Sustainable Cities and Society 26 (2016) 507–518

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Comparative life-cycle energy analysis of a new and an existing house: The significance of occupant's habits, building systems and embodied energy

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ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form 13 May 2016
Accepted 2 June 2016
Available online 11 June 2016

Keywords:
Life cycle assessment
House
Primary energy
Operation
Embodied energy
Heating systems

ABSTRACT

Buildings encompass a significant share of overall energy consumption and new houses can promote a shift towards more sustainable societies. Current building regulations only focus on reducing operational energy; however, a life-cycle perspective is important to assess new houses and existing buildings under current (heating and cooling) operational habits. This article assesses the life-cycle non-renewable primary energy improvement potential of a new house compared to an equivalent existing (25-year old) house in the Portuguese context, analyzing alternative operational assumptions: four operation patterns, four heating systems, and two electricity generation mix scenarios. Results show that new houses can effectively reduce the primary energy of residential buildings, but attention should be paid to operational conditions. The new house embodied energy offset period of time is highly dependent on operational patterns. To reduce primary energy associated with new houses, attention should be paid to building material and components, in particular to heavy-weight construction elements, since embodied energy held the majority of the life-cycle impacts. Regarding operation, wood pellets boilers or heat pump systems can significantly reduce primary energy. We also recommend including future electricity generation mix trends in LC studies of houses, which is not common practice, but can influence life-cycle results significantly.

1. Introduction

Developed countries face many challenges to shift towards more sustainable economies. The residential building sector is a key sector to address, being accountable for 68% of final energy use in European buildings (Eurostat, 2012). To promote a more sustainable built environment, efforts have mainly focused on reducing residential building operational energy; however, focusing only on operation has major limitations. In the last 15 years, Life Cycle Assessment (LCA) (ISO-14040, 2006) has been used to study buildings, and though a building is a complex unique product, research reinforces that LCA can be used to give important insights of different life-cycle (LC) phases significance, compare alternatives, and support improvements at design phase (Anderson, Wulfhorst, & Lang, 2015; Buyle, Braet, & Audenaert, 2013; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Chau, Leung, & Ng, 2015; Dixit, Fernández-Solís, Lavy, & Culp, 2012; Khasreen, Banfill, & Menzies, 2009; Ortiz, Castells, & Sonnemann, 2009).

LCA studies of houses have shown that the magnitude of operation versus construction has been changing over time due to energy efficiency. Most European studies, developed for North and West European countries concluded that operational phase accounted for the majority of LC primary energy (60–85%) (Chau et al., 2015; Cuéllar-Franca & Azapagic, 2012; Gustavsson & Joelsson, 2010). However, recently, some LC studies showed that construction can account for a significant share of impacts, in particular when heating and cooling needs are reduced due to energy efficiency, or lower users' operational patterns (Blengini & Di Carlo, 2010b; Blom, Itard, & Meijer, 2011; Brunklaus, Thormark, & Baumann, 2010; Dodoo, Gustavsson, & Sathre, 2011; Stephan, Crawford, & de Myttenaere, 2013; Thormark, 2002). New houses, developed to be low-energy or to meet the passive house standard were studied from a life cycle perspective (Berggren, Hall, & Wall, 2013; Blengini & Di Carlo,

Abbreviations: LCA, life cycle assessment; LCI, life cycle inventory; XPS, polystyrene extruded; NRPE, non-renewable primary energy; OP, operational pattern; COP, coefficient of performance.

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http://dx.doi.org/10.1016/j.scs.2016.06.002
2210-6707/

2010a, 2010b; Brunklaus et al., 2010; Citherlet & Defaux, 2007; Dodoo et al., 2011; Dodoo, Gustavsson, & Sathre, 2014; Gustavsson, Joelsson, & Sathre, 2010; Gustavsson & Joelsson, 2010; Proietti et al., 2013; Sartori & Hestnes, 2007a; Stephan et al., 2013). Generally, all studies showed that operational energy reduction is achieved with an increase in embodied energy and that the balance between these two phases is important to be studied especially for low-energy dwellings. Some studies highlighted that the LC performance of passive or low-energy houses depends not only on the building construction but also on the operational assumptions (Blom et al., 2011; Citherlet & Defaux, 2007; Gustavsson & Joelsson, 2010; Stephan et al., 2013).

Citherlet and Defaux (2007) studied three variants of a Swiss house (a standard, an energy-efficient Minergie label, and a low-energy) under two electricity production mixes (Swiss and UCTE). The low-energy house had 90% lower operational final energy than the standard new house. The authors stated that the embodied impacts should be considered especially when the final energy demand (operation) is lower than 150 MJ/m^2 y for Swiss mix electricity production, and lower than 50 MJ/m^2 y for UCTE mix. The results highlighted the influence of the electricity generation mix: the Swiss mix had generally three times lower impact than the UCTE mix.

Gustavsson and Joelsson (2010) showed that embodied energy can be up to 45% and 60% of the LC primary energy for a Swedish conventional and a low-energy dwelling, respectively. They also highlighted that the LC primary energy and CO_2 emissions from both low-energy and existing buildings depended strongly on the energy supply and heating system adopted. Depending on the systems, an existing house (with biomass-based district heating with cogeneration) could have a lower impact than a low-energy house (with electric heating). Identical conclusions were found by (Brunklaus et al., 2010), who also highlighted that Swedish new and existing houses are strongly influenced by different actors' choices (dwellers, building designers, and material producers'), and lowering overall LC burdens of housing calls for jointly actions at different levels. Blom et al. (2011), who studied an existing apartment building with gas and/or electricity consumption, also showed that changes in user behavior can significantly affect household operational impacts (a reduction up to 60%), especially those related to the use of electric appliances and domestic hot water. They highlighted that in dwellings with low heat demand, electricity consumption dominates the environmental impacts, which could be effectively reduced by changing user behavior (lowering electricity demand) or through lower electricity impacts (Blom et al., 2011).

Stephan et al. (2013) used an input-output hybrid life cycle inventory approach to study the LC energy demand of a suburban Belgian passive house over 100 years. Results showed the embodied, operational and commuting transport energy were responsible for 40%, 33% and 27% of the total LC energy, respectively. A parametric analysis showed that embodied energy represented the highest energy share in all passive house variations studied (up to 77% of the total embodied and operational energy) and that a significant variation on the total LC energy of the passive house (−30%) could be achieved integrating measures at different levels (building components; active systems and the use of gas or electricity; users operational behavior; transport choices). But, due to embodied energy magnitude, the passive house only had slightly lower LC energy than a standard new house, and depending on the energy source, the LC results of the passive house could be worse than the standard house's (Crawford & Stephan, 2013; Stephan et al., 2013).

Most LC studies of new houses were performed for cold climate locations, where usually dwellers have continuous thermal comfort during the heating season. In south European countries, as Portugal, dwellers operational heating and cooling habits are mostly partial and intermittent due to cultural and economic constraints (INE-I.P./DGEG, 2011). In this context, we are likely to assist to a high gap between expected (assuming continuous thermal comfort) and actual energy consumption of dwellers. Real heating and cooling data tend to be lower thanks to users' behavior. This phenomenon is named by (Sunikka-blank & Galvin, 2012) the *pre-bound effect*. Additionally, the LC primary energy depends not only on the building characteristics, but also on the joint effect of the energy conversion efficiency, energy source and supply chain (Gustavsson & Joelsson, 2010; Ortiz, Castells, & Sonnemann, 2010).

The options available (building construction practices; systems and electricity supply chains) vary from region to region. For instance, in south European countries, district heating, which seems to have the lowest impacts in Swedish housing, is not usually an option. Therefore, LCA studies should be applied to different contexts in other to evaluate each context idiosyncrasies and to identify overall preferable building practices. The mild Mediterranean climate and the Portuguese context have seldom been addressed, except a few LC studies on buildings retrofit (Rodrigues & Freire, 2014, 2016) and new houses (Bastos, Batterman, & Freire, 2014; Bastos, Batterman, & Freire, 2015; Gervásio, Santos, Martins, & Simões da Silva, 2014; Monteiro & Freire, 2012); however, these studies do not assess the influence of alternative operational assumptions.

New houses are expected to have lower operational energy than existing houses and at the same time offer better comfort conditions; however, current building regulations neglect embodied energy. Therefore, it is essential to assess whether the additional embodied energy (in construction) is offset by the operational savings when compared to an existing building, considering current Portuguese operational habits and assessing different operational assumption influence.

The goal of this paper is to comparatively assess the improvement potential of a new house with an equivalent existing (25-year old) house in the Portuguese context, using LCA to account for the non-renewable primary energy (NRPE). We analyzed the influence on LC results of four operational patterns (framing Portuguese dwellers heating and cooling habits), four heating systems, and two electricity generation mix scenarios. Additionally, we identified key areas that could be further studied to reduce new houses primary energy.

2. Materials and methods

2.1. Goal and scope

A life-cycle model was developed to assess two single-family houses in the Portuguese context: a new house and an equivalent existing (25-year-old) house, to be inhabited by a family of two adults and two children. Building on a previous study (Monteiro & Freire, 2012), our LC model included construction (material production and transport, building heating systems), operation (heating and cooling) and maintenance of the houses. End-of-life was out of the scope of this study (as detailed in Section 2.4). The functional unit selected was the whole building (133 m^2 of living area) over the lifespan period (50 years).

The new house and the existing house had the same architectural shape, plan, area, function, location, and orientation. Axonometric drawings of the building are presented in Fig. 1. The main differences between both houses are as follows: the existing (25-year old) house has a non-insulated exterior envelope, single-glazing windows; 1.2 ac/h total ventilation level, resistance heating and no cooling; whereas the new house has 6 cm XPS insulation (on exterior walls and roof), double glazing window with thermal break, 0.6 ac/h ventilation level, and a heat pump system installed.