A comprehensive assessment of the life cycle energy demand of passive houses

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Abstract

Residential buildings in Europe are responsible for a significant share of the final energy consumption. The improvement of their energy efficiency, notably in terms of space heating, can therefore reduce the energy demand. One of the most stringent certifications in these regards is the passive house standard which drastically reduces the final space heating energy demand.

However, most studies on passive houses totally overlook the embodied energy required to manufacture the building materials, especially the large amount of insulation. At a larger scale, most passive houses are single family detached houses located in low density suburbs with a high car usage.

This paper analyses a typical Belgian passive houses and conducts a parametric analysis as well as a comparison to alternative building types. The total life cycle energy demand, comprising embodied, operational and transport energy, is analysed using a comprehensive technique developed by Stephan et al. (2012) [1].

Results show that the embodied energy of passive houses can represent up to 76.9% of the sum of embodied and operational energy over 100 years. Also passive houses can have nearly the same energy consumption as standard new house with the same geometry, location and number of occupants. An retrofitted apartment in the city has a 15.2% lower energy consumption than a the best passive house scenario. Current building energy efficiency certifications might not ensure a lower energy demand and can, paradoxically result in an increased energy consumption because of their

narrow scope. More comprehensive system boundaries should be used to make sure that net energy savings do occur.

1 Introduction

Residential buildings in Europe represents up to 26% of the final energy consumption [2]. Therefore, there is significant scope in reducing energy consumption and related greenhouse gas emissions through the improvement of the energy efficiency of these buildings[3]. Space heating is one of the major contributors to the residential energy consumption in Europe's cold climates and therefore its reduction is crucial to achieve "low energy" buildings.

A particular type of "low energy" buildings is the passive house, a facultative certification scheme which emerged in Germany in the early 1990 and is managed by the PassivHaus Institute. A passive house can be seen as very highly insulated and airtight building in which the heating load is so low as to rely solely on a mechanical ventilation system for heating delivery [4]. A typical passive house will therefore have a yearly specific final heating demand lower or equal to 15 kWh/m² (54 MJ/m²). Compared to the typical Belgian dwelling which consumes around 120 kWh/m².year (432 MJ/m².year), the heating demand is reduced by 87.5%, as advocated by Feist [5]. This argument has been used as the driver to build passive houses across Europe. According to Lang [6], more than 25 000 passive houses have already been built in Europe and more are likely to be constructed [7].

However, the passive house certification focuses mainly on the space heating demand [8]. While it integrates a primary energy factor for some other operational energy demands such as domestic hot water, it does not take into consideration cooking, lighting and appliances which can represent a significant share of the total energy consumption [9, 10]. Moreover, passive houses generally require significant amounts of insulation and triple glazed argon filled windows with high performance framing. The additional materials required to obtain a passive house certification require a significant amount of energy to manufacture. This so-called embodied energy has rarely been taken into account in the study of passive houses.

The few studies which have considered embodied and operational energy demands of passive houses have so-far relied on the so-called process analysis technique for the quantification of embodied requirements. This technique is known to suffer from a large truncation error [11, 12]. Studies relying on this technique [13-16] therefore underestimate the embodied energy of additional materials and its contribution to the overall energy demand. Additionally, most built passive houses are single family detached dwellings in the suburbs. Indeed, according the passive house database in Belgium [17], 118 out of the 130 certified buildings fall into this category. In these low-density regions, the occupants rely mostly on cars for the mobility. It is possible that the amount of energy saved compared to a poorly insulated dwelling in the city (with a high usage of public transport) is compensated by a surge in transport energy requirements due to car use. The transport energy of building occupants should therefore be taken into consideration to verify that net energy savings do occur. While previous studies by Stephan et al. [18, 19] have proven that embodied and transport energy requirements represent more than 50% of the total life cycle energy demand of passive houses over 50 and 100 years, a detailed analysis of the life cycle energy consumption has not been undertaken so far.

This paper investigates the total life cycle energy demand of passive houses by:

- Conducting a parametric study on a representative Belgian passive house case study; and
- Comparing the passive house to alternative dwelling types to verify if net energy savings do occur.

2 Analysing the total energy consumption of a Belgian passive house

2.1 A multi-scale life cycle energy analysis

In order to conduct a comprehensive life cycle energy analysis, the building should be assessed at the different scales of the built environment across its lifecycle. At the building scale, the embodied energy of buildings materials and the operational energy demand of the building is investigated. At the city scale, the transport energy demand of building occupants, which is highly conditioned by the urban layout, and the embodied energy demand of nearby infrastructures are taken into consideration. All equations and details related to the quantification of the life cycle energy demand can be found in Stephan et al. [19]. A brief summary of the method is given below.

The embodied energy assessment relies on the comprehensive input-output-based hybrid analysis technique developed by Treloar [20]. The related database, compiled by Treloar and Crawford [21] for Australia is used in this study. While using Australian figures for a Belgian case might result in errors, the use of European process data will greatly underestimate the embodied energy demand. The embodied energy demand comprises requirements for the foundations, structure, envelope, systems and finishings. Both the initial and recurrent embodied energy demands are taken into consideration, with the latter representing the energy expenditure associated with the replacement of building materials over the useful life of the building. The average service life of building materials, which is hard to accurately forecast, is sourced from [22] and [23]. Only the recurrent embodied energy of infrastructures is considered as these already exist. The contribution of infrastructure embodied energy to the total energy demand is hence very low (less than 3%) and is not furthermore discussed in this paper.

The operational energy demand comprises requirements for space heating, ventilation, domestic hot water, lighting, cooking and appliances. Thermal energy calculations are based on static heat transfer equations while non-thermal energy demands are based on regional averages.

The transport energy consumption is calculated using average travel distances per household and the relevant energy intensities per transport mode. These energy intensities comprise both direct and indirect requirements as in Lenzen [24].

Uncertainty and variability in the data are taken into account using interval analysis. This technique provides a certain range around the nominal value in which the actual figure may lie [25]. The uncertainty on the embodied energy data is set to ±20% for process analysis data and ±40% for the input-output analysis data based on Crawford [11]. The variability in operational energy figures is set to ±20% based on Pettersen [26] and assumed to be the same for transport energy.

2.2 Case study house

The studied passive house is a 330 m² detached single family house for 4 persons in Braine-le-Château (Latitude 50.68°N, Longitude 4.27°E), located in the Walloon Brabant, 24 km south of Brussels, Belgium. Built in 2012, the house has three stories of approximately 110 m² each. It is accessed at street level to the middle floor. The plan of the house is given in Figure 1. The detailed bill of quantities of the house was obtained from the main contractor.

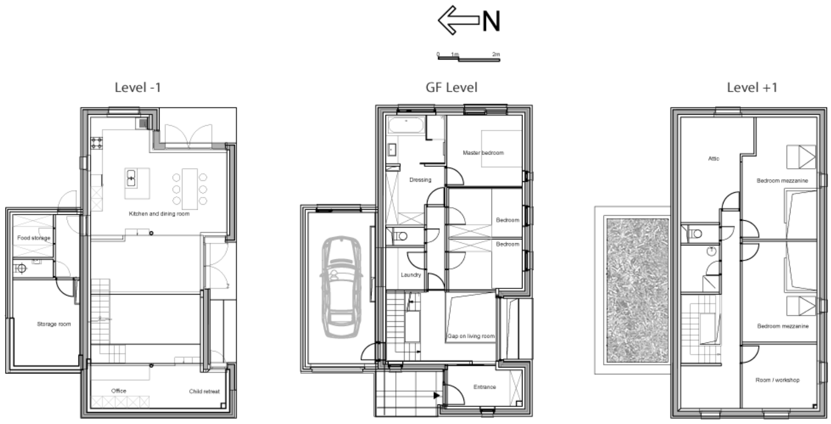

Figure 1: Plan view of the studied passive house

Foundations consist of individual reinforced concrete footings, linked by a network of concrete beams. Steel columns are anchored to the foundations and, together with the steel I-beams, constitute the load-bearing elements of the house. The ground floor slab is composed of reinforced concrete (RC) cast *in situ* while the upper floor slabs are composed of 130 mm pretensionned hollow core concrete elements. A 50 mm RC compression layer is cast on top along with a 100 mm floating screed, which is typical in Belgian construction practices.

The façade of the house is composed of 40 mm-thick bricks. These bricks are glued directly on the insulation, a new product on the Belgian market to avoid extremely thick walls for low-energy buildings.

The house is extremely insulated with 20 mm of polyurethane (PU) insulation (heat conductivity λ=0.023 W/(mK)) in the walls, 200 mm of PU under the ground floor slab, 50 mm of peripheral slab insulation (PU) and 300 mm of PU in the roof. The roof insulation is complemented by 100 mm of rock wool on the inside. All windows are triple glazed, argon-filled and low-emissivity coated with timber frames.

The internal walls of the house are composed of 100 mm thick plaster blocks. Their surface is covered with 10 mm of mortar and painted. Wooden parquet flooring is used in the living rooms, nylon carpets in the bedrooms and ceramic tiles in the kitchen and toilets.

As in any passive house, no standard heating system is installed. In this case, heat is generated by electric coils and delivered through the mechanical ventilation system which is operated 24h per day. A heat recovery system with 81.2% efficiency is installed. An electric domestic hot water (DHW) system provides the household with hot water at 55°C. According to the Passive House Planning Package calculation sheet, the annual final space heating energy demand is 14 kWh/m² (50.4 MJ/m²).

Two adults and their two children live in the house. The household owns two cars and does not use the train. Indeed, the nearest train station is located 13.6 km east from the house, in Braine l'Alleud.

This house is very representative of private passive houses built in Belgium up to date according to Plate-forme Maison Passive [17], which keeps a record of certified passive house buildings in Belgium. Most of these are located in suburban areas often with limited access to public transport. Table 1 presents the main characteristics of the studied passive house.

Table 1: Main characteristics of the studied passive house

Characteristics	Value/Details
Period of analysis	100 years
Building useful life	100 years
Gross floor area	330 m²
Number of occupants	4
Structure	Steel-framed
Façade	Glued bricks – 220 mm of polyurethane insulation -Triple glazed, argon filled, timber framed windows
Roof	Terracotta tiles – 300 mm of polyurethane insulation and 100mm of rock wool insulation
Finishings	Medium finishing standing
Average *U*-value	0.19 W/m²K
Operational energy sources	All electrical: heating (eff. 1.0), cooking (eff. 1.0), ventilation (eff.0.9), domestic hot water (eff. 1.0)
Primary energy conversion factors	Electricity: 2.5[a];Gas: 1.0[a]
Cars	1 gasoline and 1 diesel[b]
Average car travel distance per year	32 000[b] km
Average occupancy rate of cars	1.32[b]
Total energy intensity of cars	Gasoline: 3.2[b, c , d] MJ/pkm Diesel: 2.93[b, c , d] MJ/pkm

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 [9]. Sources: [a] from [27], [b] based on data from [28],[c] based on results from [29] and [d] based on [24].

2.3 Parametric study variations

Variations pertaining to the embodied, operational and transport energy demands of the studied passive house are performed in order to determine their impact on the overall life cycle energy consumption. These variations are presented in Table 2. The most energy saving variations will be combined in Section 3.2 to produce the best case scenario with the lowest life cycle energy demand. This scenario will then be used in comparison with an alternative dwelling.

Table 2: Studied parametric variations of the passive house case study

Variation	Acronym	Affected demand(s)	Description
Reinforced concrete (RC) structure	RC	EE	Replace the steel columns with 300x300 mm RC columns and the I-beams with 200x400 mm RC columns. The concrete is reinforced with 100kg of steel per m^3.
Timber framed structure	TF	EE	Remove columns and beams; Add load bearing elements in walls; Change glued bricks to brick veneer walls; change upper floor slabs to timber floors; change roof structure from concrete to timber.
Fibreglass insulation	FG	EE	Keep the same *U*-values but replace all polyurethane insulation in the walls and roof to fibreglass: 220 mm of PU in walls →420 mm of fibreglass; 300 mm of PU in roof →573 mm of fibreglass.
Replace electrical appliances with gas powered systems (heating, cooking and domestic hot water)	GAS	OPE and EE	Condensation gas boiler for heating (efficiency 1.1); Gas cooking (efficiency: 0.9); Condensation gas boiler for domestic hot water (efficiency 1.1).
Reduced operational energy	ROPE	OPE	Reduce all non-thermal energy demands by 20%

Highly reduced operational energy	HROPE	OPE	Reduce cooking and hot water energy demands by 20% and appliances and lighting by 50%
Gas cooking and heating; highly reduced operational energy with solar panels	GSHROPE	EE and OPE	Combine VROPE and GAS. Add 2.16m² of vacuum tube solar panels providing 78% of the hot water demand and using a gas auxiliary system.
Train commuting for the main income earner	TRAIN	TE	The main income earner uses the train to commute 9 600 km per year. The energy intensity of the train is 1.93 MJ/pkm[a] The household then uses one diesel car, driven 16 000 km per year.
Number of occupants	O5 and O7.35	OPE and TE (and EE per capita)	Increase the number of occupants in the house by 1 then by 3.35 as to match the national Belgian floor area per capita[b]

Note: EE = Embodied energy, OPE = Operational energy, TE = Transport energy, [a]Based on Jørgensen [30] and Lenzen [24],[b] from IBSA [31]

2.4 Comparison with alternative dwellings

In order to measure the extent to which passive houses save energy, two alternative dwellings are investigated and compared to the base case. The first alternative is a standard new house, with the same dimensions, number of occupants, and characteristics, except that it is built according to the current minimal thermal performance standards for Brussels, Belgium [27]. The standard house will also be modelled with the GAS and combination of ROPE and GAS variations (see Table 2). The changes made to the passive house in order to obtain the standard house are:

- Changed outer walls to traditional brick veneer double walls with 80 mm of expanded polystyrene (EPS) insulation (*U*-value=0.40 W/(m²K));
- Modified insulation in ground floor slab (200 mm PU→ 80 mm EPS);

- Removed peripheral insulation from upper floor slabs;
- Changed windows to aluminium framed double glazed windows (*U*-value=2.8 W/(m²K), including frames);
- Modified insulation in roof (300 mm PU and 100 mm of Rockwool→ 100 mm EPS, *U*-value=0.35 W/(m²K));
- Removed mechanical ventilation system and ducts;
- Installed a 35 kW condensation gas boiler for heating; and
- Installed 1 kW aluminium radiators for heating delivery.

The second alternative dwelling is a retrofitted apartment in the city of Brussels. This housing type is considered to compare two different housing typologies and locations. The two-façades apartment, which houses two persons, is 80 m² in size (see Figure 2) and is located in the south of Brussels, next to a major tramway line. The apartment building comprises 10 stories and 90 flats, it was built in the early 1970's. It is important to compare the suburban single family detached house to a small apartment retrofit scenario in Brussels since 75% of dwellings there are apartments and 84% of these have a floor area lower than 104 m² [9].

During the apartment retrofit no changes are made to the existing structure (foundations, columns, beams and slabs), the existing heating and domestic hot water system (central condensation gas boiler and radiators) and the internal walls. All other assemblies are changed. The retrofit consists of changing the bay windows (which represent 94% of the façade), the adjacent brick veneer walls, the flooring, all fittings, wiring, piping, doors, the toilets, etc.. The *U*-value of the new double glazed bay windows is 2.8 W/(m²K), including frames.

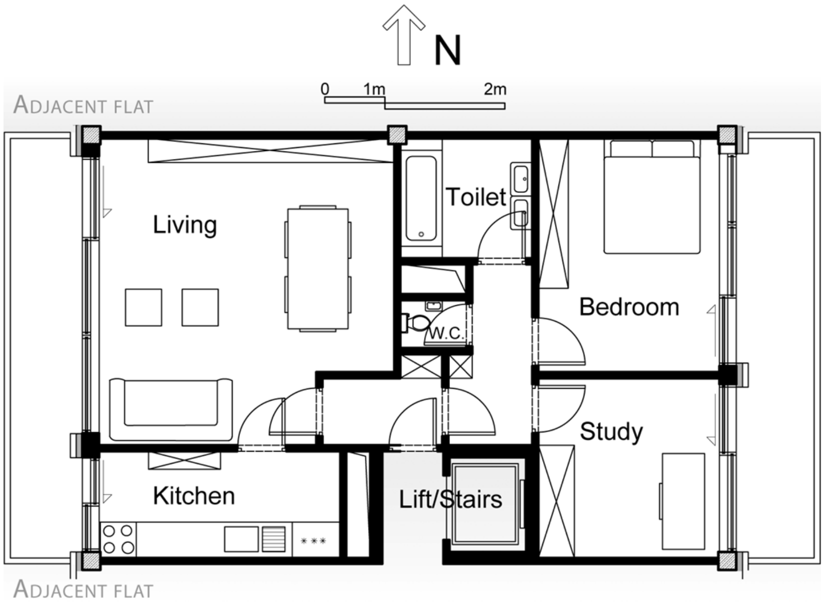

Figure 2: Plan view of the retrofitted apartment

The two occupants living in the apartment rely mainly on public transport in the city. One person is assumed to use the tramway 10 km per weekday while the other uses the subway 10 km per weekday. This results in 1200 km/capita.year of travel distance for each transport mode. The couple is assumed to own a gasoline car which is driven 6000 km per year, mainly on week-ends. The total energy intensities of tramways and subways in Brussels are respectively 2.04 MJ/pkm and 1.92 MJ/pkm. These intensities are calculated based on figures from the local public transport operators and comprise direct and indirect requirements.

3 Results

3.1 Life cycle energy demand

The breakdown of the life cycle energy demand into its three constituting components (see Figure 3) reveals many important findings. First, the embodied, operational and transport energy requirements represent respectively 40.0%, 32.8% and 27.2% of the total. If only embodied and operational energy are considered, the first represents 55.0% of the total and the second 45.0%. If only thermal and hot water energy demands are taken into consideration, as in most previous studies on passive houses, the embodied energy demand represents 67.0% of the total (excluding transport) over 100 years. This clearly underlines the importance of embodied energy in so-called “low-energy” buildings. The transport energy requirements, with 9 804 GJ, represent an important part of the total.

Combined, the so-called indirect requirements (embodied and transport) represent 67.2% of the life cycle energy consumption.

These figures are however subject to change due to uncertainty in the embodied energy data. Indeed, ±43% of variation is possible, based on the computed uncertainty (see Section 2.1). The minimal value for embodied energy, considering an unlikely scenario where all the energy coefficients of all materials are overestimated, is 8 266 GJ. Even in this case, the embodied energy requirements still represents respectively 27.7% and 41.2% of the total energy demand and the sum of embodied and operational energy. When the minimal values for embodied and transport requirements are combined with the maximum figure for operational energy, they still represent 53.2% of the total energy demand. Hence, even considering extreme uncertainty and variability numbers, indirect requirements represent more than half of the life cycle energy demand of the base case passive house.

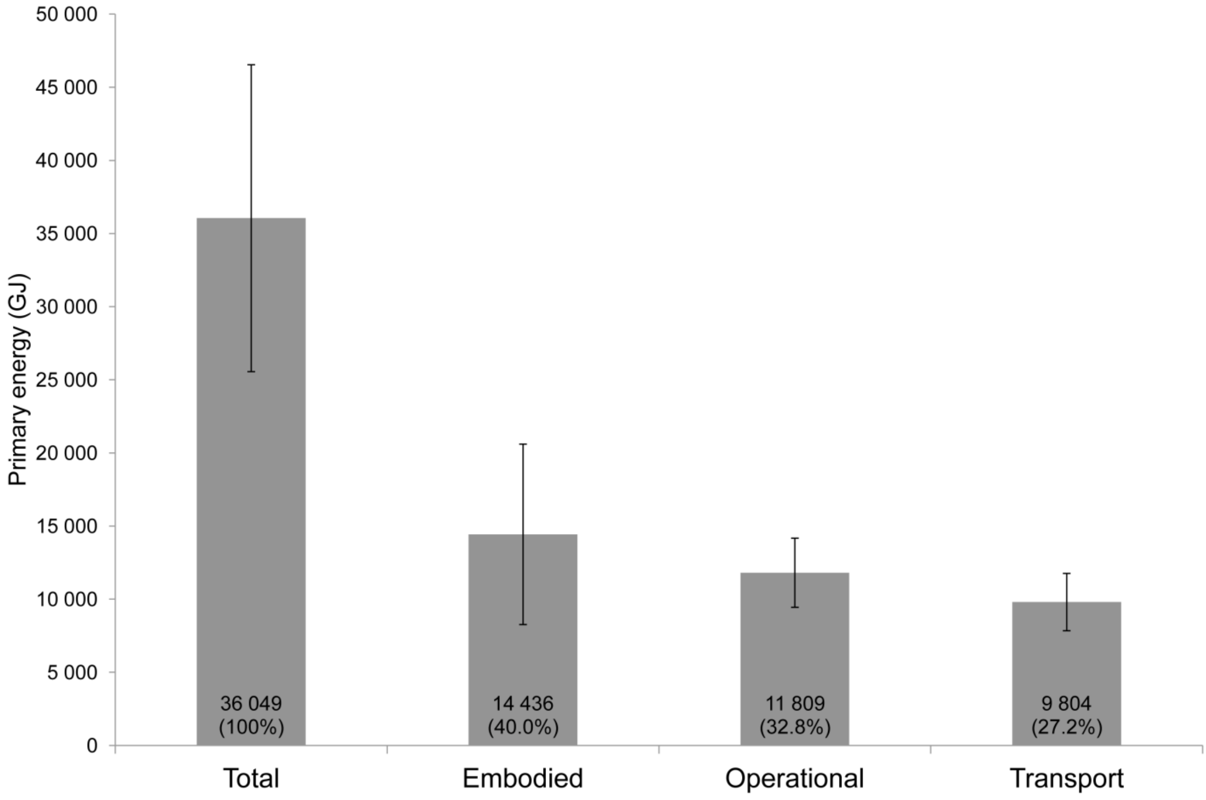

Figure 3: Life cycle energy breakdown of the base case passive house, by use

The initial embodied energy of the building is 17.26 GJ/m², which is much higher than in previous studies. Indeed, the embodied energy of passive houses is largely underestimated in the literature with numbers within 3.5-7.1 GJ/m² [based on 14, 32, 33, 34]. The use of the more comprehensive system boundaries of the input-output-based hybrid analysis, although relying on Australian data, produces significantly higher figures (2.4 to 4.9 times higher). When breaking down the embodied energy by materials, insulation represents the highest energy consumption in front of the steel structure. Another important aspect to underline is the significant recurrent embodied energy associated with the replacement of carpets and parquet floorings, over the useful life of the building.

Hot water represents the highest operational energy demand, followed by heating, appliances, cooking, lighting and ventilation. Indeed, once the heating demand is dramatically lowered, other end-uses can become more important. This finding confirms the conclusions of Blengini and Di Carlo [13].

The transport energy demand totalled 9 804 GJ over 100 years. This figure is split between direct energy (5 392 GJ, 55.0%) and indirect energy (4 412 GJ, 45.0%). The contribution of the indirect transport energy is considerable. For instance, the indirect transport energy, which is generally omitted, represents 115% of the combined primary energy requirements of heating and ventilation. The ratio between indirect transport energy and heating clearly underscores the importance of a more holistic life cycle energy assessment. While it is surely important to reduce the heating demand in a Northern European context, it is also important to optimise the transport energy consumption.

3.2 Parametric study

Figure 4 shows the relative difference, in the life cycle energy demand per capita, of the different variations made to the base case passive house. Results show a variation between -31.5% and +2.7% for all studied scenarios.

Modifying the structure to reinforced concrete or timber increases the life cycle energy demand by a negligible margin (regarding the uncertainty in the data). The replacement of polyurethane insulation by fibreglass results in a higher life cycle energy demand because of the higher replacement rate of fibreglass. The timber framed structure is selected for the best case passive house because of the renewable nature of timber, and its potential incineration at the end-of-life stage.

Among the various operational energy variations, the use of gas appliances, the installation of solar panels for hot water and the reduction of the operational energy demand resulted in a life cycle energy demand 20.9% lower than in the base case. The use of gas instead of electricity for heating, hot water and cooking resulted in a significant reduction of operational energy because of the lower primary energy coefficient. Just by modifying the behaviour of the users regarding operational energy, the overall energy consumption was reduced by up to 7.2%(ROPE and HROPE). The GSHROPE scenario is chosen for the best case.

The scenario in which the main income earner used the train instead of a car for commuting yielded a 31.0% reduction of the transport energy demand (-8.4% life cycle energy consumption). This shows the importance of using public transportation systems in comparison to cars. This variation (TRAIN), is chosen for the best case passive house.

When the number of users in the house was increased to 5 and 7.35, the overall energy demand per capita dropped by 16.9% and 31.5.% respectively. This clearly indicates that smaller living areas per capita and the sharing of cars by a higher number of people result in a more efficient energy use.

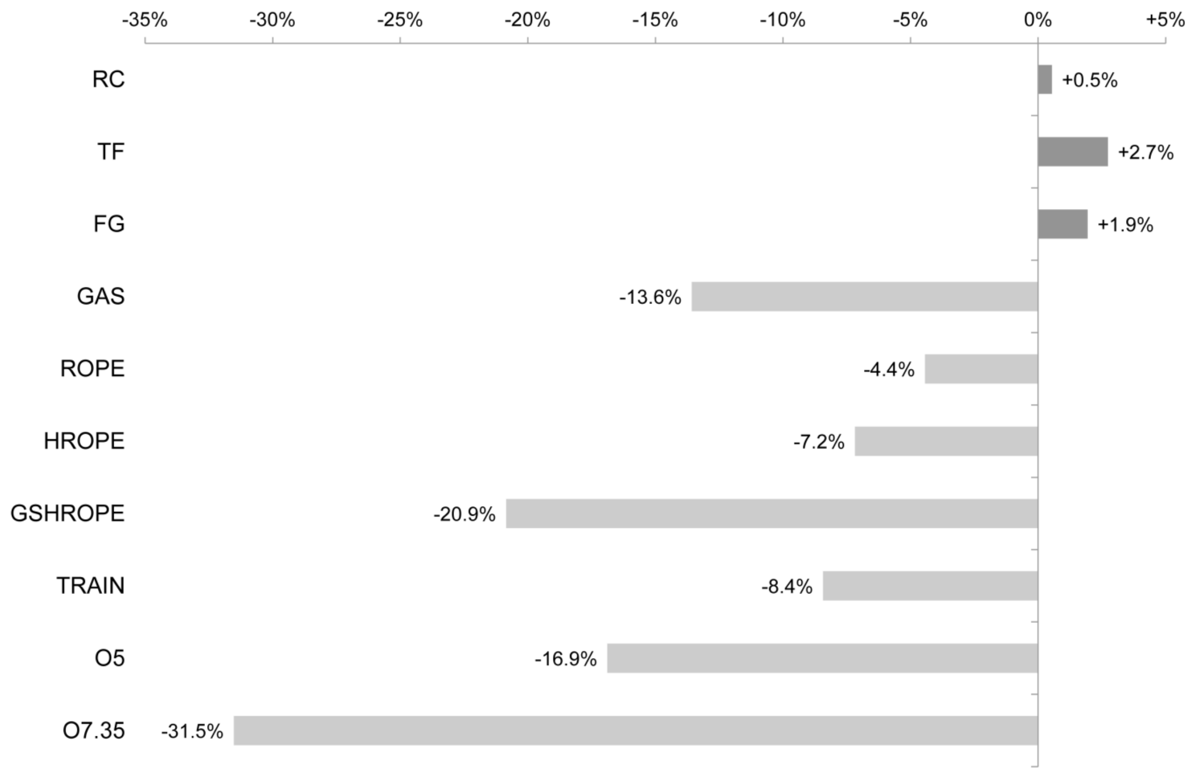

Figure 4: Relative difference in the life cycle energy demand of the different investigated variations compared to the base case passive house, per capita

Several individual measures evaluated to reduce the total energy demand of the base case (BC) passive house are combined in the best case scenario (BSTC). Based on all the choices made throughout the evaluation of the results, the best case characteristics are:

- Timber framed structure according to the variation TF (see Table 2)
- Replace nylon carpets and parquet flooring with ceramic tiles (based on the findings in Section 3.1)

- GSHROPE variation (see Table 2)
- Train commuting for the main income earner according to variation TRAIN (see Table 2)

The life cycle energy demand breakdown of the best case passive house is presented in Figure 5. In this case, the embodied energy demand is by far the most significant with 56.0% of the total, followed by transport (27.1%) and operational (16.9%). If only operational and embodied energy are considered , the latter represents 76.9% of the total over 100 years. Also, the life cycle energy demand of the best case scenario is 30.8% lower than the base case passive house. This shows that a great variability in the total energy demand of certified passive houses can occur.

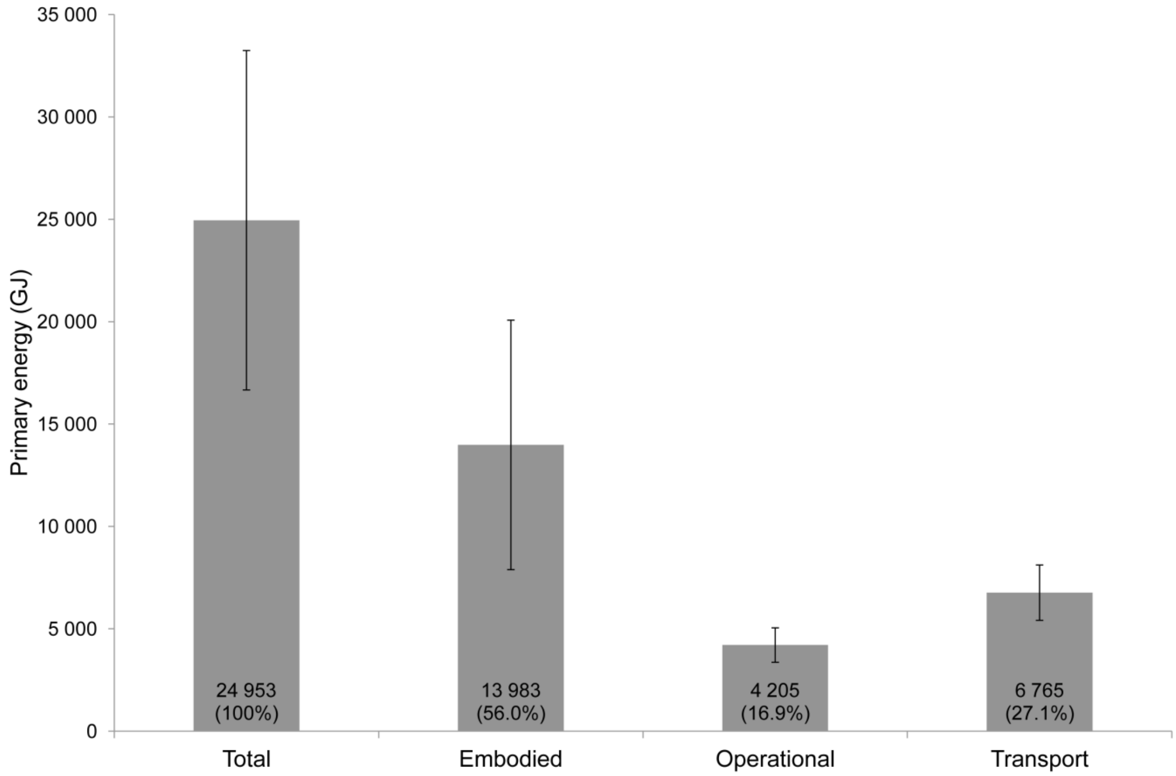

Figure 5: Life cycle energy demand breakdown of the best case passive house, by use

3.3 Passive house Vs. Standard new house

Figure 6 compares the life cycle energy demand, by use, of the passive house base case and the Standard house (see Section 2.4) with the GAS and ROPE variations (see Table 2). Results show that, over 100 years, the total energy consumption of a new standard house and a passive house are nearly the same (204 GJ difference or +0.6%). The increased insulation level of the passive house results in a lower operational energy but a higher embodied energy which counter-balances the savings. If the standard house relies on gas for heating, hot water and cooking, its total energy consumption is lower than the fully electric base case passive house (-7.2%). If the GAS variation is applied to the passive house, it outperforms a standard house by 2 285 GJ (-6.8%). Even in this case, the reduction in the overall demand is not as dramatic as what would be expected from a passive house. Nearly the same performance can be achieved by applying the ROPE and GAS variations to the standard house (see Table 2).

Also, when including the user transport energy in the assessment, the relative impact of operational energy drops. Improvements which are significant at the operational energy level, become less important when all energy flows are accounted for.

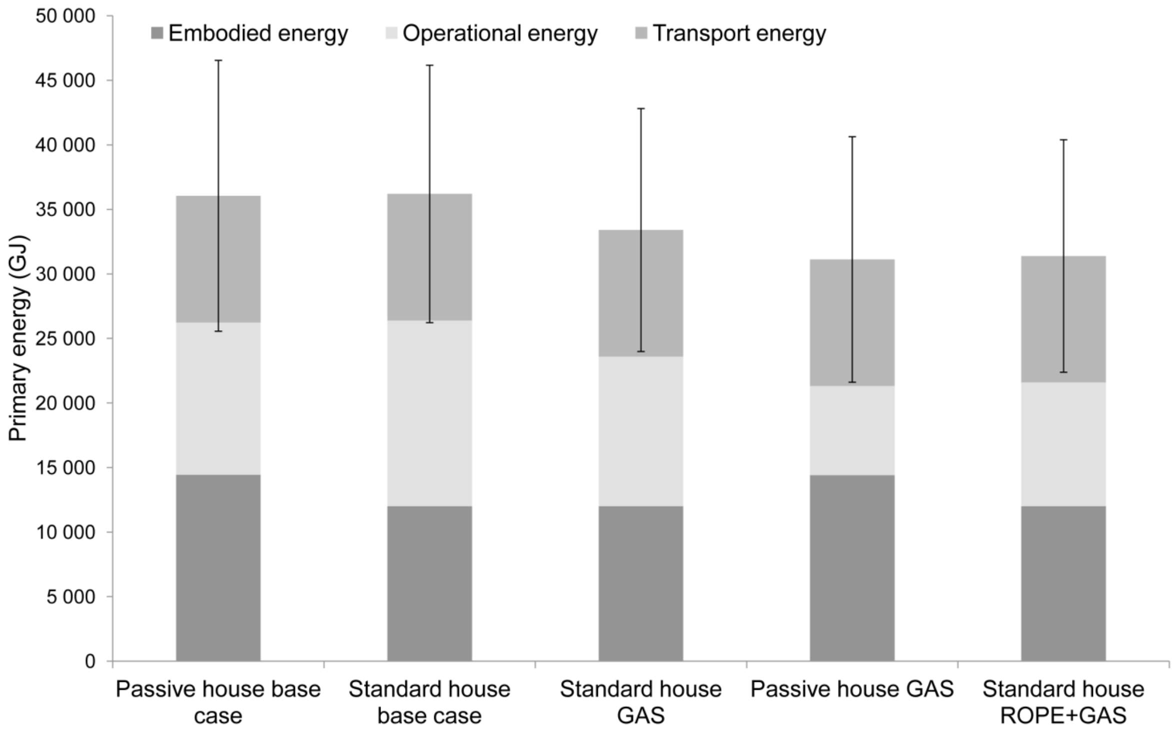

Figure 6: Life cycle energy demand of passive and standard houses variations

3.4 Passive house Vs. City apartment retrofit

Figures 7 and 8 compare the life cycle energy demand breakdown of the passive house base case (BC), the passive house best case (BSTC) and the apartment retrofit in the city of Brussels (AP). Results show that when compared on a per m² basis, the AP is the most energy intensive dwelling (146.9 GJ/m²) with BSTC being the least (84 GJ/m²). The operational energy of the AP is higher than that of the BC and the BSTC, as expected. The total embodied energy requirements of the AP are only 23.4% lower even though the apartment is retrofitted (no new structural elements). This is due to the higher proportion of carpet, parquet and glass materials in the apartment, which are very energy intensive over the life cycle. Indeed, the initial embodied energy demand (per m²) of the apartment is 58.0% lower than the BC but its recurrent embodied energy demand per m² is the same. The transport requirements of the apartment are also the highest on per m² basis. However, the per m² unit distorts the data in unwanted ways because it attributes both building and user related energy consumption to the surface of the house, and it does not take into account the number of occupants.

When compared on a per capita basis, the AP is the least energy-intensive. The difference between the BSTC and the AP is significant (-15.2%). The AP outperforms the passive house cases by far on the embodied energy aspect. Surprisingly it also bests the BC when it comes to operational energy. This is due to its reliance on gas as an energy source for heating, cooking and domestic hot water but also on the smaller area to heat per capita. Yet, the operational energy demand of BSTC is still much lower (-58.0%). The transport energy of AP is lower to that of the BC and BSTC by 41.4% and 15.0% respectively. The per capita basis is judged a more appropriate metric to compare buildings with different areas and number of users, when considering transport energy requirements as well. In their study on Toronto, Canada, Norman *et al.* [35] also underlined the importance of using the capita basis instead of the m².

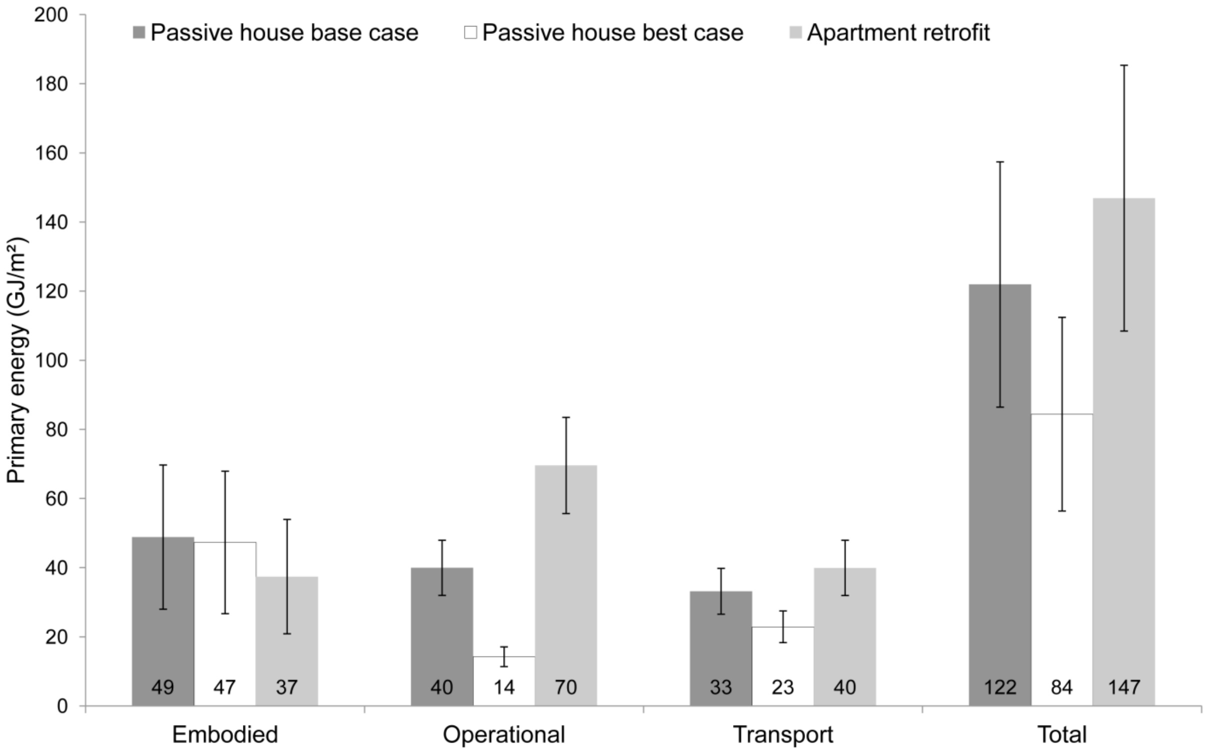

Figure 7:Life cycle energy demand breakdown of the passive house base and best case Vs. the retrofitted city apartment, per m²

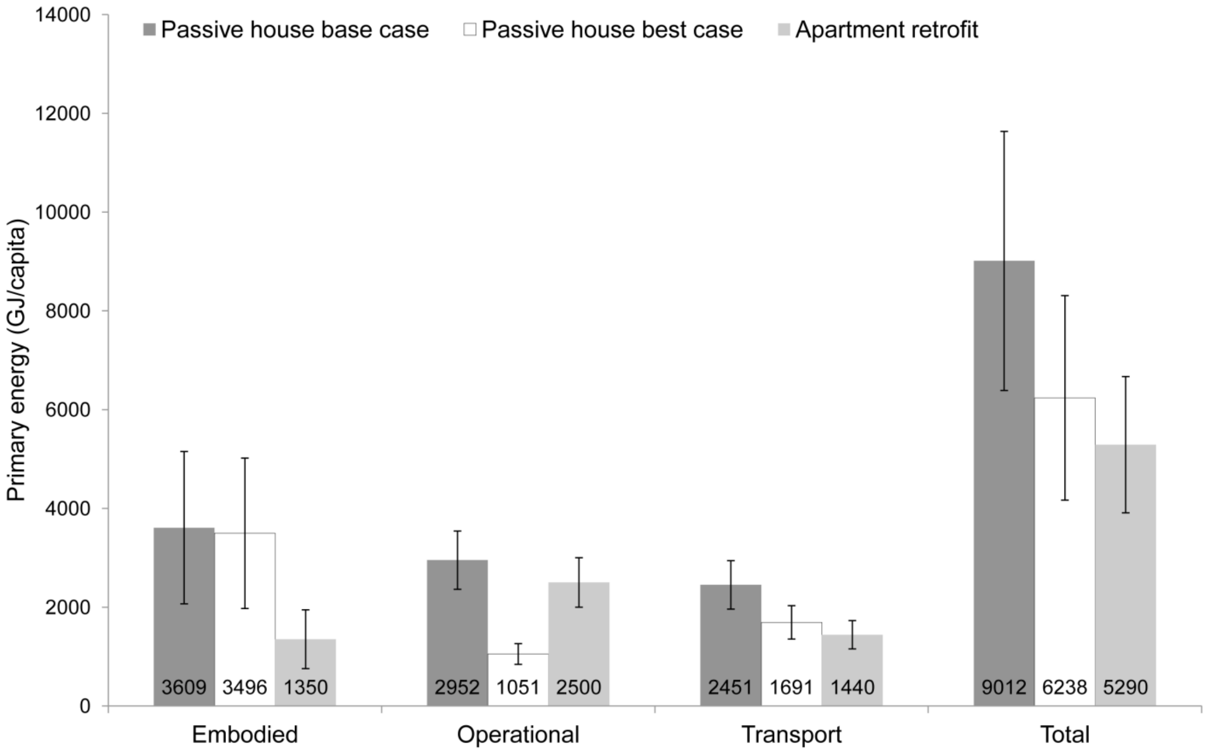

Figure 8: Life cycle energy demand breakdown of the passive house base and best case Vs. the retrofitted city apartment, per capita

4 Discussion

This paper has determined the life cycle energy demand of a passive house in one of the most comprehensive ways as of yet. Results show that the operational energy demand, which is the sole focus of most current certifications and directives represents less than 40% of the total energy consumption. Also, within operational requirements, the passive house standard focuses mainly on the space heating demand and to some extent on the hot water demand. The energy associated with appliances, lighting and cooking is not considered. This, combined with the omission of embodied and transport energy, explains why a great fluctuation in the total energy consumption is possible between two certified buildings, i.e. the best case and the base case passive houses. By addressing only one stage of the life cycle of a building, certifications such as the passive house standard can lead to an increased energy demand at other stages or at different scales of the built environment.

The embodied energy demand, quantified using the input-output-based hybrid analysis was found to be much higher than in all previous studies. Also, the embodied energy demand represented the highest share of energy consumption in all variations. Because the passive house certification does not take embodied energy into account, a passive house building can have the same life cycle energy demand as a new standard house (see Section 3.3). The reduced space heating energy comes at the price of an increased embodied energy which can counter-balances the benefits.

Selecting the energy source was found to be a very critical parameter regarding the primary operational energy demand. Indeed, be relying on gas for space heating, hot water and cooking, the operational energy demand of the passive house was reduced by 41.4%. Hence, as advocated by Gustavsson *et al.* [36], the energy source and its primary energy implications are critical elements to consider. However, the advantages of using gas from a primary energy perspective are most likely overestimated by the unitary primary energy conversion factor used in Belgium (see Table 1).

Another flaw in current building energy certifications is their focus on energy efficiency per m² of usable floor area. While passive houses strive to achieve a very low final heating demand per m², it is clear that the size of the house can counter balance this efficiency, both in terms of embodied and operational energy consumption. For instance, the exact same passive house but with a floor area of 180 m² instead of 330 m² would have the same space heating consumption per m² but a life cycle energy demand which is 19.4% lower. This effect is clearly visible in the comparison of the passive house with a city apartment. While the energy demand per m² of the apartment is much higher, its life cycle energy consumption per capita is lower than the best case passive house. Building energy certifications should include an absolute and a per capita energy consumption figures to ensure a comprehensive assessment.

The transport energy consumption, related to the building context, represented an important share of the total demand. It is crucial to include the energy required for the mobility of building occupants to ensure that net energy savings do occur. Indeed, the transport energy demand of city dwellers was found to be 41.4% lower than for the passive house occupants. If city dwellers move to a suburban passive house, the energy savings in space heating and operational energy might be counter-balanced by an increased transport energy demand. It is only by considering the life cycle energy demand at multiple scales that a realistic measure of energy consumption can occur.

However, this paper suffers from certain limitations. The reliance on a simple heat transfer model and regional averages for the determination of operational energy might also result in a divergence from the real figure. Transport energy requirements can also vary according to user habits and local conditions. The integration of uncertainty should ideally rely on probabilistic distributions for a more accurate representation, but these do not currently exist and could constitute the basis for future research. Finally, the use of an Australian database for the quantification of the embodied energy might result in possible errors, although by considering the lowest valued related to uncertainty, the embodied energy demand was still much higher than in all previous studies using process analysis. The development of an embodied energy database for Europe, using the input-output-based hybrid would constitute a major step forward to better measure this energy demand.

5 Conclusion

In conclusion, this paper has demonstrated that passive houses do not always save energy and can actually have the same overall energy consumption as a new standard building. When using wider system boundaries for the energy assessment, poorly insulated city apartments can use less energy than a very efficient passive house in the suburbs. Current European building energy certifications and regulations, which focus mainly on the space heating aspect, do not necessarily result in a lower energy consumption. If the aim of these instruments is to reduce energy consumption and associated greenhouse gas emissions and other environmental impacts, these should adopt wider system boundaries and include embodied and transport energy requirements.

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