Towards a comprehensive life cycle energy analysis framework for residential buildings

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Abstract:

Current assessments of residential building energy demand focus 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. This framework has been implemented through the development of a software tool that allows the rapid analysis of the life cycle energy demand of buildings at different scales.

Results from two case studies, 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 tool.

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1 Introduction

Buildings represent nearly 30% of final energy consumption, globally [1] and 37% in the European Union (EU) [2]. Residential buildings alone represent 26% of final energy demand in the EU [2] which makes them one of the largest single energy-consuming sectors. 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. [3]) , 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, as it can represent a large proportion of the life cycle energy demand. In their review of life cycle energy analysis of buildings, Ramesh *et al.* [4], found that embodied requirements represent, on average, only 10-20% of the total energy consumption (including embodied and operational energy demands). This figure might largely underestimate the contribution of embodied requirements because most previous life cycle energy analysis studies rely on a 'process analysis' approach for the quantification of embodied energy. While process analysis typically provides high quality and reliable data for the assessed inputs and outputs of the studied product/process, it suffers from system boundary truncation. Studies relying on the more comprehensive input-output-based hybrid analysis [5], 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 [6]. The embodied energy requirements of residential buildings should hence be taken into consideration in a more holistic assessment, as advocated by Xavier Garcia [7] and Szalay [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. a passive house), located in the suburbs, will have a dramatically reduced final heating demand but will most likely increase the occupants reliance on 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 an increase in transport energy demand. Transport energy should therefore be taken into consideration to ensure that net energy savings do occur and to measure energy performance in the building's context.

Very few studies combine embodied, operational and transport energy demand, 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, 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.

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.

The remainder of this paper first presents the approaches used to quantify the life cycle energy demand of a building. Two case study buildings, one located near Brussels, Belgium and the second near Melbourne, Australia are then used to illustrate the potential of the developed framework.

2 Quantifying life cycle energy requirements

The life cycle energy 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 and building usage. Energy demand for user transportation also occurs during the operation stage of a buildings lifespan but at the city scale. Energy associated with the end-of-life stage of the building (i.e. demolition) is not included since it typically represents less than 1% of the total energy demand of a building [16].

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 conciseness, only the main equations and aspects are presented in this paper. The full details of the research will be published 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.

2.1 Embodied energy

Embodied energy can be defined as all of the necessary energy inputs required to produce and construct a building, across the entire supply chain. The initial embodied energy accounts for the energy associated with the construction of the building, while recurring embodied energy accounts for the energy required to produce replacement materials, over the life of the building.

While a growing body of literature discusses 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 at 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. Hybrid analysis is the combination of both techniques. It consists of using process data where available and filling 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 a process analysis. For instance, in their reviews of life cycle energy studies, Ramesh *et al.* [4] 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. [6]). Hence, this work relies on the comprehensive input-output-based hybrid analysis approach for the quantification of embodied energy. More detail about available the embodied energy assessment techniques and hybrid analysis in particular can be found in [5, 6, 23].

To simplify the assessment of embodied energy based on hybrid analysis, factors known as hybrid energy coefficients have been developed by Treloar and Crawford [24], combining available process data for individual materials with national average input-output data (for Australia).

The initial embodied energy of the building is obtained by multiplying the relevant hybrid energy coefficients by the final quantities of the respective materials contained within the building (including wastage) as per Equation 1.

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

Where: IEE_b = Initial embodied energy of the building in GJ; Q_m = Quantity of material m in functional unit (e.g. ton, m³); EC_m = Hybrid energy coefficient of material m in GJ per functional unit; 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 P_b = Price of the building in currency units.

Recurrent embodied energy requirements are determined by summing the embodied energy of replaced materials across the life 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 [25]. The same material could hence have very different useful lives depending on the context in which it is used.

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 life of the building and their respective hybrid energy coefficient as per Equation 2. The algorithm also accounts for energy associated with non-material inputs based on the material price. Note that the number of replacements is rounded to its integer component (e.g. 2.66 → 2).

$$REE_b = \sum_{m=1}^{M} \left[\left(\frac{UL_b}{UL_m} - 1 \right) \times \left[Q_m \times EC_m + TER_n - TER_m - TER_{i \neq m} \times P_m \right] \right] \qquad (2)$$

Where: REE_b = Recurrent embodied energy of the building in GJ; UL_b = Useful life of the building; UL_m = useful life of the material m; $TER_{i \neq m}$ = Total energy requirements of all input-output pathways not associated with the installation or production process of material m being replaced, in GJ per currency unit; and P_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.

$$LCEE_b = IEE_b + REE_b \tag{3}$$

In addition to 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. Since infrastructures belong to a separate economical sector, including input-output requirements requires the extraction of related pathways and associated sectors which is beyond the scope of this work. The embodied energy of each infrastructure is 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.

$$LCEE_{if} = \sum_{i=1}^{I} \left(LCEE_i \times D_i \times \frac{NO}{PD} \right) \tag{4}$$

Where: $LCEE_{if}$ = Life cycle embodied energy of infrastructures in GJ; $LCEE_i$ = Life cycle embodied energy of infrastructure i in GJ/m; D_i = Density of infrastructure i in m/km²; NO = Number of occupants 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) [3], 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 [26], 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 [27], these should be converted to primary energy figures in order to provide a measure of the overall energy 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 modelling 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 for the particular location. The temperature used for the calculation of the heating degree hours should take into account average internal and solar gains. Losses through the ground are neglected, but might have 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 system with heat recovery is installed, ventilation losses are reduced by the heat recovery system efficiency (η_{HR}). The heating demand is calculated as per Equation 5.

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

Where: OPE_h = Operational final heating energy demand in kWh; HDH = Thousands of heating degree hours for the building site in Kh; U_b = Average heat transfer coefficient for the building 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 (OPE_C) is determined using Equation 5, by replacing heating degree hours with cooling degree hours. The latter should be calculated by taking into account internal and solar gains which will result in 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.

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

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

The domestic hot water, appliances and cooking final energy demands are determined by multiplying regional per capita averages by the number of users in the house. Lighting is calculated by multiplying average yearly consumption per m² by the usable floor area of the building. Average regional data is generally compiled by governmental bodies (e.g. [28, 29])

All energy consumption figures are converted to primary energy terms 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. Solar fractions represent the percentage of the final energy demand (for an end-use) provided by solar hot water or photovoltaic panels.

$$LCOPE_b = UL_b \times \sum_{e=1}^{E} \left(1 - SF_e\right) \times \frac{OPE_e}{\eta_e} \tag{7}$$

Where: $LCOPE_b$ = 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*; OPE_e = Yearly operational primary 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 associated with the operation of the transport mode, such as burning fuel in a car engine. Indirect requirements include all other inputs across the supply chain for the production, maintenance of the transport mode and all associated infrastructures. Indirect requirements are often overlooked in transport energy studies but Lenzen [30] and Jonson [31] have established that they can represent up to 45% of the total energy 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 within 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 [30] for Australia and Jonson [31] 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 (e.g. [32, 33]) if no post-occupancy figures are available. The total energy intensity by mode is calculated as the sum of direct and indirect requirements.

$$LCTE_b = UL_b \times \sum_{tm=1}^{TM} \left[TD_{tm} \times \; DEI_{tm} + IEI_{tm} \; \right] \qquad (8)$$

Where: $LCTE_b$ = Life cycle transport energy demand of users in the building *b* in ; UL_b = Useful life of the building *b*; TD_{tm} = Total yearly travel distance of all users using the transport mode *tm*, in km; DEI_{tm} = Direct energy intensity of the travel mode *tm* in GJ/km; and IEI_{tm} = Indirect energy intensity of the travel mode *tm* in GJ/km.

2.4 Total life cycle 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:

$$LCE_b = LCEE_b + LCEE_{if} + LCOPE_b + LCTE_b \qquad (9)$$

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 framework 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 [34]. 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 [34].

Different uncertainty classes have been identified in life cycle assessment and building energy simulation tools [35, 36], 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. 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. 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 variability in user behaviour which is rarely included in previous building energy assessments [37].

While probabilistic methods, such as Monte Carlo simulation, are increasingly used for building energy simulation [38], 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 [39]. 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 [40]. 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 with 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 be easily updated when necessary. The software allows the assessment of single buildings or whole districts. It also 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 an example screenshot is presented in Figure 1.

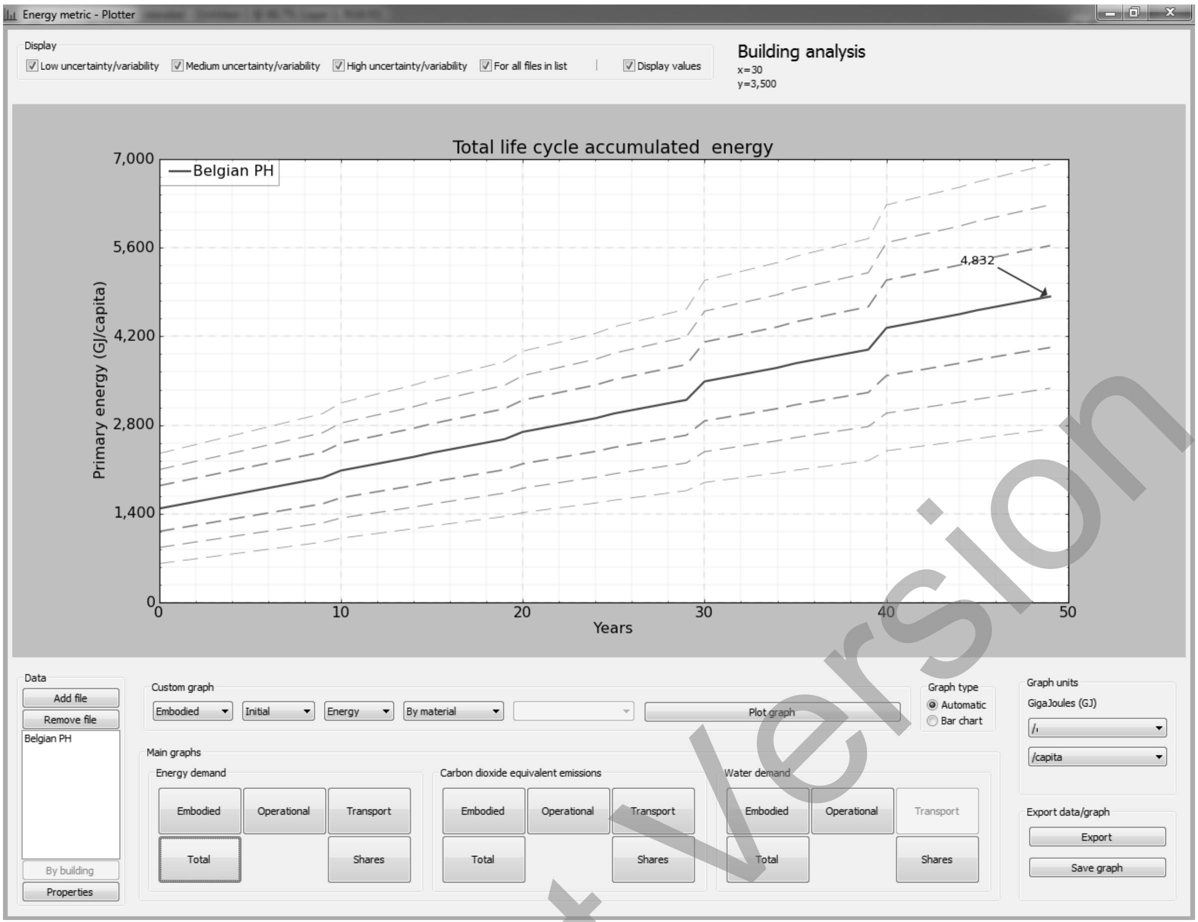

Figure 1: Screenshot of the plotting module of the developed software

3 Application of the developed framework to two case studies

In order to illustrate the potential of the developed framework, 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 in this case.

3.1 Description of the cases

Two case studies, one located near Brussels, Belgium and the other near Melbourne, Australia are used to demonstrate the framework and to show its applicability in different countries. Both cases are single family detached houses built in the outer 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 demand. The Australian house is also built to high national energy efficiency standards, i.e. 7-stars [41]. Table 1 summarizes the main characteristics of the houses.

Table 1: Main characteristics of the two case studies used to illustrate the potential 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 (m^2)	330	297
Number of occupants	4	5
Structure	Steel-framed	Timber-framed
Façade	Glued bricks – 220 mm of polyurethane insulation -Triple glazed, argon filled, timber framed windows	Brick veneer wall – 100 mm of fiberglass insulation - Double glazed aluminium framed windows
Roof	Terracotta tiles – 300 mm of polyurethane insulation	Concrete tiles – 200 mm of fiberglass insulation
Finishings	Medium finishing standing	Medium finishing standing
Average U-value (W/m^2K)	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[a]	Electricity: 3.4[b] Gas: 1.4[b]
Cars	1 gasoline and 1 diesel[c]	2 gasoline[d]
Average car travel distance per year (km)	32 000[c]	36 000[d]
Average occupancy rate of cars	1.32[c]	1.6[d]
Total energy intensity of cars (MJ/pkm)	Gasoline: 3.2[c, e , f] Diesel: 2.93[c, e , f]	4.41[f]

Note: eff. represents the efficiency of the end-use system. Delivered energy figures are used for lighting and appliances because no information is available about the efficiency of the devices used. All average figures for operational energy consumption are derived from [29] for Brussels and from [28] for Melbourne. [a] from [42], [b] from [43], [c] based on data from [32], [d] based on [44], [e] based on results from [31] and [f] based on [30].

Both cases rely on the hybrid embodied energy database developed by Treloar and Crawford [24]. 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 [45]. Only the recurrent embodied energy of nearby infrastructures is taken into account, since it is assumed that these already exist in the two cases (no initial embodied energy requirements considered). The uncertainty associated with the input-output and process data used in the hybrid embodied energy model are assumed to be ±50% and ±20% respectively [6]. The variability in operational and transport energy is set to ±20% based on Pettersen [46] and Bazzani *et al.* [47] respectively.

3.2 Analysis of case studies

Figure 2 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 significant shares among the embodied, operational and transport components: 44.1%, 30.5% and 25.4% for the Belgian passive house and 29.6%, 36.6% and 33.8% for the Australian 7-Star house.

Embodied energy requirements represent the highest contribution over 50 years for the Belgian case study (44.1%) while the operational energy demand has the highest share (36.6%) in the Australian case study. The dramatically increased level of insulation and use of 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 59.1% 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 embodied energy rises to 70.6% over 50 years. This clearly proves the need to integrate embodied energy requirements for a more comprehensive understanding of the life cycle energy implications of buildings.

Transport energy requirements are significant in both cases. The lower consumption of the Belgian case 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 proportionally more significant.

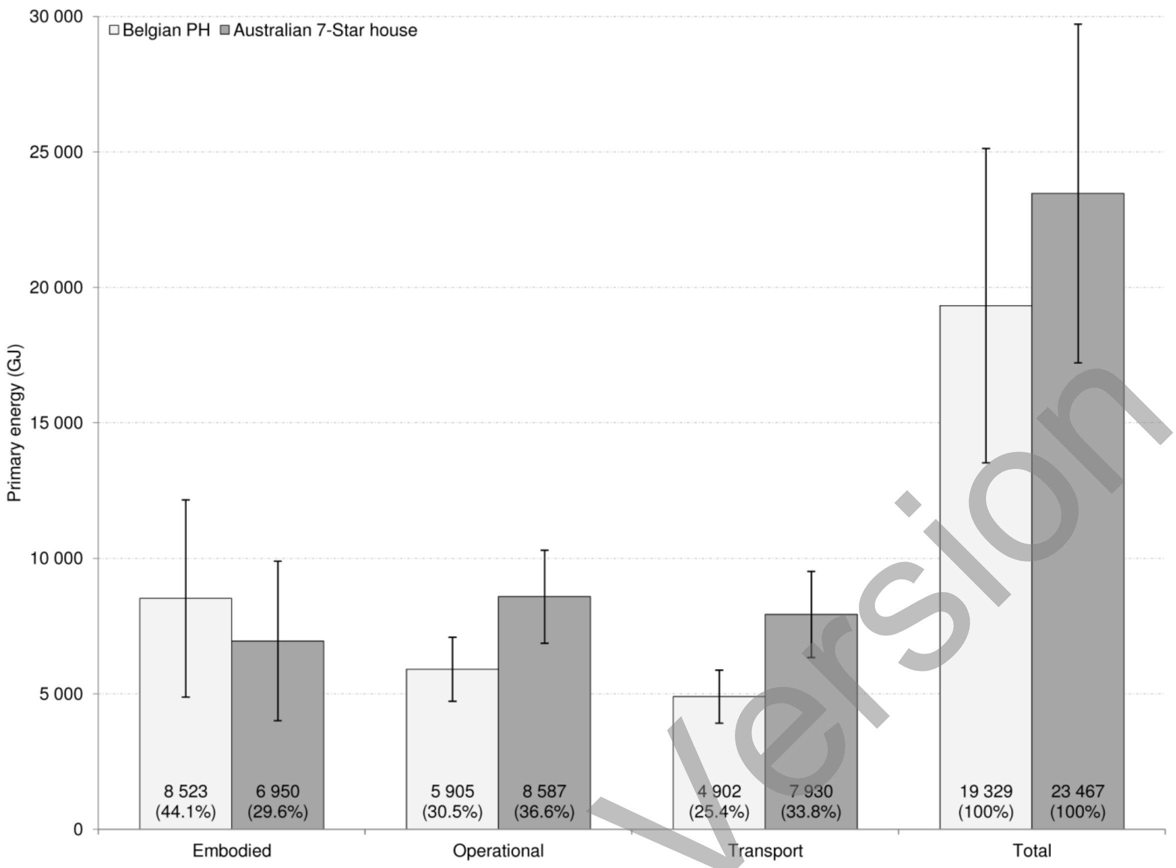

Figure 2: Life cycle energy demand bar plot breakdown of the Belgian passive house (PH) and the Australian 7-Star house

When considering the uncertainty in the data, the values presented above can fluctuate greatly. For instance, the minimum value for embodied energy for the Belgian passive house is 27.4% while the maximum share would be 58.5% of the life cycle energy demand, for actual values of operational and transport energy. The order of magnitude of the fluctuation for the two other components 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 framework to comprehensively assess the life cycle energy requirements of residential buildings and their users. The proposed framework, 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 their study on Toronto, Canada, using pure input-output figures, Norman *et al.* [48] found that embodied energy represented only 7-9% of the overall energy consumption of single family detached houses in a low density neighborhood. The use of more comprehensive techniques for the quantification of embodied and transport requirements is therefore crucial.

A software tool has been developed in order to conduct such a complex assessment. The developed software tool provides architects and building designers with a powerful means to effectively reduce the overall energy consumption of residential buildings. For instance, the coupling of embodied and thermal requirements helps to ensure that additional insulation does not result in 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 framework uses a basic operational energy quantification algorithm, relying on statistical data and static heat transfer equations. This might result in differences between post-occupancy measures. Also an Australian hybrid database for embodied energy was used for the Belgian building due to the unavailability of comparable data for 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, and will form the next stage of the research.

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.

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