Energy and Buildings 69 (2014) 344–353

Contents lists available at ScienceDirect

Energy and Buildings

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

# Life-cycle energy and greenhouse gas analysis of three building types in a residential area in Lisbon

Joana Bastos [a], Stuart A. Batterman [b], Fausto Freire [a,*]

[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II Campus, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[b] Department of Environmental Health Sciences, University of Michigan, 109 Observatory Drive, Ann Arbor, MI 48109-2029, USA

ARTICLE INFO

*Article history:*
Received 5 April 2013
Received in revised form
25 September 2013
Accepted 1 November 2013

*Keywords:*
Life-cycle assessment (LCA)
Residential buildings
Primary energy
Greenhouse gas (GHG)

ABSTRACT

Residential buildings consume a large fraction of energy and thus represent a major opportunity for reducing energy requirements and greenhouse gas (GHG) emissions. This article presents a life-cycle energy and GHG analysis of three representative residential building types in a well-known area in Lisbon (*Bairro de Alvalade*). The life-cycle model focused on building construction, retrofit and use phases, applied an econometric model to estimate energy use in Portuguese households, and considered two functional units: per square meter per year and per person per year. Over the buildings' 75-year lifespan, the use phase accounted for most (69–83%) of the primary energy requirements and GHG emissions. Larger buildings have lower life-cycle energy requirements and GHG emissions on a square meter basis. On a per person basis, however, this pattern is reversed and larger buildings are associated with higher energy requirements and GHG emissions. Due to the considerable variability and uncertainty associated with life-cycle analyses of buildings, the use of both occupancy- and area-based functional units is recommended.



## 1. Introduction

In 2010, residential buildings accounted for around 27% of the final energy consumption in the EU-27 and about 16% in Portugal [1]. Thus, residential buildings represent a major opportunity for reducing energy requirements and greenhouse gas (GHG) emissions [2]. The potential of urban and architectural design to reduce energy and GHG emissions has been discussed for some decades [3–5], and research is needed to assess and ideally to confirm its specific influence on energy requirements and GHG emissions [4,6,7]. However, life-cycle (LC) analyses of buildings present many methodological issues and choices, some of which are associated with high uncertainty and variability regarding use phase energy requirements, building lifespan, energy production mix, and other factors that lead to a large range of LC results and that can impede interstudy comparisons.

This paper presents a life-cycle (LC) energy and GHG analysis of three building types in a residential area in Lisbon, Portugal. The assessment examines construction, retrofit and use phases. The main objectives are to quantify the primary energy requirements and GHG intensity of the building types, to assess contributions of each phase, and to compare the three building types. Two functional units are considered in the comparative analysis: per square meter per year and per person per year. The subsequent sections of the paper review LC studies of residential buildings in urban areas, characterize the building types, describe the life-cycle model, present and discuss the results, and give study conclusions.

### 1.1. Life-cycle studies of residential buildings

Over the last several decades, many authors have highlighted the importance of a LC perspective to understand the environmental impacts associated with buildings [e.g. 8–11]. Table 1 summarizes selected LC studies of residential buildings, focusing on conventional buildings, i.e., built according to practice prevailing at the time and location [12], as opposed to passive or low energy designs. In one of the first LC studies of buildings, Adalberth [8] calculated the LC energy demand of three dwellings in Sweden and found that the operating phase was associated with 85% of the energy demand. Keoleian et al. [13] calculated LC energy and GHG emissions of a standard house (SH) and an energy efficient house (EEH), both in Michigan, USA. The LC energy and GHG emissions were approximately 1400 MJ/($m^2$ year) and 89 kg $CO_2$eq/($m^2$ year) for the SH, and 560 MJ/$m^2$ year and 32 kg $CO_2$eq/($m^2$ year), for EEH, nearly three times lower. These and most other studies examining residential buildings have several common findings, such as the operation phase of buildings being responsible for the major share

* Corresponding author. Tel.: +1 351 239790739; fax: +1 351 239790701.
*E-mail addresses:* jbastos@student.dem.uc.pt (J. Bastos), stuartb@umich.edu (S.A. Batterman), fausto.freire@dem.uc.pt (F. Freire).

0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.11.010

**Table 1**
Life-cycle (LC) studies of residential buildings.

| Author | Year | Analysis | Case-study | Location | LC phases | Lifespan (years) | Functional units | Main results |
|---|---|---|---|---|---|---|---|---|
| Adalberth [8,15] | 1997 | Life cycle energy use of three dwellings | 3 single-unit dwellings | Sweden | (1) Construction (2) Use (3) End-of-life | 50 | 1 $m^2$ × year 1$m^2$ × 50 years | Construction 810–1020 kWh/$m^2$ (manufacturing: concrete 19–28%, wood 16–28%, plastic 18–23%) Total energy 7600–8800 kWh/$m^2$-50 years, 152–172 kWh/$m^2$ year |
| Fay et al. [19] | 2000 | Primary energy analysis of a detached house and an alternative with additional insulation | Detached house | Melbourne, Australia | (1) Construction (2) Use | 100 | 1 $m^2$ × 100 years | Embodied energy 35.4 (base) and 36.5 GJ/$m^2$ (add. insulation) LC energy 140 GJ/$m^2$ (base) and 133 GJ/$m^2$ (add. insulation) |
| Adalberth [10] | 2001 | Assessment of four multi-family buildings | 4 apartment buildings | Sweden | (1) Construction (2) Use (3) End-of-life | 50 | 1 $m^2$ × 50 years | Use phase 70–90% of all LC impacts (85% of energy requirement) LC GHG 1.5 ton $CO_2$eq/$m^2$-50 years for all buildings LC energy 6100–9100 kWh/$m^2$-50 years |
| Keoleian et al. [13] | 2001 | LC energy, GHG and costs of a standard house (SH) and of an energy efficient house (EEH) | Detached house and alternative | Michigan, USA | (1) Construction (2) Use (3) End-of-life | 50 | 1 house 1 $m^2$ × year | LC energy 6400 (EEH) and 16,000 GJ (SH) LC GHG 370 (EEH) and 1010 (SH) metric tons $CO_2$eq (EEH) Use phase 91% (SH) |
| Norman et al. [6] | 2006 | Energy use and GHG emissions from a low density (LD) and a high density (HD) development | Apartment building and detached dwellings | Toronto, Canada | (1) Construction (2) Use (3) Users transportation | 50 | 1 $m^2$ × year 1 person x year | Construction energy 5 (HD) to 7(LD) GJ/person-year, 92 (LD) to 109 (HD) MJ/$m^2$ year Use energy 28 (HD) to 50(LD) GJ/person-year, 619 (LD) to 643 (HD) MJ/$m^2$ year |
| Asif et al. [25] | 2007 | Embodied energy and other environmental impacts of a house | Semidetached house | Scotland | (1) Construction | n/a | 1 house | Embodied energy 227 GJ (concrete 61%, ceramic tiles 15% and timber 14%) $CO_2$ around 120 ton (99% concrete and mortar) |
| Citherlet and Defaux [22] | 2007 | Comparison of three house variations (insulation, energy production and use of renewable energy) | Single-family house (3 variants) | Lausanne, Switzerland | (1) Construction (2) Use (3) End-of-life | n/a | 1 $m^2$ × year | LC energy (Swiss mix) = 580 (standard house) to 40 MJ/$m^2$ year LC GHG 27 (standard house) to 10 kg $CO_2$eq/$m^2$ year |
| Blengini [18] | 2009 | Primary energy, GHG emissions and other environmental impacts, with alternative end-of-life scenarios | Apartment building | Turin, Italy | (1) Construction (2) Use (3) End-of-life | 40 | 1 $m^2$ × year | Construction phase 91 MJ/$m^2$ year and 8 kg $CO_2$/$m^2$ year LC energy 999 MJ/$m^2$ year (93% use) and 67 kg $CO_2$eq/$m^2$ year (90% use) |
| Gustavsson and Joelsson [16] | 2010 | Primary energy and $CO_2$ emission of conventional and low-energy buildings | 11 buildings (5 types with variations) | Sweden | (1) Construction (2) Use | 50 | 1 $m^2$ × 50 years | Embodied energy 550–1050 kWh/$m^2$ (conventional buildings) LC energy (coal based resistance heating) 7500–11,500 kWh/$m^2$ |
| Ortiz-Rodriguez et al. [26] | 2010 | Primary energy consumption and environmental impacts of a dwelling in Spain and another in Colombia | 2 single-family houses | Spain and Colombia | (1) Construction (2) Use (3) End-of-life | 50 | 1 $m^2$ | Construction energy 4940 (Colombia) and 4180 MJ/$m^2$ (Spain), GHG 238 (Colombia) and 192 kg $CO_2$eq/$m^2$ (Spain) Use phase GHG 2250 (Spain) and 599 kg$CO_2$eq/$m^2$ (Colombia) |
| Nemry et al. [11] | 2010 | Analysis of 72 building types representative of the building stock for the EU-25 | 72 building types | EU-25 | (1) Construction (2) Use (3) End-of-life | 20–40 years | 1 $m^2$ × year | Use phase is the most important LC phase; Buildings geometry was reflected in the higher energy demand in single-family houses as compared to multi-family and high-rise buildings |
| Monteiro and Freire [17,21] | 2012 | Assessment of a house considering two operational patterns (different occupancy and comfort levels) | Single-family house | Coimbra, Portugal | (1) Construction (2) Use | 50 | total living area × 50 years | LC primary energy 800–1600 GJ (average 182 MJ/$m^2$ year) LC GHG 58–115 ton $CO_2$eq (average 13 kg $CO_2$eq/$m^2$ year) |