Towards a comprehensive life cycle energy analysis framework for residential buildings

André Stephan[a,b,c,1], Robert H. Crawford[c], Kristel de Myttenaere[b]

[a]Aspirant du F.R.S.-FNRS - Belgian National Fund for Scientific Research Doctoral Fellow
[b]Building, Architecture and Town planning, Université Libre de Bruxelles, 50 Av.F.-D. Roosevelt, Brussels 1050, Belgium
[c]Faculty of Architecture, Building and Planning, The University of Melbourne, Victoria 3010, Australia

Abstract:

The current energy assessment of residential buildings focuses mainly on their operational energy demand, notably in terms of space heating and cooling. The embodied energy requirements of buildings and the transport energy consumption of their users are typically overlooked. Recent studies have shown that these two energy demands can represent more than half of the life cycle energy of a residential building over 50 years.

This article presents a framework which takes into account energy requirements at the building scale, i.e. the embodied and operational energy of the building and its maintenance and refurbishment, and at the city scale, i.e. the embodied energy of nearby infrastructures (such as roads, power lines, etc.) and the transport energy (direct and indirect) of its users.

Results from two test cases, located in Brussels, Belgium and Melbourne, Australia, confirm that each of the embodied, operational and transport requirements are nearly equally important. By integrating these three energy flows, the developed framework and associated software provides architects, building designers, planners and decision makers with a powerful tool to effectively reduce the overall energy consumption and associated greenhouse gas emissions of residential buildings.

Keywords: Life cycle energy analysis - Residential buildings - Embodied energy - Transport energy - Operational energy - Software

Preprint version

1 Introduction

1.1 Background

Buildings represent nearly 30% of the final energy consumption in the world [1] and 37% in the European Union (EU) [2]. Residential buildings alone represent 26% of the final energy demand in the EU [2] which makes them one of the largest single energy-consuming sector. Since energy production

[1] Corresponding author:
Faculty of Architecture, Building and Planning, The University of Melbourne, Victoria 3010, Australia
e-mail: astephan@ulb.ac.be
Tel: +32 485 443 248
+61 452 50 28 55

still relies heavily on non-renewable and polluting sources, measuring energy consumption in buildings is a good indicator of their associated environmental impacts [3]. It is therefore crucial to lower the energy consumption of residential buildings. However, measuring the operational energy demand, with a specific emphasis on thermal aspects (e.g. [4]) , overlooks a large part of the overall energy consumption of residential buildings and their users.

Indeed, the embodied energy in building materials and the energy associated with construction and maintenance should be taken into account. In their review of life cycle energy analysis of buildings, Ramesh et al. [5], found that embodied requirements represent, on average, only 10-20% of the total consumption (including embodied and operational energy demands). This figure might largely underestimate the contribution of embodied requirements because most life cycle energy analysis studies up to date rely on the so-called “process analysis” technique for the quantification of embodied energy. While process analysis supplies high quality data for the assessed inputs and outputs of the studied product/process, it suffers from a system boundary truncation. Studies relying on the more comprehensive input-output-based hybrid analysis [6], which combines process and input-output data, have found that embodied energy requirements can represent around 45% of the total energy consumption of a residential dwelling over 50 years [7]. The embodied energy requirements of residential buildings should hence be taken into consideration in a more holistic assessment, as advocated by Xavier Garcia [8].

Besides embodied requirements, energy consumption associated with the building users mobility should also be accounted for. Indeed, residential buildings represent the constituting brick of the urban fabric which largely conditions transport energy consumption [9-12]. Although socio-economic factors play an important role [11, 13], the building location has a large impact on the total energy consumption of its inhabitants. For instance, a very energy efficient building (e.g. passive house), located in the suburbs, will have a dramatically reduced final heating demand but will require its users to use cars for their mobility. Compared to a normal house in a city, what is saved in terms of operational energy, could be counter-balanced by transport energy requirements. Transport energy should therefore be taken into consideration to ensure that energy savings do occur.

Very few studies combine embodied, operational and transport energy requirements, yet they highlight the importance of each of the three energy flows, from a life cycle perspective. The study of Stephan et al. [14] on Brussels, Belgium, (over 50 years) or of Fuller and Crawford [15] on Melbourne,

Preprint version

Australia (over 100 years) demonstrate that, on average, embodied and transport requirements can represent more than 50% of the total life cycle energy requirements. Therefore, a more comprehensive energy assessment framework is required to realistically measure the energy consumption associated with residential buildings.

1.2 Aim

The aim of this work is to develop a comprehensive framework to measure the embodied, operational and transport energy requirements of a residential building over its life cycle. By integrating the three energy flows in a single assessment, the developed framework can be used to reduce the overall energy consumption of residential buildings at both the building and city scales.

1.3 Scope and plan

The framework includes energy consumption for the raw material extraction, manufacturing, construction and operation of the building. The embodied energy of the nearby infrastructure is also included. The operation stage comprises the maintenance, material replacement, building usage and user transportation. Energy associated with the end-of-life stage of the building (i.e. demolition) is not taken into consideration since it often represents less than 1% of the embodied and operational demands over the lifespan of the building [16].

This article first presents the quantification aspects of the developed method. Two case study buildings, one located near Brussels, Belgium and the second near Melbourne, Australia illustrate the potential of the framework. Results are used as a ground for discussion.

2 Quantifying life cycle requirements

Developing a single framework to quantify embodied, operational and transport energy requirements is, by essence, a complex endeavor involving hundreds of different parameters. For clarity and length purposes, only the main equations and aspects are presented in this article. The full details of the research can be found in Stephan [17]. This section describes the main equations used for the quantification of embodied, operational, transport and total energy requirements as well as aspects pertaining to uncertainty and variability. A brief description of the developed software tool is also provided.

Preprint version

2.1 Embodied energy

Embodied energy can be defined as all the necessary energy inputs to produce and construct a building, across the whole supply chain. The initial embodied energy qualify the embodied requirements of the building, as built, while recurring embodied energy accounts for the replacement of materials, over the lifespan of the building.

While a growing body of literature is discussing the importance of embodied energy, most studies (e.g. [18-20]) rely on process analysis (see Section 1.1) for its quantification. This bottom-up technique truncates the system at a certain stage of the supply chain and hence does not account for inputs a higher stages or in related supply chains. Input-output analysis is a top-down statistical technique, based on financial transactions, which is systemically complete. Relying on input-output tables (see [21]), it determines the energy intensity of economic sectors and hence quantifies the energy requirements of a product, based on its price. While this technique considers the whole national economy as a system, it suffers from a so-called “aggregation error”. Indeed, all products within a sector have the same energy intensity per monetary unit. This assumption is evidently not very realistic and implies a large uncertainty in the data, contrarily to process analysis figures. Hybrid analysis is the combination of both techniques. It consists of using process data where available and to fill the systemic gaps with input-output data in order to assess the entirety of the supply chain of a product. This typically results in much higher embodied energy figures compared to process analysis. For instance, in their reviews of life cycle energy studies, Ramesh et al. [5] and Sartori and Hestnes [22] find, on average, an initial embodied energy of 2.5-4.5 GJ/m² of gross floor area. These figures are much lower than in studies using input-output-based hybrid analysis where 12-15 GJ/m² are obtained (e.g. [7]). Hence, this work relies on the comprehensive input-output-based hybrid analysis for the quantification of embodied energy. More details about the life cycle assessment techniques and hybrid analysis in particular can be found in [6, 7, 23].

The initial embodied energy of the building is obtained by multiplying the hybrid energy coefficients of its constituting materials by their final quantities in the building (including wastage) as per Equation 1.

$$IEE_b = \sum_{m=1}^{M} Q_m \times EC_m + \left(TER_n - \sum_{m=1}^{M} TER_m \right) \times \$_b \qquad (1)$$

Preprint version

Where: IEE_b = Initial embodied energy of the building b in GJ; Q_m = quantity of material m; EC_m = hybrid energy coefficient of material m; TER_n = total energy requirements of the building construction-related input-output sector n in GJ/currency unit; TER_m = total energy requirements of the input-output pathways representing the material production processes for which process data is available in GJ/currency unit; and $\$_b$ = price of the building in currency units.

Recurrent embodied energy requirements are determined by summing the embodied energy of replaced materials across the lifespan of the building. The replacement rate of building materials is based on an average useful life. The determination of the useful life of a material is a complex process depending on many variables, such as weather, work execution, maintenance and others, as described in ISO 15686-1 [24]. The same material could hence have very different useful lives.

The recurrent embodied energy of the building (REE_b) is obtained similarly to its initial embodied energy, by multiplying the material quantities by their number of replacements over the lifespan of the building as per Equation 2 and adding the input-output remainder associated with each material, based on its price. Note that the number of replacements is rounded to its integer component (e.g. 2.66 → 2).

$$REE_b = \sum_{m=1}^{M}\left(\frac{UL_b}{UL_m}-1\right)\times Q_m \times EC_m + \sum_{m=1}^{M}\left(\frac{UL_b}{UL_m}-1\right)\times\left(TER_n - \sum_{m=1}^{M} TER_m\right)\times \$_m \qquad (2)$$

Where REE_b = Recurrent embodied energy of the building b in GJ; UL_b = Useful life of the building b; UL_m = useful life of the material m; and $\$_m$ = price of the material m in currency units. All other variables are the same as in Equation 1.

The total embodied energy of the building ($LCEE_b$) is then obtained by adding the initial and recurrent embodied energy requirements as per Equation 3. The $LCEE_b$ comprises embodied requirements for all materials and assemblies in the building, including structure, envelope, systems and finishings. The embodied energy of potential solar systems is also considered.

$$LCEE_b = IEE_b + REE_b \quad (3)$$

Besides the embodied energy of the building itself, the embodied energy of the surrounding infrastructures : roads, power lines, water and gas distribution, and sewage, is also taken into account (city scale). The calculations are made using the same Equations 1 and 2 as for the building but without adding the input-output remainder, which results in process-based hybrid analysis figures with slightly less comprehensive system boundaries. The embodied energy of each infrastructure is

Preprint version

calculated based on the infrastructure density in m/km² and attributed to the building based on the population density and the number of users as per Equation 4.

$$LCEE_{if} = \sum_{i=1}^{I} LCEC_i \times D_i \times \frac{NU}{PD} \quad (4)$$

Where: $LCEE_{if}$ = life cycle embodied energy of infrastructures *if* in GJ; $LCEE_i$ = life cycle embodied energy coefficient of infrastructure *i* in GJ/m; D_i = density of infrastructure *i* in m/km²; *NU* = number of users in the building; and *PD* = population density in inhabitants/km².

2.2 Operational energy

Operational energy comprises energy requirements for heating, cooling, ventilation (if present), lighting, domestic hot water, cooking and appliances. Most building energy efficiency schemes, such as the Energy Performance of Buildings Directive (EPBD) [4], focus on thermal aspects. The energy efficiency criterions are generally expressed in terms of final energy, excluding primary requirements for fuel production. However, the EPBD does include a primary energy consumption indicator. While this is a praiseworthy step, the requirements for lighting, cooking and appliances are not taken into consideration. Knowing that electricity has a very high primary energy conversion factor in most countries, and that the appliances energy demand is steadily increasing [25], omitting these aspects from the energy assessment could overlook a significant part of the energy consumption. All operational energy demands should be taken into account. As demonstrated by Gustavsson and Joelsson [26], these should be converted to primary energy figures in order to measure a realistic overall consumption.

All final operational requirements are determined on a yearly basis. In order to simplify the assessment, static equations are used for the determination of the heating and cooling demand. While dynamic simulation tools might produce more accurate results, the ease of implementation and flexibility of static calculations render their use preferable for an early stage assessment. Full dynamic modeling is preferred for advanced stages of design. The heating and cooling as well as other operational energy demands figures can therefore be replaced with more accurate data if available.

The heating demand is determined by multiplying the average heat transfer coefficient of the building (U_b) by the heat loss area (outer walls, windows and roof) and the number of heating degree hours. The balance temperature for the calculation of the heating degree hours should take into account average internal and solar gains. Losses through the ground are neglected and might have

Preprint version

an impact on the overall heating demand. Ventilation losses are taken into account and are based on an average air change rate over the year. If a mechanical ventilation with heat recovery is installed, ventilation losses are reduced by the heat recovery efficiency. The heating demand is calculated as per Equation 5.

$$OPFHE = HDH \times \left[U_b \times A_{ht} + \left(1 - \eta_{HR}\right) \times V_{ht} \right] \quad (5)$$

Where: *OPFHE* = Operational final heating energy demand in KWh; *HDH* = number of heating degree hours for the building site in kKh; U_b = Average heat transfer coefficient for the building b in W/(m²K); A_{ht} = Area of heat transfer in m²; η_{HR} = Efficiency of the heat recovery system if present; and V_{ht} = Ventilation heat transfer in W/K.

The cooling demand is determined using Equation 5, by replacing heating degree hours by cooling degree hours. The latter should be calculated by taking into account internal and solar gains which imply additional cooling.

Ventilation energy requirements are determined based on the average mechanical ventilation flow and a fixed fan power per volume ratio, as per Equation 6.

$$OPFVE = V_f \times H_v \times P_v \quad (6)$$

Where: *OPFVE* = Operational final ventilation energy in kWh; V_f = average mechanical ventilation flow in m³/h; H_v = thousands of hours of mechanical ventilation per year in kh; and P_v = average volumic fan power in W/m³.

The domestic hot water, appliances and cooking final energy demands are determined by multiplying regional averages per capita by the number of users in the house. Lighting is calculated by multiplying average yearly consumption by the usable floor area of the building.

All final energy consumptions are converted to primary energy according to the efficiency of the end-use system and the energy source. The life cycle primary operational energy consumption of the building is calculated as the sum of the yearly primary energy demands of all end-uses multiplied by the useful life of the building, as per Equation 7. If solar systems are installed, solar fractions are deduced from the final energy consumption of related end-uses.

$$LCPOPE_b = UL_b \times \sum_{e=1}^{E} \left(1 - SF_e\right) \times \frac{OPFE_e}{\eta_e} \quad (7)$$

Preprint version

Where: $LCPOPE_b$ = Life cycle primary operational energy of the building b in GJ; UL_b = Useful life of the building b; SF_e = solar fraction for the end-use e; $OPFE_e$ = yearly operational final energy demand of the end-use e in GJ; and η_e = average efficiency of the end-use e.

2.3 Transport energy

The Transport energy consumption comprises all inputs associated with the mobility of building users. It can be broken down into so-called “direct” and “indirect” requirements. Direct requirements are directly associated with the process, such as burning fuel in a car engine. Indirect requirements consider all other inputs across the supply chain to allow the process, e.g. car manufacturing. Indirect requirements are often overlooked in transport energy studies but Lenzen [27] and Jonson [28] have established that they can represent up to 45% of the total requirements (direct and indirect) for road transport and sometimes more for other transport modes. It is hence important to take into account all energy requirements necessary for the mobility of building users to provide a comprehensive life cycle energy analysis.

While direct energy requirements are easy to determine based on figures from manufacturers, indirect requirements require an input-output analysis of the transport sector. Only a few studies of indirect transport requirements have been undertaken so far. Examples of such studies are those conducted by Lenzen [27] for Australia and Jonson [28] for Sweden.

The energy demand associated with the mobility of the building users is determined based on their annual travel distances and the total energy intensity of used transport modes as per Equation 8. Annual travel distances are based on regional census data if no post-occupancy figures are available. The total energy intensity by mode is calculated as the sum of direct and indirect requirements.

$$LCTE_b = UL_b \times \sum_{m=1}^{M} TD_m \times DEI_m + IEI_m \qquad (8)$$

Where: $LCTE_b$ = Life cycle transport energy demand of users in the building b in ; UL_b = useful life of the building b; TD_m = total yearly travel distance of all users using the transport mode m, in km; DEI_m = direct energy intensity of the travel mode m in GJ/km; and IEI_m = indirect energy intensity of the travel mode m in GJ/km.

Preprint version

2.4 Total energy

The total life cycle energy demand of the residential building and its users (LCE_b) is obtained by adding the life cycle requirements at both the building and city scale . The calculation is performed according to the following equation:

$$LCE_b = LCEE_b + LCEE_{if} + LCPOPE_b + LCTE_b \quad (9)$$

2.5 Addressing uncertainty and variability

Any model is a representation of the real world based on assumptions, experiments, theories, etc.. The assumptions and approximations made during the development of a model will hence imply a divergence from the real studied phenomenon or process. The model developed in this work follows the same rules. However, the sources of error are numerous since different data sources are used at both the building and city scales.

Uncertainty relates to the lack or absence of knowledge for a certain parameter while variability is associated with the fluctuations of a certain parameter [29]. For example, there is uncertainty regarding the exact number of people in a specific household while the number of people in a typical household can present a certain variability. Even though uncertainty and variability have different meanings, the ways to tackle them are highly similar [29].

Different uncertainty classes have been identified in life cycle assessment and building energy simulation tools [30, 31], notably parameter uncertainty, model uncertainty and uncertainty due to choices. Parameter uncertainty is related to the quality of the data used while parameter variability accounts for possible deviations from average values. In this work, parameter uncertainty, related to embodied energy figures, is taken into account as well as parameter variability in operational and transport energy figures. The latter can be related to the user behaviour which is rarely included in current methods [32].

The developed framework relies on different data sources at each scale of the built environment: hybrid embodied energy coefficients for building and infrastructure materials, average domestic hot water, lighting, cooking and appliances energy consumption of building users, approximated heating and cooling energy demand, and statistics regarding the travel patterns of users. The uncertainty in embodied energy figures and variability present in operational and transport energy results should hence be tackled.

Preprint version

While probabilistic methods, such as Monte Carlo simulation, are increasingly used for building energy simulation [33], they require probabilistic distributions of the input parameters. In this case, the very high number of parameters and the unknown probability distribution of each make it impossible to use this kind of approach.

For these reasons, interval analysis, which is a simpler way of integrating uncertainty and variability, is used. This technique is based on ranges of values for each parameter without their related probabilistic distribution [34]. Interval analysis hence consists of providing a range of values for each input parameter instead of a single value. The output is given in the form of an interval. The range of values for each parameter should be determined through experimental, empirical or theoretical evidence. It is hence easier to provide a reasonable range of values for a given parameter than a probabilistic distribution [35]. In case no sufficient information is available to define the interval for a parameter, assumptions should be made.

2.6 Implementing a software tool

An advanced software tool, programmed in Python and compatible on all operating systems, has been developed to automate all calculations and formalize the framework. The software relies on different databases of: materials, assemblies, urban areas, cities and countries, which can easily accommodate including more data. The software allows the assessment of single buildings or whole districts. It allows exporting data to comma separated files for use in third party software. A specific data visualization module, allowing the comparison of up to seven different buildings or districts, and direct access to any of the computed variables has also been implemented and is presented in Figure 1.

Preprint version

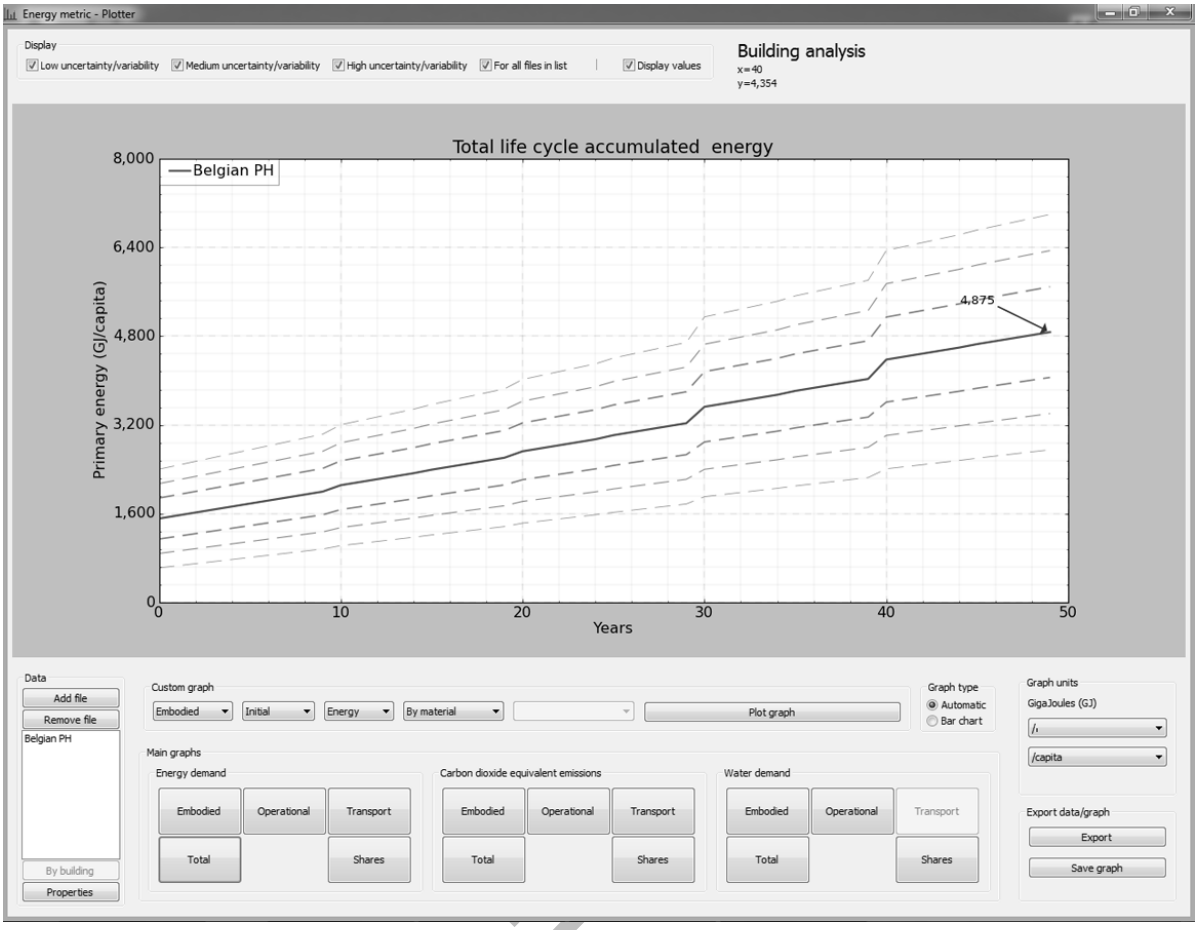

Figure 1: Screenshot of the plotting module of the developed software

3 Application of the developed framework to two case studies

In order to illustrate the potential of the developed method and provide larger grounds for discussion, two short case studies are investigated. While the framework can provide a much more detailed breakdown of the energy consumption, only the life cycle embodied, operational and transport requirements are presented to support the following discussion.

3.1 Short description of the cases

Two case studies, one located near Brussels, Belgium and the other near Melbourne, Australia are used to scrutinize the framework and to show its applicability in different countries. Both cases are single family detached houses built in the suburbs of the two cities. These suburban areas are typically characterized by low population density and high car usage. The sizes of the houses are also typically larger than the respective national averages, per capita. The Belgian house is a passive house, i.e. an extremely insulated and airtight building with a dramatically reduced final space heating

Draft version

demand. The Australian house is also built to high national energy efficiency standards, i.e. 7-stars [36]. Table 1 summarizes the main characteristics of the dwellings.

Table 1: Main characteristics of the two case studies used to demonstrate the applicability of the framework

Characteristics	Belgian passive house	Australian 7-star house
Period of analysis (years)	50	50
Building useful life (years)	50	50
Gross floor area (m²)	330	297
Number of users	4	5
Structure	Steel	Timber-framed
Façade	Glued bricks – 22 cm of polyurethane insulation -Triple glazed, argon filled, timber framed windows	Brick veneer wall – 10 cm of fiberglass insulation - Double glazed aluminum framed windows
Roof	Terracotta tiles – 30cm of polyurethane insulation	Concrete tiles – 20 cm of fiberglass insulation
Finishings	Medium finishing standing	Medium finishing standing
Average U-value (W/m²K)	0.19	0.58
Operational energy sources	All electrical: heating (eff. 1.0), cooking (eff. 1.0), ventilation (eff.0.9), domestic hot water (eff. 1.0)	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).
Primary energy conversion factors	Electricity: 2.5‡	Electricity: 3.4† Gas: 1.4†
Cars	1 gasoline and 1 diesel*	2 gasoline~
Average car travel distance per year (km)	32 000*	36 000~
Average occupancy rate of cars	1.32*	1.6~
Total energy intensity of cars (MJ/pkm)	Gasoline: 3.2*, ^, # Diesel: 2.93*, ^, #	4.41#

*Note: eff. Represents the efficiency of the end-use system. Delivered energy figures are used for lighting and appliances. All average figures for operational energy consumption are derived from [37] for Brussels and from [38] for Melbourne. * based on data from [39], ^ based on results from [28], # based on [27], ~ based on [40], † from [41] and ‡ from [42].*

Both cases rely on the hybrid embodied energy database developed by Treloar and Crawford [43]. While other, more relevant databases are available for the Belgian case, all of them rely on the process analysis technique and are therefore likely to underestimate the embodied energy. The useful life of materials is based on various sources such as [44]. Only the recurrent embodied energy of nearby infrastructures is taken into account since it is assumed that the infrastructures already exist.

Preprint version

The uncertainty on the input-output and process data in the model are assumed to be ±50% and ±20% respectively. The variability in operational and transport energy is set to ±20%.

3.2 Results

Figure 2 (which is taken directly from the plotter module of the developed software) shows the breakdown of the life cycle energy demand of each case study. The life cycle energy demands of both case studies are split in equally important shares among the embodied, operational and transport flows: 44.6%, 30.3% and 25.1% for the Belgian passive house and 30.0%, 36.4% and 33.6% for the Australian 7-stars house.

Embodied energy requirements represent the highest contribution over 50 years for the Belgian case study (44.6%) while the operational energy demand has the highest share (36.4%) in the Australian case study. The dramatically increased insulation and triple glazed windows explain this rise in embodied energy for the passive house (PH). It is also important to note that if only embodied and operational energy are considered, the embodied energy share rises to 59.5% for the PH. When only heating, ventilation and domestic hot water primary energy demands are considered, such as in the majority of previous studies on passive houses, the share of EE rises to 71.0% over 50 years. This clearly proves the need to integrate embodied energy requirements for a more comprehensive analysis.

Transport energy requirements are significant in both cases. The lower consumption of the PH is due to the more efficient vehicles and lower indirect requirements (as well as a slightly lower travel distance per year). Transport requirements represent around 300% of the primary heating energy consumption for both cases. With the increased energy efficiency and the lowered heating demand, other aspects become preponderant.

Preprint version

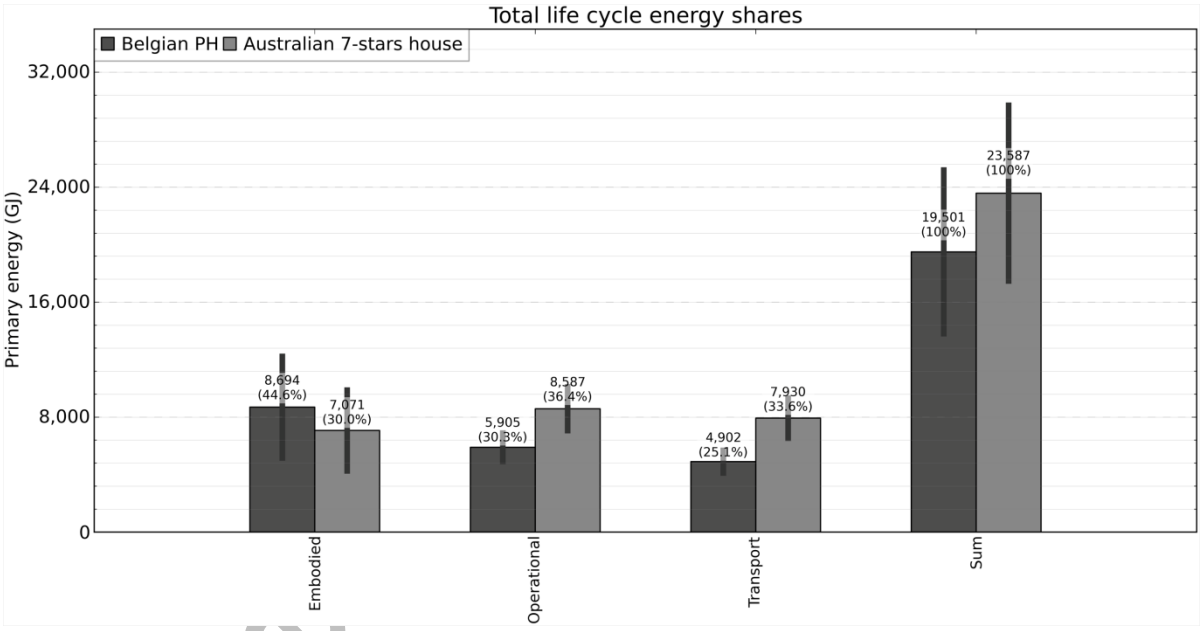

Figure 2: Life cycle energy demand bar plot breakdown of the Belgian passive house (PH) and the Australian 7-stars house as generated by the developed software tool

When considering the uncertainty in the data, the shares presented above can fluctuate greatly. For instance, the minimum share for embodied energy for the Belgian passive house is 27.7% while the maximum share would be 59.0%. The order of magnitude of the fluctuation for the two other flows is lower because of a smaller imposed variability. Considering all possible variations due to uncertainty and variability, the three energy flows remain significant and the sum of the embodied and transport requirements always represent more than 50% of the life cycle energy consumption of each house and its users. This confirms the importance of a more holistic energy assessment of residential buildings.

4 Discussion and conclusion

This article presents a method to comprehensively assess the life cycle energy requirements of residential buildings and their users, over the life cycle of the building. The proposed method, applied to the two test cases, confirms that a more holistic perspective to energy consumption should be adopted in order to effectively reduce energy consumption. Indeed, results show that focusing solely on operational energy (and on thermal aspects in particular), overlooks more than 50% of the energy demand over 50 years (of the two case studies), whether in Belgium or Australia and regardless of the uncertainty and variability in the data. Embodied requirements have been quantified using the input-output-based hybrid analysis and are therefore higher than in previous studies. For instance, in

preprint version

their study on Toronto, Canada, using purely input-output figures, Norman et al. [45] found that embodied energy represented only 7-9% of the overall energy consumption of low density setups. The use of more comprehensive techniques for the quantification of embodied and transport requirements is therefore crucial.

A software has been developed in order to conduct such a complex assessment and to formalize the method into a usable tool. The developed software provides architects and building designers with a powerful means to effectively reduce the overall energy consumption of residential buildings through a comprehensive analysis. For instance, the coupling of embodied and thermal requirements ensures that additional insulation does not imply a higher overall energy consumption because of the increased embodied energy requirements. The tool can also be used at a larger scale of the built environment, by planners or decision makers to evaluate the impact of developing various housing forms.

The method uses a basic operational energy quantification algorithm, relying on statistical data and static heat transfer equations. This might imply differences with post-occupancy measures. Also an Australian hybrid database for embodied energy was used for the Belgian building due to the unavailability of comparable data in Belgium. Hence, embodied energy figures may vary due to the inappropriateness of the data but also due to adopted useful lives of materials. Transport energy requirements can also vary according to user habits and local conditions. While general results are in concordance with previous studies using the same techniques [14, 15], the output has yet to be validated by comparison with an existing case. This will determine the accuracy of the method and its validity.

In conclusion, the developed framework will allow architects, building designers, planners and decision makers to optimize the environmental performance of residential buildings by informing their designs with a comprehensive life cycle energy analysis at both the building and city scale. This will ultimately contribute to the reduction of the energy consumption of residential buildings and related greenhouse gas emissions.

Preprint version

Acknowledgments

This research is funded by the Belgian National Fund for Scientific Research (F.R.S. - FNRS), by an excellence scholarship from Wallonia-Brussels International (WBI) and by a BRIC scholarship from the Université Libre de Bruxelles, Belgium.

References

[1] IEA, *World Energy Outlook 2011*, 2011, International Energy Agency: Paris. p. 600.

[2] Perez-Lombard, L., J. Ortiz, and C. Pout, *A Review on Buildings Energy Consumption Information.* Energy and Buildings, 2008. 40(3): p. 394-8.

[3] Junnila, S., *The Environmental Impact of an Office Building Throughout Its Life Cycle*, 2004, Helsinki University of Technology Construction Economics and Management: Espoo.

[4] European Parliament and the Council of the European Union, *Directive 2002/91/Ec of the European Parliament and the of the Council of 16 December 2002 on the Energy Performance of Buildings*, 2002, Official Journal of the European Communities: Brussels. p. 7.

[5] Ramesh, T., R. Prakash, and K.K. Shukla, *Life Cycle Energy Analysis of Buildings: An Overview.* Energy and Buildings, 2010. 42: p. 1592-600.

[6] Treloar, G.J., *Extracting Embodied Energy Paths from Input-Output Tables: Towards an Input-Output-Based Hybrid Energy Analysis Method.* Economic Systems Research, 1997. 9(4): p. 375-91.

[7] Crawford, R.H., *Life Cycle Assessment in the Built Environment* 2011, London; New York: Spon Press.

[8] Xavier García, C., *Analysis of Building Energy Regulation and Certification in Europe: Their Role, Limitations and Differences.* Energy and buildings, 2006. 38(5): p. 381-92.

[9] Newman, P. and J. Kenworthy, *Sustainable Urban Form: The Big Picture*, in *Achieving Sustainable Urban Form,* M. Jenks, K. Williams, and E. Burton, Editors. 2000, E & FN Spon: London ; New York. p. xii, 388 p.

[10] Newman, P. and J.R. Kenworthy, *Sustainability and Cities : Overcoming Automobile Dependence* 1999, Washington, D.C.: Island Press. xviii, 442 p.

[11] van de Coevering, P. and T. Schwanen, *Re-Evaluating the Impact of Urban Form on Travel Patterns in Europe and North-America.* Transport Policy, 2006. 13(3): p. 229-39.

[12] Golob, T.F. and D. Brownstone, *The Impact of Residential Density on Vehicle Usage and Energy Consumption*, 2005, UC Irvine: Institute of Transportation Studies (UCI): Irvine.

[13] Stead, D., J. Williams, and H. Titheridge, *Land Use, Transport and People: Identifying the Connections*, in *Achieving Sustainable Urban Form*, M. Jenks, K. Williams, and E. Burton, Editors. 2000, E & FN Spon: London ; New York. p. xii, 388 p.

[14] Stephan, A., R.H. Crawford, and K. de Myttenaere, *Towards a More Holistic Approach to Reducing the Energy Demand of Dwellings.* Procedia Engineering, 2011. 21(0): p. 1033-41.

[15] Fuller, R. and R. Crawford, *Impact of Past and Future Residential Housing Development Patterns on Energy Demand and Related Emissions.* Journal of Housing and the Built Environment, 2011. 26(2): p. 165-83.

[16] Crowther, P. *Design for Disassembly to Recover Embodied Energy*. in *Passive and Low-Energy Architecture*. 1999. Melbourne-Brisbane-Cairns.

[17] Stephan, A., *Towards a Comprehensive Energy Assessment of Residential Buildings. A Multi-Scale Life Cycle Energy Analysis*, in *ULB-BATir - Building, Architecture and Town planning & UoM-ABP - Architecture, Building and Planning* 2013, Université Libre de Bruxelles & The University of Melbourne: Brussels.

[18] Cole, R.J. and P.C. Kernan, *Life-Cycle Energy Use in Office Buildings.* Building and Environment, 1996. 31(4): p. 307-17.

[19] Dahlstrøm, O., *Life Cycle Assessment of a Single-Family Residence Built to Passive House Standard*, in *Department of Energy and Process Engineering*2011, Norwegian University of Science and Technology: Trondheim. p. 125.

[20] Dodoo, A., L. Gustavsson, and R. Sathre, *Life Cycle Primary Energy Implication of Retrofitting a Wood-Framed Apartment Building to Passive House Standard.* Resources Conservation and Recycling, 2010. 54(12): p. 1152-60.

[21] Leontief, W., *Environmental Repercussions and the Economic Structure: An Input-Output Approach.* The Review of Economics and Statistics, 1970. 52(3): p. 262-71.

[22] Sartori, I. and A.G. Hestnes, *Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article.* Energy and Buildings, 2007. 39: p. 249-57.

[23] Suh, S., M. Lenzen, G.J. Treloar, H. Hondo, A. Horvath, G. Huppes, et al., *System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches.* Environmental Science and technology, 2004. 38(3): p. 657-64.

[24] International Standard 15686-1, *Buildings and Constructed Assets. Service Life Planning. General Principles and Framework*, 2011, International Organization for Standardization (ISO): Geneva. p. 34.

Pre-Print Version

[25] Calwell, C., *Is Efficient Sufficient? The Case for Shifting Our Emphasis in Energy Specifications to Progressive Efficiency and Sufficiency*, 2010, European Council for an Energy Efficient Economy: Stockholm.
[26] Gustavsson, L. and A. Joelsson, *Life Cycle Primary Energy Analysis of Residential Buildings.* Energy and Buildings, 2010. 42(2): p. 210-20.
[27] Lenzen, M., *Total Requirements of Energy and Greenhouse Gases for Australian Transport.* Transportation Research Part D-Transport and Environment, 1999. 4(4): p. 265-90.
[28] Jonson, D.K., *Indirect Energy Associated with Swedish Road Transport.* European Journal of Transport and Infrastructure Research, 2007. 7(3): p. 183-200.
[29] Heijnungs, R. and M. Huijbregts, *A Review of Approaches to Treat Uncertainty in Lca*, 2004. p. 8.
[30] Huijbregts, M., *Application of Uncertainty and Variability in Lca.* The International Journal of Life Cycle Assessment, 1998. 3(5): p. 273-80.
[31] De Wit, S., *Uncertainty in Building Simulations*, in *Advanced Building Simulation*, A. Malkawi and G. Augenbroe, Editors. 2003, Spon Press: New York. p. 252.
[32] Ryan, E.M. and T.F. Sanquist, *Validation of Building Energy Modeling Tools under Idealized and Realistic Conditions.* Energy and buildings, 2012. 47(0): p. 375-82.
[33] Burhenne, S., D. Jacob, and G.P. Henze. *Uncertainty Analysis in Building Simulation with Monte Carlo Techniques*. in *Fourth National Conference of IBPSA-USA*. 2010. New York: IBPSA.
[34] Moore, R.E., R.B. Kearfott, and M.J. Cloud, *Introduction to Interval Analysis* 2009, Philadelphia, PA: Society for Industrial and Applied Mathematics. xi, 223 p.
[35] Alefeld, G. and G. Mayer, *Interval Analysis: Theory and Applications.* Journal of Computational and Applied Mathematics, 2000. 121(1-2): p. 421-64.
[36] Australian Building Codes Board, *Energy Efficency Provisions for Bca 2010 Volume Two - Information Handbook*. Vol. 2. 2010, Canberra: Australian Building Codes Board.
[37] IBGE, *Bilan Énergétique De La Région De Bruxelles-Capitale 2008*, 2010, Institut Bruxellois pour la Gestion de l'Environnement,: Brussels.
[38] DEWHA, *Energy Use in the Australian Residential Sector 1986-2020*, 2008, Department of the Environment, Water, Heritage and Arts: Canberra.
[39] Bureau Fédéral du Plan, *Transport Routier,*, B.F.d. Plan, Editor 2012: Brussels.
[40] BITRE, *Population Growth, Jobs Growth and Commuting Flows in Melbourne*, in *Melbourne, Report 125*2011, BITRE: Canberra ACT. p. 404.
[41] Treloar, G.J., *A Comprehensive Embodied Energy Analysis Framework*, 1998, Deakin University: Geelong.
[42] RBC, *Arrêté Du Gouvernement De La Région De Bruxelles-Capitale Déterminant Des Exigences En Matière De Performance Énergétique Et De Climat Intérieur Des Bâtiments*, in *2008 — 326*, Ministère de la région Bruxelles-capitale, Editor 2008, Moniteur Belge: Brussels. p. 443.
[43] Treloar, G.J. and R.H. Crawford, *Database of Embodied Energy and Water Values for Materials*, 2010, The University of Melbourne: Melbourne.
[44] NAHB and Bank of America, *Study of Life Expectancy of Home Materials*, J. Jackson, Editor 2007, National Association of Home Builders: Washington DC. p. 15.
[45] Norman, J., H.L. MacLean, and C.A. Kennedy, *Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions.* Journal of Urban Planning and Development, 2006. 132(1): p. 10-21.

Preprint version