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ScienceDirect
Energy Reports 8 (2022) 526–532
www.elsevier.com/locate/egyr

The 8th International Conference on Energy and Environment Research ICEER 2021, 13–17 September

Integrated life cycle assessment of a southern European house addressing different design, construction solutions, operational patterns, and heating systems

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Received 22 January 2022; accepted 9 February 2022
Available online xxxx

Abstract

The construction industry is responsible for a substantial fraction of materials and energy consumption, waste generation, CO_2 and other pollutant emissions. Life cycle assessment (LCA) can be used to study and compare the environmental impacts of buildings under different scenarios. This study comparatively assesses the impact of several design options, envelope solutions and operational conditions on the energy life cycle (LC) of a single-family house in southern Europe (Portugal) taken as case-study. The following parameters are evaluated: location, orientation, building shape, windows placement and sizing, insulation level, exterior wall construction, operational pattern, ventilation level, heating system, and end-of-life (EoL) scenarios. The non-renewable primary energy (NRPE) results are presented for the total LC of the house. Afterward, the overall embodied energy is analyzed and the results are presented per component and LC process of the house, in order to assess the contribution of each component. Finally, different circular economy EoL scenarios are analyzed to assess their potential benefits. As buildings are typically unique, complex, and difficult to compare with each other, the results of this paper will contribute for future comparison purposes, in order to foster LCA studies devoted to Mediterranean houses.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Energy and Environment Research, ICEER, 2021.

Keywords: End-of-life; LCA; Life cycle; Mediterranean house; Parametric study; Primary energy

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1. Introduction

The rising evidence for climate change associated to the human-induced greenhouse gas (GHG) emissions emphasizes the need to shift human activities towards a low-carbon society. Buildings have a considerable share of worldwide energy use, resources consumption, and waste generation, among other environmental hazards. To meet carbon reduction goals, a built environment with reduced energy needs, lower GHG emissions and reduced waste is

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https://doi.org/10.1016/j.egyr.2022.02.101

Peer-review under responsibility of the scientific committee of the 8th International Conference on Energy and Environment Research, ICEER, 2021.

required [1]. Life cycle assessment (LCA) is a scientific methodology that can be applied to estimate the potential environmental burdens of buildings during the different phases of their life cycle (LC): from material extraction, processing, building construction and use, till their end-of-life (EoL). Therefore, LCA can help establishing more sustainable buildings, with more environmentally friendly construction choices and procedures. It can also be used for comparison purposes, for example to compare the environmental impacts of alternative construction and/or different operational scenarios, such as different design, building envelopes, systems, operational conditions, and EoL options.

In the last years, priority has been given to reduce the operational energy of buildings and to assess cost-efficient energy-renovation measures [2], since operation is the longest LC stage of buildings, neglecting somehow the relative environmental impacts associated with construction and EoL phases. However, this trend is shifting, since reducing the operational impact, may boost the relative impacts of construction and EoL phases when an integrated LCA study is performed [3]. Moreover, the colossal volume of construction and demolition waste (C&DW) calls for a more circular economy approach, and the need of converting building EoL materials into more sustainable innovative value-added products. Indeed, one of the key targets pointed out by the European Union's green deal is the reduction of the impacts of residential buildings [4]. This study aims at comparing the impact of several design solutions, building envelopes and operational conditions in the LC energy of an independent house in southern Europe (Portugal), taken as a case-study. For that purpose, some data published by the authors (devoted to the same house) and scattered in the literature was compiled, comparatively analyzed and discussed in this article [3,5–7]. In a first paper, Monteiro and Freire [7] evaluated seven alternative types of exterior walls and compared three life cycle impact assessment (LCIA) methods. In a second paper, Monteiro et al. [6] evaluated the LC non-renewable primary energy (NRPE) improvement potential of the house by analyzing four heating/cooling operational patterns (different schedules and set-points), four heating systems (operating with different energy sources), and alternative electricity generation mix scenarios. In another work, Monteiro et al. [3] evaluated three typologies of exterior walls, six insulation materials, five degrees of insulation and four ventilation levels. Moreover, insulation thickness tipping-points were identified for alternative operational patterns and walls, considering six environmental impact categories. Recently, Monteiro et al. [5] evaluated the impact of three design parameters on the primary energy and environmental performance of the same house: building orientation, shape and openings sizing.

This paper provides a big picture of the work carried out so far, summarizing previous results in an integrated way and comparing the LC influence of options at different levels. Indeed, several sets of alternative scenarios related with different design and operational parameters are evaluated (*e.g.*, location, building orientation, building shape, windows placement and sizing, insulation level, exterior wall type, operational pattern, ventilation level, HVAC system, etc.) and the NRPE results are presented for the total LC of the house. Afterward, the embodied energy of the house is presented per process and building component in order to evaluate the initial and recurrent embodied impact of each component. The potential benefits of different circular economy EoL scenarios are also evaluated.

2. Methodology

2.1. Life cycle assessment and case study definition

An independent house located in southern Europe (40.2 North, 8.4 West) was taken as case study, based on previous research [3,5–7]. Inhabited by a household of four people, the 133 m^2 building had typical Portuguese construction elements: brick walls, concrete structure, aluminum windows. Fig. 1 shows the east and west (front) facades of the house. Following the LCA methodology (ISO 14040/14044), attributional LCA studies have been performed for the house during 50 years life time — functional unit. Aiming to comparatively analyze the LC influence of building options at different levels, the main parameters considered in this parametric study are presented in Fig. 1. All the information required for the LC inventory, embodied energy of production, transport, construction (A1–A5), maintenance (B3–B4), and model simplifications are presented in Refs. Monteiro et al. [3,5,6] and Monteiro and Freire [7]. LC results are accounted for non-renewable primary energy from cumulative energy demand method.

To evaluate the LC impact of alternative building design decisions, several aspects were considered:

- Eight building orientations (starting from base case West–East and assuming a 45° rotation among alternatives) assuming the windows are placed in opposite facades (as shown in Fig. 1).

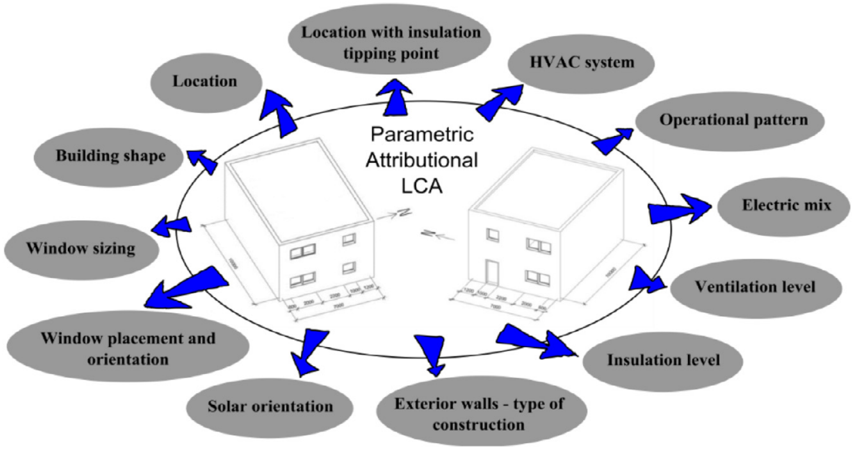

Fig. 1. East and west facades of the reference house and main building options considered in the parametric LCA.

- Different windows placement: H1 W_i (Fig. 1) and H1 W_i-b, as explained in Ref. Monteiro et al. [5]. H1 W_i scenario has five openings placed in the front-facade and six openings in the back-facade, while H1 W_i-b alternative has the same windows (number and area) as H1 W_i (for the same i area factor), but place them in three facades: two in the front, seven in the lateral, and two in the back-facade.
- Four window-to-wall ratios (WWR): 5, 10, 15 and 20% WWR. This means that the influence of incremental window sizes (W_i, $i = 1, 2, 3, 4$) were analyzed for the windows placement options referred. The base-case building (Fig. 1) corresponds to a 5% WWR (W_i, $i = 1$) with all windows totalizing 11 m^2 facade area [5].
- Alternative building shapes: the compact base case (H1), a single-ground floor house (H2), and a less compact house with two floors (H3).

More details about this parametric study can be found in Ref. Monteiro et al. [5].

To assess the impact of the exterior walls three constructions were evaluated: double hollow brick masonry, lightweight concrete block masonry, and wooden wall (wood frame and cladding). More information about the exterior walls can be found in Ref. Monteiro et al. [3]. Moreover, five insulation thickness (0, 3, 6, 9 and 12 cm), and six insulation materials (XPS, XPS-CO_2, cork, rock wool, EPS, PUR) were evaluated for the base brick-wall case house [3].

To assess the influence of the operational conditions, three different operational patterns were considered: OP_{100}, OP_{50} and OP_{25}. The OP_{100} considers continuous indoor thermal comfort conditions 365 days a year, with temperature set-points between 20–25° C (heating–cooling season). It also considers 4 W/m^2 of internal heat gains per useful area. The OP_{50} represents an average occupancy of the house with a medium HVAC level, requiring around half of the OP_{100}'s energy consumption (simulated). The OP_{25} operational pattern exemplifies a modest occupancy and a low HVAC level, comparable to statistical data (from Portuguese households), and it includes only a quarter of OP_{100}'s simulated energy consumption. The annual HVAC energy demand for the building alternatives were obtained using DesignBuilder 3.0, which runs on EnergyPlus thermal dynamic simulation. More details on the operational patterns and energy simulations can be found in Refs. Monteiro et al. [3,5,6]. Four total ventilation levels (0.3, 0.6, 0.9 and 1.2 ac/h) were also considered in the parametric study as explained in Ref. Monteiro et al. [3]. Six locations were also considered (Coimbra, Bragança, Évora, Porto, Lisbon and Faro) as presented in [8]. To evaluate the impact of the heating system selection, four systems and three electric generation mixes were considered as reported by Monteiro et al. [6]: resistance heaters, heat pump (air–water), natural gas condensing boiler and wood pellets boiler.

Lastly, to assess the EoL stage impact, three EoL scenarios for C&DW were modeled: EoL 1 (landfill); EoL 2 (material recycling for secondary construction works replacing gravel and backfilling materials); EoL 3 (material recycling to substitute both gravel/backfilling materials (50%) and cement powders (50%), and window and door elements recovery and reuse).

3. Results and discussion

3.1. Joint influence of building envelope, design, and operational conditions

Fig. 2 shows the variation on life cycle NRPE of the house induced by the alternative construction, design, and operational options studied. The variation is coded in three colors: black bars result from varying both embodied and operational energy; red bars, present mainly an operational energy variation; blue bars, depicted a variation due to embodied energy. As can be seen, many construction and design parameters affect both operation and embodied impact (black), usually with trade-offs. Nevertheless, some operational and design parameters may hold identical embodied energy and affect differently the operational requirements (red).

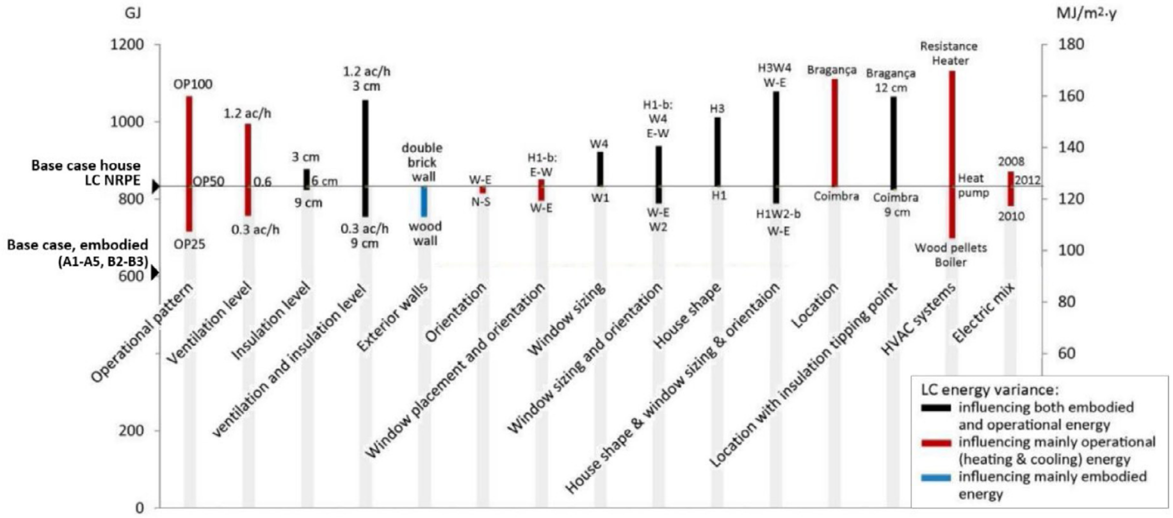

Fig. 2. LC NRPE variation of the base case house for the building envelope, design and operational options assessed (black bars result from varying both embodied and operational energy; red bars, present mainly an operational energy variation; blue bars, depicted a variation due to embodied energy).

Regarding users influence, the simulated heating and cooling loads to achieve a continuous comfort condition (OP_{100}), represent 43% of LC energy, being far above typical energy requirements of Portuguese households. As Portuguese dwellers usually adapt to widespread interior comfort conditions compared to north-Europeans, the operational requirements in a mild climate can be between a quarter to a half of OP_{100}, which results in a reduced LC impact of operational stage (16%–28%), even without changing the house embodied burdens.

Alternative construction options known to critically influence the thermal performance of buildings were also assessed, such insulation thickness and ventilation rates. Despite thermal insulation is usually considered one of the key measures to cut-down heating requirements, results show that adopting a lower ventilation level (an air-tight house with 0.3 ac/h) has a higher influence than increasing thermal insulation thickness above 6 cm to reduce LC NRPE. Results also depict that high ventilation levels (for instance, 1.2 ac/h, due to users) can easily thwart the benefit of having an adequate thermal insulation level. In addition, the LC primary energy savings achieved with an increased insulation level (*e.g.*, from 3 to 9 cm XPS) are inferior to the reduction attained by using alternative construction components such wooden walls, as a substitute of the base-case brick walls. These results highlight the importance of accounting the embodied energy, especially in new Mediterranean houses, agreeing with other LC studies [9,10]. More specifically, this work reveals that the life cycle impact of use phase thermal requirements may be significantly lower than those incorporated in building components. Thus, at building design stage, designers should consider the influence of specific building components and their initial and recurring embodied energy, as a decision factor, since it may represent 3 to 7 times the thermal operational energy (if OP_{50} with a heat pump or a wood pellets heater are selected, respectively). In buildings and climate conditions where thermal energy needs have a potentially small contribution, the current building regulations, which are mainly focused on operational performance, may miss relevant LC impacts and opportunities for improvement towards a low carbon built environment.

Analyzing the impact of simple design decisions (house orientation, window sizing and distribution, building shape), the study shows that these may induce a life cycle NRPE variation that exceeds the effect of varying thermal insulation from 3 to 9 cm. Thus, if the influence of design options is disregarded from a LC perspective, unthinking design may overshadow the potential use stage savings of using adequate thermal insulation and airtightness. Indeed, simple design choices appear to be as significant as the envelope construction options and hence should be simultaneously assessed.

Life cycle NRPE is also shown to be highly influenced by operational conditions: operational patterns (representing alternative forms to inhabit a building), HVAC systems, and the energy supply chain. Under mild climatic environments and culturally low operational patterns, designing the buildings for reasonable operational conditions that represent the users' behavior variability is imperative.

A new dwelling with electric heating or even with a natural gas condensing boiler may be responsible for a higher LC NRPE than a less insulated house using a wood-pellets boiler, despite the new building improved thermal performance and lower final energy needs. Previous literature also pointed out that, depending on the heating system adopted, passive buildings may have close or higher LC impact than standard or conventional buildings [11]. Some authors defended that the supply chain of energy sourcing heating requirements had a greater influence on primary energy than building construction options [12].

The results of this paper support preceding studies, extending their reach for a different climatic and operational context. Typically, the cold climate passive dwellings previously analyzed are designed to have continuous interior thermal comfort, being characterized by thick insulation layers, triple-glazing windows, and ventilation systems with heat recovery. In contrast, in this research, the studied building is a standard Portuguese new house, which meets the passive house standard, due to mild southern European climatic conditions (*i.e.* Coimbra location) and characteristic Portuguese dweller behavior (partial and intermittent use of HVAC systems). Assessing different Portuguese locations showed that the operational stage magnitude can be significantly increased in cold-winter and hot-summer locations such as Bragança, but it remained small in other Portuguese locations (*i.e.* Coimbra, Lisbon, Faro, Porto).

The use stage NRPE of the house varied about 37%, solely due to the changes of the Portuguese electric generation mix (over 5 years). Such wide variation did not affect the selection of the HVAC system with the lowest NRPE (wood pellets boiler), but with the electric mix having a lower impact, using a resistance heating system may have similar NRPE to using a natural gas boiler. Other authors [11], studied the effect of the energy supply chain and electricity production mix in operational results. They highlighted that besides heating needs, other household energy needs can highly influence total operational impact, since these represent a significant share of new houses operation. Lowering the LC impact of these needs can be mostly achieved through energy-conscious user behavior, appliances efficiency and supply-chain improvements.

3.2. Embodied energy and EoL scenarios

Fig. 3 shows the embodied energy per construction component per life cycle to present their magnitude in terms of initial (construction A1–A5) and recurrent (maintenance and repair B2–B3) embodied impacts, compared to operational energy use (B6) and to the alternative EoL scenarios (C1–C3) including the potential avoided burdens (D), when applicable.

NRPE results are presented for the whole house over 50 years. Fig. 3shows that the primary energy associated to the house components (construction A1–A5, and maintenance-repair B2–B3) was roughly 4.7 GJ/m^2, from which 87% was required to construct the house, prior its use (A1–A5). These quantitative results are align with the range found on previous literature: 3.1–7.6 GJ/m^2 [13,14]. The ratio among use phase B2–B3 activities and the initial embodied energy is small (15%), which is justified by socio-economic drivers and the way Portuguese dwellers inhabit and maintain their buildings. In the context covered, maintenance activities are still mostly corrective, as pointed out by other studies [15].

The most impactful building construction element were the exterior walls (double hollow brick), which were accountable for about 40% of the house initial embodied energy (A1–A5) and about half of recurring energy (B2–B3). It is interesting to note that the embodied energy of exterior walls was higher than the thermal use stage energy

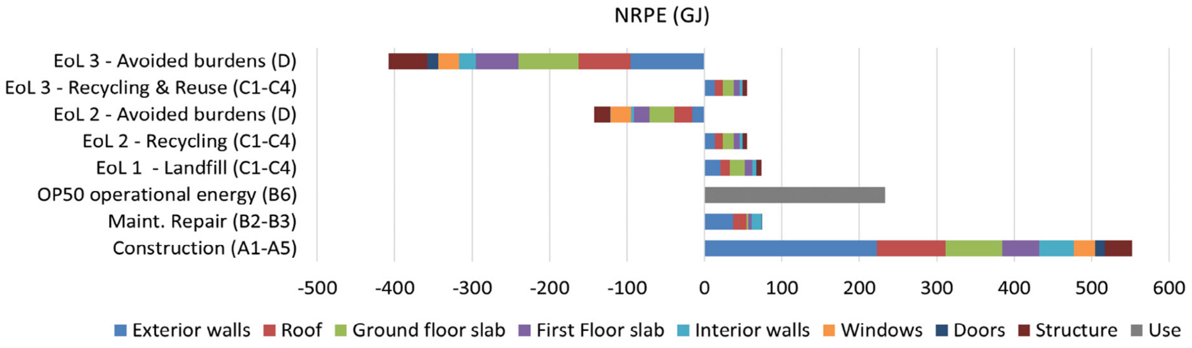

Fig. 3. House LC primary energy per LC stage and construction component.

of the house with OP_{50} (B6). Other significant construction components in terms of initial embodied energy were by descending order: the floors (23%), the roof (16%), and the interior walls (9%). These results are aligned with previous literature for Mediterranean dwellings that found that both external walls, and slabs (floors and roofs) were the elements that affected most the house's embodied energy [16].

The analysis of the EoL results shows that landfill (EoL 1) is the worst scenario. Demolish, transport and landfill more than 230 tons of C&DW represents an additional LC NRPE of 8% (C1–C4). The two scenarios assuming recycling (EoL 2 and EoL 3), take advantage of C&DW, presenting around 6% additional NRPE to demolish and process these materials to be recycled (C1–C3). When considering a system expansion, recycling avoids the extraction of primary materials (such as gravel and backfilling material) offsetting significant primary energy (*i.e.*, a net reduction of 16% of A1–A5 in EoL 2 and 64% in EoL 3). Overall, the results show that circular economy solutions, namely focused in dismantling and reuse building components (*e.g.*, doors and windows) and to use mineral C&DW to produce secondary aggregates and powder able to replace burdensome primary materials (*e.g.*, cement) should be preferred (EoL 3). Thus, improving EoL of C&DW and adopting circular economy solutions can reduce the embodied energy levels in buildings and promote resource efficiency

4. Conclusion

This study comparatively assessed the impact of alternative design options, building envelope solutions and operational conditions in the LC energy of a southern European independent house located in Portugal. In the parametric study, alternative parameters were evaluated: location, building orientation, building shape, window placement and sizing, insulation level, exterior wall typology, operational pattern, ventilation level, heating system, and end-of-life scenario. It is concluded that in mild Mediterranean climate, the embodied energy of construction elements (*e.g.* concrete structure, slabs, brick exterior and interior walls) may represent most of LC NRPE of houses. The results suggest that design options are as significant as the envelope construction options and therefore, they should be simultaneously addressed. C&DW represents massive waste flows. The EoL scenarios assessed showed that new circular economy solutions, namely focused in dismantling and reuse building components (*e.g.*, doors and windows) and to produce secondary aggregates and powders from C&DW to replace burdensome primary materials (*e.g.* cement) can promote material resource efficiency and reduce the embodied energy levels of future built environment and construction works.

CRediT authorship contribution statement

Helena Monteiro: Investigation, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nelson Soares:** Writing – original draft, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work builds on research funded by FCT SFRH/BD/33736/2009 and, it is aligned with research focused on industrial sustainability of building and construction industry developed in the scope of European Union's Horizon 2020 research and innovation programme under the Grants Agreement 894511, and 810764.

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