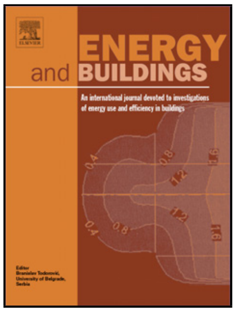

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Author: Joana Bastos Stuart A. Batterman Fausto Freire

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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

E-mails: jbastos@student.dem.uc.pt, stuartb@umich.edu, fausto.freire@dem.uc.pt

Corresponding author: fausto.freire@dem.uc.pt, Tel.: +351 239790701; fax: +351 239790739

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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 [3,4,5], 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. 8,9,10,11]. 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_2eq/(m^2·year) for the SH, and 560 MJ/m^2 year and 32 kg CO_2eq/(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 of the energy consumption and GHG emissions [e.g. 6,8,14]. These studies have many methodological differences, such as the building lifespan, the LC phases considered, whether final or primary energy is considered, the final energy conversion factor, and the functional unit considered, as discussed next.

Table 1 – Life-cycle studies of residential buildings

Building lifespan can be highly variable and difficult to predict. Most LC studies have considered new buildings and a 50-year use phase [e.g. 10,15,16,17], however, lifespans from 40 [18] to 100 years [19, 20] have been considered. Several authors have considered existing buildings (and end-of-life), e.g., Fay *et al*. [19] and Blengini [18] evaluated the actual lifespan of their case studies (40 and 100 years). Nemry *et al.* [11] estimated different lifespans: existing building types had a minimum residual service life (time from assessment to end-of-life) of 20 years, and new building types had generally a 40-year lifespan.

Most studies have emphasized construction and use phases, the most significant for the building LC [e.g. 16,17,21]. Sartori and Hestnes [12] reviewed 60 building LC studies (residential and non-residential) conducted in 9 countries. In all of the studies that considered construction on-site, demolition and transportation of materials, energy for these activities was either negligible or around 1% of the total LC energy. Nemry *et al*. [11] developed a typology of buildings representative of the residential building stock for the EU-25, and assessed primary energy requirements and global warming potential (GWP), among other impacts. Three LC phases were considered: construction, use and end-of-life. The use phase was found to dominate the environmental impacts (81% to 89% in energy requirement and 80% to 81% in GWP); the construction phase embodied a considerable contribution (12% to 18% in energy requirement and 19% to 20% in GWP). Again, end-of-life impacts were limited, accounting for less than 5% of the total environmental impacts in most cases.

Different energy metrics have been used in LC building studies [12]. Although most studies have used primary energy [e.g. 9,16], some present results in final energy [e.g. 15], and others do not specify whether the analysis used final, primary or some mix of primary and final energy [12]. In a LC study of four buildings in Sweden, Adalberth *et al.* [10] conducted a sensitivity analysis evaluating the influence of the electricity production mix, the building material data used to calculate environmental impacts during the construction phase, and the energy consumption calculated in the use phase. The electricity production mix had the most influence. GHG emissions were 1.5 tons of CO_2eq/m^2 over the 50-year lifespan using the electricity mix of the European OECD countries, but 75% lower using the Swedish electricity mix. The other two parameters had a minor influence on results.

Building LC studies have used three functional units. Some have provided the total energy demand over the whole building lifespan [e.g. 13,17]. Others have provided results with reference to the living area on an annual basis (per m^2 per year) [e.g. 10,18,22], and Norman *et al.* [6] used both area and number of occupants to focus on an urban scale and compare a high density (HD) residential development near the Toronto city core and a low density (LD) development in the periphery. The analysis considered the urban context, including building materials, surrounding infrastructure, operational building requirements and transportation of users. Embodied energy and GHG emissions from material production were 1.5 times higher for the LD settlement per inhabitant; however, per square meter of living area, the HD settlement was 1.25 more intensive in terms of energy and GHG emissions in material production. For building operation and on a per living area basis, the LD settlement used 1.8 times more energy than the HD development while GHG emissions were equivalent. However, on the basis of per square meter of living area, LD and HD developments consumed a similar amount of energy. Transportation was the only LC component that was higher in the LD development, both on the basis of inhabitants (3.7 times higher) and living area (2 times higher).

1.2 Key issues in building LC studies

Differences in methodology, climate, building type, behavior and functional unit, as well as uncertainty and variability, can lead to a large range of LC results and impede comparisons between studies. Ramesh [24] found that LC energy demand in conventional residential buildings ranged from 150 to 400 kWh/($m^2\cdot$year); Sartori and Hestnes [12] estimated a range from 290 to 1180 kWh/($m^2\cdot$year).

Most published LC studies of buildings have been completed in developed countries and in cold regions, such as Norway and Sweden [24]. In Scotland, Asif [25] performed a detailed LCA of a detached house focusing on five main construction materials. The total embodied energy was 227 GJ. Citherlet [22] examined a family house in Switzerland, comparing three alternatives with different insulation, energy production systems and use of renewable energies. For the standard house, and considering the Swiss electricity production mix, the LC energy was 580 MJ/($m^2\cdot$year) and the GHG intensity was 27 kg CO_2eq/($m^2\cdot$year).

Only a few LC building studies have been completed in southern Europe, none comparing existing buildings. Blengini [18] performed a detailed LCA of a residential building in Italy, focusing on end-of-life (demolition and recycling potential) and alternative waste disposal scenarios, and estimated a recycling potential of 29% and 18% in energy and GHG emissions, respectively. Ortiz-Rodriguez *et al.* [26] compared the LC energy and environmental impacts of dwellings in Spain and Colombia. The Spanish house emitted approximately 2470 kg CO_2eq/m^2 during the 50-year lifespan (2248 in the use phase, including maintenance, 198 in the construction and 25 kg CO_2eq/m^2 in the end-of-life), while the Colombian dwelling emitted 862 kg CO_2eq/m^2 (595, 241 and 26 in the same three phases). Different results in the use phase were attributed to differences in climate and consumption behavior in the two countries. Few LC studies of buildings have been developed for Portugal [17,21,27,28]. Monteiro and Freire [17,21] considered a single-family house in Portugal with seven alternative exterior wall types and two operational patterns, and differing in occupancy and comfort levels. LC primary energy ranged from 800 to 1600 GJeq and GHG emissions from 58 and 115 ton CO_2eq. Assuming the average operational pattern, a 50-year lifespan, and a living area of 132 m^2, the primary energy requirement was 182 MJ/(m^2·year) and the GHG emissions were 13 kg CO_2eq/(m^2·year).

The linkage between building design, energy use and GHG emissions is dependent on and sensitive to climate and socio-demographic characteristics that are geographically and culturally variable. Thus, it is highly relevant to provide comparative studies of existing buildings in different regions. The Lisbon case study described in the present paper compared three long-lived buildings of the same typology, location and materials, which allows an analysis of the effect of building design, a topic that has received little attention in the literature. In addition, we applied a comprehensive econometric model that integrates the building design and socio-demographic characteristics, recently developed for Portugal. This model estimated household energy consumption based on the number of occupants, building age, dwelling area, dwelling type, urbanization level and region using recent statistical data. The approach is efficient and broadly applicable to circumstances when historical and representative energy data is not available, and it circumvents the need for many assumptions and parameters used in engineering or demand-type models of household energy consumption.

2. Calculation

2.1 Residential case study

The building types considered are in a residential area in *Bairro de Alvalade,* in Lisbon, Portugal. The master plan for *Bairro de Alvalade* was the most significant public development for the expansion of Lisbon in the 1940s, and was planned by the architect Faria da Costa [29]. The development consists of a low rent housing area, presented in Figure 1, designed by Jacobetty Rosa. The area is characterized by a regular urban morphology with *standardized* elements: dwellings, buildings and techniques were repeatedly used. The analysis compares three building types (of the nine existing in the area), described next.

Figure 1 – Schematic plan of the urban area showing the types of residential buildings in the *Bairro de Alvalade*

Figure 2 presents schematic drawings of the three selected building types. The buildings have three or four stories, two dwellings per story, and a common staircase. Type 2 is the smallest: it has a gross area of 122 m^2 per story, three stories (total gross area of 367 m^2), and each dwelling unit has two bedrooms. Type 3 has a gross area of 157 m^2 per story, three stories (total gross area of 472 m^2), and three bedrooms per dwelling unit. Type 8, the largest, has a gross area of 260 m^2 per story, four stories (total gross area of 1041 m^2), and the dwelling units have five bedrooms.

Figure 2 –Floor plans and elevations for building types 2, 3 and 8

2.2 Functional units and building lifetime

The building life was assumed to be 75 years, since the buildings date from the 1940s. Two functional units were selected: per floor area per year (m^2/year) and per inhabitant per year (person/year). The model assumes an average occupancy of 1.5 persons per dwelling unit, based on statistical urban area data from 2011 [30]. The average occupancy was calculated from block-scale statistical units in the case-study area, which contained 88 to 276 people and 10 to 31 buildings each.

2.3 Construction phase

For the construction phase, primary energy requirements and GHG emissions were calculated using the *Inventory of Carbon and Energy* (ICE) *Version 2.0* [31]. The ICE lists the embodied energy, carbon and GHG (measured in grams of CO$_2$ equivalent, g CO$_2$eq) for a large number of building materials. The "embodied energy" (EE), defined as the total primary energy (MJ$_p$) required by the building materials, is the energy consumed in the extraction of raw materials, production of building materials and transportation to the building site ("cradle-to-site") [32]. Similarly, the "embodied GHG" (EGHG) emissions comprise the GHG emissions from the extraction of raw materials to the building site. In the

ICE, the term "embodied carbon" is used for both carbon and GHG emissions. The present paper addresses GHG intensity on a 100-year time horizon, which is the relevant indicator for climate change, and the expression "embodied GHG" (EGHG) is adopted.

Seven building elements were considered: (i) external walls using hydraulic stone masonry and hollow brick masonry, (ii) interior walls using solid and hollow brick masonry, (iii) floors, both wooden beams/planks and reinforced concrete slabs, (iv) staircases in concrete with reinforced concrete landings, (v) roofs, with wood structure and roof tiles, (vi) fenestrations in glass and (vii) interior doors in wood. For external walls, quantity was provided in volume (m^3) because thicknesses vary. In building types 2 and 3, external walls are 0.50 m thick in the ground floor and 5 cm less every upper floor. In building type 8, the external ground floor walls are 0.55 m in thickness, and 5 cm less on upper floors. Interior walls vary depending on structural and functional characteristics (from 0.15 to 0.25 m).

Details regarding building materials were obtained from the original drawings and other project documents maintained at the Municipal Archive of Lisbon (also in [33]). The type of stone used in exterior wall masonry was assumed to be limestone, based on contemporary construction materials [34,35]. For each building element or material, volume was based on project documents, and density was on construction material providers and a technical reference [36].

2.4 Retrofit phase

Energy requirements for the building retrofit phase used an intervention scenario with the measures considered listed in Table 2. Based on the survey by Alegre [33], roughly half of the buildings in the case-study area have replaced the wooden floors and windows. Energy conservation measures considered included the addition of insulation in external walls and roof, replacement of the roof tiles, and a partial replacement of wall masonry. The embodied energy and GHG emissions associated with these retrofit measures were based on the ICE [31] (see construction phase).

Table 2 – Retrofit phase: intervention measures

2.5 Use phase

The use phase represents household energy demand. Buildings use electricity and natural gas or liquefied petroleum gas (LPG). The total energy use per year was calculated based on the ratio between residential electricity use and natural gas or LPG from the *Lisbon Energy Matrix* [37], which provides estimates of energy use in Lisbon building stock using 2002 data. Electricity accounts for 60% of the final energy consumption in residential buildings, while natural gas or LPG account for 40%.

Annual electricity consumption was calculated using regression model 2a proposed by Wiesmann *et al*. [38]. These authors developed an econometric analysis of residential electricity expenditures in mainland Portugal using 2005 data. The total electricity consumption was based on a price of 0.141€/kWh. At the household level, electricity consumption in model 2a depends on ten variables: (i) persons per household (1.5); (ii) building age (65 years, based on the 2005 reference year); (iii) dwelling area (46, 62 and 100m^2 for buildings type 2, 3 and 8, respectively); (iv) dwelling type (apartment in building with less than 10 apartments); (v) urbanization level (mainly urban); and (vi) region (Lisbon). Regarding (vii) income and (viii) number of appliances, the average for mainland Portugal was considered [38]. Finally, (ix) children were considered to be present in half of the dwellings for each building type (mainland average was 58%), and (x) all dwellings were considered to be owned by the household.

The primary conversion factor for electricity, used to calculate the primary energy requirement, depends largely on the mix of generation technologies. Two conversion factors were considered: 2.5 MJ_p/MJ_f (suggested in the European Directive 2006/32/EC [39], which allows comparisons with other studies), and 2.0 MJ_p/MJ_f (average of the Portuguese electricity system between 2003 and 2012). The GHG intensity for electricity generation was 450 g CO_2 eq/kWh, based on the average for Portuguese generation between 2003 and 2012. For natural gas, the primary energy conversion factor was 1.13 MJ_p/MJ_f [40], and the GHG emission factor was 72 g CO_2 eq/MJ [40].

3. Results and discussion

3.1 Construction phase

Table 3 presents the life-cycle inventories for the three building types, including the quantity of each construction element and the ratio between the quantity and the building's gross built area. Table 4 characterizes the main construction elements in terms of volume, mass, density, embodied energy and GHG.

Table 3 - Life-cycle inventory: construction elements by building type

Table 5 presents EE and EGHG per building type. On a per square meter basis, larger buildings have lower EE and EGHG, primarily due to the smaller contributions of walls. Building type 2 has the highest EE (3433 MJ/m^2) and EGHG (212 kg CO_2eq/m^2). In comparison, the type 3 building attains a reduction of 2% in EE and 5% in EGHG, and the type 8 building has a 10% decrease in both EE and EGHG.

Table 4 – Main characteristics of the construction elements, including embodied energy (EE) and greenhouse gas (EGHG)

Table 5 – Construction phase: embodied energy (EE) and embodied greenhouse gas (EGHG) per building type

3.2 Retrofit phase

The retrofit energy requirement for the 75-year period is presented in Table 6. The total energy and GHG emissions are higher in larger buildings. However, on a per square meter basis, energy requirement and GHG emissions are slightly lower in larger buildings. This is probably due to the higher ratio of building envelope/floor area in smaller buildings. The only retrofit measure that has higher impacts per square meter in building type 8 is the replacement of floors, which is the only measure that does not affect the building envelope.

Table 6 – Retrofit phase: primary energy requirement and GHG emissions

3.3 Use phase

Table 7 presents the annual primary energy requirement and GHG emissions of the use phase for the different building types. In absolute terms, the smallest building (type 2) is associated with the lowest energy demand and GHG emissions; the largest building (type 8) has 44% higher energy requirements and emissions. However, the trend is reversed on a per square meter basis for building types 3 and 8 where energy and GHG emissions are 20 and 49% lower than building type 2, respectively. The lower energy requirement per square meter in larger buildings is due to area/volume and area/occupancy ratios. The area/volume ratio is generally lower in larger buildings, which means that the same living space requires less building envelope surface, which can result in lower energy consumption. The area/occupancy ratio is the highest in building type 8 (87 m^2/person), followed by type 3 (52 m^2/person) and by type 2 (41 m^2/person). A larger area per inhabitant can contribute to lower energy requirement on the basis of per square meter.

Table 7 – Use phase: household primary energy requirement and GHG emissions (per year)

3.4 Life-cycle analysis

Figures 3 and 4 present the LC primary energy requirements and GHG emissions per building type. The error bars result from the two primary energy conversion factors used for household electricity consumption. The use phase has the greatest primary energy demand and GHG emissions for the three building types, representing 69-83% of both. The construction phase accounts for 14-25% of both energy and GHG emissions, while the retrofit phase accounts for less than 7% in all cases.

Figure 3 – Life-cycle primary energy requirement, by building type
(error bars present the use phase primary energy calculated with 2.0 and 2.5 factors)

Figure 4 – Life-cycle greenhouse gas emissions, by building type

Figure 5 shows the LC primary energy requirements using the two functional units. On a per square meter basis, building type 2 has the highest requirement (283 to 324 MJ/(m^2·year)), followed by type 3 and type 8, which are 17% and 42% lower, respectively. This pattern is reversed when energy requirements are expressed on a per person basis: building type 2 has the lowest requirements (11554 to 13237 MJ/(person·year)), while building types 3 and 8 are 7% and 23% higher, respectively.

Figure 5 – Annual energy requirement per square meter and per person
(error bars present the use phase primary energy calculated with 2.0 and 2.5 factors)

Figure 6 – Annual greenhouse gas emissions per square meter and per person

Figure 6 shows GHG emissions for the two functional units. Building type 2 has the highest GHG emissions per square meter (18 kg CO_2eq/(m^2·year)), followed by types 3 and 8 (lower by 17% and 42%, respectively). On a per person basis, type 2 has the lowest emissions (731 kg CO_2eq/(person·year)), while types 3 and 8 are 7% and 24% higher, respectively.

The estimated LC energy use for the three building types is comparable to that in recent literature. The single-family house in Barcelona, Spain examined by Ortiz-Rodriguez [26] had LC GHG emissions of 2470 kg CO_2eq/m^2, higher than found here (781 to 1343 kg CO_2eq/m^2). The difference is likely associated with differences in the building typologies. A single-family house is generally associated with higher use phase energy consumption on a square meter basis due to its relatively larger envelope area [11]. The Portuguese single-family house assessed by Monteiro and Freire [17,21] had a primary energy requirement of about 136 MJ/(m^2·year) in a base case scenario with moderate occupancy. The study considered use phase energy consumption for heating, cooling and maintenance, but excluded other uses, such as lighting, water heating, cooking and washing appliances. In our study, primary energy requirement ranges from 172 to 298 MJ/(m^2·year). The present paper uses an econometric model recently developed for Portugal that accounts for all household energy use, and thus represents an LC estimate that is improved over earlier studies.

Comparison with other LC studies, as noted in the Introduction, is affected by methodological choices in the LC analysis methods, climate, the uniqueness of each building, consumption habits of occupants, and other factors. For example, Sartori and Hestnes [12] found somewhat higher use, 1040 to 4250 MJ/(m^2·year). In their review of 60 case studies, the studies of residential buildings (33), considered only six countries, mostly in cooler climates: Sweden (14), Australia (3), Germany (6), USA (2), New Zealand (3) and Norway (5); only two studies considered multi-family buildings, and all studies were completed between 1978 and 2004. In 2010, Ramesh [24] estimated 540 to 1440 MJ/(m^2·year), which is higher than our results: if a 50-year lifespan was considered LC energy requirement of the three building types would be 190 - 352 MJ/(m^2·year). Our analysis calculated energy consumption in the use phase based on case-specific characteristics. This is likely to be lower than average comfort standards and other studies, because this is generally a low-income residential area with low occupancy. Despite the inherent variability and uncertainty associated with buildings LC analyses, the estimated LC energy and GHG emissions are comparable to the range of results provided by the studies in south European context.

3.5 Model assumptions and uncertainties

LC analyses of buildings involve many assumptions and simplifications associated with the energy production mix, building use phase energy requirements, building lifespan, LC phases considered, functional units and building data.

Primary energy incorporates not only final energy consumption, but also the (upstream) energy used to produce and deliver it. Energy use should be quantified in terms of primary energy since this incorporates the life-cycle efficiency of the different energy types and electricity generation mix [12,41] and reflects the true environmental implications of energy use. However, the technology and generation mix can evolve and change significantly during a building's long lifespan. In this paper, two primary energy conversion factors for electricity were evaluated (2.0 and 2.5 MJ_p/MJ_f) which changed the building's total LC energy use by 11-13%. The impact of electricity production mix, highlighted by Adalberth [10], is important for identifying potential improvements that can reduce energy requirements; however, it can make comparisons between LC studies of buildings more difficult.

Energy consumption during the use phase also changes, and predictions over the building LC (e.g., 75 years) are highly uncertain. We assumed a constant consumption rate based on data from 2002 and 2005. Energy consumption depends mainly on the energy use per capita, number of persons per household, and floor area per capita. Historically, energy use per capita in Portuguese households increased from 0.23 in 1989 to 0.30 toe/capita in 2009 [42] (1 tonne of oil equivalent (toe) corresponds to approximately 42 GJ). Occupancy rates in *Bairro de Alvalade*, the study area, as in other urban areas, decreased from 4 to 1.5 inhabitants per dwelling from 1940 to 2001 [30], which greatly increased floor area per capita. These trends are similar to those in the EU-25: between 1990 and 2004, energy use per capita in residential buildings increased from around 25 to 28 GJ, persons per household decreased from 2.8 to 2.5, and floor area per capita increased from 30 to 35 m^2 [43]. Such trends, also difficult to anticipate, highlight the importance of considering functional units other than building area, such as occupancy.

Building lifespan is also variable and difficult to predict [11]. While many buildings in Europe were built in the last few decades, over 40% of residential buildings were built before the 1960s and some are hundreds of years old [44]. We considered a 75-year lifespan (buildings were constructed in the 1940s), which has the effect of lowering energy and environmental burdens compared to the 50-year lifespan used in most previous studies. For the three building types considered, a 50-year life would give primary energy requirements from 190 to 352 $MJ/(m^2 \cdot year)$ and GHG emissions between 12.0 and 19.7 kg $CO_2eq/(m^2 \cdot year)$. The construction, use and retrofit phases would account for 22-31%, 60-76% and 4-9% of the overall energy requirements, respectively. Considering a 50-year lifespan would reduce the overall LC energy and GHG emissions by 23 to 28%.

Building end-of-life phase is considered negligible in the overall energy requirement and GHG emissions [24,9,11,12], and thus was not considered in the present analysis. In addition, dismantlement and waste treatment scenarios can be difficult to foresee (see section 2). The exclusion of this phase is not expected to substantially alter results.

The selection of functional units depends on the goal and scope of the LC study. Most LC studies of buildings have adopted area-based functional units, which allow the comparison of design alternatives for a house, for example. Using an area-based functional unit, larger dwellings have lower energy requirements and lower GHG emissions for the same occupancy, but these indicators do not necessarily translate to better environmental performance. In contrast, the use of an occupancy-based functional unit (often used in studies at the urban scale) can overlook the building's performance, e.g., high occupancy could compensate for poor environmental performance. Thus, to provide comprehensive and useful insight on the environmental impacts associated with buildings, we recommend the use of both functional units.

The building design and materials were obtained mainly from original project documents. Few project data were unavailable, i.e., the type of stone in exterior walls masonry and material densities. Embodied energy and GHG emissions of building materials were based on data provided by the ICE [31], which is derived from U.K. production processes. Although these uncertainties are not expected to significantly change results, more appropriate and site-specific data would improve the accuracy of the analysis.

4. Conclusion

Life-cycle analyses of primary energy and GHG emissions were developed for three building types located in a residential area in Lisbon. Three types of buildings were compared, and building construction, retrofit and use phases were considered. The use phase was dominant, accounting for 69-83% of the total energy requirement and GHG emissions over the buildings' 75-year lifetime. Considering the construction phase, walls represent the largest embedded energy requirement and GHG emissions, e.g., across the three building types, exterior walls represented 30-33% and 34-37% of energy and GHG burdens, respectively; interior walls accounted for 23-24% and 34%, and floors contributed 30-37% and 18-23%. In the largest building, these burdens are lower by 9-11% for energy and GHG emissions expressed on a per square meter basis. However, these differences are relatively small since the construction phase accounts for less than 25% of the overall life-cycle burden.

The results highlight the importance of functional units when comparing among different building types. Results expressed on the basis of built area or occupancy showed opposite trends, e.g., larger buildings had higher energy and GHG emissions per person, but lower energy and GHG emissions per square meter.

LC analyses of buildings are associated with considerable variability and uncertainty, and LC studies of buildings present many methodological differences that impede comparisons. To provide LC analyses that are consistent and that account for site-specific differences, we recommend the use of both occupancy- and area-based functional units. We also recommend the use of primary energy to quantify life-cycle energy requirements of buildings. Lastly, further studies are needed for different climatic and socio-economic contexts, particularly in southern European countries.

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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 x year 1m^2 x 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, Treloar and Iyer-Raniga [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 x 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 x 50 years	Use phase 70-90% of all LC impacts (85% of energy requirement) LC GHG 1.5 ton CO_2eq/m^2-50 years for all buildings LC Energy 6100 - 9100 kWh/m^2-50 years
Keoleian, Blanchard and Reppe [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 x year	LC energy 6400 (EEH) and 16000 GJ (SH) LC GHG 370 (EEH) and 1010 (SH) metric tons CO_2eq (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 x 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, Muneer and Kelley [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 x year	LC energy (Swiss mix) = 580 (standard house) to 40 MJ/m^2.year LC GHG 27 (standard house) to 10 kg CO_2eq/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 x 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_2eq/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 x 50 years	Embodied energy 550-1050 kWh/m^2 (conventional buildings) LC energy (coal based resistance heating) 7500-11500 kWh/m^2
Ortiz-Rodriguez, Castells and Sonnemann [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_2eq/m^2 (Spain) Use phase GHG 2250 (Spain) and 599 kgCO_2eq/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 to 40 years	1m^2 x 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 x 50 years	LC primary energy 800-1600 GJ (average 182 MJ/m^2.year) LC GHG 58-115 ton CO_2eq (average 13 kg CO_2eq/m^2.year)

Table 2 – Retrofit phase: intervention measures

Exterior walls	Replacement of 20% of stone and brick masonry Additional 40mm mineral wool insulation
Floors	Replacement of 100% wood floors with reinforced concrete slabs and terrazzo tiles
Roof	Replacement of 100% of clay roofing tiles Additional 40mm mineral wool insulation
Fenestrations	Replacement of 100% fenestrations with double glass

Table 3 - Life-cycle inventory: construction elements by building type

Elements	Description	Building type 2 ($367\ m^2$)		Building type 3 ($472\ m^2$)		Building type 8 ($1041\ m^2$)	
		total	per m^2	total	per m^2	total	per m^2
Walls							
External Walls	Hydraulic stone masonry (m^3)	116	0.32	139	0.29	268	0.26
	Hollow brick masonry (m^3)	6	0.02	7	0.01	14	0.01
Interior walls	Solid brick masonry (m^3)	23	0.06	23	0.05	33	0.03
	Hollow brick masonry (m^3)	54	0.15	72	0.15	166	0.16
Floors							
Wood floors	Wooden beams and planks (m^2)	208	0.57	289	0.61	653	0.63
Concrete floors	Reinforced concrete slabs (m^2)	90	0.25	104	0.22	265	0.25
Staircases							
Landings	Reinforced concrete landings (m^2)	16	0.04	18	0.04	27	0.03
Stairs	Concrete stairs (m^3)	1	0.004	1	0.004	2	0.002
Roofs	Wood structure and roof tiles (m^2)	141	0.38	174	0.37	282	0.27
Fenestrations	Glass doors and windows (m^2)	59	0.16	66	0.14	115	0.11
Interior doors	Wooden doors (m^2)	48	0.13	57	0.12	158	0.15

Table 4 – Main characteristics of the construction elements, including embodied energy (EE) and greenhouse gas (EGHG)

Elements	Description	Material	Volume (m^3)	Density (kg/m^3)	Mass (kg)	EE (MJ)	EGHG (kg CO_2 eq)
External Walls	Hydraulic stone masonry (m^3)	Limestone	0.860	2400	2064	3096	185.76
		Concrete mortar	0.140	2100	294	285	45.86
	Hollow brick masonry (m^3)	Brick	0.840	1300	1092	3276	262.08
		Concrete mortar	0.160	2100	336	326	52.42
Interior walls	Solid brick masonry (m^3)	Brick	0.840	1800	1512	4536	362.88
		Concrete mortar	0.160	2100	336	326	52.42
	Hollow brick masonry (m^3)	Brick	0.840	1300	1092	3276	262.08
		Concrete mortar	0.160	2100	336	326	52.42
Floors	Wooden beams and planks (m^2)	Wood	0.287	600	172	1722	53.38
	Reinforced concrete slabs (m^2)	Reinforced concrete	0.100	2500	250	305	34.63
Staircases	Reinforced concrete slabs (m^2)	Reinforced concrete	0.100	2500	250	305	34.63
	Concrete stairs (m^3)	Concrete	1.000	2400	2400	1680	240.00
Roofs	Wooden structure and	Wood	0.064	600	38	384	11.90
	Roof tiles (m^2)	Ceramic tiles	-	-	44	528	34.32
Fenestrations	Glass doors and windows (m^2)	Glass	0.004	2500	10	150	9.10
Interior doors	Wooden doors (m^2)	Wood	0.030	600	18	180	5.58

Table 5 – Construction phase: embodied energy (EE) and embodied greenhouse gas (EGHG) per building type

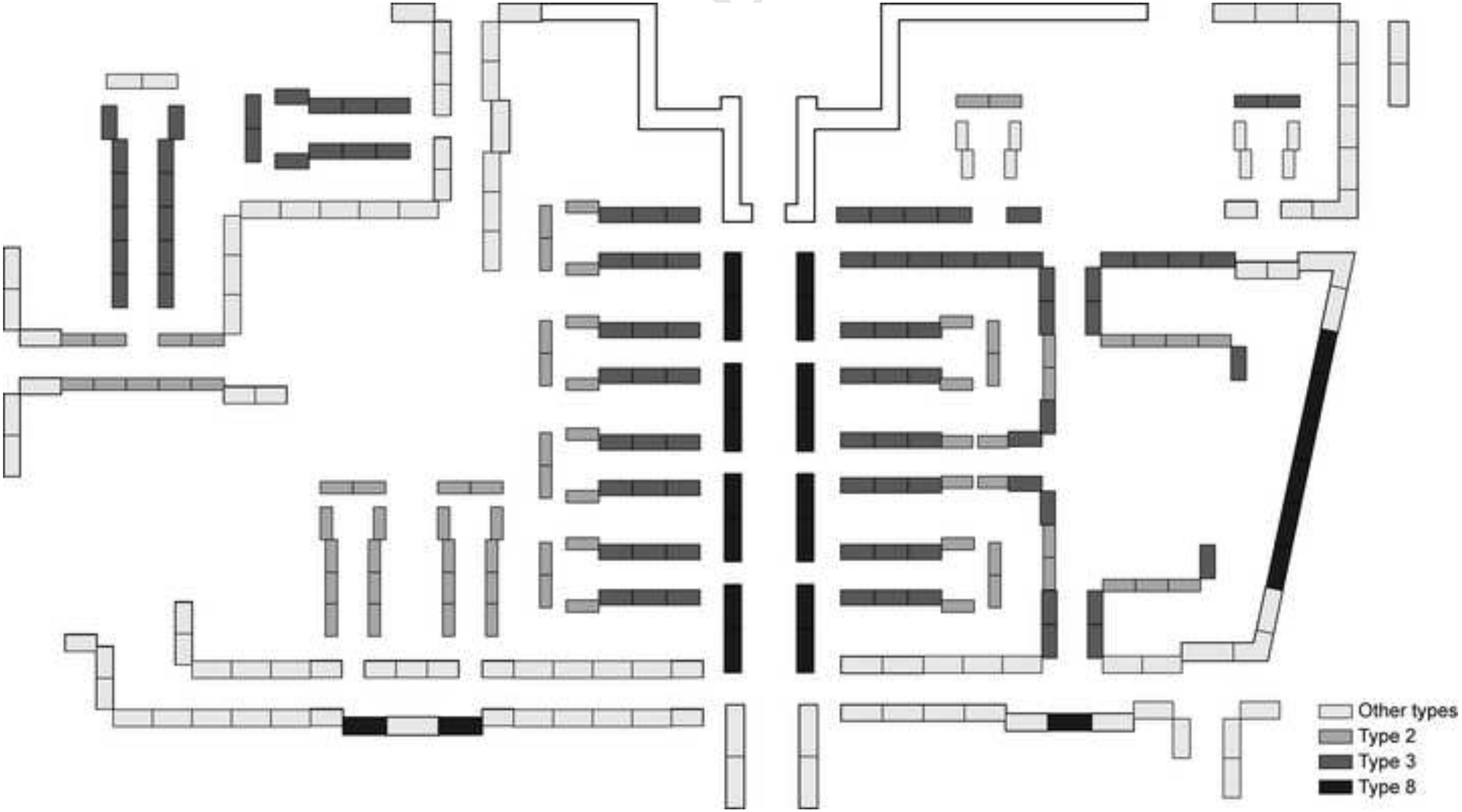
Elements		Building type 2				Building type 3				Building type 8			
		EE (MJ)		EGHG (kg CO_2 eq)		EE (MJ)		EGHG (kg CO_2 eq)		EE (MJ)		EGHG (kg CO_2 eq)	
		total	per m^2	total	per m^2	total	per m^2	total	per m^2	total	per m^2	total	per m^2
Walls	External	414076	1127.7	28776	78.4	494796	1047.9	34371	72.8	955023	917.0	66349	63.7
	Interior	307633	837.8	26645	72.6	371368	786.5	32211	68.2	756379	726.3	65740	63.1
Floors	Wood	358142	975.3	11102	30.2	498071	1054.8	15440	32.7	1123915	1079.2	34841	33.5
	Concrete	27514	74.9	3124	8.5	31568	66.9	3584	7.6	80807	77.6	9174	8.8
Staircases	Landings	4883	13.3	554	1.5	5435	11.5	617	1.3	8327	8.0	945	0.9
	Stairs	2218	6.0	317	0.9	2218	4.7	317	0.7	3545	3.4	506	0.5
Roofs		128701	350.5	6523	17.8	158998	336.7	8059	17.1	257248	247.0	13038	12.5
Fenestrations		8904	24.2	540	1.5	9876	20.9	599	1.3	17223	16.5	1045	1.0
Interior doors		8554	23.3	265	0.7	10217	21.6	317	0.7	28512	27.4	884	0.8
Total		1260625	3433	77847	212.0	1582546	3351	95515	202.3	3230978	3102	195523	184.9

Table 6 – Retrofit phase: primary energy requirement and GHG emissions

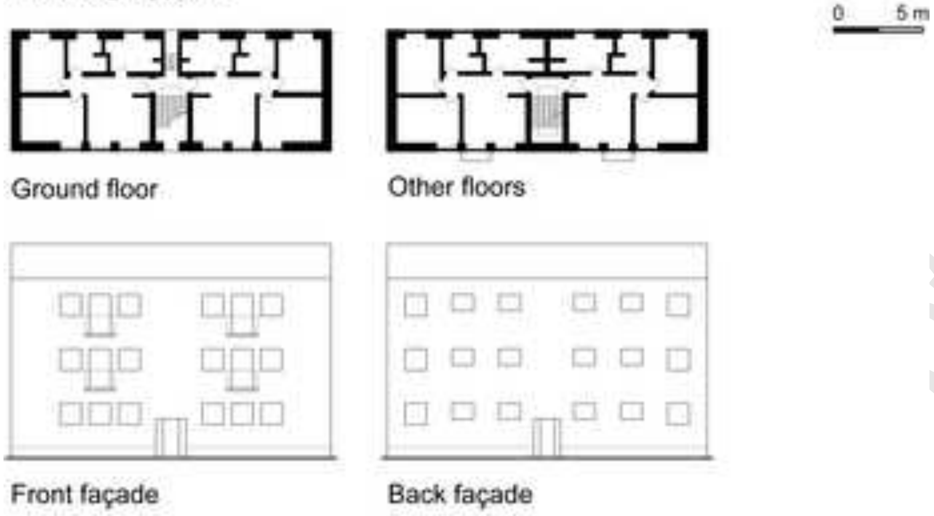
	B. type 2				B. type 3				B. type 8			
	EE (MJ)		EGHG (kg CO_2eq)		EE (MJ)		EGHG (kg CO_2eq)		EE (MJ)		EGHG (kg CO_2eq)	
	total	per m^2	total	per m^2	total	per m^2	total	per m^2	total	per m^2	total	per m^2
Exterior walls	99319	271	7028	19.1	118735	252	8399	17.8	229136	220	16210	15.6
Floors	83088	226	8886	24.2	115551	245	12358	26.2	260746	250	27886	26.8
Roof	81539	222	5385	14.7	100734	213	6653	14.1	162980	157	10764	10.3
Fenestrations	8904	24	540	1.5	9876	21	599	1.3	17223	17	1045	1.0
Total	272850	743	21839	59.5	344896	731	28009	59.3	670085	644	55904	53.7

Table 7 – Use phase: household primary energy requirement and GHG emissions (per year)

	Energy				GHG emissions	
	Factor 2.0		Factor 2.5			
	total (MJ)	per m^2 (MJ/m^2)	total (MJ)	per m^2 (MJ/m^2)	total (kg CO_2 eq)	per m^2 (kg CO_2 eq/m^2)
B. type 2	83539	227.5	98685	268.7	5248	14.3
B. type 3	85389	180.8	100870	213.6	5364	11.4
B. type 8	119931	115.2	141675	136.0	7534	7.2


Other types
Type 2
Type 3
Type 8

Building Type 2



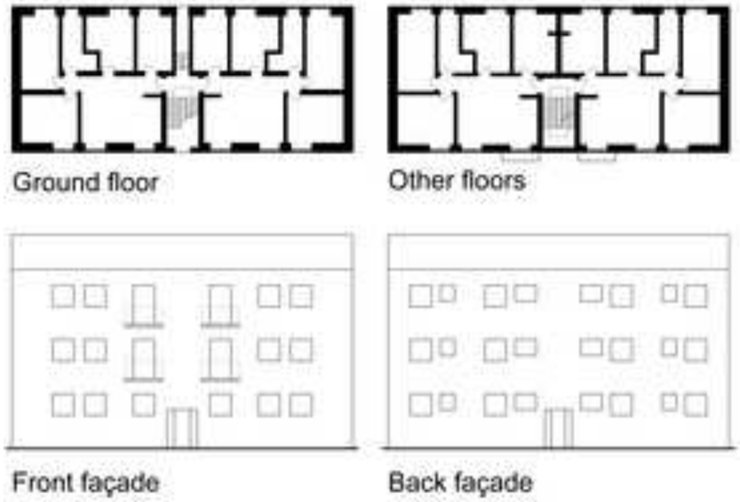
Ground floor

Other floors

Front façade

Back façade

Building Type 3



Ground floor

Other floors

Front façade

Back façade

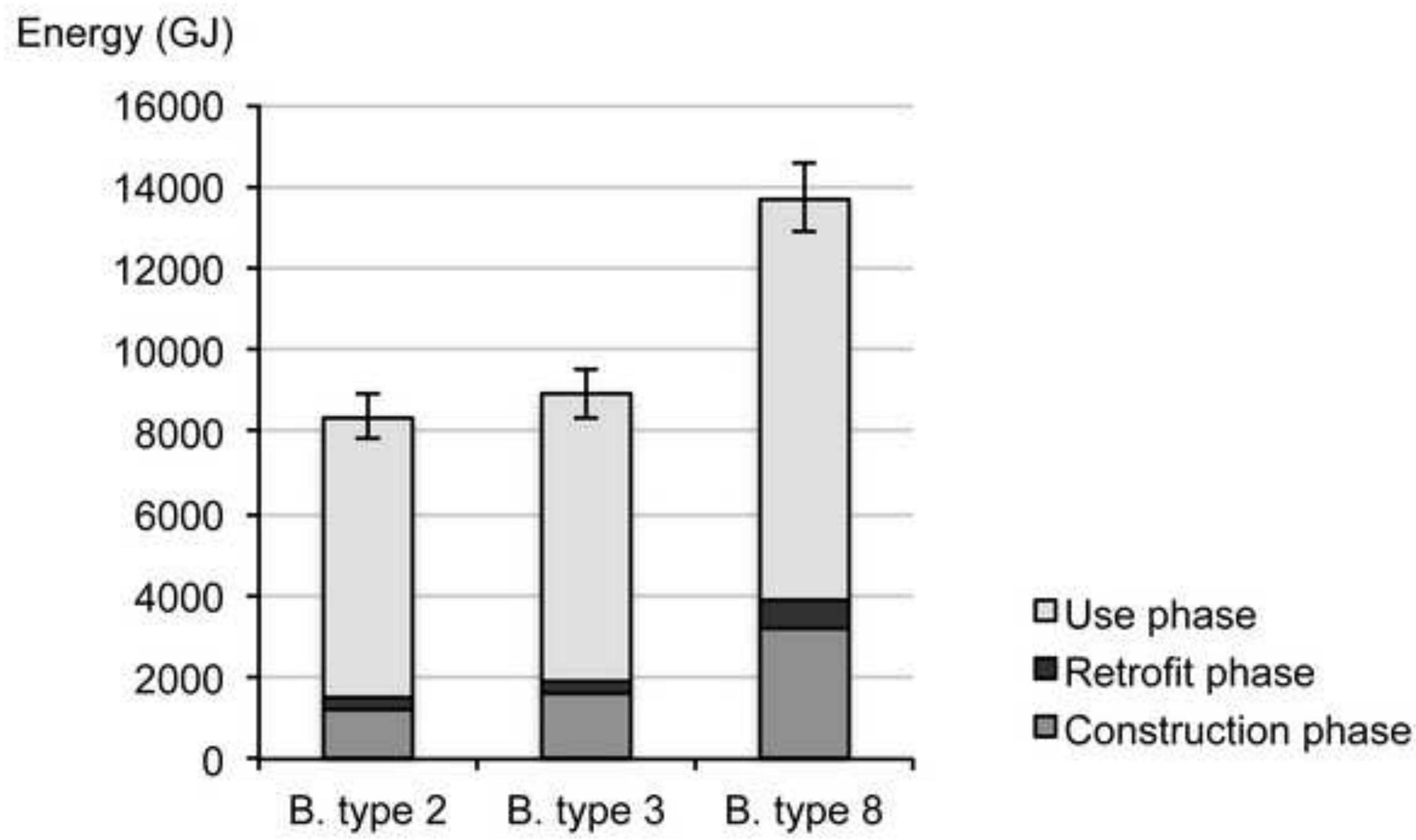
Building Type 8

Ground floor

Other floors

Front façade

Back façade


Energy (GJ)
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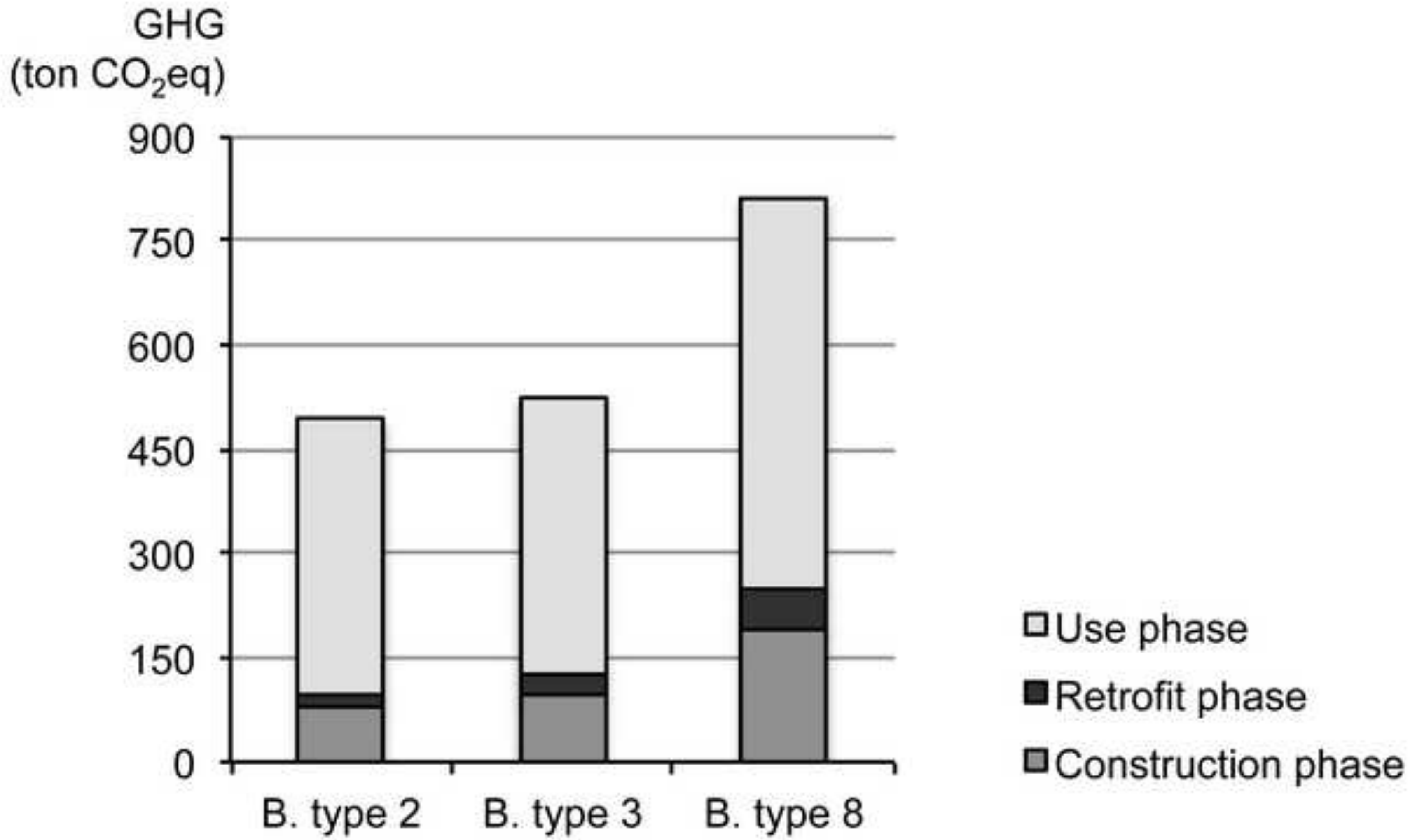
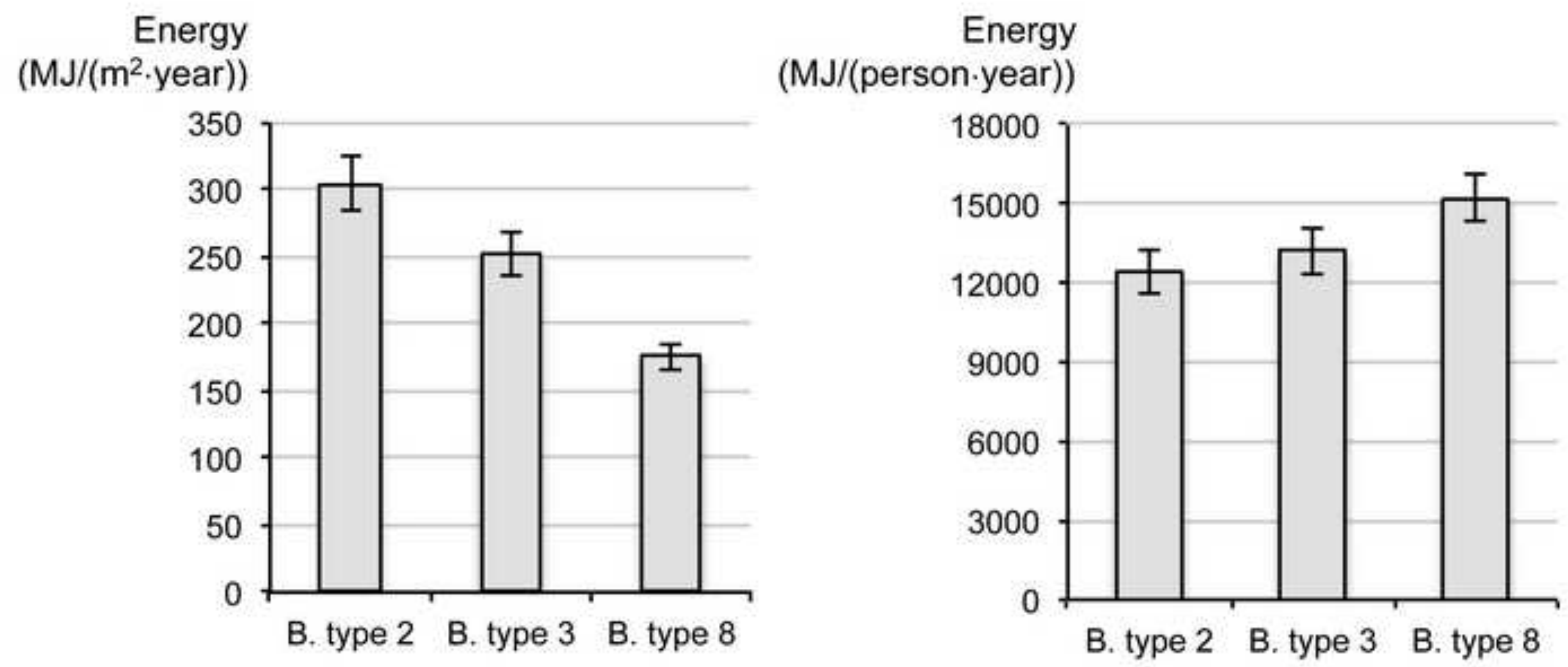
14000
12000
10000
8000
6000
4000
2000
0
B. type 2
B. type 3
B. type 8
Use phase
Retrofit phase
Construction phase


GHG
(ton CO_2eq)
900
750
600
450
300
150
0
B. type 2
B. type 3
B. type 8
Use phase
Retrofit phase
Construction phase

Figure(s)


Energy
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350
300
250
200
150
100
50
0
B. type 2
B. type 3
B. type 8
Energy
(MJ/(person·year))
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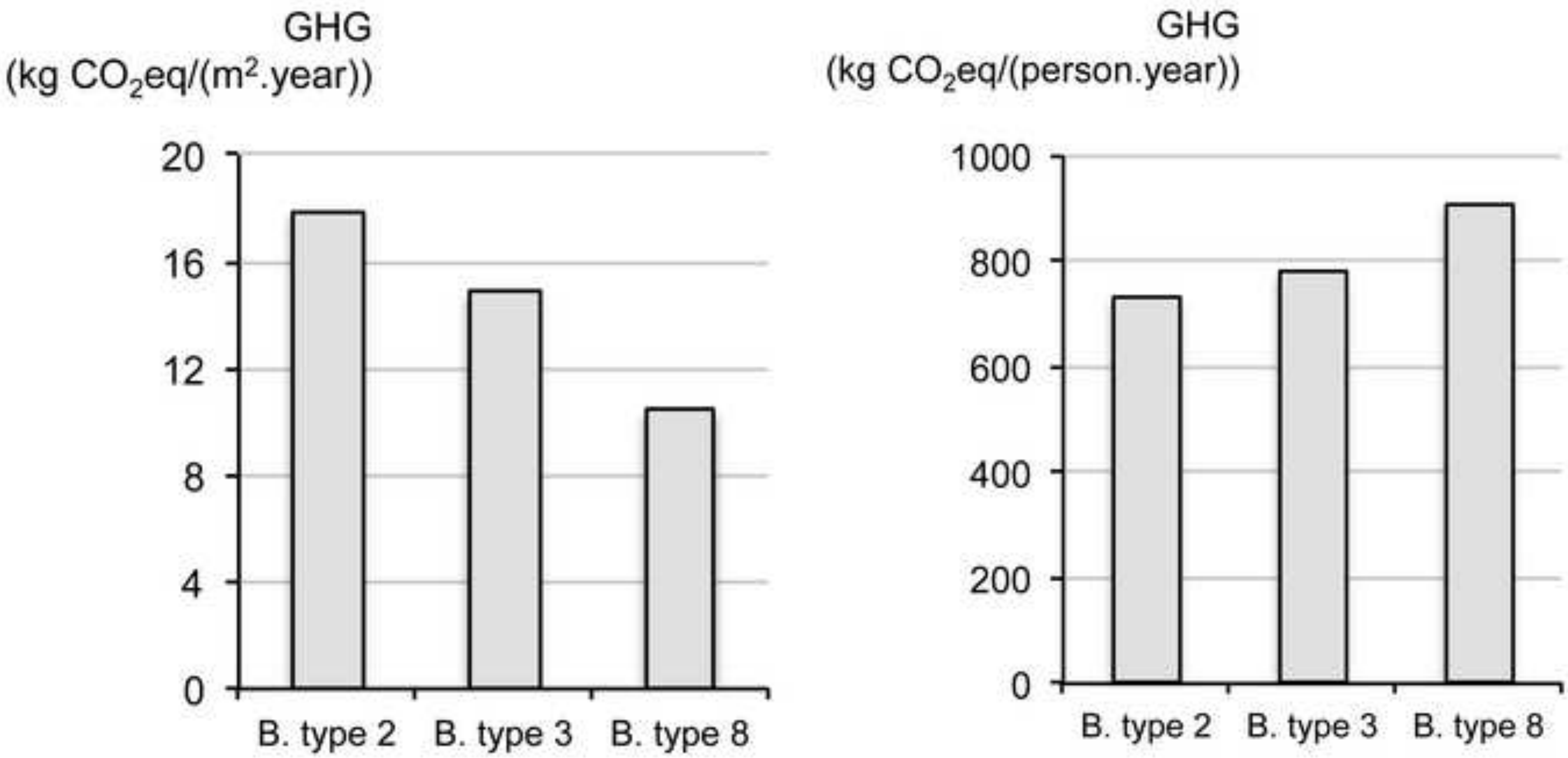
15000
12000
9000
6000
3000
0
B. type 2
B. type 3
B. type 8

Figure(s)


GHG
(kg CO_2eq/(m^2.year))
20
16
12
8
4
0
B. type 2
B. type 3
B. type 8
GHG
(kg CO_2eq/(person.year))
1000
800
600
400
200
0
B. type 2
B. type 3
B. type 8

Highlights

- A comparative LC analysis of 3 residential building types In Lisbon was performed.
- The use phase accounts for over 69% of the life-cycle energy and GHG emissions.
- Energy and GHG intensity in larger buildings are lower per m^2, but higher per person.