R. Latino-amer. em Aval. do Ciclo de Vida, Brasília, v. 1, n. 1, p. 9-44, jul./dez. 2017

The influence of functional unit on life cycle assessment of lamps: a review of results

A influência da unidade funcional na avaliação do ciclo de vida de lâmpadas: uma revisão dos resultados

La influencia de la unidad funcional del análisis del ciclo de vida de lámparas: una revisión de resultados

Submetido em 11 junho 2016 | Aceito em 31 janeiro 2017 | Disponível em 7 junho 2017

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Abstract

Lamps have been developed since incandescent technology, to fluorescent and light emitted diode (LED), increasing lighting conversion efficiency, extending product's life span, and, consequently, decreasing environmental impacts. However, improving the use phase of lamps demand a more complex production system, including (sometimes) hazardous materials, what have worsened final disposal as well. Life Cycle Assessment (LCA) has been addressed to lamps since 1996, and now with its evolution, comparisons are getting more common. These studies lead to different results, wherein functional unit (FU) plays a key role to generate these differences, even when product systems are similar, making difficult the overall understanding of comparisons. We aimed to analyze the scientific production of LCA of lamps, developing a framework of the product systems, the FU definition and the results to indicate trends and patterns of the LCA methodology application, including comparison possibilities. The proposed methodology was an integrative literature review applied to scientific databases and further papers content analysis. The survey identified 16 papers, where it is clear the recent increase on comparative LCA studies addressed to lighting technologies. There were 4 different

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FU definitions in papers. However, complementary description of product performance enable one to equalize FU into a common basis, wherein values for climate change have shown that LED lamps are preferable than fluorescents, that are preferable than incandescent. Even though this was possible, FU should be clearly indicated and represent products function, in this case: an amount of lumen-hour.

Keywords: *functional unit, integrative review, lamps, LCA, life cycle assessment*

Resumo

As lâmpadas foram desenvolvidas da tecnologia incandescente, para a fluorescente e para o diodo emissor de luz (LED), o que aumentou a eficiência na conversão da iluminação e estendeu a vida útil do produto, consequentemente ocasionando na diminuição dos impactos ambientais. No entanto, a melhoria da fase de uso das lâmpadas, exige um sistema de produção mais complexo, incluindo (por vezes) materiais perigosos, o que piorou também sua disposição final. Estudos de Avaliação do Ciclo de Vida (ACV) são desenvolvidos desde 1996 envolvendo lâmpadas, e agora, com a evolução da tecnologia, as comparações estão ficando mais comuns. Esses estudos geram resultados variados, em que a unidade funcional (UF) desempenha um papel fundamental para gerar essas diferenças, mesmo quando os sistemas de produto são semelhantes, dificultando a compreensão das comparações. O objetivo deste artigo é analisar a produção científica de ACVs de lâmpadas, desenvolvendo um panorama dos sistemas de produto e suas definições de UF, bem como dos resultados, para indicar tendências e padrões da aplicação neste tema. A metodologia proposta foi de uma revisão integrativa da literatura aplicada a bases de dados científicos e outros documentos. A pesquisa identificou 16 artigos, onde ficou evidente o recente aumento dos estudos de ACVs comparativos. Nesta amostragem foram encontradas quatro diferentes definições de UF. Contudo, uma descrição complementar do desempenho do produto permite equalizar a UF numa base comum, em que os valores para a mudança climática têm mostrado que as lâmpadas LED são preferíveis às lâmpadas fluorescentes, que são preferíveis às incandescentes. Embora a comparação tenha sido possível, a UF deve ser claramente indicada para representar a função dos produtos, neste caso: a quantidade de lúmen.horas.

Palavras-chave: *unidade funcional, revisão integrativa, lâmpadas, ACV, avaliação do ciclo de vida*

Resumen

Las lámparas se han desarrollado a partir de la tecnología incandescente, fluorescente, y un diodo emisor de luz (LED), lo que significa un aumento de la eficiencia de conversión de luz, que extiende la vida útil del producto y reduce así el impacto ambiental. Sin embargo, mejorar la fase de uso de las lámparas requiere un sistema de producción más complejo, incluyendo (a veces) materiales peligrosos, lo que empeora la disposición final. La Análisis del Ciclo de Vida (ACV) se ha dirigido a las lámparas desde 1996, y ahora con su evolución, las comparaciones son cada vez más comunes. Estos estudios llevan a resultados diferentes, donde la unidad funcional (UF) tiene un papel clave para la generación de estas diferencias, mismo cuando los sistemas de productos son similares, lo que dificultaría la comprensión general de las comparaciones. El objetivo fue analizar la producción científica de ACV de lámparas, el desarrollo de un marco de sistemas de productos, la definición de UF y los resultados para indicar tendencias y normas de aplicación de la metodología del ACV, incluyendo las posibilidades de comparabilidad. La metodología propuesta fue una revisión integrativa de la literatura aplicada a bases de datos científicas y análisis de contenido de documentos adicionales. La investigación identificó 16 artículos, donde está claro el reciente aumento en los estudios comparativos de ACV dirigidos a las tecnologías de iluminación. Había 4 diferentes definiciones de UF en los documentos. Sin embargo, la descripción adicional del rendimiento del producto permite equiparar el UF a una base común, donde los valores para el cambio climático han demostrado que las lámparas LED son mejores que las fluorescentes, que a su vez son preferibles que las incandescentes. Aunque esto podría ser posible, UF debe estar siempre claramente indicado y representar la función de los productos, en este caso la cantidad lúmen.hora de una lámpara

Palabras clave: *unidad funcional, revisión integradora, lámparas, ACV, análisis del ciclo de vida*

1. Introduction

In the last 40 years, our lifestyle has required more natural resources and emitted more environmental burdens than the earth was able to manage (Bielek et al., 2013; Borucke et al., 2013; Hoekstra and Wiedmann, 2014; WWF, 2014, 2016). This imbalance should be enough to generate concern and to direct efforts towards sustainability. However, only with large scale effects of this situation, including natural disasters enhancement (potentiated by anthropic activities), resources scarcity and the human needs for arable land related to the population growth and food security, we started to develop effective actions in order to minimize our environmental footprint. Reflex of that is present in the way society pressure government and industries to manage the environmental impacts of their activities, as it can be noticed by the creation of international treaties (UN, 1998) and the increase of environmental policies (e.g. Brasil, 2010; Brasil, 2009), environmental laws (e.g. CONAMA, 2002) and programs as the European Climate Change Programme (EC, 2003), Water Framework Directive (EC, 2000), the directive regarding waste management (EC, 2008) and for sustainable production (e.g. Programa Nacional de Conservação de Energia Elétrica – PROCEL, 2006).

Specifically, the energy industry stands as one of the main sources of environmental impacts. The impacts of the energy sector are related to some unique characteristics: a) all production chains need energy; b) there is a high and constant demand of consumption from direct and indirect customers; c) the energy grids have a great potential to generate environmental impacts, specially related to climate change; d) there are important losses during voltage transformation and in the transmission network. In 2013, for example, the world offer of primary energy exceeded 13,000 megatons of equivalent oil (Mtoe), in which 31% and 29% were from fossil fuel and from coal power generation, respectively (IEA, 2014). These are some of the reasons why reduction targets on energy consumption (or GHG emission associated to the energy production) were set in many intergovernmental and sectorial arrangements as a strategy in the short, medium and long term (e.g. CPUC, 2008; EC, 2005; UN, 2010; 2008; BRASIL, 2009; EPA, 2009).

Recently, Brazil established reduction goals for GHG emissions until 2020 including a low carbon production and distribution of energy and the reduction of energy demand at the end-of-chain user (end consumer).

Therefore, the Brazilian government invested in initiatives to promote a more conscious consumption, as for instance, the replacement of common lamps (i.e. incandescent) by the latest technologies is one of the alternatives to reduce the energy consumption (Brasil, 2011). The rationale behind the concern with lamps is that we are highly dependent on illumination whereas they have a bad energy conversion rate. Lamps are responsible for 17% to 25% of daily energy usage worldwide (Lister et al., 2004; OECD/IEA, 2006; MME, 2013) in which 70% of this consumption is spent due to inefficiency (OSRAM, 2009). As a consequence, the illumination is also considered one of the main sources of GHG emissions from energy consumption, which at global level is responsible for 650 Mtoe of primary energy consumption and result in almost 1900 million tons (Mt) of CO2 emissions (OECD/IEA, 2006).

Concomitantly to those directives, it can be noticed studies related to incandescent, fluorescent and/or LED lamps and its connection to the environmental management area (see for instance Bergesen et al., 2016 and Lim et al., 2013). These studies are aligned with Lindstrom and Middlecamp (2016) statement that lighting trends worldwide are shifting toward greater energy efficiency as incandescent light bulbs are being discarded in favor of higher efficiency compact fluorescent lights (CFLs) and light-emitting diodes (LEDs). However, these improvements in some cases are reached through environmental trade-offs. In this context, life cycle assessment (LCA) plays a key role as an important methodology applicable to define the metrics and environmental profile of a product, and may represent a path to the creation/support of programmes, public requirements and to guide consumers to a better choice.

1.1. The Life Cycle of Lamps

A good performance of a lamp is strictly associated with a lower consumption of electricity at the use stage and an extended lifespan, characteristics that positively cause environmental impact reduction. However, independent of the different types of technologies for lamps production, they all have a common feature, the long-standing use phase associated with energy consumption as the main environmental aspect. The energy demanded by use phase can reach up to 90% of all energy in the life cycle of the product (DOE, 2012a).

The latest technologies of lamps production require less energy (at the use stage) and tend to require even less through the years. According to Shahzad et al (2015), to ensure the same quantity of illumination, the CFLs and LED lamps consume 20% of the energy demanded by incandescent lamps. Other authors (Parson, 2006; Ramroth, 2008; OSRAM, 2009; Trifunovic et al., 2009) have shown similar values of energy consumption of fluorescent lamps compared to incandescent. Thus, it is a common sense that LED lamps are more beneficial than the others as pointed by Yu et al., (2016), position reinforced by directives from International Energy Agency (OECD/IEA, 2006), federal government (Brasil, 2011) and states governments (Paraná, 2015; São Paulo, 2001).

However, despite the evident energy savings of the fluorescent and LED lamps, there are impacts on the manufacturing and final disposal phase that are not clear and need to be known (Elijošiutė et al., 2012; DOE, 2012a).

Generally, products with higher technology require complex manufacturing processes. For instance, fluorescent lamps introduce toxic elements, such as mercury, turning its production and final disposal harmful. Environmental problems associated with the mercury in fluorescent lamps often are a subject of interest in researches (see Asari et al., 2008; Eckelman et al., 2008; Hu and Chen, 2012; Liang et al., 2015; Rhee et al., 2014; Zhang et al., 2016). Ramroth (2008) illustrates this aspect stating that this type of lamp could be actually worst to the environment due to its high mercury content, the impact of short “on” times on the life of the lamps, and the energy used during their manufacturing process (30 times higher compared with an incandescent lamp).

Regarding to the LED lamps, it also represents a technology with low energy consumption. It is considered that LED lamps can be 5 times more efficient than incandescent lamps, with the benefit of being free from mercury components (OSRAM, 2009). However, they have semiconductors that demand high energy consumption and require a completely sterile environment to the manufacturing process (Quirk, 2009). Nevertheless, it is still possible to improve the LED lamps technology while the fluorescent lamps already have reached its theoretical limits (OSRAM, 2009; Quirk, 2009).

Therefore, these stages of the life cycle (i.e. production and disposal) when considered in the system boundaries can influence the environmental performance of a lamp. In the study developed by Sangwan et al. (2014) comparing fluorescent, incandescent and LED lamps, the results varied considerably when the manufacturing and disposal stages were included in the system boundaries. Similarly, Quirk (2009) states that the knowledge of all life cycle stages of the lamps is crucial for the development of public policies addressing climate changes issues and to improve the LED lamps technology (DOE 2012a).

1.2. Functional Unit Definition and Influences

Although LCA has been standardized by ISO series 14040 and 14044 (ISO 2006a; ISO 2006b), the methodology is still flexible, allowing the practitioner to decide among different paths when conducting a LCA study. The flexibility of LCA is mainly related to definitions made during the goal and scope phases. The choice between function of a product system, functional unit, system boundary, allocation procedure, impact categories, among others, remain as an unsolved problem (Reap et al. 2008).

Specifically the functional unit (FU) of a LCA study can generate contrasting results. An illustrative example can be found in Prudêncio da Silva et al. (2014), in which the authors compared two broiler chicken production systems, based on a LCA cradle-to-gate: (1) conventional and (2) the Label Rouge. Analyzing the impacts of both production systems considering a FU based on mass (i.e. 1 tone of cooled and packaged chicken), the authors could conclude that the conventional system has lower environmental impacts than the Label Rouge system. However, even though the use of a FU based on quantity (mass or volume) be very common for food products (Schau and Fet, 2008), it could be argued that a FU based on such metrics does not represent the real function of a product but a reference flow. In this sense, Prudêncio da Silva et al. (2014), also evaluated the two production systems with a FU based on economic prices (i.e. 1.000 € of chicken live weight at the farm gate) attempting to represent the producer remuneration function of the product. In this case, the results change significantly, positioning the Label Rouge system as the most preferable to decrease the environmental impacts of broiler chicken production.

The aforementioned situation is undesirable for a decision-making point of view. Both approaches/definitions made by Prudêncio da Silva et al. (2014) are acceptable, despite the greater differences that could be observed in the results. Thus, thinking on public policy development the major question is: which production system should be encouraged in order to reduce the environmental impacts. This problem arises from the difficulty to establish a correct function for a product system and its correct correlation with a measurement unit, i.e. the functional unit.

Although we presented the FU problem to food products this can also be applied to others products such as wastewater treatment or even, lamps, as pointed out by Welz et al (2011) in a LCA of lighting technologies. According to the authors the comparison between their results with the ones from literature was very difficult, what directed them to claim that it is “important to explore the issue of the functional equivalence of lighting devices more precisely”.

To address the problematic related to the impacts of lamps and the FU definition, we present an integrative review of studies published in the main international and Brazilian databases on life cycle assessment (LCA) of incandescent, fluorescent and LED light bulbs. The focus of the analysis was the methodological definition of functional unit and results to climate change. Our purpose is to analyze the academic-scientific production of LCA of lamps, developing a framework of the product systems analyzed by the documents, the FU and the results of the life cycle impact assessments.

The results allow to identify how the variability on methodological choices (i.e. FU) in LCA can influence the results of the analysis. Thus, we also intend to provide a guide for future studies on this topic by encouraging further work and acting as a reference for researchers and industries concerned on LCA of lamps production.

2. Materials and Methods

To address the goals of this paper we adopted the method of integrative literature review. This methodology is based on the research of significant studies developed on a specific field or theme to further analysis, comparison and content correlation. The method allows including experimental and non-experimental studies, which encompasses different approaches around the topic of interest, such as the definition of concepts, review of theories and the evidence and analysis of methodological problems. Therefore, the results summarize the main findings of the topic and gives support to the knowledge application (Broome, 1993). The methodology was systematically structured following the six basic stages of an integrative review, as described by Mendes et al. (2008):

1st Stage: To identify the integrative review questions or topic;

This paper was developed considering LCA studies applied on incandescent, fluorescent and LED light bulbs, in order to identify the methodological definitions of functional unit (FU); and the influence of this scoping definition topic on the LCA results. In a wide sense, this research aims to respond the following questions: is the common sense that the technological evolution of lamp production is strictly related to the decrease of environmental impacts, accepted or rejected? Does FU variation enable result comparisons from different authors?

2nd Stage: Criteria definition for inclusion of the documents;

The main scientific databases worldwide that conduct this research are Scopus, Web of Knowledge (WoK) and Scielo. These scientific sources are the most used to support integrative review studies due to its international (Scopus and WoK) and national (Scielo) coverage. Additionally, official and technical reports from governments and private companies of lamps production were also included in the search sampling. The time span for the search was stated from 2002 to 2016. The rationale for the aforementioned time span is because the year of 2002 was very important to disseminate and consolidate the LCA methodology worldwide, represented by the foundation of the Life Cycle Initiative by the United Nations Environment Programme (UNEP) and by the Society for Environmental Toxicology and Chemistry (SETAC). On top of that, the number of publications on LCA increased at the early 2000s, as pointed out by several authors (Chen et al., 2014; Cherubini and Ribeiro, 2015; Hou et al., 2015; Zanghelini et al., 2016).

3rd Stage: Documents identification and selection

We divided the data collection in two stages. First, it was considered two combinations of keywords: "LCA" and "lamps"; and "life cycle assessment" and "lamps" (for the Brazilian database – Scielo: "ACV" and "lâmpadas"; and "avaliação do ciclo de vida" and "lâmpadas"). The second stage of data collection was the analysis of title and the abstract of the papers. This process excluded from the analysis documents without the keywords in title, abstract and in the keywords and the ones that were not on LCA of incandescent, fluorescent and/or LED lamps. In addition of the research in the scientific databases, it was also applied the snowball technique (Bezerra et al., 2014; Jalali and Wohlin, 2012) which consists in use cited references of the selected papers by the former steps. In this case, the articles that have met with the definitions of scope and purpose of this research were included in the integrative review.

4th Stage: Study categorization

In this phase, the selected documents were analyzed to provide the data required for the discussions and comparison of the results. Special attention was dedicated to functional unit definition and the outputs from the life cycle impact assessment (LCIA). Another important issue analyzed was the technical indicators of the product systems (i.e. the lamps), e.g. power, luminous flux and lifetime of each lamp. Although the focus of the discussion was the influence of functional unit, some other information are essential for the interpretation of the results.

5th Stage: Results interpretation

This phase of the integrative review methods aims to identify the patterns of the studies and the methodological preferences, correlating the findings of each study with the methodology used. It identifies motivations and reasons for differences between results from different papers (for instance: a variation in LCA results due a different Life Cycle Impact Assessment method applied by two different authors). Therefore, considering the comparative nature of LCA and the need of a fair comparison that must be based on consistent methodological decisions, this analysis is vital to understand the results, its variability and limitations. For the comparison of the studies from different authors, the results of the impact category of Climate Change (CC) it was defined CC as the indicator for two main reasons: (i) this is the most common impact category and it is present in almost all papers in our sample, and (ii) CC follows the same characterization model (Global warming potential from IPCC).

The CC of each lamp was equalized to the same FU of 15,000 lumen.hour of lighting. This value was based on the Brazilian standard for interior lighting (ABNT NBR ISO/CIE 8995-1:2013) that recommends a lighting flow between 100 and 200 lux per room. We equalized the results considering a place with 100m² with a 150 lux condition (1 lux represents 1 lumen/m²). Therefore, Table 4 compiles the results converted to the FU of 15,000 lumens-hour. This conversion was possible due to complementary information found in articles related to the performance of the products, generally included on product system description.

For this task, we considered only LCAs with the same system boundary (from cradle-to-grave) and it was assumed a proportionality of aspects and environmental impacts (i.e. if a lamp had as reference 1 lumen.hour, when converted to 2 lumen.hour, its aspects and impacts follows the same order of magnitude). Other aspects, such as variations in inventories inputs and outputs (for instance different electricity grids) and different actualizations of GWP characterization model were considered when interpreting results.

6th Stage: Presentation of the integrative review/summary of the knowledge

In order to synthesize the knowledge gathered by the review, the methodological definition of each study, composition of products and the environmental impacts related to each type of lamp, the data were compiled and presented in a descriptive way. Finally, we compared the three types of lamps emphasizing the differences between the methodological definitions of each study.

3. Results and Discussion

By means of applying 'LCA' and 'lamps' to Scopus database, it was possible to identify 47 publications, of which 11 fulfilled the choice criteria proposed: Apisitpuvakul et al. 2008; Weltz et al., 2011; Lim et al. 2013; Tahkamo et al. 2013; Hadi et al. 2013; Principi and Fioretti, 2014; Sangwan et al. 2014, Tahkamo et al. 2014, Tan et al. (2015), Yu et al. (2016) and Bergesen et al. (2016). By changing the keywords for 'life cycle assessment' and 'lamps' and applying for the same database, 38 publications were found, however, all papers that fit in the criteria were already identified by the first survey. Similarly, we did not find other relevant publication when using the same combinations of keywords to Web of Knowledge database.

Finally, the research in the Scielo database showed no publication using the combinations of keywords 'ACV' + 'lâmpadas' and 'avaliação do ciclo de vida' + 'lâmpadas'. Applying the snowballing technique to enlarge the set of publications, it was possible to obtain two reports from the Department of Energy of the United States of America (DOE 2012a; 2012b). Both are recurrent in the most recent publications related to international scientific journals. Analyzing those 13 papers, we noticed other 09 publications that were not on our previous surveys. They were published in other media as repositories of universities or linked to the industry in technical and scientific reports, between 2002 and 2016. These documents met the criteria for choosing articles, despite not being available in scientific databases. Therefore they were included on this review due to their importance in the field: Parson (2006); Michaud and Belley (2008); Ramroth (2008); OSRAM (2009); Quirk (2009), DEFRA (2009); Dale et al. (2011); Durlinger et al. (2012) and Elijošiutė et al. (2012). Table 1 compiles the 22 publications selected for this review as other relevant information.

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Table 1. Identified publications in the integrative review

	Title	Authors	Location	Type	Year
1	The environmental impact of compact fluorescent lamps and incandescent lamps for Australian conditions	Parson	Australia	Scientific	2006
2	LCA of spent fluorescent lamps in Thailand at various rate of recycling	Apisitpuvakul et al.	Thailand	Scientific	2008
3	Comparison of life-cycle analyses of compact fluorescent and incandescent lamps based on rated life of compact fluorescent lamp	Ramroth	USA	Report	2008
4	Comparative life cycle assessment of light bulbs: incandescents and compact fluorescents	Michaud and Belley	Canada	Report	2008
5	Life cycle assessment of illuminants: a comparison of light bulbs, compact fluorescent lamps and led lamps	OSRAM	Germany	Report	2009
6	Life-cycle assessment and policy implications of energy efficient lighting technologies	Quirk	USA	Academic Advisory	2009
7	Life Cycle Assessment of Ultra-Efficient Lamps	DEFRA	England	Report	2009
8	Environmental impacts of lighting technologies: life cycle assessment and sensitivity analysis	Weltz et al.	Switzerland	Scientific	2011
9	Preliminary Comparative Life-Cycle Impacts of Streetlight Technology	Dale et al.	USA	Scientific	2011
10	Life cycle assessment of compact fluorescent and incandescent lamps: comparative analysis	Elijošiut et al	Lithuania	Scientific	2012
11	A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia	Durlinger et al.	South east Asia	Scientific	2012
12	Life-cycle assessment of energy and environmental impacts of led lighting products, part 1: review of the life-cycle energy consumption of incandescent, compact fluorescent, and LED lamps	Department of Energy	USA	Report	2012a
13	Life-cycle assessment of energy and environmental impacts of led lighting products, part 2: LED manufacturing and performance	Department of Energy	USA	Report	2012b

(Continues)

14	Potential environmental impacts from the metals in incandescent, compact fluorescent lamp (CFL), and light-emitting diode (LED) bulbs	Lim et al.	South Korea	Scientific	2013
15	Life cycle assessment of light-emitting diode downlight luminaire: a case study	Tähkämö et al.	Finland	Scientific	2013
16	Comparative life cycle assessment (LCA) of streetlight technologies for minor roads in United Arab Emirates	Hadi et al.	United Emirates	Scientific	2013
17	A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs light emitting diode (LED): A case study	Principi e Fioretti	Italy	Scientific	2014
18	Life cycle assessment of incandescent, fluorescent, compact fluorescent and light emitting diode lamps in an Indian scenario	Sangwan et al.	India	Scientific	2014
19	Life cycle assessment of a fluorescent lamp luminaire used in industry: a case study	Tahkamo et al.	Finland	Scientific	2014
20	The environmental performance of fluorescent lamps in China, assessed with the LCA method	Tan et al.	China	Scientific	2015
21	Potential Long-Term Global Environmental Implications of Efficient Light-Source Technologies	Bergesen et al.	USA	Scientific	2015
22	The Effect of Consumer Behaviour on the Life Cycle Assessment of Energy Efficient Lighting Technologies	Yu et al	Australia	Scientific	2016

Even if the consolidation of the LCA can be considered relatively recent (Chen et al., 2014; Hou et al., 2015; Zanghelini et al., 2016), the number of papers is still little expressive, especially when we critically analyze the amount that has been published in international journals (15 articles). Although, this scenario may improve as it can be expected a considerably increase on publishing following the development of LED lamps in the next years. When it comes to recent technological development, generally there is a demand for evidences (to examine that they are better choices than the obsolete goods), and in this case, LCA studies may indicate whether the technology is evolving

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aligned with environmental impact reduction. This pattern can already be seen from the articles compiled in Table 1, in which LED lamps are present in 83% of the publications from 2012 to date.

Regarding that timeline, no publication was identified prior to 2006, whereas there is an expressive growth in 2012. Although this phenomenon cannot be considered a growth trend due to the small number of publications, this behavior follows a pattern that have already been reported in other bibliometric studies that analyzed LCA publications in a broader way (Chen et al., 2014; Hou et al., 2015). Accordingly, Zanghelini et al., (2016), considering a sampling of 51 LCA studies carried out in Brazil, demonstrated a significant increase from the year 2009 onwards.

3.1. Product System

The product system predominantly analyzed in LCA studies was the fluorescent lamp technology, present in 82% of the papers, followed by the LED and, incandescent lamps both present in 64% e 54% of studies, respectively (Table 2). The nature of most of these publications is comparative. In this sense, 66% of the articles compared different technologies (five authors compared: incandescent vs. fluorescent; three compared fluorescent vs. LED, and seven compared the all technologies: incandescent vs. fluorescent vs. LED). The remaining 32% of the articles comprises individual assessments, where LED lamps are more targeted with four publications, followed by three studies of fluorescent lamps. The incandescent technology does not have individual assessment.

Regarding the product system boundary, 19 studies covered the entire product life cycle - raw materials acquisition, production, use and final disposal – of the product. This behavior is at some degree, expected, mainly when considering recent developments in LCA methodology and even the recent maturing of consumers and industries with regard to life cycle thinking and environmental management in general.

Incandescent bulbs were already considered obsolete in the 90's. It generally awakes only comparative interests, serving as a base to establish the progress in terms of functionality and impact reduction in relation to the latest technologies. Fluorescent bulbs dominate the group of papers because, by the end of the last decade, it was the dominant technology widely encouraged by governments and organizations, and coincided with the development and spread of LCAs. The insertion of LED lamps on the market is quite recent, and many authors also point out that they will evolve significantly in the coming years. That is one of the reasons related to the minor number of studies directed to this product system. Similar to the previous technology, LED is associated strictly to studies comparing available technologies, in this case, with fluorescent and even incandescent bulbs (which still work as an illustrative reference). The trend is that LED lamps will dominate the market in the coming years, with accessible prices, growing in quantity and variations according to the maturity of the technology itself.

Naturally, the studies vary with respect to the analyzed lamps (see Table 2). This behavior is due to the extensive range of products on the market that are available to meet the diverse consumption demands, as illustrated by Hadi et al. (2013): the lighting technology varies widely in many aspects such as luminous efficacy, color rendering index, power, lifetime, etc. For instance, Tähkämö et al. (2013), Hadi et al. (2013) and DOE (2012b) conducted an LCA exclusively for LED lamps; however, they differ qualitatively and quantitatively with respect to: brand, applied power usage, finishing, application, among others.

DOE (2012b) evaluates one Philips Endura LED lamp with 12,5 Watts (LED lamp bulb), Tähkämö et al. (2013) analyze one 19-W LED downlight luminaire (flat lamp suitable for embedded use), while Hadi et al. (2013) addressed the LED lamp for lighting in public streets, larger and more robust than previous. This behavior continues to other studies that insert LED technology in comparisons and analyze other lighting possibilities (i.e. incandescent and fluorescent).

3.2. Functional Unit

As the system products examined in this group of articles, the functional unit (FU) is presented in different ways (Table 2). As it was anticipated by Welz et al, (2011) and DOE (2012a), this situation, occurs due to an inherent characteristic of LCA methodology: FU is influenced by system product function, which also varies according to the objectives and nature of the study. For example, Sangwan et al. (2014) traced the main objective of its LCA as - identify the highest environmental efficiency among the four lighting technologies used domestically in India. Therefore, the FU was defined in terms of luminous efficiency or provide a certain amount of illumination over a reference period of time: 36,375,000.00 lumen hour. On the other hand, Apisitpuvakul et al. (2008), aimed to assess the end of life (EoL) stage of fluorescent lamps, comparing alternatives of treatment and final disposal. In this case, the FU was established in terms of product, a unit of tubular lamp, complemented by information as power (36 Watts), weight (200 grams) and service life (13,600 hours).

Table 2.Product systems and functional units

	INC.*	FLU.*	LED*	Functional Unit
1	X	X		A 18W compact fluorescent lamp (≈ 100W incandescent)
2		X		Tubular lamp (36W, 200 g and 13.600 hours of lifetime)
3	X	X		10,000 hours of lighting with 1600 lumens
4	X	X		10,000 hours of lighting (range between 500 and 900 lumens)
5	X	X	X	range of 345 to 420 lumens (25,000 hours)
6	X	X	X	1 million lumen.hour of useful light
7	X	X	X	1 Mega-lumen.hour (Mlm-hr) of light

(Continues)

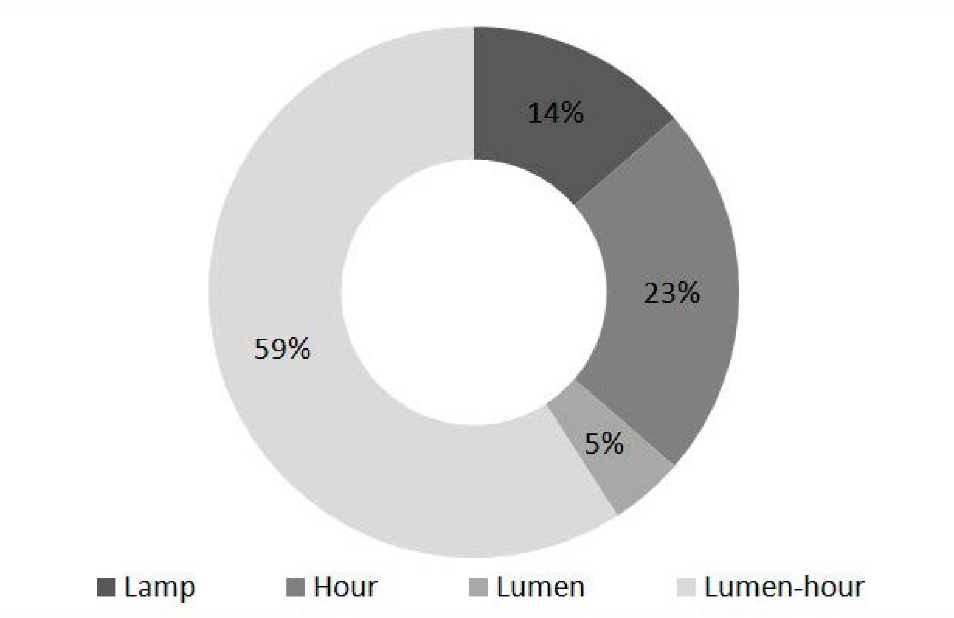
8	X	X		1 hour of lighting
9			X	100,000 hours of light
10	X	X		10,000 hours of lighting (800-850 lumens)
11		X	X	100 lumens, for 3 hour a day, during one year
12	X	X	X	20 million lumen.hour
13			X	20 million lumen.hour
14	X	X	X	50,000 hours of lighting
15			X	19W - 50,000 hours of lighting with 1140 lumens and CRI ≈ 80.
16			X	60,000 hours of lighting
17		X	X	1 lumen for 50,000 hours and/or 1 lux for 50,000 hours of lighting
18	X	X	X	36,375,000 lumen-hour
19		X		20 years and 4,000 hours/year, with 8,600 lumens (688 Mlm-hour).
20		X		1 unit CFL (and 1,25 unit LFL)
21	X	X	X	1 mega lumen-hour (Mlm-hr) of light.
22		X	X	200 million lumen hours of lighting

* INC.= incandescent; FLU. = fluorescent; LED = light emitted diode

Besides the variability in terms of function definition of the lamps, the FU was influenced by two different characteristics used by authors related to the product performance: (i) production efficiency measured in hours of lighting, and (ii) illumination intensity (Table 2). Example of the first concept can be found in Weltz et al., (2011), Elijošiutė et al. (2012), Lim et. al., (2013) and Hadi et al. (2013), while the second feature is present in OSRAM (2009). Other authors applied a mixed relationship, relating lighting efficiency over a period of time, also known as luminous flux. Examples are Ramroth, (2008), Quirk (2009), DOE (2012a, 2012b), Tähkämö et al. (2013), Principi and Fioretti (2014), Sangwan et al. (2014) and Tahkamo et al. (2014). Thus, the prevailing FU in LCA of lamps are: hour (23% of the articles), and the lumen-hours (59% of the total amount), with variations for product unit (14%) or only luminous intensity (lumen) (5%) as shown in Figure 1. Similar results were found by

DOE (2012a): the functional units employed varied between studies analyzed, however, the three most common were hours of life of lamps, lamp (unit) and lumen-hours.

Fig.1. Functional units applied in LCA lamps



A correct definition of FU is always a matter of debate in the scientific community and by the LCA practitioners (Choudhary et al., 2014; Prudêncio da Silva et al., 2014; Reap et al., 2008; Tyszler et al., 2014). This occurs (i) by the aforementioned potential influence that this definition may cause at the results, and (ii) because FU definition is somewhat flexible

To discuss which FU best suits for LCA of lamps, both concepts must be confronted: the function of lamps, and based on this, the best performance

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indicator to fulfill that function. If we establish a complete life cycle (i.e. from cradle to grave), which was dominant in our sampled publications, the most relevant function of a lamp is the light production in a reference period, after all, when a consumer buys a lamp for purposes of home lighting, he/she expect lighting at an intensity (previous defined or not). Therefore, we seek the light intensity in the lamps, and the completion of the period (e.g. a certain amount of hours) is aligned with the use step of the product system. Thus, the most suitable FU is the intensity for an amount of time, where lumen-hours is the most commonly used to describe this service (DOE, 2012a).

3.3. Results, comparisons and influences

The results presented in the publications, as anticipated and expected, are often influenced by goal and scope variations of each LCA. Consequently, the comparisons are affected. In the case of lamps, the results are influenced more pronouncedly in terms of LCIA methods (more specifically, by defining midpoint or endpoint approaches), impact categories (large variation that exists at both levels of cause-effect chain), product system (e.g. street light bulb VS household light bulb) and functional unit (as shown in Table 2). Thus, results can vary considerably, for example, 0.32 kg of CO2 equivalent (Principi and Fioretti, 2014) to 3,300 kg CO2 equivalent (Hadi et al, 2013) for LED LCAs, as can show similarities, 115.4 kg of CO2 equivalent (OSRAM, 2009) to 112 kg CO2 equivalent (Tähkämö et al., 2013). Other methodological definitions (e.g. boundaries and inventory) do not differ significantly, and therefore do not imply the same degree of influence on the results.

Table 3 shows the results of the LCAs for climate change impact, the most commonly used impact category in the selected publications. Some of the results were left aside because they (i) were calculated at endpoint level (e.g. Parson, 2006; Apisitpuvakul et al, 2008), (ii) omit full values of product system (Quirk, 2009), or (iii) even focus on other impact categories at midpoint level (Lim et. al., 2013).

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Table 3.LCIA results for Climate Change (midpoint level)

INC.	FLU.	LED	LCIA Method	
3	734.00 kg CO2 eq.	184.00 kg CO2 eq.	-	IPCC GWP 100a
4	100 %	29 %	-	IMPACT 2002/ LUCAS
5	567.50 kg CO2 eq.	115.20 kg CO2 eq.	115.40 kg CO2 eq.	CML
7	36.52 kg CO2 eq	6.41 kg CO2 eq	9.21 kg CO2 eq	CML 2001
8	100 %	22 %	20%	IPCC GWP
10	3,876.03 kg CO2 eq.	916.97 kg CO2 eq.	-	CML 2001
13	1,031.64 kg CO2 eq.	304.88 kg CO2 eq.	251.02 kg CO2 eq.	CML 2001/EDIP2003
15	-	-	112.00 kg CO2 eq.	CML 2001
16	-	-	3,300.00 kg CO2 eq.	Ecoindicator 99 (H)
17	-	0.54 kg CO2 eq.	0.32 kg CO2 eq.	IPCC GWP
18	2,815.07 kg CO2 eq.	500.70 kg CO2 eq.	576.10 kg CO2 eq.	CML
19	-	253.2 kg CO2 eq.	-	CML 2001
20	-	252 - 283 kg CO2 eq.	-	CML 2001/ Ecoindicator 99
21	60.00 kg CO2eq.	16.00 kg CO2eq.	12.00 kg CO2eq.	ReCiPe 2008
22*	-.	9E-11 world person eq.	6E-11 world person eq.	CML 2001

INC.= incandescent; FLU. = fluorescent; LED = light emitted diode
* Values from the scenario of 2010.

When similar product systems are compared from different studies with different FUs, the LCIA results were affected. For instance, when comparing the LCA outcomes from studies n.20 and n.7 regarding the fluorescent lamps. Both used CML 2001 as the LCIA method and similar scope definitions, e.g. cradle to grave, recycling and landfilling as final disposal, power of system products are near (20W and 23W for study n.20 and n.7 respectively) and the inputs/outputs in the LCI are close in terms of magnitudes (quantities of each flow). Besides the FU defined by each study, the most important difference in scope is the electricity grid considered in the use phase. While [7] reflects the United Kingdom (UK); [20] represents the Chinese (CN) conditions.

Analyzing the impacts from the electricity grid of each country shows that the difference is up to 2 times superior for Chinese grid (i.e. the GWP for Electricity, high voltage, at grid/GB U and Electricity, high voltage, at grid/CN U with CML2001 at SimaPro, are 0.59 and 1.16 kg of CO2 eq./kW.h, respectively). However, the outcomes for climate change impacts from the studies are 6.41 kg CO2 eq in GB and 283 kg CO2 eq in CN. This difference is up to 44 times superior to the Chinese lamps. The main reasons for this high variation are due to the different FU used by the authors. While paper n.7 analyzed 1 Megalumen.hour (Mlm-hr) of light, study n.20 assessed 1 unit of the product (CFL). When the FU are set up to represent the same function (15,000 Lumen-hour) the results are 0.096 kg CO2 eq. for GN and 0.32 kg CO2 eq. for CN (see table 4), a difference up to only 3 times superior.

However, even with the different results between the studies, a pattern is easily perceived: when compared, the ranking of preferable technology in terms of impacts reduction did not change across the publications, i.e. incandescent lamps have a higher emission than fluorescent lamps, which in turn, emit the same amount or are above LED lamps emissions. Incandescent lamps have shown 5 times higher emissions in comparison to fluorescent lamps and LED. According to OSRAM (2009), incandescent lamps always have very high values in terms of GHG emissions, while fluorescent and LED have similarly low results. This phenomenon occurs because the fluorescent lamps consume five times less electricity in the use phase compared to incandescent (Parson, 2006). All the comparative studies indicate this condition (Michaud and Belley, 2008, DEFRA, 2009; Ramroth, 2008; OSRAM, 2009; Weltz, et al., 2011; Elijošiutė et al, 2012; DOE, 2012b,Tähkämö et al., 2013; Hadi et al., 2013; Principi e Fioretti, 2014; Sangwanet al., 2014; Tahkamo et al., 2014; Bergesen et al., 2015; Tan et al., 2015; Yu et al., 2016).

DOE (2012b) and OSRAM (2009) already indicate that LED lamps will be able to reduce more emissions when achieving its technological apex. DOE (2012b) points to the constant improvement of these lamps over the years, which provided a reduction of 92% in GHG emissions from 2007 to 2011. According to the same study, further improvements should focus on increasing the durability of the lamps (to provide a positive balance on the LCA stages of raw material acquisition and final disposal) and increase conversion efficiency (watts to lumens) reducing energy consumption in the use phase. However, as pointed out by DOE (2012b) these positive alternatives regarding to climate change, can result in tradeoffs between impact categories. The publication indicates that some categories are still presenting negative balances compared to fluorescent lamps; i.e. hazardous waste landfill impact category (from EDIP 2003) indicates that LED lamps show higher impacts than compact fluorescent lamps, because of the large amount of aluminum in the product.

The use phase represents a range that varies from 88% to 99% of impacts, characterizing it as the main hotspot in lamps life cycle. According to OSRAM (2009), less than 2% of the consumed energy is related to manufacturing step and final disposal (treatment) of obsolete lamps. This behavior is partly because use phase is the largest energy consumption point in life cycle steps, which also explains overall better performance of fluorescent and LED (lower ratio watts.lumens-hour). Sensitivity analysis were performed by Tähkämö et al. (2013), Principi and Fioretti, (2014), Tahkamo et al. (2014) and Tan et al. (2015) to examine the variation on final results when changing possible energy grid. The study of Tan et al. (2015) demonstrates that a “clean” energy mix can reduce by 19% the overall impacts related to lighting whereas Tähkämö et al. (2013), reached a 90% of reduction comparing Finnish electricity grid to a hydropower energy source. Thus, the authors indicate that amongst possibilities, hydropower energy would reach better reductions. Principi and Fioretti (2014) confirms this conclusion, emphasizing the importance of renewable energies for optimal results.

In order to carry out a comparison between studies, an equalization of climate change values was performed, converting all possible studies into a common FU. Noteworthy that, if comparisons are made strictly respecting

FU as defined by authors (i.e. without complementary information about the performance of the product), conclusions about the environmental preferable product system could be unfair. In this sense, although the FU in LCA of lamps are diverse and often did not represent correctly the function of the product system (see Figure 1), the description of technical indicators (or even, use phase description inside system boundaries) allow one to infer comparison possibilities.

Table 4.Results for climate change (in kg CO2 eq.), equalized to 15,000 lumens.hour

INC.	FLU.	LED	
3	0.68	0.17	-
5	0.85	0.17	0.17
7	0.55	0.096	0.14
10	7.04	1.67	-
13	0.77	0.23	0.19
15	-	-	0.03
16	-	-	0.10
17	-	0.16	0.10
18	1.16	0.21	0.24
19	-	0.069	-
20	-	0.29 – 0.32	-
21	0.90	0.24	0.18

* INC.= incandescent; FLU. = fluorescent; LED = light emitted diode

Analyzing Table 4, it is possible to perceive a similar condition on results in orders of magnitude of results, exception made to the publication no.10 that showed values higher than average, and papers 15 and 19 which showed similar results and below average. The climate change (CC) values equalized for incandescent lamps varies from 0.55 kg CO2 eq. (DEFRA, 2009) to 7.04 (Elijošiutė et al., 2012) a 1,035% of variation. Despite of CC presented by

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Elijošiutė et al., (2012), the variation decrease to 70%, ranging from 0.68 to 1.16 kg CO2 eq. (Sangwan et al., 2014). Other three values are intermediate, being very similar to DEFRA, (2009) – 0.68, 0.77 and 0.85 kg CO2 eq. from Ramroth (2008), DOE (2012b) and OSRAM (2009) respectively.

The reason why publication no.10 presents values far beyond the others, despite of using the inventory from Ramroth (2008), similar FU and boundaries and the same LCIA method for climate changes (GWP 100 years versus CML 2001) is not clear. There is lack of information that can lead one to find a possible argument. This paper presents the same discrepancy when interpreting Fluorescent CC (see third column at Table 4).

When verifying fluorescent impacts on CC, we can attest the decrease on environmental impacts if compared to incandescent lamps. Despite the large increase in complexity in terms of materials and production, fluorescent is strongly preferred to incandescent (Parson, 2006). All comparative publications indicate this behavior and even those, which addressed fluorescent lamps only, also demonstrate impact reduction.

Apart from the aforementioned discrepancy from Elijošiutė et al. (2012), other fluorescent CC impact varies from 0.069 to 0.32 kg CO2 eq. (~ 460% of variation). The explanation for this range may be the different energy grids used in modeling by each author. Being the use phase the main hotspot for this product category due to energy consumption, any difference in grids may result in greater influence on final CC impacts. For instance, Tahkamo et al. (2014) assessed the use phase with Finnish energy grid (0.392 kg CO2 eq. per kWh), Osram (2009) applied the European average power mix (according to authors, 1,0 kWh has a CO2 output of 0.55 kg) whereas Tan et al. (2015) used electricity mix in two different regions, Beijing and China.

Other reasons for the variation in the results can be the differences on LCA scope definition due to differences on system products, including size and type (e.g. compact fluorescent lamp, linear fluorescent lamp), inventory (primary and secondary data) and EoL treatment (e.g. landfilling, recycling). All studies analyzed lamps from cradle to grave applying CML or IPCC with different characterization factors (e.g. IPCC, 2007) set a characterization factor for 1,0 kg of CH4 that represent 23 times 1.0 kg of CO2, while in IPCC (2013) 1,0 kg of CH4 represents 30 kg of CO2 (fossil)),as the LCIA method (see Table 3). The recent study by Tahkamo et al. (2013) stands out the average (in terms of magnitude), although, differently from Elijošiutė et al. (2012), it demonstrates CC lower than all others, 0.069 kg CO2 eq. In this case, apart from the reasons aforementioned, other possibility is described by the authors when system product was compared to literature values - the luminaire in this study has a more simple structure, lower system weight, higher light output (Mlmh) (Tahkamo et al., 2013).

If compared to fluorescents, LED lamps have demonstrated similar results or slightly lower CC, ranging from 0.03 to 0.24 kg CO2 eq. The reasons that drive the variations on CCs are similar to fluorescent lamps, including energy grid differences and scope peculiarities. As described before and aligned with many authors, LED lamps are (technologically) evolving, and its development has not yet reached the apex (like fluorescent lamps), in a way that this system product will further reduce its impacts.

In a broader view, after equalized, LED CC impacts from different studies are closer to each other if compared with variations between fluorescent and incandescent lamps CC results. This behavior may indicate a higher similarity on defined scopes (in LED LCA studies) including LCI and product performance. One possible explanation may be related to LCA maturity itself. LED LCA studies are more recent than the others, sometimes facing new data quality requirements and enjoying methodological developments and strengths. Concomitantly, new technological companies are created in an environment that requires more control of its inputs and outputs.

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4. Conclusions

This paper aimed to review the group of LCAs addressed to assess lamps. In this group we found three major different kinds of lamps (or category of lamps): incandescent, fluorescent and light emitting diode (LED).

Regarding to the definition of the system boundary in our sample of studies, this decision had minor influence on the results since the greatest impact of lamps was at the use stage, which was considered in all the studies

LCA studies have shown diverse scope possibilities resulting in the most different order of results. Nevertheless, the aforementioned preference pattern is always perceptible: for Climate Change impact category, LED is equal/ preferable than fluorescent that is preferable than incandescent. Additionally, the use phase is the hotspot for any study because of energy consumption during the long period of life span.

However, direct comparison of the product systems is impaired when one of the main scope inconsistencies are the different functional units (FU) used by different authors. In the group of papers, FU varied from product unit to product performance (e.g. lamp unit to an amount of lumen.hour per a certain life span). In this context, although FU varied, complementary information given by authors enables one to understand products performance and convert all FU into a common basis (based on main function: provide light at a given intensity for a period of time). Other scope definitions have shown similar adoptions, including system boundaries (generally, from cradle-to-grave) and life cycle impact assessment (LCIA) method (for instance, dominated by CML or IPCC GWP 100 years for climate changes impact category).

Thus, equalizing FUs into product performance (15,000 lm-hour) and assuming proportionality of impacts, it was possible to compare environmental indicators in an equal basis. Results related to climate change impact category were used in order to illustrate product comparisons. The equalization allowed to perceive similar values related to product categories (especially in order of magnitude). In contrast to expected, comparison was possible (but only, using complementary information) even with the high variety in FU definitions. Therefore, proportionality is an assumption that may allow a comparison, although it should be considered carefully, as may not represent accurately product conditions.

Complementary, as the use phase is the main hotspot due to energy consumption, variations on CC impacts are more likely to be related to different energy grids applied to each reality. In this case, special attention should be destined to energy grid description to allow a better perception by LCA practitioners and other stakeholders.

References

ABNT - Associação Brasileira de Normas Técnicas. ABNT NBR ISO/CIE 8995-1: 2013: Iluminação de ambientes de trabalho Parte 1: interior. Rio de Janeiro, versão digital, 2013.

APISITPUVAKUL, W.; PIUMSOMBOON, P.; WATTS, D.J.; KOETSINCHAI, W. LCA of spent fluorescent lamps in Thailand at various rates of recycling. Journal of Cleaner Production, 2008, vol. 16, p. 1046-1061.

ASARI, M.; FUKUI, K.; SAKAI, S. Life-cycle flow of mercury and recycling scenario of fluorescent lamps in Japan. Science of The Total Environment, 2008, vol. 393, nº1, p. 1–10.

BERGESEN, J. D.; TÄHKÄMÖ, L.; GIBON, T.; SUH, S. Potential long-term global environmental implications of efficient light-source technologies. Journal of Industrial Ecology, 2016, vol. 20, p.263-275.

BEZERRA, F. L; FAVACHO, C. H; SOUZA, R. N; DE SOUZA, C. R. B. Towards supporting systematic mappings studies: an automatic snowballing approach, In: Proceedings of the XXIX Simpósio Brasileiro de Banco de Dados (SBBD), 2014, Curitiba, PR.

BIELEK, M; BIELEK, B; HIRES, J. Technology in architecture: low energy building versus green and sustainable building. Advanced Materials Research, 2013, vol. 649, p. 207-210.

BORUCKE, M., MOORE, D., CRANSTON, G., GRACEY, K., IHA, K., et al.. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecological Indicators, 2013, vol. 24, p. 518–533.

BRASIL, Lei n 12.187, de 29 de Dezembro de 2009, Política Nacional sobre Mudança do Clima– PNMC, D.O.U. DE 29/12/2009, 109 (Edição Extra)

_______, Lei n 12.305, de 02 de Agosto de 2010, Política Nacional de Resíduos Sólidos – PNRS, D.O.U. DE 03/08/2010, Seção 2.

________, Ministério do Meio Ambiente – MMA. Plano de Ação para Produção e Consumo Sustentáveis – PPCS, 2011. Available from Internet: <http://www.mma.gov.br/responsabilidade-socioambiental/producao-e-consumo-sustentavel/plano-nacional>.

BROOME, M.E. Integrative literature reviews for the development of concepts. In Concept Development in Nursing, 2º ed. (Rodgers B.L. & Knafl K.A., eds), W.B. Saunders Co., Philadelphia, PA, 1993, p. 231–250.

CHEN, H.; YANG, Y; YANG, JIANG, W; ZHOU, J.A bibliometric investigation of life cycle assessment research in the web of science databases. International Journal of Life Cycle Assessment, 2014, vol.19, p. 1674–1685.

CHERUBINI, E; RIBEIRO, P. Projeto Diálogos Setoriais Brasil: União Europeia sobre Análise do Ciclo de Vida: Brasília, 2015.171 p.

CHOUDHARY, S.; LIANG, S.; CAI, H.etal. Reference and functional unit can change bioenergy pathway choices. International Journal of Life Cycle Assessment, 2014, vol.19, p. 796–805.

CONAMA - Conselho Nacional do Meio Ambiente. Resolução nº 297/2002. Estabelece os limites para emissões de gases poluentes por ciclomotores, motociclos e veículos similares novos. Data da legislação: 26/02/2002. Publicação DOU nº 051, de 15/03/2002, p. 86-88.

CPUC - California Public Utilities Commission. California long term energy efficiency strategic plan. Adopted by the CPUC in February of 2008, Available from Internet: http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=5305.

DALE, A. D., BILEC, M. M., M; MARRIOTT, J; HARTLEY, D; JURGENS, C; ZATCOFF, E. Preliminary Comparative Life-Cycle Impacts of Streetlight Technology. Journal of Infrastructure Systems, 2011, vol. 17, nº 4, p.193-199.

DEFRA. Life Cycle Assessment of Ultra-Efficient Lamps, 2009. Navigant Consulting Europe, Ltd., A research report completed for the Department for Environment, Food and Rural Affairs, May 2009. Available from Internet: <http://randd.defra.gov.uk/Document.aspx?Document=EV0429_8060_FRP.pdf>.

DOE. Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 1: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps. US Department of Energy (DoE), 2012a. Washington DC, Available from Internet: <http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf>.

_______. Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products, Part 2: LED Manufacturing and Performance.US Department of Energy (DoE), 2012b. Washington DC, Available from Internet: <http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21443.pdf>.

DURLINGER, B; REINDERS, A; TOXOPEUS, M. A comparative life cycle analysis of low power PV lighting products for rural areas in South East Asia. Renewable Energy 41, 2012, p. 96 – 104.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Accessed on January 2017. Available at <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060>.

_______, 2003. Second ECCP Progress Report Can we meet our Kyoto targets? Second ECCP Progress Report. Accessed on January 2017. Available at:<https://ec.europa.eu/clima/sites/clima/files/eccp/docs/second_eccp_report_en.pdf>.

_______, 2005. Directive 2005/32/EC of the European Parliament and of the Council; establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/ EC of the European Parliament and of the Council.

_______, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Accessed on January 2017. Available at <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098>.

ECKELMAN, M.J; ANASTAS, P.T; ZIMMERMAN, J. B. B. Spatial Assessment of Net Mercury Emissions from the Use of Fluorescent Bulbs. Environmental Science & Technology, 2008, vol. 42, p. 8564-8570.

ELIJOŠIUTĖ, E.; BALCIUKEVIČIŪTĖ, J.; DENAFAS, G. Life Cycle Assessment of compact fluorescent and incandescent lamps: comparative analysis. Environmental Research, Engineering and Management, 2012, vol. 3, nº 61, p. 65-72.

EPA, 2009. Scope 1 and 2 GHG emissions reduction goal. EPA's Greenhouse Gas Reduction Goals and Strategies, 2.

HADI, S. A.; AL KAABI, M. R.; AL ALI, M. O.; ARAFAT, H. A. Comparative Life Cycle Assessment (LCA) of street light technologies for minor roads in United Arab Emirates. Energy for Sustainable Development, 2013, vol. 17, p. 438-450.

HOEKSTRA, A.Y.; WIEDMANN, T. O. Humanity's unsustainable environmental footprint. Science, 2014, v. 344, n. 6188, p. 1114-1117.

HOU, Q.; MAO, G.; ZHAO, L.; DU, H.; ZUO, J. Mapping the scientific research on life cycle assessment: a bibliometric analysis. International Journal of Life Cycle Assessment, 2015, vol. 20, p. 541-555.

HU, Y; CHEN, H. Mercury risk from fluorescent lamps in China: Current status and future perspective. Environment International, September 2012, vol. 44, nº 1, p. 141–150.

IEA - International Energy Agency. Key World Energy Statistics. International Energy Agency, 2014, 82 p.

IPCC, Intergovernmental Panel on Climate Change, 2007, Climate Change 2007: The Scientific Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [S. Solomon et al. (eds)], Cambridge Univ. Press, New York.

IPCC, Intergovernmental Panel on Climate Change, 2013. Summary for Policymakers, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stoker, T.F., D. Qin, G-K. Plattner, et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York.

ISO 14040: 2006(a), Environmental management: Life cycle assessment: Principles and framework. Available from Internet: <http://www.iso.org/iso/catalogue_detail?csnumber=37456>.

ISO 14044: 2006(b), Environmental management: Life cycle assessment: Requirements and guidelines. Available from Internet: <http://www.iso.org/iso/home/store/catalogue_tc/catalogue_detail.htm?csnumber=38498>.

JALALI, S. and WOHLIN, C. Systematic literature studies: database searches vs. backward snowballing. In Proceedings of the ACM-IEEE International Symposium on Empirical Software Engineering and Measurement, ESEM'12, Lund, Sweden, 2012, p. 29–38.

LIANG, P; FENG, X; ZHANG, C; ZHANG, J; CAO, Y; YOU, Q; LEUNG, A.O.W; WONG, M; WU, S. Human exposure to mercury in a compact fluorescent lamp manufacturing area: By food (rice and fish) consumption and occupational exposure. Environmental Pollution, March 2015, vol. 198, p. 126–132.

LIM, S.; KANG, D.; OGUNSEITAN, O.A.; SCHOENUNG, J.M. Potential Environmental Impacts from the Metals in incandescent, Compact Fluorescent Lamp (CFL), and Light-Emitting Diode (LED) bulbs. Environmental Science and Technology, 2013, vol. 47, p. 1040-1047.

LINDSTROM, Timothy; MIDDLECAMP, Catherine. A Triple-Bottom-Line Analysis of Energy-Efficient Lighting. In: Learner-Centered Teaching Activities for Environmental and Sustainability Studies. Springer International Publishing, 2016. p. 187-193.

LISTER, G.G; LAWLER, J.E; LAPATOVICH, W.P; GODYAK, V.A. The physics of discharge lamps. Reviews of Modern Physics, 2004, vol. 76, p. 541.

MENDES, K. D. S.; SILVEIRA, R. C. C. P.; GALVÃO, C. M. Revisão integrativa: método de pesquisa para a incorporação de evidências na saúde e na enfermagem. Texto & Contexto Enfermagem, 2008, vol. 17, nº 4, p. 758-764.

MICHAUD, R., BELLEY, C. 2008. Comparative life cycle assessment of light bulbs: Incandescents and Compact Fluorescents. Final Report. CIRAIG -Interuniversity Research Centre for the Life Cycle of Products, Processes and Services. École Polytechnique de Montréal.

MINISTÉRIO DE MINAS E ENERGIA – MME. Balanço Energético Nacional, Brasil, MME, 2013. Available from Internet: <https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2013.pdf>.

OECD/IEA. Organization for Economic Co-operation and Development and International Energy Agency. World Energy Outlook, 2006. Head of Publications Service, Paris, France, 2006. Available from Internet: <https://www.iea.org/publications/freepublications/publication/ weo2006.pdf>.

OSRAM. Life Cycle Assessment of Illuminants: a comparison of light bulbs, compact fluorescent lamps and LED lamps. OSRAM, SIEMENS, November, 2009. Available from Internet:<http://www.indiaenvironmentportal.org.in/files/OSRAM_LED_LCA_Summary_November_2009.pdf>.

PARANÁ. Richa lança programas que ajudam a economizar energia. Seção Mais Economia. Agência de Notícias do Paraná, junho 2015. Available from Internet:<http://www.aen.pr.gov.br/modules/noticias/article php?storyid=84690>

PARSON, D. The environmental impacts of compact fluorescent lamps and incandescent lamps for Australian conditions. Journal of the Society for Sustainability and Environmental Engineering, Institution of Engineers, Australia, 2006, vol. 7, p. 8-14.

PRINCIPI, P., FIORETTI, R. A comparative Life Cycle Assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED) – a case study. Journal of Cleaner Production, 2014, vol. 83, p. 96-107.

PROCEL - Programa Nacional de Conservação de Energia Elétrica. Dicas de economia de energia. PROCEL Info, 2006. Available from Internet: <http://www.mma.gov.br/estruturas/a3p/_arquivos/decreto_45643_36.pdf>.

PRUDÊNCIO DA SILVA, V.; VAN DER WERF, H. M. G.; SOARES, S. R.; CORSON,M. S. Environmental impacts of French and Brazilian broiler chicken production scenarios: an LCA approach. Journal of Environmental Management, 2014, vol. 133, p. 222–231.

QUIRK, I. Life-Cycle assessment and policy implications of energy efficient lighting technologies. Lighting Life-Cycle Assessment, 2009.

RAMROTH, L. Comparision of Life-Cycle Analyses of compact fluorescent and incandescent lamps on rated life of compact fluorescent lamps. From the Reports of Rocky Mountain Institute, 2008.

REAP, J.; ROMAN, F.; DUNCAN, S.; BRAS, B.A survey of unresolved problems in life cycle assessment. Part 1: goal and scope and inventory analysis. International Journal of Life Cycle Assessment, 2008, vol. 13, p. 290–300.

RHEE, S; CHOI, H; PARK, H. Characteristics of mercury emission from linear type of spent fluorescent lamp. Waste Management, June 2014, vol 34, nº 6, p. 1066–1071.

SANGWAN, K.S., BHAKAR, V., NAIK, S., ANDRAT, S.N. Life cycle assessment of incandescent, fluorescent, compact fluorescent and light emiting diode lamps in an India scenario. 21st CIRP Conference of Life Cycle Engineering, 2014, p. 467-472.

SÃO PAULO. Decreto nº 45.643, de 26 de janeiro de 2001. Dispõe sobre a obrigatoriedade da aquisição pela Administração Pública Estadual de lâmpadas de maior eficiência energética e menor teor de mercúrio, por tipo e potência, e dá providências correlatas. Available from Internet: <http://www.mma.gov.br/estruturas/a3p/_arquivos/decreto_45643_36.pdf>.

SCHAU, E. M. and FET, A.M. LCA studies of food products as background for environmental product declarations. International Journal of Life Cycle Assessment, 2008, vol. 13, p. 255–264.

SHAHZAD K., REHAN M., ISMAIL I.M.I., SAGIR M., TAHIR M.S., BERTOK B., NIZAMI A. Comparative life cycle analysis of different lighting devices. Chemical Engineering Transactions, 2015, vol. 45, p. 631-636.

TÄHKÄMÖ, L., BAZZANA, M., RAVEL, P., GRANNEC, F., MARTINSONS, C., ZISSIS, G. Life cycle assessment of light-emitting diode downlight luminaire: a case study. International Journal of Life Cycle Assessment, 2013, vol. 18, p. 1009 – 1018.

TÄHKÄMÖ, L.; BAZZANA, M.; ZISSIS, G.; PUOLAKKA, M.; HALONEN, L. Life cycle assessment of a fluorescent lamp luminaire used in industry–a case study. Lighting Research & Technology, 2014, v. 46, n. 4, p. 453-464.

TAN, Q., SONG, Q., LI, JINHU, I. The environmental performance of fluorescent lamps in China, assessed with the LCA method. International Journal of Life Cycle Assessment, 2015, vol. 20, p. 807-818.

TRIFUNOVIC, J; MIKULOVIC, Z; DJURISIC, M; DJURIC, M; KOSTIC. Reductions in electricity consumption and power demand in case of the mass use of compact fluorescent lamps. Energy, 2009, vol. 34, p. 1355–1363.

TYSZLER, M.; KRAMER, G.; BLONK, H. Comparing apples with oranges: on the functional equivalence of food products for comparative LCAs. Int J Life Cycle Assess, 2014, vol. 19, p. 1482–1487.

UN - United Nations. Kyoto Protocol to the United Nations Framework Convention on Climate Change. 1998. 21p.

R. Latino-amer. em Aval. do Ciclo de Vida, Brasília, v. 1, n. 1, p. 9-44, jul./dez. 2017

______. Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009. Part Two: Action taken by the Conference of the Parties at its fifteenth session. United Nations, FCCC/CP/2009/11/Add.1 30 March 2010, 30.

WELZ, T., HISCHIER, R., HILTY, L.M. Environmental impacts of lighting technologies: life cycle assessment and sensitivity analysis. Environmental Impact Assessment Review, 2011, vol. 31, p. 334-343.

WWF - World Wildlife Fund., 2014. Living Planet Report 2014: species and spaces, people and places, WWF International, Gland, Switzerland, 180 p.

_______. World Wildlife Fund. 2016. Living Planet Report 2016. Risk and resilience in a new era. WWF International, Gland, Switzerland. 149 p.

YU, Z. Y.; SOO, V. K.; DOOLAN, M. The effect of consumer behaviour on the life cycle assessment of energy efficient lighting technologies. Procedia CIRP, 2016, v. 40, p. 185-190.

ZANGHELINI, G.M; SOUZA JUNIOR, H.R.A; KULAY, L; CHERUBINI, E; RIBEIRO, P.T; SOARES, S.R. 2016. A bibliometric overview of Brazilian LCA research. The International Journal of Life Cycle Assessment, May 2016, v. 21, nº 12, p. 1759-1775.

ZHANG, J; CHEN, S; KIM, J; CHENG, S. Mercury flow analysis and reduction pathways for fluorescent lamps in mainland China. Journal of Cleaner Production, October 2016, vol. 133, nº 1, p. 451–458.