A Comparison of the Life Cycle Energy Profile of Residential Buildings in Different Countries

Abstract: *Buildings are responsible for significant energy use and greenhouse gas emissions, globally. Life cycle energy analysis if often used to assess the total energy use of buildings and identify relevant reduction measures. However, most existing studies underestimate embodied energy, do not consider the occupant's transport-related energy and focus on a single country. This study relies on a comprehensive life cycle energy analysis framework to assess three different dwellings in Australia, Belgium and Lebanon. Results show that the life cycle energy profile varies significantly depending on the location and is influenced by a range of factors. This study shows that the proposed method can be applied in different contexts as long as the required data is available. By relying on a comprehensive life cycle energy analysis framework, building designers can prioritise the most effective measures to reduce energy use and ultimately the environmental impact of buildings.*

Life cycle energy analysis; dwellings; different countries; indirect requirements

Introduction

Climate change and global warming are likely to disrupt the lives of millions of people across the world. They are driven by anthropogenic emissions of vast quantities of greenhouse gas (GHG) into the earth's atmosphere at an unprecedented rate [1], the vast majority of which are due to energy use [2].

The operation of buildings alone is responsible for 32% of the final energy use and 19% of GHG emissions, globally [3]. This contribution more than doubles if indirect energy requirements and associated GHG emissions are considered [4]. These include embodied requirements in building materials and the energy required for the mobility of building occupants. Due to this huge impact, buildings yield a large potential for reducing energy use and associated GHG emissions at a global scale.

A life cycle perspective is required to assess energy use in buildings and to identify appropriate strategies for its reduction [5]. This approach ensures that reductions during one life cycle stage are not shifted to another. Life cycle energy analysis (LCEA) quantifies all energy inputs across the different life cycle stages of a process or product.

Most previous studies applying LCEA to buildings suffer from a range of issues. Firstly, they often rely on the so-called process analysis technique to quantify embodied energy. This technique can underestimate embodied energy by up to four times at a whole building level [5]. This explains why most reviews of LCEA in buildings, e.g. [6,7], conclude that embodied energy represents only 15-25% of the life cycle embodied and operational energy use over 50 years. Secondly, the vast majority of existing studies focus on the building scale alone ignoring the urban scale, i.e. the transport-related energy use of building occupants and the embodied energy in infrastructures needed to operate buildings. Stephan [4] has established that requirements at the urban scale are often significant. Thirdly, the majority of building LCEA studies focus on a specific case study in a particular country such as Sweden [8]. One of the rare comparative studies was recently undertaken by Mosteiro-Romero et al. [9] who compared the life cycle profile (including a range of environmental impact categories) of a Swiss low-energy house and a US house (in New Jersey). While some reviews compile studies from different geographical areas, they often provide aggregated results and compare studies with different system boundaries. In addition, most existing studies assess buildings in developed economies.

The aim of this paper is to use the same LCEA framework to establish and compare the LCE use profile of new dwellings in different countries and evaluate the applicability of the method in various contexts.

Method

This section provides a summary of the LCEA framework and a brief description of the case studies.

A LCEA framework that comprises all the life cycle stages of the building (except the end-of-life stage) as well as the different scales of the built environment is used in this paper. This framework was developed by Stephan [4] and is described in detail in Stephan and Crawford [10]. Only a summary is provided here.

Primary energy inputs across the following building life cycle stages are taken into account: raw material extraction; material manufacture, processing and transport; construction; and operation and maintenance. The end-of-life stage is not taken into account due to the huge uncertainties about the fate of the building after a very long useful life.

Embodied energy includes the initial embodied energy of the building as-built and the recurrent embodied energy associated with material replacement over its useful life. Embodied energy is quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar [11]. This technique combines bottom-up process data which are collected from material manufacturers and top-down input-output data that are based on average sectorial energy intensities at a national economy level. Process data is of higher quality, more specific and more reliable but does not cover the entire supply chain due to the difficulty of gathering information for processes further upstream in the supply chain. Input-output data covers the entire supply chain but provides sectorial averages and fails to differentiate accurately between products from the same sector. Hybrid analysis combines both techniques, eliminates their flaws and cumulates their strengths by relying on reliable process data where available and filling the gaps with average input-output data to ensure systemic completeness [5,12]. Practically, embodied energy is calculated by multiplying the quantity of each material in the building (based on the material bill of quantities) by a hybrid embodied energy coefficient [13] and the number of replacements over the useful life of the building (including the initial installation). Average material service lives, based on a range of sources, e.g. Ding [14], are used to estimate the number of replacements.

The embodied energy of nearby infrastructure systems (roads, water distribution, gas distribution, electricity distribution and sewage) is taken into account and allocated to the household based on the number of occupants and the average population density in the neighbourhood. This ensures that infrastructure systems that are essential to the operation of a building are considered.

Operational energy includes heating; cooling; ventilation (where applicable); lighting; hot water; appliances and cooking. It is quantified using steady-state heat transfer equations for thermal requirements and regional averages for non-thermal requirements. All final and delivered energy uses are converted to primary energy using primary energy conversion factors based on the energy source and location.

Transport energy requirements include both direct energy (e.g. burning fuel in a car engine) and indirect energy (e.g. manufacturing a car, insurance, registration and maintenance). They are based on the average travel distance per transport mode and per household. Direct energy intensities are based on local figures where available and on Lenzen [15] otherwise. Indirect energy intensities are determined using input-output analysis and are based on Lenzen [15].

The total LCE is the sum of the embodied, operational and transport requirements, over the useful life of the building. It is expressed in GJ/capita in this study in order to take into account the lifestyle of occupants.

This life cycle framework is applied to three different case study dwellings, each typical of recent construction in its country: an energy efficient single family house 25 km west of Melbourne, Australia; a single family passive house 26 km south-east of Brussels, Belgium; and an apartment unit in a four-storey residential building in Sehaileh, Lebanon, 26 km north-east of the capital Beirut. Australia and Belgium are chosen as representative of developed economies (for which the framework was developed) and Lebanon as a developing economy. Table 1 provides a summary of the characteristics of the case study dwellings.

Table 1: Main characteristics of the three case study dwellings

Characteristics	Australian 7-Star house (AH)	Belgian passive house (BPH)	Lebanese apartment (LA)
Period of analysis (years)	50	50	50
Building useful life (years)	50	50	50
Köppen climate classification	Oceanic climate - Cfb	Oceanic climate - Cfb	Warm Mediterranean climate - Csa
Infrastructure systems	New	Existing	Existing
Gross floor area (m²)	297	330	154
Usable floor area (m²)	267	300	113
Number of occupants	5	4	4
Structure	Timber-framed	Steel-framed	Reinforced concrete
Façade	Brick veneer wall; 100 mm of fibreglass insulation; Double glazed aluminium-framed windows	Glued bricks; 220 mm of polyurethane insulation; Triple glazed, argon-filled, timber-framed windows	Natural stone cover; Double concrete block wall with a 100 mm air gap; Double glazed aluminium-framed windows
Roof	Concrete tiles; 200 mm of fibreglass insulation	Terracotta tiles; 300 mm of polyurethane insulation	Terracotta tiles; No insulation
Finishes	Water-based paint; Nylon carpet in bedrooms; Ceramic tiles in other spaces; Tiled kitchen and bathroom walls	Water-based paint; Parquet flooring in bedrooms; Ceramic tiles in other spaces; Tiled kitchen and bathroom walls	Water-based paint; Ceramic tiles in all rooms; Tiled kitchen and bathroom walls
Average U-value (W/(m²K))	0.58	0.19	1.2
Operational energy sources	Gas heating (eff. 0.7) and cooking (eff. 0.9); Electrical cooling (eff. 2.5); Solar domestic hot water with gas auxiliary system (eff. 0.9).	All electrical: heating (eff. 1.0), cooking (eff. 1.0), ventilation (eff.0.9), domestic hot water (eff. 1.0)	Gas heating and cooking (eff. 0.9); Electrical cooling (eff. 2.5); Electrical domestic hot water (eff. 1.0)
Primary energy conversion factors	Electricity: 3.4[a] Gas: 1.4[a]	Electricity: 2.5[b]	Electricity 3.2[c] Gas 1.1[d]
Cars	2 gasoline[e]	1 gasoline and 1 diesel[f]	2 gasoline[g]
Total car travel distance per year (km)	36 000[e]	32 000[f]	40 000[g]
Total energy intensity of cars (MJ/vkm)	Gasoline: 4.41[i]	Gasoline: 3.2[e, h, i] Diesel: 2.93[e, h, i]	Gasoline: 4.13[i]

Note: eff. represents the efficiency of the end-use system. All average figures for operational energy use are derived from [16] for Brussels, from [17] for Melbourne and are based on [18] for Sehaileh. [a] from[19], [b] from [20], [c] calculated by the authors based on the average electricity mix in Lebanon, [d] assumed, [e] based on data from [21], [f] based on [22], [g] based on an interview of the inhabitants, [h] based on results from [23] and [i] based on [15].

Results

This section compares the LCE profiles of the case studies and identifies areas of improvement. It provides the basis of the discussion.

Figure 1 shows the LCE profiles of the three case study dwellings, by use. The Australian house (AH) has the highest LCE (4 894 GJ/capita) followed by the Belgian passive house (BPH) (4 833 GJ/capita) and the Lebanese apartment (LA) (4 019 GJ/capita). The LCE of the LA is 20-22% lower than the two other cases. The variation in LCE values results from different contributions from embodied, operational and transport requirements.

The BPH has the highest embodied energy (2 131 GJ/capita; 44% of the total). This is due not only to the significant amount of additional insulation required for the house (see the *Envelope* category in Figure 1) but also to the larger usable floor area per capita, i.e. 75 m², compared to 53.4 m² and 28.3 m² for the AH and the LA, respectively. While the LA has an energy intensive reinforced concrete structure and shares common spaces with other apartments, its embodied energy is two times and nearly three times lower compared to the AH and the BPH, respectively. The small living area per capita and the highly durable nature of construction materials, leading to a small recurrent embodied energy, are responsible for this difference. Note the contribution of the often neglected new infrastructure systems in the AH (242 GJ/capita; 15% of the embodied energy).

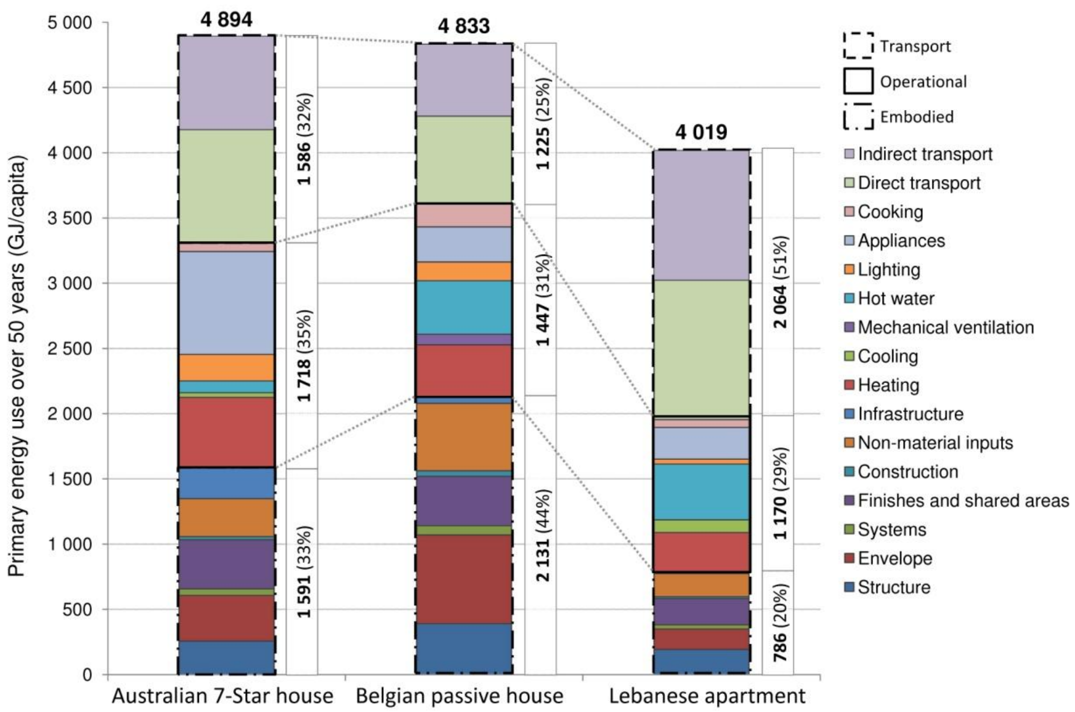

Figure 1: Life cycle energy profile of the three case study dwellings over 50 years, by use.

The AH has the highest operational energy use (1 718 GJ/capita), which is dominated by appliances (46%) and heating (31%). The BPH has a more balanced operational energy use with hot water and heating representing 28% and 27%, respectively, followed by appliances (18%), lighting (12%) and cooking (10%). Operational energy use in the LA is due mainly to hot water (37%), heating (26%) and appliances (21%). The installation of solar collectors for hot water could significantly reduce the operational energy use of the BPH and the LA by substituting electricity with a local renewable energy source, as per the AH.

ransport-related energy use is the highest in the LA case (2 064 GJ/capita; 51% of the total) followed by the AH (1 586 GJ/capita; 32% of the total) and the BPH (1 225 GJ/capita; 25% of the total). This results from the larger travel distances in the Lebanese case which are due to the reliance on cars even for proximity trips and the absence of public transport. The suburban location of all the assessed dwellings explains the high contribution of transport-related requirements (25-51%).

Discussion and conclusion

This paper shows that the LCE profile of new dwellings varies significantly between different countries and economies. While the Australian case is the most balanced, with each category representing almost one third of the total, the Belgian and the Lebanese cases are dominated by embodied (44%) and transport (51%) requirements, respectively. This screening allows building designers to identify hot spots in the energy profile and to identify solutions that can yield the most significant reductions. For instance, using energy efficient appliances, selecting a high performance insulation material with a low embodied energy and reducing travel distances while using a fuel efficient car are specific solutions for the Australian, Belgian and Lebanese cases, respectively. Replacing electricity by another fuel source with lower primary energy requirements (such as solar or gas) is a global solution that is relevant to all cases, as highlighted by studies in different countries [8,9]. For example, installing solar collectors for domestic hot water can reduce the LCE use of the BPH and the LA by 3% and 8%, respectively. The 8% reduction (332 GJ/capita) in the LA case is equivalent to the combined energy use for lighting, appliances and cooking, over 50 years. These savings take into account the additional embodied energy required to install and replace solar collectors. This study demonstrates that by adopting wide system boundaries when establishing LCE profiles, the net total benefit of potential solutions can be more reliably assessed.

Apart from establishing the LCE profile of different dwellings, this paper shows that a single life cycle framework can be applied in developed and developing economies. This is possible because specific data, relevant to each case study, can be fed into the framework. The latter provides a sufficient level of abstraction to be transposable to different contexts. Also, by adopting wide system boundaries, the proposed framework is able to capture shifts between life cycle stages or between scales of the built environment (a city-based case study vs. a suburban case study). The proposed framework can be used seamlessly in different contexts as long as the data is available.

However, this study suffers from a number of limitations. Firstly, it relies on Australian data for the calculation of the embodied energy in all cases, due to the unavailability of hybrid data for other locations. Secondly, it uses steady-state thermal energy equations for the determination of thermal requirements, while dynamic simulations can provide more accurate estimations. Thirdly, the framework has been applied to three different dwellings, one in each country. A larger sample of dwellings should be assessed to fully evaluate the applicability of the framework. This sample should ideally include existing dwellings, city-based buildings and cases relying on public transport. Fourthly, since the framework is quantitative, it systematically suffers from uncertainty in the data. The latter can greatly hinder the performance of the framework since large uncertainties can be present in embodied energy figures [24], in operational energy figures [25] and in transport energy figures [4]. More robust databases, notably regarding embodied energy requirements, are needed. Finally, this study has focused on energy use only. More environmental impact categories (such as toxicity, ozone depletion and others) should be considered to ensure that environmental impacts are not simply shifted from one category to another.

To conclude, this paper has demonstrated how a single LCEA framework can be applied to case studies located in developing and developed economies. The framework can establish the LCE profile of dwellings. By using this framework, building designers can prioritise measures to reduce energy use and associated greenhouse gas emissions. Future research includes comparing a larger sample of dwellings in different countries and improving the assessment framework to include more environmental impact indicators.

References

[1] IPCC (2013) Climate change 2013: the pysical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. edited by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. Cambridge: Cambridge University Press

[2] IEA (2012) World energy outlook 2012. Paris: International Energy Agency

[3] IEA (2012) CO_2 emissions from fuel combustion. Paris: International Energy Agency

[4] Stephan, A. (2013) Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework. Ph.D. thesis, ULB-BATir - Building, Architecture and Town planning and UoM-ABP - Architecture, Building and Planning, Université Libre de Bruxelles and The University of Melbourne, Brussels.

[5] Crawford, R.H. (2011) *Life cycle assessment in the built environment*. London: Spon Press.

[6] Ramesh, T., Prakash, R. and Shukla, K.K. (2010) Life cycle energy analysis of buildings: An overview. *Energy and Buildings* 42:1592-1600 doi: 10.1016/j.enbuild.2010.05.00.

[7] Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G. and Castell, A. (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews* 29 (0):394-416 doi: 10.1016/j.rser.2013.08.037.

[8] Gustavsson, L. and Joelsson, A. (2010) Life cycle primary energy analysis of residential buildings. *Energy and Buildings* 42 (2):210-220 doi: 10.1016/j.enbuild.2009.08.017.

[9] Mosteiro-Romero, M., Krogmann, U., Wallbaum, H., Ostermeyer, Y., Senick, J.S. and Andrews, C.J. (2014) Relative importance of electricity sources and construction

practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts. *Energy and Buildings* 68, Part A (0):620-631 doi: 10.1016/j.enbuild.2013.09.046.
[10] Stephan, A. and Crawford, R.H. (2014) A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. *Architectural Science Review* 57 (1):39-48 doi: 10.1080/00038628.2013.837814.
[11] Treloar, G.J. (1997) Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. *Economic Systems Research* 9 (4):375-391
[12] Majeau-Bettez, G., Strømman, A.H. and Hertwich, E.G. (2011) Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology* 45 (23):10170-7
[13] Treloar, G.J. and Crawford, R.H. (2010) Database of embodied energy and water values for materials. Melbourne: The University of Melbourne.
[14] Ding, G. (2004) The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities. Ph.D. thesis, School of the Built Environment, University of Technology, Sydney.
[15] Lenzen, M. (1999) Total requirements of energy and greenhouse gases for Australian transport. *Transportation Research Part D-Transport and Environment* 4 (4):265-290
[16] IBGE (2010) Bilan énergétique de la région de Bruxelles-Capitale 2008. Brussels: Institut Bruxellois pour la Gestion de l'Environnement
[17] DEWHA (2008) Energy use in the Australian residential sector 1986-2020. Canberra: Department of the Environment, Water, Heritage and the Arts
[18] Ruble, I. and El Khoury, P. (2013) Lebanon's market for domestic solar water heaters: Achievements and barriers. *Energy for Sustainable Development* 17 (1):54-61 doi: 10.1016/j.esd.2012.11.004.
[19] Treloar, G.J. (1998) A comprehensive embodied energy analysis framework. Ph.D. Thesis, School of Architecture and Building, Deakin University, Geelong.
[20] RBC (2008) Arrêté du gouvernement de la région de Bruxelles-Capitale déterminant des exigences en matière de performance énergétique et de climat intérieur des bâtiments. In *Paper 2008 — 326*, Edited by Ministère de la région Bruxelles-capitale. Brussels: Moniteur Belge.
[21] BITRE (2011) Population growth, jobs growth and commuting flows in Melbourne. In *Melbourne, Report 125*. Canberra ACT: Bureau of Transport, Infrastructure and Regional Economics
[22] Bureau Fédéral du Plan (2012) Transport routier. Edited by BFP. Brussels.
[23] Jonson, D.K. (2007) Indirect energy associated with Swedish road transport. *European Journal of Transport and Infrastructure Research* 7 (3):183-200
[24] Wang, E. and Shen, Z. (2013) A hybrid Data Quality Indicator and statistical method for improving uncertainty analysis in LCA of complex system – application to the whole-building embodied energy analysis. *Journal of Cleaner Production* 43 (0):166-173 doi: 10.1016/j.jclepro.2012.12.010.
[25] Topouzi, M. (2011) The effect of 'default user' inputs in modelling tools and methods in energy use. *Proceedings of 27th International Conference on Passive and Low-Energy Architecture*, Louvain-la-Neuve, 15.07.2011.