of Energy (2012) mixture of materials.

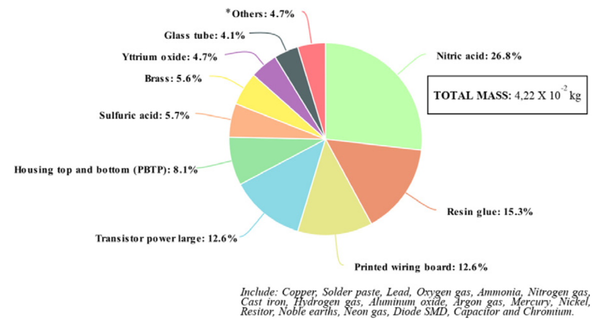


**Fig. 28.** CFL lamp assembly: material input. Based on U.S. Department of Energy (2012) mixture of materials.

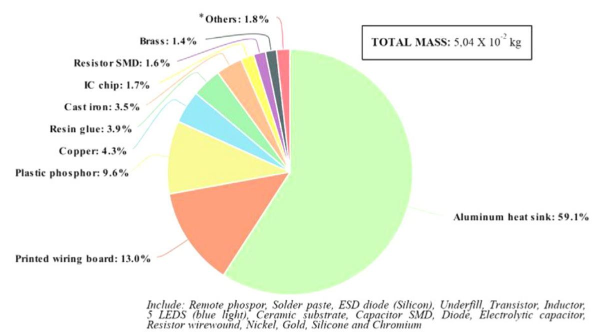


**Fig. 29.** LED lamp assembly: material input. Based on U.S. Department of Energy (2012) mixture of materials.

fluorescent, sodium, mercury vapor, and mixed lights. However, despite major consumption of these types of lamps and the existence of appropriate disposal technologies, very little progress is made so far, in establishing and maintaining a reverse logistics system at the national level (Fernandes Mourão et al., 2012).

## 10.4. Impacts assessment

The impacts assessment was performed using the Simapro 7.3 program and the EDP (Ecosystem Potential Damage) method with the following six categories of impact (Osram, 2009; Renouf et al., 2015):

• Global warming: an index that measures the contribution to global warming due to the emission of substances into the atmosphere such as the so-called greenhouse gases like methane ($CH_4$) and carbon dioxide ($CO_2$). This category of impact is expressed in kg of $CO_2$ equivalent.

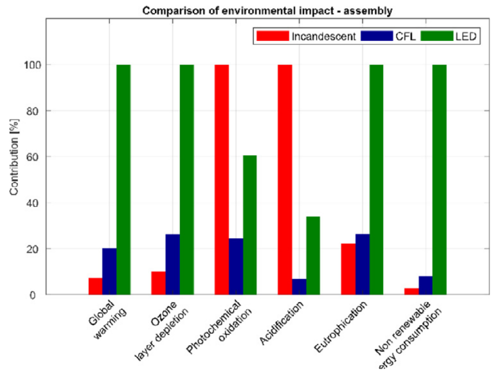


**Fig. 30.** Environmental impact in the manufacturing phase.

• Ozone layer depletion: an index related to the production and emission of gases that have the potential to destroy the stratospheric ozone layer. The unit is kg of CFC-11 equivalent. CFC-11 indicates any chlorofluorocarbon-family gas.

• Photochemical Oxidation: an index concerning the formation of ozone at the ground level, which is toxic to humans in high concentrations. The reaction of volatile organic compounds (VOCs) and oxides of nitrogen ($NO_x$) in the presence of heat and sunlight forms ozone. This category is involved in the formation of summer smog and has units of kg of $C_2H_4$ (ethane) equivalent.

• Acidification: an index concerning the acidification of soil and water caused by the emission of acidifying pollutants, such as sulfur dioxide ($SO_2$), oxides of nitrogen ($NO_x$) and ammonia ($NH_3$). Once in the atmosphere, these gases react with water vapor to form acids that are deposited via rain, snow, or dry deposition. Acid rain is known as a common effect of acidification, which has units of kg of $SO_2$ equivalent.

• Eutrophication: an index associated with the reaction of an ecosystem to the entry of excessive nutrient loads. For example, in an aquatic ecosystem, the influx of effluents rich in phosphorus and nitrogen encourages rapid algal growth, which causes degraded water quality and mortality in other species. Eutrophication is measured in kg of phosphate ($PO_4^{3-}$) equivalent.

• Non-renewable energy consumption: this index expresses the consumption of non-renewable energy of fossil origin. It is expressed in energy units (MJ).

Table 16 presents the impacts calculated in the manufacturing phase of the lamps using the inputs of matter and energy mentioned in the previous section.

In order to facilitate comparative analysis of the results, the data are normalized to those results that presented the greatest impacts. Fig. 30 shows a histogram of the categories of impact related to the lamps studied.

It is clear that, during the manufacturing phase, LED lamps possess more associated impacts, as the lamps require more components and have greater mass. Due to the simplicity of its construction, the impacts of halogen incandescent lamp assembly are relatively small.

Table 17 presents the impacts resulting from the use of the lamps studied. Fig. 31 shows the standardized results with the highest impacts in relation to the halogen incandescent lamp.

The environmental impacts due to usage, are markedly greater for halogen incandescent lamps. This can be explained by the low efficiency of these lamps, which consume more electric energy per lumen produced. These impacts are primarily related to the generation of electric energy, which results in the emission environmental pollutant and greenhouse gas. These impacts are minimized due to the large share of renewable energy sources in Brazil. Higher values can be obtained for energy matrices that

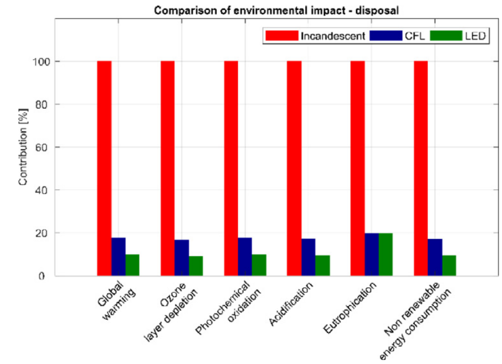


**Fig. 31.** Environmental impacts in the use of lamps phase.

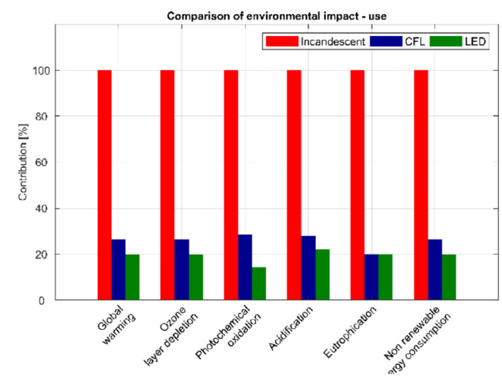


**Fig. 32.** A comparison of environmental impacts in the disposal phase.

have a larger share of fossil sources, which are more polluting (Hu and Cheng, 2012). This study verified the emission of lead due to the burning of coal, which is the relevant primary energy in the Chinese energy matrix.

Table 18 shows the impacts arising from the disposal of the lamps. Data are normalized by considering the most severe category as 100% (Fig. 32).

During disposal, the CFLs and LEDs presented similar impacts despite having different compositions. In this phase, the number of bulbs analyzed has great influence because, despite containing toxic products, the CFLs still have smaller impacts than incandescent lamps. In addition, the presence of mercury may not be captured by the analyzed impact categories. It is necessary to evaluate other impact categories such as ecotoxicity.

Finally, the data in Table 19 account for all of the impacts arising from the life cycles of the studied lamps, according to the described scope. A histogram with normalized data is presented in Fig. 33.

From the methodology and the input data, it is clear that incandescent lamps are responsible for the greatest environmental impact, followed by LED lamps. Although the CFLs consist of toxic materials, they presented the lowest impact.

It is emphasized herein that the life cycle assessment is used as an indication of the environmental impacts that occur during the various phases of a product's life cycle. Hence, it does not actually quantify the environmental impacts in the life cycle of a product. Life cycle assessment is a difficult task, considering the complex conditions that exist during production, transportation, use and disposal.

## 11. Conclusions

After considering a number of variables, this study shows that there is indeed a great potential for the adoption of LED

**Table 16**
Environmental impacts in the manufacturing phase.

| Impact category | Halogen incandescent (852 un.) | CLF (88 un.) | LED (49 un.) |
|---|---|---|---|
| Global warming (kg $CO_{2\,eq}$) | 206.83 | 566.92 | 2780.33 |
| Ozone layer depletion (kg CFC-$11_{eq}$) | $2.00\times10^{-5}$ | $5.21\times10^{-5}$ | $1.97\times10^{-4}$ |
| Photochemical oxidation (kg $C_2H_{4\,eq}$) | 1.71 | 0.42 | 1.03 |
| Acidification (kg $SO_{2\,eq}$) | 34.39 | 2.32 | 11.69 |
| Eutrophication (kg $PO_{4\,eq}$) | 2.16 | 2.58 | 9.69 |
| Non-renewable energy consumption (MJ) | 5406.98 | 15,044.90 | 181,747.24 |

**Table 17**
Environmental impacts during use.

| Impact category | Halogen incandescent (852 un.) | CLF (88 un.) | LED (49 un.) |
|---|---|---|---|
| Global warming (kg $CO_{2\,eq}$) | 168.45 | 44.86 | 33.51 |
| Ozone layer depletion (kg CFC-$11_{eq}$) | $8.12\times10^{-6}$ | $2.16\times10^{-6}$ | $1.62\times10^{-6}$ |
| Photochemical oxidation (kg $C_2H_{4\,eq}$) | 0.07 | 0.02 | 0.01 |
| Acidification (kg $SO_{2\,eq}$) | 0.18 | 0.05 | 0.04 |
| Eutrophication (kg $PO_{4\,eq}$) | 0.05 | 0.01 | 0.01 |
| Non-renewable energy consumption (MJ) | 1144.54 | 304.80 | 227.71 |

**Table 18**
Environmental impacts in the disposal phase.

| Impact category | Halogen incandescent (852 un.) | CLF (88 un.) | LED (49 un.) |
|---|---|---|---|
| Global warming (kg $CO_{2\,eq}$) | 9.32 | 1.66 | 0.93 |
| Ozone layer depletion (kg CFC-$11_{eq}$) | $1.65\times10^{-8}$ | $2.76\times10^{-9}$ | $1.54\times10^{-9}$ |
| Photochemical oxidation (kg $C_2H_{4\,eq}$) | $2.92\times10^{-3}$ | $5.20\times10^{-4}$ | $2.89\times10^{-4}$ |
| Acidification (kg $SO_{2\,eq}$) | $1.58\times10^{-3}$ | $2.75\times10^{-4}$ | $1.53\times10^{-4}$ |
| Eutrophication (kg $PO_{4\,eq}$) | 0.05 | 0.01 | 0.01 |
| Non-renewable energy consumption (MJ) | 3.47 | 0.59 | 0.33 |

**Table 19**
Environmental impacts throughout the lamp life cycle.

| Impact category | Halogen incandescent (852 un.) | CLF (88 un.) | LED (49 un.) |
|---|---|---|---|
| Global warming (kg $CO_{2\,eq}$) | 83,859.21 | 10,396.03 | 8831.41 |
| Ozone layer depletion (kg CFC-$11_{eq}$) | $1.02\times10^{-2}$ | $1.16\times10^{-3}$ | $8.43\times10^{-4}$ |
| Photochemical oxidation (kg $C_2H_{4\,eq}$) | 68.75 | 7.88 | 5.49 |
| Acidification (kg $SO_{2\,eq}$) | 452.93 | 47.29 | 37.81 |
| Eutrophication (kg $PO_{4\,eq}$) | 107.94 | 14.38 | 16.79 |
| Non-renewable energy consumption (MJ) | 1,134,419.72 | 140,217.37 | 256,282.07 |

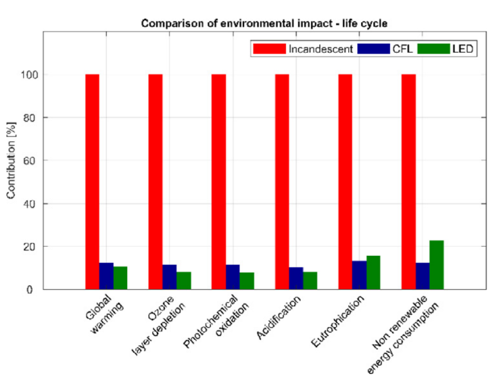


**Fig. 33.** A comparison of environmental impacts throughout the lamp life cycle.

lamps in place of conventional incandescent and CFLs. There are products that already meet the residential lighting requirements standards and have efficiencies significantly higher than the systems currently in use. The prices of LED have shown a tendency to decrease when compared with CFLs, because there has been a marked drop in their costs of production over the years, with corresponding growth in luminous efficiency. Thus, the data suggest that LED technology will be increasingly competitive in coming years and become accessible to a large part of the population.

This study also suggests that lamp manufacturers do not adequately disclose characteristics of their products. This disclosure is fundamental, because it enables the consumer to choose equipment based on performance characteristics such as color temperature, color reproduction index, luminous efficiency, power factor and current harmonic distortion. Besides that, this research may aid lawmakers by showing the actual market status of the lighting technologies.

For the purpose of comparison, the values of the lamps tested herein are close to the stated luminous flux. The lamps were acquired at the lower cost available in the city of Sao Paulo (SP), so that representativeness is restricted. There may be LED and CFLs technologies with significantly better indicators than those presented. The data herein show that low-quality products negatively affect the operation of the electric distribution system, either through low power factors that reduces the active power transmission capacity on the network, or via nonlinear load characteristics that introduce current harmonics into the network.

Measurements of the photometric magnitudes show the importance of providing data to clients as well as ensuring data accuracy by using measurements by laboratories accredited by Federal Government.

For the consumer, choosing the best lighting technology for each environment is of fundamental importance, because it ensures that the design suits the activities undertaken in that location.

The economic analysis underscores the practicality and feasibility of LED technology use in all of the scenarios studied, including lighting efficiency, through verification of the entire technology life cycle and based on 10 years of analysis. Currently, the use and feasibility of LED technology are growing with its positive market outlook.

In satisfying the lighting requirements of the specified functional unit, the use of the LED lamps resulted in lower overall life cycle impacts. Halogen lamps were associated with the highest impact. CFLs resulted in lower impacts than LED lamps in only two categories (i.e. acidification and non-renewable energy consumption). This arises from the production of LED lamps because they require a high demand for energy and raw materials and thus, have a higher impact on the environment.

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## References

ABNT NBR 14539, 2000. Self-ballasted lamps for general lighting services - Performance requirements, Associação Brasileira de Normas Técnicas, pp. 1–11.

ABNT NBR 14671, 2001. Tungsten filament lamps for domestic and similar general lighting purposes - Performance requirements, Associação Brasileira de Normas Técnicas. Rio de Janeiro, pp. 1–26.

Achão, C., Schaeffer, R., 2009. Decomposition analysis of the variations in residential electricity consumption in brazil for the 1980–2007 period: Measuring the activity, intensity and structure effects. Energy Policy 37 (12), 5208–5220. http://dx.doi.org/10.1016/J.ENPOL.2009.07.043, Elsevier.

Aman, M.M., et al., 2013. Analysis of the performance of domestic lighting lamps. Energy Policy http://dx.doi.org/10.1016/j.enpol.2012.09.068.

Archer, S.A., Murphy, R.J., Steinberger-Wilckens, R., 2018. Methodological analysis of palm oil biodiesel life cycle studies. Renew. Sustain. Energy Rev. 94, 694–704. http://dx.doi.org/10.1016/J.RSER.2018.05.066, Pergamon.

Braga, M.F., et al., 2014. 60w incandescent lamp alternatives found in brazilian market. In: 2014 11th IEEE/IAS International Conference on Industry Applications. IEEE, pp. 1–8. http://dx.doi.org/10.1109/INDUSCON.2014.7059475.

Brazil, 2010. Interministerial Ordinance nº 1.007 of December 31, 2010. Brazil. Available at: http://www.mme.gov.br/documents/10584/904396/Portaria_interminestral+1007+de+31-12-2010+Publicado+no+DOU+de+06-01-2011/d94edaad-5e85-45de-b002-f3ebe91d51d1?version=1.1.

CAPAZ, R.S., 2009. Estudo do desempenho energético da produção de biocombustíveis: aspectos metodológicos e estudos de caso. Available at: https://repositorio.unifei.edu.br/xmlui/h{and}le/123456789/1780 (Accessed: 30.01.19).

Chen, H.-T., Tan, S.-C., Hui, S.Y.R., 2015. Nonlinear dimming and correlated color temperature control of bicolor white led systems. IEEE Trans. Power Electron. 30 (12), 6934–6947. http://dx.doi.org/10.1109/TPEL.2014.2384199.

Dai, Q., et al., 2018. Spatial and spectral illumination design for energy-efficient circadian lighting. Build. Environ. 146, 216–225. http://dx.doi.org/10.1016/J.BUILDENV.2018.10.004, Pergamon.

De Almeida, A., et al., 2014. Solid state lighting review - Potential and challenges in Europe. Renew. Sustain. Energy Rev. 34, 30–48. http://dx.doi.org/10.1016/j.rser.2014.02.029, Elsevier.

DiLaura, D., Houser, K., 2011. The lighting handbook, Illuminating …. http://dx.doi.org.10.1021/jp902267g.

Elijošiute, E., Balciukevičiūte, J., Denafas, G., 2012. Life cycle assessment of compact fluorescent and incandescent lamps: Comparative analysis. Environ. Res. Eng. Manag. 61 (3), 65–72. http://dx.doi.org/10.5755/j01.erem.61.3.2425.

EPE - Empresa de Pesquisa Energética, 2014. Ten-Year Energy Expansion Plan 2026 (Brazil), Epe.Gov.Br. Rio de Janeiro. Available at: http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/Plano-Decenal-de-Expansao-de-Energia-2024.

Fernandes Mourão, R., Satoshi, E., Seo, M., 2012. LOGÍSTICA REVERSA DE LÂMPADAS FLUORESCENTES. Available at: http://www3.sp.senac.br/hotsites/blogs/InterfacEHS/wp-content/uploads/2013/07/NOVO_76_Artigo_5_vol7n3.pdf (Accessed: 30.01.19).

Geller, H., et al., 2000. Update on Brazil's national electricity conservation program (PROCEL). Energy Sustain. Dev. 4 (2), 38–43. http://dx.doi.org/10.1016/S0973-0826(08)60241-0, Elsevier.

Ghisi, E., Gosch, S., Lamberts, R., 2007. Electricity end-uses in the residential sector of brazil. Energy Policy 35 (8), 4107–4120. http://dx.doi.org/10.1016/J.ENPOL.2007.02.020, Elsevier.

Golasi, I., et al., 2019. Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations. Energy Build. 185, 112–122. http://dx.doi.org/10.1016/J.ENBUILD.2018.12.026, Elsevier.

Hu, Y., Cheng, H., 2012. Mercury risk from fluorescent lamps in china: Current status and future perspective. Environ. Int. 44, 141–150. http://dx.doi.org/10.1016/J.ENVINT.2012.01.006.

Hunt, J.D., Stilpen, D., de Freitas, M.A.V., 2018. A review of the causes, impacts and solutions for electricity supply crises in Brazil. Renew. Sustain. Energy Rev. 88, 208–222. http://dx.doi.org/10.1016/J.RSER.2018.02.030, Pergamon.

IEC, 1998. 'IEC 61000-3-2', International Standard.

IEEE, 2014. 'IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems', IEEE Std 519-2014 (Revision of IEEE Std 519-1992). http://dx.doi.org.10.1109/IEEESTD.2014.6826459.

IESNA, 2008. 'IES Approved Method: Measuring Lumen Maintenance of LED Light Sources. IES LM-80-08', IES Subcommittee on Solid-State Lighting of the IES Testing Procedures Committee. http://dx.doi.org.10.1177/0272989X15576487.

International Commission on Illumination, 1982. Calculations for interior lighting: applied method. Bureau central de la CIE. Available at: http://www.cie.co.at/publications/calculations-interior-lighting-applied-method (Accessed: 30.01.19).

International Commission on Illumination, 1996. Calculations for interior lighting : basic method. Commission internationale de l'eclairage. Available at: http://www.cie.co.at/publications/calculations-interior-lighting-basic-method (Accessed: 30.01.19).

ISO 14040, 2006. Environmental management — Life cycle assessment — Principles and framework. http://dx.doi.org.10.1136/bmj.332.7550.1107.

ISO 14044, 2006. The International Journal of Life Cycle Assessment, The International Journal of Life Cycle Assessment, http//dx.doi.org.10.1007/s11367-011-0297-3.

Judd, D.B., 1936. Estimation of chromaticity differences and nearest color temperature on the standard 1931 ici colorimetric coordinate system*. J. Opt. Soc. America 26 (11), 421. http://dx.doi.org/10.1364/JOSA.26.000421, Optical Society of America.

Judd, D.B., et al., 1964. Spectral distribution of typical daylight as a function of correlated color temperature. J. Opt. Soc. Amer. 54 (8), 1031. http://dx.doi.org/10.1364/JOSA.54.001031, Optical Society of America.

Li, X.P., Chen, L., Chen, M., 2011. An approach of led lamp system lifetime prediction. In: 2011 IEEE International Conference on Quality and Reliability. IEEE, pp. 110–114. http://dx.doi.org/10.1109/ICQR.2011.6031691.

Lobão, J.A., Devezas, T., Catalão, J.P.S., 2015. Energy efficiency of lighting installations: software application and experimental validation. Energy Rep. 1, 110–115. http://dx.doi.org/10.1016/J.EGYR.2015.04.001, Elsevier.

Mankiw, N.G., 2007. Principles of Microeconomics. Thomson South-Western.

Martinot, E., Borg, N., 1998. Energy-efficient lighting programs: Experience and lessons from eight countries. Energy Policy 26 (14), 1071–1081. http://dx.doi.org/10.1016/S0301-4215(98)00052-4, Elsevier.

Mendes, N.C., et al., 2015. Avaliação de impacto do ciclo de vida: revisão dos principais métodos' production. Assoc. Brasil. Eng. Prod. 26 (1), 160–175. http://dx.doi.org/10.1590/0103-6513.153213.

Molina, J., Sainz, L., 2014. Model of electronic ballast compact fluorescent lamps. IEEE Trans. Power Deliv. 29 (3), 1363–1371. http://dx.doi.org/10.1109/TPWRD.2013.2284095, IEEE.

Monteiro, R.V.A., et al., 2014. LED Tubular lamps and tubular fluorescent: Power quality. In: 2014 16th International Conference on Harmonics and Quality of Power (ICHQP). IEEE, pp. 400–404. http://dx.doi.org/10.1109/ICHQP.2014.6842778.

Nassif, A.B., Xu, Wilsun, 2009. Characterizing the harmonic attenuation effect of compact fluorescent lamps. IEEE Trans. Power Deliv. 24 (3), 1748–1749. http://dx.doi.org/10.1109/TPWRD.2009.2021022.

Osram, 2009. Life Cycle Assessment of Illuminants Life Cycle Assessment of Illuminants A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps. Available at: http://seeds4green.net/sites/default/files/OSRAM_LED_LCA_Summary_November_2009.pdf (Accessed: 30.01.19).

Principi, P., Fioretti, R., 2014. A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (cfl) vs light emitting diode (led) – a case study. J. Cleaner Prod. 83, 96–107. http://dx.doi.org/10.1016/J.JCLEPRO.2014.07.031, Elsevier.

Rastello, M.L., Miraldi, E., Pisoni, P., 1996. Luminous-flux measurements by an absolute integrating sphere. Appl. Opt. 35 (22), 4385. http://dx.doi.org/10.1364/AO.35.004385, Optical Society of America.

Renouf, M.A., et al., 2015. Best Practice Guide for Life Cycle Impact Assessment (LCIA) in Australia ALCAS Impact Assessment Committee Version 2. Available at: https://www.surveymonkey.com/s/XHDGM3B (Accessed: 30.01.19).

Ryckaert, W.R., et al., 2012. Linear LED tubes versus fluorescent lamps: An evaluation. Energy Build. 49, 429–436. http://dx.doi.org/10.1016/J.ENBUILD.2012.02.042, Elsevier.

Sangwan, K.S., et al., 2014. Life cycle assessment of incandescent, fluorescent, compact fluorescent and light emitting diode lamps in an Indian scenario. Procedia CIRP 15, 467–472. http://dx.doi.org/10.1016/J.PROCIR.2014.06.017, Elsevier.

Schanda, J., International Commission on Illumination, 2007. Colorimetry : understanding the CIE system. CIE/Commission internationale de l'eclairage.

Schipper, L., Meyers, S., Stockholm Environment Institute, 1992. Energy Efficiency and Human Activity: Past Trends, Future Prospects. Cambridge University Press, Available at: https://books.google.com.br/books?hl=pt-BR&lr=&id=xqV4Gs4hKoEC&oi=fnd&pg=PR9&dq=Energy+Efficiency+and+Human+Activity:+Past+Trends,+Future+844+Prospects&ots=nQMRpaaJaS&sig=yoWhLvQA5x7N2GtzjTmLF8cSXyE#v=onepage&q&f=false (Accessed: 29.01.19).

Schlischting, M.W., et al., 2016. Analysis of reactive power flow in the lighting system of a consumer unit. In: 2016 17th International Conference on Harmonics and Quality of Power (ICHQP). IEEE, pp. 1014–1019. http://dx.doi.org/10.1109/ICHQP.2016.7783419.

Tawfik, M., Tonnellier, X., Sansom, C., 2018. Light source selection for a solar simulator for thermal applications: A review. Renew. Sustain. Energy Rev. 90, 802–813. http://dx.doi.org/10.1016/J.RSER.2018.03.059, Pergamon.

The International Commission on Illumination (CIE), 2002. ISO 8995- Lighting of Indoor Work Places, Iso 8995 Cie S 008/E. http://dx.doi.org.10.3403/02609865.

U.S. Department of Energy, 2012. Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 2: LED Manufacturing and Performance. Available at: www.yole.fr (Accessed: 30.01.19).

Welz, T., Hischier, R., Hilty, L.M., 2011. Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis. Environ. Impact Assess. Rev. 31 (3), 334–343. http://dx.doi.org/10.1016/J.EIAR.2010.08.004, Elsevier.