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Sustainability constraints in techno-economic analysis of general lighting retrofits

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ABSTRACT

Several governmental programs seek the adoption of measures to promote energy efficiency through the substitution of old incadescent light bulbs by CFLs (compact fluorescent lamps). However, fluorescent lamps emit UV, pollute the environment with mercury and rare earths if disposed recklessly. These also present higher performance degradation levels, lower efficiency and shorter lifespans if compared to LEDs (light emitting diodes), which require higher initial investment. We advocate that retrofits shall have a broader scope, pursuing beyond the achievement of short term efficiency and profitability, but the long term sustainability. Thus, selecting which technology to use in a retrofit requires thorough feasibility study comparing alternatives. We propose a framework using equivalent annual costs (EAC) as a metric for comparing substitute technologies in lighting retrofits, considering sustainability constraints as reverse logistics, waste management, performance degradation, lifespan, luminous efficiency and energy prices. The results of a simulated general lighting retrofit comparing LED tubes, CFLs and fluorescent tubulars demonstrate CFL as the highest annual cost and toxic waste disposal in most scenarios, fluorescent tubular as the most economic alternative, but if their lifespans shorten, LED prices drop or achieve higher efficiency LED becomes the most sustainable and economically attractive alternative.

1. Introduction

Energy efficiency has become a major goal for most countries. According to Parker [1] no single technology can provide a long-term solution to address actual energy problems. Models utilized in many countries are similar, using public funding to retrofit lighting systems, motors, air-conditioning and ventilation, among other efficiency upgrades [2]. However, most actions currently implemented are merely aiming the increase of energy efficiency through the substitution old incadescent light bulbs by CFLs (compact fluorescent lamps). We present in Fig. 1 the results of the national energy efficiency program in Brazil (Procel), for the year of 2011. Nearly 32% of retrofits were addressed to substitution of incadescent light bulbs for CFLs. The newer lighting technology HB-LED (high-brightness light emitting diode) was detected in 4.3% of the projects [2,3].

Literature survey showed that 23 W CFL, 21 W EEFL (electrode less fluorescent lamps), 18 W fluorescent tube or 15 W LED lamps emit almost the same quantity of luminous flux (lumens) as a standard 100 W incandescent lamp. However, tubes, LED, CFL and EEFL lamps worsen electric power quality of low voltage networks due to high current harmonic distortions (THD) and poor power factors (PF) [3]. Fluorescent lamps emit UV and may pollute the environment with mercury and phosphorus at the end of their life cycle [5]. Despite these issues, the lighting market for more efficient sources, as CFLs and LEDs, is in expansion. The last poll regarding electricity Brazilian consumers profile Sinpha [3] showed that almost 50% of Brazilian homes were still using incadescent light bulbs that ought to be replaced (Fig. 1b). The adoption rate of innovations in lighting also varies geographically as presented in Fig. 2. Many countries are in process of banning (e.g. Japan, Canada, Mexico) or have already banned (e.g. Cuba, Argentina, Australia) the use of incadescent light bulbs [6]. We present rough data regressions based on statistics from [7–9] in Figs. 2 and 3 in order to illustrate forecasting of the Brazilian lamp market, therefore a preview of the lighting systems retrofits that will come along.

A 9 W CFL includes about 2.5 mg of mercury in its composition [10], having toxicity characteristic leaching procedure (TCLP) of 0.004 mg of mercury per liter, bellow the maximum allowable TCLP concentration for mercury in USA (0.200 mg/l) and Canada (0.100 mg/l) [11]. Looking at the cradle-to-cradle picture, a CFL installed used during 5 h a day will last about 2.5 years. Brazilian consumers possessed 191.5 millions of CFL units in 2007 [9]. Thus, the waste generated in 2009 by these retrofits produced around 478.75 kg of mercury, and it will reach about 1.5 tons per year of this toxic waste released in the environment by 2020 if the bulbs

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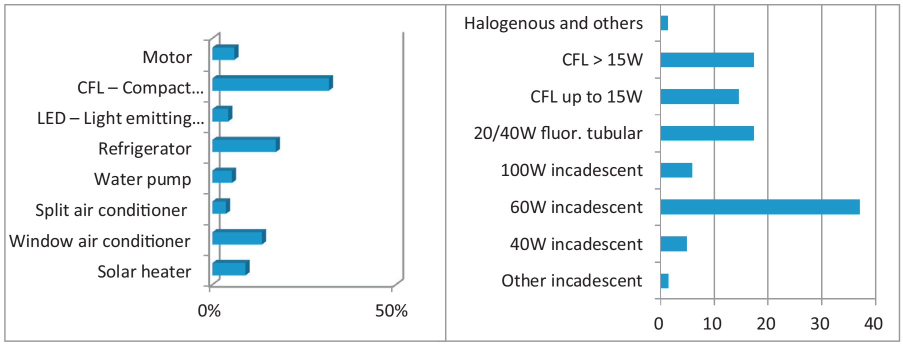

Fig. 1. (a) Brazilian consumers profile; (b) results of Brazilian energy efficiency program.

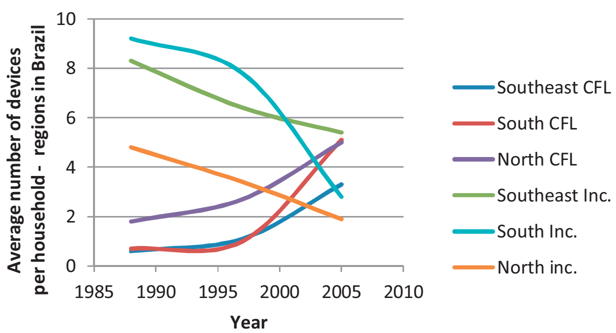

Fig. 2. CFL adoption rates for different Brazilian regions.

are not properly collected and treated. In Brazil only 6% of fluorescent lights have adequate disposal through qualified companies. Even developed countries do not have proper reverse logistics for this technology yet [12], hence there is no argument about the environmental impacts that CFLs are causing worldwide.

Therefore retrofits are reducing energy consumption but project designers are not always providing the most sustainable solutions, since waste analysis of many technologies has been left out of the decision chart. If one is to analyze the major picture of an investment aiming energy efficiency, considering life cycle assessments (LCA) of the evaluated options, the most efficient and lowest acquisition cost alternative technologies, which tend to result higher economic attractivity, may also present negative environmental impacts along the supply chain and reverse logistics that have been underestimated. Energy efficient building design architects and engineers often need to identify which parameters will influence future building energy demand significantly [13]. Cost optimal performance levels of buildings, which stands for the energy performance leading to minimum life cycle cost, calculated with net present value method is an actual practice in order to develop nearly zero energy buildings (nZEB) [14]. Since reduction of energy

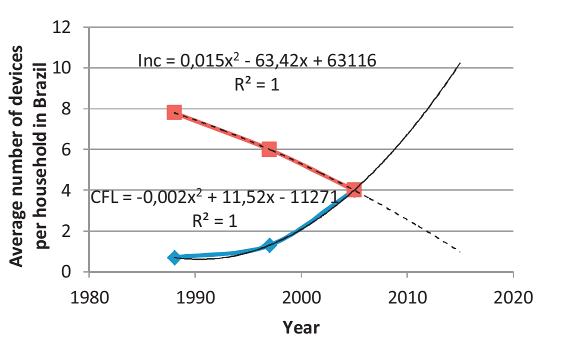

Fig. 3. Rough forecast of the Brazilian consumer profile for lighting devices.

consumption decreases costs and provides lower risk, demonstrated in a techno-economic analysis, energy efficiency is indeed a major appeal for retrofitting [15]. Statistical methods, regression equations, and regression models have been used by scholars to correlate building energy demand with relevant climatic variables and building physical variables in order to predict energy demand [13].

However, we argue that techno-economic analysis of retrofits in scenarios where there are considerable differences among the alternative technologies, in terms of overall impacts, we shall consider a broader range of aspects in the investment analysis. In spite of this, we propose a framework for viability analysis of lighting system retrofits, comparing substitute technologies considering cradle-to-cradle issues. Our approach covers proper management, processing and logistics costs of waste disposed and the reduction of predictable environmental impacts. In order to perform this task we propose the use of sustainability constraints to support the investment analysis, as reverse logistics, waste management and treatment costs concerning the end-of-life chain, along with efficiency issues as lifespan and performance degradation.

The paper is divided in sections in order to clarify the relevance of each parameter in such analysis. Section 2 presents arguments to develop cost functions for all the parameters we propose to analyze, as well as the understanding of equivalent annual costs (EAC) as a means to measure the performance of investments on energy efficiency. Section 3 sets the study parameters for simulations of a general lighting retrofit, comparing LEDs, CFLs and fluorescent tubulars as technically viable substitutes. The results are discussed and used as benchmark for further sensitivity analysis in Section 4, where different scenarios are approached.

2. Techno-economic analysis of lighting system retrofits

Retrofitting lighting systems aim the achievement of a desired illuminance consuming less energy at a reasonable and affordable cost [15]. Sensitivity and risk analysis is also usually performed in order to assess the profitability of the investment, which in general means different levels of energy consumption. A feasibility study makes use of parameters as the project internal rate of return (IRR), net present value or equivalent annual value (EAV) in order to evaluate its economic viability [16]. While the IRR and NPV are the most common ones to compare the project's financial return to an alternative investment [17], represented by the minimum attractivity rate (MAR), the comparison of different alternatives of equipments usually requires the use of parameters as NPV and equivalent annual cost (EAC) [18,19]. EAC is the most suitable for techno-economic analysis of energy efficiency retrofits, which also takes into consideration performance issues [15].

EAC is calculated by annualizing the project's cash flow. The most straightforward way to annualize complex cash flows is to