The Significance of Embodied Energy in Certified Passive Houses

Robert H. Crawford, André Stephan

Abstract**—** Certifications such as the Passive House Standard aim to reduce the final space heating energy demand of residential buildings. Space conditioning, notably heating, is responsible for nearly 70% of final residential energy consumption in Europe. There is therefore significant scope for the reduction of energy consumption through improvements to the energy efficiency of residential buildings.

However, these certifications totally overlook the energy embodied in the building materials used to achieve this greater operational energy efficiency. The large amount of insulation and the triple-glazed high efficiency windows require a significant amount of energy to manufacture. While some previous studies have assessed the life cycle energy demand of passive houses, including their embodied energy, these rely on incomplete assessment techniques which greatly underestimate embodied energy and can lead to misleading conclusions.

This paper analyses the embodied and operational energy demands of a case study passive house using a comprehensive hybrid analysis technique to quantify embodied energy.

Results show that the embodied energy is much more significant than previously thought. Also, compared to a standard house with the same geometry, structure, finishes and number of people, a passive house can use more energy over 80 years, mainly due to the additional materials required.

Current building energy efficiency certifications should widen their system boundaries to include embodied energy in order to reduce the life cycle energy demand of residential buildings.

Keywords**—**Embodied energy, Hybrid analysis, Life cycle energy analysis, Passive house.

I. Introduction

BUILDINGS are responsible for around 40% of final energy consumption in most developed economies [1]. In Europe, residential buildings account for 26% of final energy consumption [2]. This important share has lead to the emergence of building energy certification policies such as the Energy Performance of Buildings Directive [3] or facultative certifications such as the Passive House certification [4]. Thousands of passive houses have already been built across Europe [5].

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The Passive House Standard focuses on significantly reducing the space heating demand (lower than 15 kWh/m².year or 54 MJ/m².year) and imposes that the overall primary operational energy consumption should be lower than 120 kWh/m².year (432 MJ/m².year) [6]. In order to reduce the space heating demand, passive houses typically require high performance thermal envelopes with additional insulation, triple-glazed windows with high efficiency frames, a high level of airtightness and the installation of a mechanical ventilation system to recover the heat from the outgoing air. Therefore, compared to a normal house, a passive house requires a significant amount of additional materials.

All building materials require energy to manufacture. This energy is known as a material's embodied energy. According to most studies in the literature, embodied energy accounts for around 20% of the combined embodied and operational energy demand of a residential building over its useful life [7]. Previous studies assessing the life cycle energy demand of passive houses found that their embodied energy is higher than conventional housing [8], [9].

However, previous research on the embodied energy of passive houses relies on a 'process analysis' technique to quantify the embodied energy. This technique (which is described in Section II.B) rarely includes all of the energy requirements across the construction supply chain, resulting in an underestimation of the embodied energy. Based on previous studies, the average embodied energy intensity of passive houses is between 3.1 and 7.6 GJ/m² [7], [8], [9], [10], [11], [12]. In contrast, studies relying on the comprehensive hybrid analysis technique to quantify embodied energy [13], [14], [15], found that the embodied energy intensity of standard houses is between 11.7 and 14.1 GJ/m².

Therefore, the embodied energy of passive houses is likely to be greatly underestimated in previous studies. It is therefore critical to examine the life cycle energy demand of a passive house based on a comprehensive embodied energy system boundary to ensure that passive houses result in net life cycle energy savings.

The aim of this paper is therefore to demonstrate the importance of integrating embodied energy, using a comprehensive quantification technique, into the passive house certification.

Section II defines the system boundaries and presents the equations used for the calculation of the embodied energy as well as the approach used to calculate the operational energy demand. The description of the case study passive house and its standard house alternative are also provided in Section II. Section III presents the results of this study which are then discussed in Section IV.

II. Calculating the Life Cycle Energy Demand of a Passive House

A. System boundary and functional units

In this study the life cycle energy demand of a case study passive house, located in Belgium is calculated. The life cycle energy demand comprises energy requirements for raw material extraction and processing, material manufacture, construction, operation and maintenance, as depicted in Fig. 1. The maintenance stage comprises the replacement of building materials over the useful life of the building. The end-of-life stage of the life cycle is not considered as studies have demonstrated that it often represents less than 1% of the total energy demand of a building [16], [17].

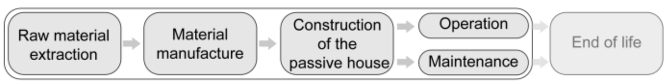

Fig. 1 System boundary of the life cycle energy analysis of the case study passive house

The building is assessed over 80 years, which is the average building useful life proposed by the IEA [18] and adopted in some of the previous life cycle energy studies on passive houses, such as [8].

Results are provided in GJ/m² of usable floor area to facilitate the comparison with similar studies.

B. Embodied energy calculations

Three main techniques exist to quantify embodied energy: process analysis, input-output analysis and hybrid analysis. Process analysis, consists of auditing the energy expenditures associated with each process of the supply chain of a specific product (e.g. iron ore extraction for steel). Therefore, the assessor maps the supply chain of a product and compiles its embodied energy by adding the contribution of each process. However, at a certain point, upstream in the supply chain, the data regarding specific processes can be scarce or unavailable. Here, the assessor draws the system boundary and ignores all energy demand outside of this limit. This results in a ‘truncation error’. Crawford [19] has shown that this truncation error can be as great as up to 87% of the embodied energy of a building material or product. Process analysis can therefore greatly underestimate embodied energy.

Input-output analysis relies on financial transactions at a national or regional scale to establish the energy intensity of economic sectors in GJ/currency unit. Using the price of a building material, its embodied energy is determined based on the energy intensity of the economic sector to which the material belongs. While being easy to use and more comprehensive than a process analysis, input-output analysis suffers from an ‘aggregation error’ which assumes that all materials belonging to one sector have the same energy intensity. Also, the sector-based linear correlation between price and embodied energy can distort the calculations as a more expensive product does not necessarily require more energy to produce. Nevertheless, input-output analysis includes the complete system boundary as all the processes in the supply chain are covered.

Hybrid analysis, as its name suggests, combines process and input-output analysis in order to minimize their respective flaws. By using process analysis for known processes and filling the gaps with input-output data, hybrid analysis is systemically complete and uses the most reliable data for known processes. The input-output-based hybrid analysis technique, developed by Treloar [20] is used in this paper as it is currently the most comprehensive embodied energy quantification technique available. Hybrid embodied energy coefficients for Australian building materials are sourced from the database compiled by Treloar and Crawford [21]. While using Australian data might induce some errors in the results, there are no equivalent hybrid coefficients for building materials in Europe. Relying solely on European process data is therefore very likely to underestimate the embodied energy demand of the passive house, as in previous studies.

Embodied energy can be divided into two main components: initial embodied energy, i.e. the energy embodied in a building’s initial construction, and recurrent embodied energy, i.e. the energy required to manufacture and replace building materials across the useful life of the building. The initial embodied energy is calculated as per (1), the recurrent embodied energy as per (2) and their sum, the life cycle embodied energy, as per (3).

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

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 requirement 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.

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

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 (1).

The useful lives of materials have been sourced from [22], [23].

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

Where: $LCEE_b$ = Life cycle embodied energy of the building in GJ.

The life cycle embodied energy of the house has also been calculated using process analysis, input-output analysis and process-based hybrid analysis to compare with the input-output-based hybrid analysis figures.

C. Operational energy calculations

In order to facilitate a comparison with other studies, the operational energy demand for all end-uses is based on the Passive House Planning Package (PHPP) calculation sheet developed by the PassivHaus Institute. This sheet relies on static heat transfer equations to determine the yearly heating demand. Other operational energy requirements such as ventilation, hot water, lighting, cooking and appliances are based on an average occupancy pattern of four people: two adults and two children.

The life cycle primary operational energy is obtained by converting the final energy demand of each end-use to primary energy terms based on the primary energy factor of the energy source and the useful life of the building as per (4).

$$LCOPE_b = UL_b \times \sum_{e=1}^{E} \frac{PEF_e \times OPE_e}{\eta_e} \quad (4)$$

Where: $LCOPE_b$ = Life cycle primary operational energy of the building b in GJ; UL_b = Useful life of the building b; PEF_e = Primary energy conversion factor for the end-use e; OPE_e = Annual final operational energy demand of the end-use e in GJ; and η_e = Average efficiency of the end-use e (≤ 1).

The primary energy conversion factors for gas and electricity (which are the two energy sources used in this building) are taken from the PHPP sheet for Belgium and are equal to 1.1 and 2.7, respectively.

D. Life cycle energy calculations

The life cycle energy demand (LCE_b) represents the sum of the life cycle embodied energy ($LCEE_b$) and the life cycle operational energy demand ($LCOPE_b$). It is determined as per (5).

$$LCE_b = LCEE_b + LCOPE_b \quad (5)$$

E. Description of the case study passive house

A 330 m² Belgian detached passive house (gross floor area), built in 2012 and housing 4 occupants is used as a case study. The house, is located in Braine-le-Château (Latitude 50.68°N, Longitude 4.27°E), in the Walloon Brabant, 24 km south of Brussels, Belgium. The three storey house is accessible from the street at the middle floor. The floor plans of the house are given in Fig. 2.

The house is steel and concrete-framed with concrete slabs and punctual concrete footings. The façade of the house consists of 40 mm bricks which are directly glued to the insulation.

As for any passive house, the house is extremely well insulated with 220 mm of polyurethane (PU) in the walls (*U*-value = 0.12 W/(m².K)), 200 mm of PU under the ground floor slab (*U*-value = 0.11 W/(m².K)), 50 mm of peripheral slab insulation (PU) and 300 mm of PU in the roof, directly under the roof sheeting. The roof insulation is complemented by 100 mm of rock wool on top of the ceiling (roof *U*-value = 0.09 W/(m².K)). All windows are triple-glazed and argon-filled and have timber frames (*U*-value = 0.6 W/(m².K); *g*-value = 0.52).

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

The mechanical ventilation system is also used as the heating delivery system. The ventilation rate is 0.33 ach^{-1} and the heat recovery system has an efficiency of 81.2%. The air is heated by coils within the system which are operated by electricity.

Hot water and cooking are run on gas while lighting and appliances run on electricity.

With 297 m² of usable floor area, this house is representative of passive houses in Belgium. Indeed, according to [24], which keeps a record of certified passive house buildings in Belgium, most of these are located in suburban areas and are single family detached houses.

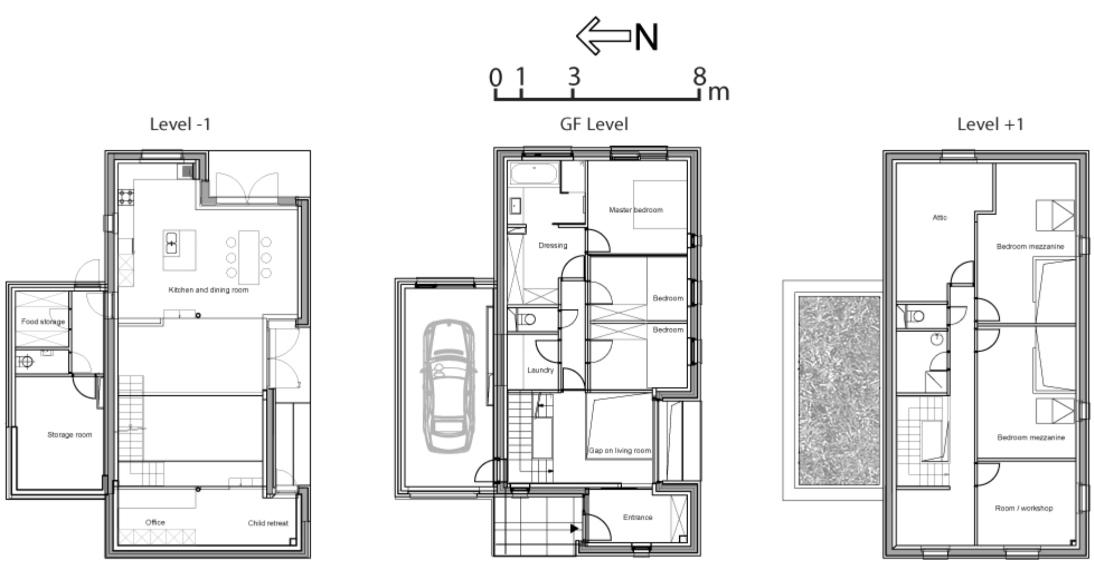

Fig. 2 Floor plans of the case study passive house

F. Comparison with a standard house

In order to assess the benefits of a passive house, a hypothetical new standard house is modeled. This standard house is the same case study house with some modifications.

The modifications entail the reduction of the insulation thickness in the walls, roof and slab and the removal of the peripheral insulation from the upper floor slabs. Also, the triple-glazed windows are replaced with double-glazed windows. Radiators are installed to deliver heat which is produced by a condensation gas boiler. Newly built residential buildings in Belgium can be considered as energy efficient since they must comply to the Energy Performance of Buildings Directive [25].

All non-thermal energy demands are kept constant for the sake of comparison. Only the heating demand is recalculated using the PHPP and the ventilation energy demand is removed as the standard house relies on natural ventilation.

Therefore, the standard house uses less materials overall and costs less to construct but has the same geometry, number of occupants and non-thermal operational energy demand as the case study passive house.

III. RESULTS

A. Embodied energy

The embodied energy of the case study passive house, calculated using process analysis, input-output analysis, process-based hybrid analysis and input-output-based hybrid analysis, is presented in Fig. 3.

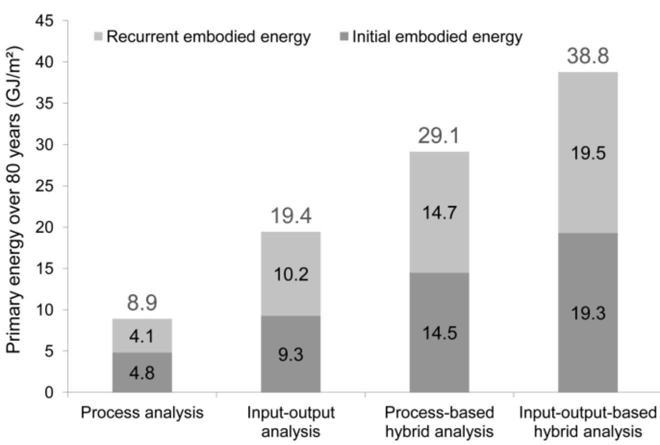

Fig. 3 Life cycle embodied energy demand of the case study passive house, by embodied energy quantification technique, per m² of usable floor area. Note: figures may not sum due to rounding.

Results show a significant difference between the input-output-based hybrid analysis and the process analysis (a factor of 4.36). Moreover, the process analysis figure for the initial embodied energy (4.8 GJ/m²), calculated using Australian process data, falls within the range of previous studies of passive houses which rely on European process data (see Section I). This suggests that when comparing energy intensities at a whole building level, the differences in the industrial processes of particular products and the energy sources used in a specific country tend to be evened out.

Also, the embodied energy is nearly evenly split between the initial (49.7%) and recurrent (50.3%) demands. In most previous studies such as [13], [26], the recurrent embodied energy represented around 30-50% of the initial embodied energy, or 23-33% of the life cycle embodied energy. The more comprehensive material replacement algorithm used in this paper (see (2)), results in a recurrent embodied energy demand at the higher end of the scale.

Fig. 4 compares the contributions of each building element towards the life cycle embodied energy of the case study passive house. Results show that the envelope, comprising the insulation and triple-glazed windows is the highest contributor with 34.4% of the total. The insulation materials represent a higher proportion of the initial embodied energy than the structural steel in the house. This clearly highlights the significance of the additional embodied energy of the insulation in a passive house. The insulation material should therefore be carefully chosen based on its thermal and hygroscopic properties but also on its embodied energy content.

The ‘other elements’ category, which is only taken into account when using the input-output-based hybrid analysis approach, reveals the significance of the embodied energy typically excluded when utilizing other embodied energy quantification techniques. Indeed, the ‘other elements’ category represents 24.9% of the life cycle embodied energy demand.

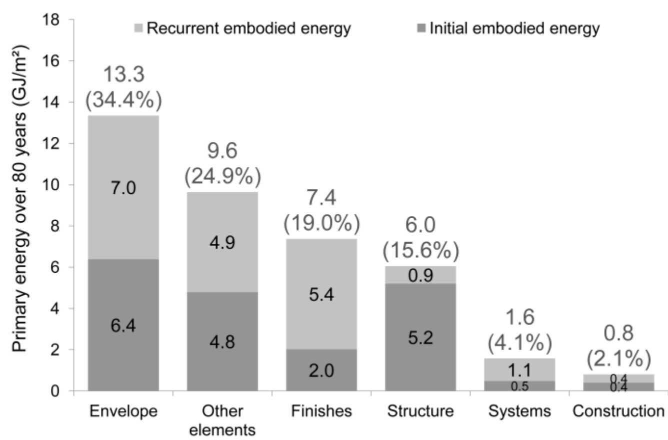

Fig. 4 Life cycle embodied energy of the case study passive house, by element, per m² of usable floor area. Note: figures may not sum due to rounding.

Another interesting result is the significance of the recurrent embodied energy of the finishes (5.4 GJ/m²) which is higher than the initial embodied energy of the structure of the house (5.2 GJ/m²). The replacement of nylon carpets and repainting of the house every 10 years results in a high recurrent embodied energy for this element. Also, while the recurrent embodied energy of the finishes represents the majority of the contribution of this element, the opposite trend can be observed for the structure element. The latter’s initial embodied energy represents the major part of its life cycle embodied energy. This suggests that maximizing the durability and service life of finishes is critical - something that is already inherent in the structural elements.

Finally, the embodied energy associated with building systems and with the construction process of the house, combined, represent only 6.2% of the total embodied energy demand.

B. Operational energy

The operational energy demand is presented in Fig. 5, by end-use. Although the final energy demand for space heating is greatly reduced compared to a standard house, the associated primary energy demand still contributes the most to the operational energy consumption (11.7 GJ/m² or 39.8% of the operational energy). The primary energy consumption associated with appliances is the second highest contributor with 30.3% of the total, followed by hot water (13.1%) and lighting (10.6%).

The most energy intensive end-uses (space heating and appliances) are those operated on electricity. This is due to the high primary energy conversion factor for electricity (2.7), caused by losses in the grid as well as the efficiency of current power plants in Belgium (mostly nuclear and gas). While the heating demand is the most significant operational energy demand for most houses in Belgium (around 70%), passive houses have a different energy profile. Once the heating demand is reduced, other demands become nearly as significant as highlighted by Blengini and Di Carlo [27].

Additional savings can be achieved by installing a gas system for space heating or a heat pump. Efficient electrical appliances, a solar hot water system and high efficiency LED lighting can also contribute to a reduction in the operational energy consumption.

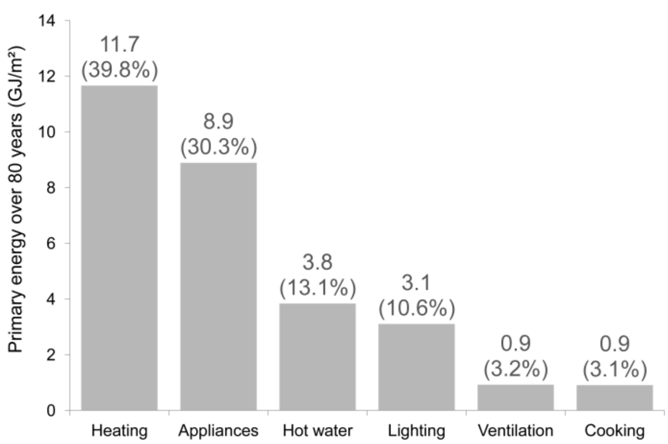

Fig. 5 Life cycle operational energy demand of the case study passive house, by end-use, per m² of usable floor area. Note: figures may not sum due to rounding.

C. Life cycle energy

The life cycle energy demand of the passive house, combining embodied and operational energy, is presented in Fig. 6, by use. As shown, there is no single major contributor to the total life cycle energy (at most 19.6% from one category). Therefore reducing the life cycle energy demand requires multiple interventions which tackle different building elements and systems.

The single largest contributor is the envelope embodied energy (13.3 GJ/m²; 19.6%), followed by heating (11.7 GJ/m²; 17.1%), the 'other elements' (9.6 GJ/m²; 14.2%), the appliances operational energy demand (8.9 GJ/m²; 13.1%), the finishes (7.4 GJ/m²; 10.8%) and the structure (6.0 GJ/m²; 8.9%). The other building elements or operational energy end-uses contribute, at most, 5.6% of the total life cycle energy demand.

Another observation is the very significant contribution of the embodied energy (38.8 GJ/m² or 56.9%). The passive house certification, which focuses solely on operational energy, therefore overlooks more than 50% of the energy demand.

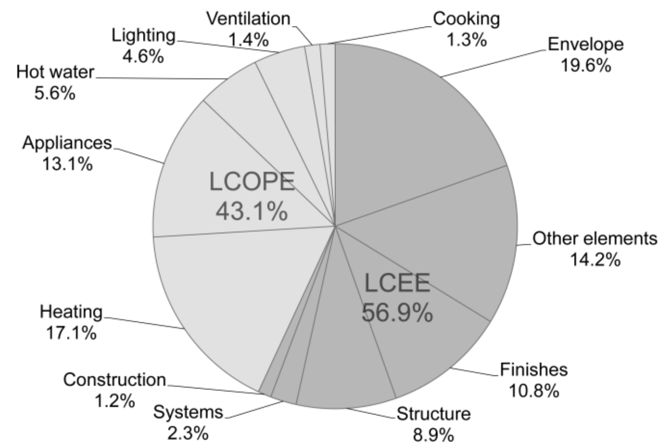

Fig. 6 Life cycle energy demand of the case study passive house over 80 years, by use. Note: LCEE = life cycle embodied energy and LCOPE = life cycle operational energy

D. Comparison to a standard house

The life cycle energy demand of a standard house is compared to that of the case study passive house in Fig. 7. Results show a significant increase in the envelope embodied energy of the passive house compared to the standard house (+49.4%) and a slight increase for the other embodied energy elements (+12.4%). The latter is due to the additional ducting systems and a higher construction price which increases the input-output component of the embodied energy.

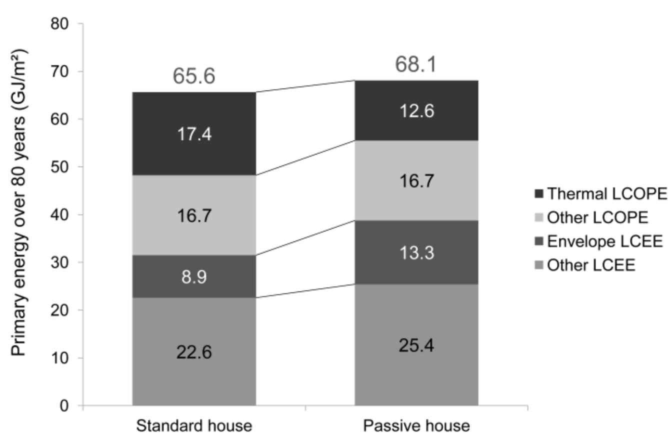

Fig. 7 Life cycle energy demand of the case study passive house and a standard house alternative, per m² of usable floor area. Note: LCOPE = life cycle operational energy and LCEE = life cycle embodied energy.

The increased embodied energy of the passive house, related mainly to the additional insulation, is partly offset by a reduction in the space heating demand. However, the reliance on an electrical source for space heating, compared to gas for the standard house, results in a high primary energy demand. The energy source is therefore crucial to ensure that the primary energy consumption is reduced, as highlighted by Gustavsson and Joelsson [28].

When the total life cycle energy demand is compared, the passive house surprisingly uses more energy than the standard house. The additional embodied energy and the use of electricity for space heating result in a higher overall energy demand (+3.8%). Certified passive houses may therefore consume more energy than supposedly less energy efficient buildings.

IV. Discussion

This study has assessed the life cycle energy demand of a Belgian passive house over 80 years using hybrid analysis for the quantification of the embodied energy and the Passive House Planning Package (PHPP) sheet for the calculation of the operational energy.

The main finding is that the embodied energy demand, calculated as per the input-output-based hybrid analysis, is much higher than in previous studies which rely on a process analysis. In fact, the contribution of the embodied energy was found to be 38.8 GJ/m² (56.9% of total life cycle energy). The difference lies in the more comprehensive system boundary of a hybrid analysis. Indeed, if the embodied energy was quantified using process, input-output or process-based hybrid analysis, its contribution to the total life cycle energy of the passive house would be 13.1%, 28.5% or 42.8%, respectively, instead of 56.9%. The use of the input-output-based hybrid analysis is therefore necessary for a more comprehensive quantification of embodied energy.

Embodied energy is not taken into account in the passive house certification. Results have shown that this energy demand can represent more than half of the life cycle energy consumption of a passive house. With the additional materials and insulation needed to achieve the Passive House Standard, it is critical that the embodied energy of these additional materials is considered.

The need to consider embodied energy is further reinforced by the comparison of the passive house with the standard house alternative. Even if the thermal energy demand of the passive house is lower than for the standard house, this is offset by a higher embodied energy. Therefore, taking embodied energy into consideration is crucial to ensure that net energy savings actually occur. Embodied energy should thus be integrated into current building energy efficiency policies and certifications as advocated by Garcia-Casals [29] and Szalay [30].

This study does suffer from a number of limitations. Firstly, the reliance on an Australian database for a Belgian house might induce some errors in the findings. Also, there is a high level of uncertainty in embodied energy figures which can fluctuate by ±40% when calculated using a hybrid analysis [15]. More comprehensive embodied energy figures are needed, notably through the development of a hybrid embodied energy coefficient database for Europe.

V. Conclusion

In conclusion, this paper has established that certified passive houses do not always result in net energy savings compared to less energy efficient buildings. It was shown that a standard house with the same geometry, structure, finishes, and number of occupants can have a lower life cycle energy demand. The additional materials required in a passive house, combined with the choice of energy source have a significant impact on their total energy demand.

Current European building energy certifications and regulations, which focus mainly on space heating and operational energy aspects, do not necessarily result in a lower overall energy consumption. If the aim of these regulations and schemes is to reduce energy consumption and associated greenhouse gas emissions, these instruments must adopt wider system boundaries, including the embodied energy in building materials.

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