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The relationship between house size and life cycle energy demand: implications for energy efficiency regulations for buildings

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Abstract

House size has significantly increased over the recent decades in many countries. Larger houses often have a higher life cycle energy demand due to their increased use of materials and larger area to heat, cool and light. Yet, most energy efficiency regulations for buildings fail to adequately include requirements for addressing the energy demand associated with house size.

This study quantifies the effect of house size on life cycle energy demand in order to inform future regulations. It uses a parametric model of a typical detached house in Melbourne, Australia and varies its floor area from 100 to 392m² for four different household sizes. Both initial and recurrent embodied energy requirements are quantified using input-output-based hybrid analysis and operational energy is calculated in primary energy terms over 50 years.

Results show that the life cycle energy demand increases at a slower rate compared to house size. Expressing energy efficiency per m² therefore favours large houses while these require more energy. Also, embodied energy represents 26-50% across all variations. Building energy efficiency regulations should incorporate embodied energy, correct energy intensity thresholds for house size and use multiple functional units to measure efficiency. These measures may help achieve greater net energy reductions.

Keywords

House size; life cycle energy analysis; functional unit; embodied energy; energy efficiency regulations.

1 Introduction

It is important that greenhouse gas emissions from human activities are reduced in order to limit further major disruptions to the Earth's climate and ecosystems. Already, the ten hottest years on record have occurred in the last 15 years [1]. The operation of buildings alone is responsible for more than a third of global final energy demand and associated greenhouse gas emissions [2] and for much more if indirect energy demand and emissions are included [3]. Buildings therefore have a central role to play in mitigating climate change [4] and in paving the way towards a more energy efficient built environment.

Residential buildings constitute the largest share of the global building stock and are responsible for most of the operational energy demand within the building sector, as evidenced by studies such as Perez-Lombard *et al.* [5]. This has pushed many countries to develop and enforce building energy efficiency regulations. These often focus solely on thermal performance such as in Australia [6] through the 6-Star standard or in Europe [7] through the Energy Performance of Buildings Directive (EPBD). These regulations can help reduce the operational energy demand, notably when they consider primary energy use such as in the EPBD. However, one of the major drawbacks of building energy efficiency regulations is their lack of consideration of embodied energy. Unless they consider the entire life cycle of the building by including its embodied energy, they cannot result in a net reduction of energy demand as demonstrated by a large number of studies, *inter alia* [8-10]. This disregard for embodied energy becomes even more critical when another key characteristic is considered: house size.

The size of a building is proportional to the amount of materials required for its construction, the associated embodied energy, as well as the area to heat, cool and light. While several studies have quantified the relationship between house size and operational energy (e.g. Clune *et al.* [11], Guerra Santin *et al.* [12], Wilson and Boehland [13] and Yohanis *et al.* [14]), very few have analysed the relationship between house size and life cycle energy demand, e.g. Fuller and Treloar [15] and Fuller and Crawford [16]. The latter rely on a very small sample of different house sizes which are built to different specifications and are therefore not comparable. The relationship between house size and life cycle energy demand is therefore not well understood, even though it can have a significant effect on the effectiveness of building energy efficiency regulations, for three main reasons.

Firstly, many countries have witnessed a significant increase in average house size over recent decades. In Australia, where houses are among the largest in the world, the average new house size was 241 m² in 2012 [17] compared to 167 m² in 1984. Houses in the USA have seen a similar increase in floor area over the same time period, rising from 163 m² in 1984 to 215 m² in 2012 (based on data from [18] and [19]). While standalone houses in France have also increased in size over the last 30 years, it is to a much lesser extent, rising from 96 m² in 1984 to 112 m² in 2013 (based on data from [20] and [21]). These larger houses inherently require more materials and more operational energy. The increase in housing operational energy efficiency from 1984 until today may have been offset by the increased need for heating and cooling, as suggested by Calwell [22], let alone the extra embodied energy in larger houses. House size should therefore be a key consideration in any energy efficiency regulation. While there is a size correction factor as part of the Australian regulations, size is barely considered in the EPBD.

Secondly, the increase in house size over recent decades was paralleled by a decrease in average household size according to the same sources. This combination results in a significant increase in the average floor area per capita and therefore in additional embodied energy per capita. For example, the average floor area per person in Australian new detached houses went from ~57 m²/capita in 1984 to ~94 m²/capita in 2012 (+65%, based on [17, 23]). This figure went from 33 m²/capita to 44 m²/capita in France over the same time period (+33%, based on [20] and [21]). Given that the initial embodied energy of one square metre of floor area lies within 10-19 GJ (based on results from [24-27]), each Australian is responsible for an additional 370-703 GJ in 2012 compared to 1984 for the increased floor area, or enough energy to drive around Australia ~8-15 times (in a car with a fuel efficiency of 10L/100km, considering that the energy content of gasoline is 32.4MJ/L and based on 14 500 km per roundtrip). Capturing house size in building energy efficiency regulations is therefore critical.

Thirdly, the relationship between house size and embodied energy is not currently well understood. The majority of existing life cycle energy studies provide results on a per square metre of gross or usable floor area basis [28-31]. While this metric theoretically allows the comparison of houses with different sizes, it is not clear how the embodied energy intensity increases with floor area as the quantity of material does not increase in a strictly linear (1:1) manner. For example, the amount of internal walls per square metre tends to be lower in large houses as these have larger rooms. If embodied energy does not increase linearly with house size, this could mean that studies that use average embodied energy intensities per m² to quantify embodied energy could be flawed as the embodied energy intensity will be tied to the original house size it was derived from. This study will help understand how embodied energy varies with house size.

1.1 Aim and scope

The aim of this study is to quantify and understand the effect of house size on life cycle energy demand in order to inform more effective building energy efficiency regulations that can result in a net reduction of energy demand.

The focus is on energy because it is a good proxy for other environmental effects of buildings as demonstrated by studies in Finland [32], Belgium [33] and Spain [34].

The life cycle stages taken into account comprise raw material extraction, material manufacture, processing and transport, construction and operation and maintenance. The end-of-life stage is not taken into account because of the huge uncertainties regarding the fate of the building many decades into the future. Furthermore, studies have shown that the end-of-life stage often represents less than 1% of a building's total life cycle energy demand, e.g. Winistorfer *et al.* [35]. This paper quantifies the embodied energy of all building materials (including all energy inputs across the entire supporting supply chains) as well as the operational energy used for heating, cooling, lighting, hot water, appliances and cooking. All results are expressed in primary energy terms.

2 Existing studies on house size and energy demand

Few studies have investigated the relationship between house size and energy demand. Among these, most have focused on operational energy and none have analysed the effect of house size on the life cycle energy demand in a systematic manner. This section reviews these existing studies, including those focusing on operational energy and those that consider the life cycle energy demand.

Before presenting studies relating house size to energy use, it is important to underline the significance of the reference area or house size in existing building energy efficiency regulations or certifications such as the PassivHaus. The latter emphasises the importance of the reference area in [36] and describes the calculation steps and explains how using different reference areas can result in different energy efficiency ratings for the same house. However there is no comparison of different house sizes and embodied energy is omitted. This is not the case in the report by Bowick *et al.* [37] that provides guidelines on integrating life cycle assessment in green building programs. Among the multiple aspects covered, the authors emphasise the importance of 'functional equivalence', that is to correct for buildings for their size when comparing them. This is a praiseworthy calculation approach but the report does not provide a quantified and systematic evaluation of the relationship between house size and life cycle energy demand.

Beyond the aspects covered above, several studies rely on large sample sizes of houses and households, collecting data for a broad range of variables including household size, floor area, age, gender and occupation of the occupants, level of education, income as well as energy demand. These studies then correlate the different variables to create regression models that identify those that are most significant. For example, Yohanis *et al.* [14] have evaluated the effect of household and house characteristics on the electricity use of dwellings in Northern Ireland. Within their sample building stock, they found that annual electricity use is strongly correlated with floor area and that every additional square metre of floor area results on average in 49 kWh (176.4 MJ) of additional electricity use, per annum. Paulsen and Sposto [38] also found a strong correlation between dwelling size and electricity use in social housing in Brazil. Another study by Guerra Santin *et al.* [12] evaluated the energy demand for space and hot water heating in Dutch dwellings by evaluating the effect of the occupants behaviours. Among the multiple variables considered is the floor area. Their study found that the useful floor area was again a good predictor of energy demand: larger houses use more energy in total. In another study that considered increased thermal performance and the construction of larger houses, Clune *et al.* [11] found that the additional heating and cooling demands required for the extra spaces offset a significant share of the energy and greenhouse gas emissions reductions achieved through increased thermal performance for houses in Australia. These findings reproduce at a larger scale those of Wilson and Boehland [13] who compared small thermally inefficient houses in the USA to large energy efficient houses. The USA-based study found that these smaller houses use the same amount of energy as their larger, yet more efficient counterparts and calls for reduced house sizes for better energy and resource efficiency. All these studies highlight the significance of floor area and its effect on operational energy but none considers embodied energy.

Nichols and Kockelman [39] have quantified the life cycle energy demand, including user-transport energy, for Austin, Texas, United States. They also rely on multiple datasets including socio-economic factors and built environment characteristics. Their findings reveal strong positive correlations between house size, and embodied energy, life cycle energy and operational energy, from strongest to weakest, respectively. However, their results are aggregated at the neighbourhood level and rely on average embodied energy intensities per square foot and on process data (see Section 3.3 for more information on process data) for the calculation of embodied energy. They do not therefore provide the resolution nor the accuracy needed to thoroughly evaluate the relationship between house size and life cycle energy demand.

Fuller and Treloar [15] and Fuller and Crawford [16] have quantified the embodied, operational and user-transport energy requirements for different dwelling types around Melbourne. These studies consider both embodied and operational energy and use comprehensive system boundaries to quantify both. While they assess different dwelling types with different sizes, they rely on a very small sample size of different house sizes that are built using different assemblies. Their studies do not therefore evaluate the relationship between house size and life cycle energy demand.

More recently, Takano *et al.* [40] have evaluated the life cycle energy demand of different Finnish residential building types, i.e. detached, semi-detached, terraced and apartment buildings, using different structural materials. Using hypothetical buildings, they show that apartment buildings have the lowest life cycle energy demand, regardless of the structural material. Of relevance to this study, they evaluate the effect of increasing the number of stories and enlarging the building on the life cycle energy demand. While their study provides valuable information on the relationship of different geometrical factors on the life cycle energy demand, its focus is different dwelling types and not on house size (or floor area). In addition, not all assemblies are included (e.g. systems and doors are not considered), the same flooring material is assumed for all spaces (no differentiation for bathrooms, etc.) and they rely on the *ecoinvent* database (process data, see Section 3.3 for more details) for the quantification of embodied energy.

In a recent study Khajehzadeh and Vale [41] have evaluated the life cycle energy demand of large and small housing in New Zealand. They relied on an online survey to gather data from 96 couples living with or without children. Based on information in the survey, notably the number of rooms, and figures from existing studies the authors derived the embodied energy demand and the life cycle energy demand over 25, 50, 75 and 100 years. They find that larger houses have a much higher embodied energy demand per unit of floor area. The general trends identified by Khajehzadeh and Vale [41] provide a precedent against which findings of this paper can be compared, more so because their study is located in New Zealand which shares many historical and cultural characteristics with Australia. However, their calculation of embodied energy relies on previously reported figures based on process-analysis and therefore underestimates embodied energy. For instance, they report an initial embodied energy intensity of 2.31 GJ/m^2 for a 200 m^2 timber-framed brick veneer house based on Vale and Vale [42]. This is much lower than the intensity reported by Fay *et al.* [25] who used a hybrid approach to calculate an initial embodied energy of 14.1 GJ/m^2 for a 128 m^2 house in Australia, using a similar construction technique. In addition, Khajehzadeh and Vale [41] have only considered five different house sizes to derive embodied and operational energy intensities. While general trends derived from these calculations are valid, absolute energy intensities and the contribution of embodied and operational energy can be unreliable. Existing studies on house size and life cycle energy demand tend to either rely on a small sample of house sizes or to significantly underestimate embodied energy. There is therefore a need to better understand this relationship in order to inform more comprehensive and effective building energy efficiency regulations.

3 Quantifying the effect of house size on the life cycle energy demand

This section describes the overall modelling approach used to address the aim of the study and the quantification algorithms used to estimate the bill of quantities and calculate life cycle embodied and operational energy use.

3.1 Overall modelling approach and case study building

In order to evaluate the relationship between house size and the life cycle energy demand, a large sample of houses and household sizes is needed. Collecting the necessary data in order to conduct a life cycle energy analysis on existing houses (e.g. bill of material quantities) can be a prohibitive and time consuming task. There is also a concern regarding consistent data quality across the surveyed houses. Using a computer model can streamline the process, ensure a systematic approach and help to isolate key variables.

This paper uses a case study house located in Melbourne, Australia. The case study is located in the Australian state of Victoria not only because it has the largest houses in Australia but also because Melbourne is the fastest growing city in Australia in terms of population, with an estimated population of 10 million by 2051. It is therefore expected to substantially increase its housing stock in the coming decades [43]. Understanding the relationship between house size and the life cycle energy demand is therefore particularly critical in this context.

Typical construction assemblies for the location are used to ensure the broadest possible representativeness. The characteristics of the case study house are presented in Table 1. These comprise a brick veneer wall, which has been the most dominant for of construction for houses in Melbourne for the last four decades [44] and a floor to ceiling height of 2.4 m which is the minimum height for residential buildings in Australia [45] and the one adopted by developers for the majority of houses. In addition, a 30% window to wall ratio is used for all variations based on the window to wall ratio (27.7%) of the representative Housing Industry Association (HIA) house. Indeed, that house was developed by the HIA as a representative sample of new Australian houses for costing purposes. The insulation thicknesses are based on achieving the minimum 6-Star energy efficiency rating as per Section J of the current Building Code of Australia [45]. The efficiencies of operational energy sources are sourced from [46] and are based on the most representative technology in Victoria, Australia.

Table 1: Characteristics of the studied house and its simulated size variations.

Characteristic	Value(s)
Width (m)	*10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, 14*
Depth (m)	*10, 12, 14, 16, 18, 20, 22, 24, 26, 28*
Household size (number of occupants)	*2, 3, 4, 5*
Floor to ceiling height (m)	2.4
Location	Melbourne, Victoria, Australia
Period of analysis (years)	50
Structure type	Timber-framed; Reinforced concrete slab on ground.
Façade	Brick veneer wall; 90 mm of fibreglass insulation; Double glazed aluminium-framed windows (30% window to wall ratio)
Roof	Concrete tiles; 160 mm of fibreglass insulation
Flooring	Carpet in bedrooms and living rooms; ceramic tiles in wet areas
Internal walls	10 mm painted plasterboard
Average *U*-value of the building ($W/(m^2 \cdot K)$)	~0.58
Ventilation rate during 5 hours/day (ach^{-1})	3
Operational energy sources	Ducted gas heating (eff.: 70%) and gas cooking (eff.: 90%), Electrical cooling (COP: 2.5)

Note: characteristics in *italic* are varied, eff = efficiency, COP = coefficient of performance.

The house is modelled using the advanced software tool developed by Stephan [47] and described in Stephan and Crawford [48]. The tool is capable of automatically modifying the dimensions of the house (width and depth), estimating the bill of quantities of each house size, varying the number of occupants and quantifying its initial and recurrent embodied energy as well as operational energy over any period of analysis. Outputs of the tool have been validated in Stephan [47] by comparing them to: TRNSYS simulation results for thermal energy use, average energy use figures for non-thermal energy outputs, detailed material take-offs from existing buildings for bills of material quantities and embodied energy figures per assembly, per assembly category and per building from exiting studies relying on hybrid analysis for embodied energy. While the tool is also able to model multi-storey houses and apartment buildings as well as calculate life cycle water and greenhouse gas emissions, these aspects were considered to be outside the scope of this study. More details about the equations used in the tool are provided in Sections 3.2, 3.3, 3.4 and 3.5.

The tool starts with a 10 × 10 m house and incrementally increases its width and depth until the maximum dimensions of 14 × 28 m. For each house size, four different occupancy levels are evaluated (two, three, four and five occupants) and the associated life cycle energy demand is calculated. The total number of variations includes nine widths, ten depths and four household sizes (360 variations). These variations are based on typical dimensions of houses built by major developers in Australia. The household sizes are representative of the most common households living in detached houses according to the latest Australian Census [24]. Lone person households were not considered as these typically reside in apartment units based on the same census data.

Similar floor areas that result from different combinations of width and depth (e.g. 10 × 14 m and 14 × 10 m) have both been evaluated because they result in different material quantities and therefore embodied energy. Apart from the geometrical dimensions of the house and the number of occupants, all other variables in the model are kept constant. These include thermal performance, building systems, building materials and embodied energy coefficients. This allows a consistent and rigorous comparability of results and isolates the studied variables. A summary of the method is presented in Figure 1.

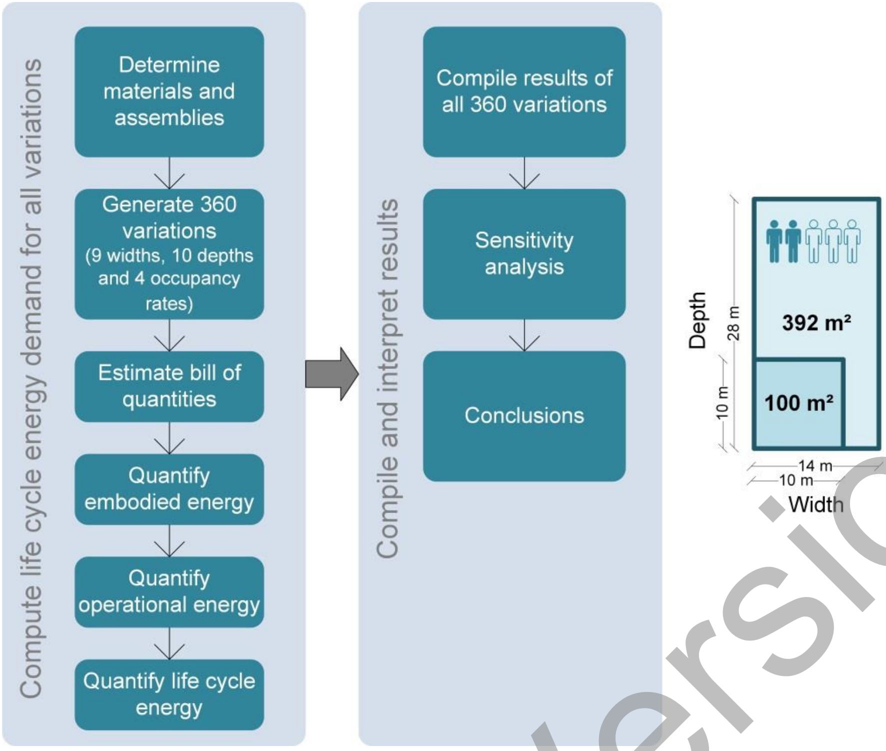

Figure 1: Flowchart diagram of the method

3.2 Estimating the bill of material quantities

The bill of material quantities is central to the calculation of embodied energy requirements. It is therefore imperative to reliably estimate the quantities of assemblies and constituent materials for each house size. This is done by using the algorithms developed by Stephan [47]. These have been verified and validated using a typical Australian suburban detached house that is very similar to the houses modelled in this study. This approach combines a so-called ‘archetypal’ approach that relies on typical construction assemblies and their compositions, a numerical approach which generates the geometry of the different house sizes and associated quantities and real figures from actual buildings to verify that generated quantities are valid. The main equations used to derive the gross floor area, the area of outer walls, the area of the windows, the area of the roof, the heat transfer area, the area of inner walls and the pipe and wire length are given below. The calculation of other quantities is explained afterwards.

$$GFA = w \times d \times NS \quad (1)$$

$$A_{ow} = \left(1 - \alpha_{w \to f}\right) \times \left[2 \times \left(w + d\right)\right] \times h \times NS + \frac{\tan(RS) \times w^2}{2} \quad (2)$$

$$A_w = \alpha_{w \to f} \times \left[2 \times \left(w + d\right)\right] \times h \times NS \quad (3)$$

$$A_r = 2 \times \frac{w}{\cos(RS)} \times d \quad (4)$$

$$A_{ht} = A_{ow} + A_w + A_r \quad (5)$$

$$A_{iw} = \left(3 \times w + 2 \times d\right) \times h \times NS \quad (6)$$

$$L_{p,w} = GFA \times \alpha_{GFA \to UFA} \times L_{p,w \to UFA} \quad (7)$$

Where (final results are indicated in bold):

GFA = Gross floor area of the building in m²;

w = Width of the house in m;

d = Depth of the house in m;

NS = Number of storeys of the house (=1 storey in this case);

$\boldsymbol{A_{ow}}$ = Area of outer walls in m² (excluding windows and including gables);

$\alpha_{w \to f}$ = Windows to façade ratio (=0.3 based on an average figure for new detached houses);

NF = Number of façades of the house, i.e. 2, 3 or 4 (=4);

h = Floor to ceiling height in m (=2.4m);

RS = Slope of the roof along the depth, in degrees (=17°);

$\boldsymbol{A_w}$ = Window area in m²;

$\boldsymbol{A_r}$ = Roof area in m²;

$\boldsymbol{A_{ht}}$ = Heat transfer area in m² (heat transfer through the ground is not considered);

$\boldsymbol{A_{iw}}$ = Internal walls' area in m²;

$\boldsymbol{L_{p,w}}$ = Length of pipes or wires in m;

$\alpha_{GFA \to UFA}$ = Coefficient transforming GFA to UFA (0.9 based on [49]);

UFA = Usable floor area of the house in m²; and

$L_{p,w \to UFA}$ = Length of pipes or wires per unit of UFA in m/m² (=0.55 and 0.6 m/m² based on figures from [50]).

The number of doors and heating and cooling delivery units is based on the average number of rooms in the house which is obtained by dividing the usable floor area by the average room size (in this case 15 m²). The amount of steel and concrete in the concrete footings is calculated based on an average slab thickness of 30 cm and a reinforcement rate of 100 kg of steel/m³ of concrete.

These equations result in quantities that deviate at most by ±10% from the actual bill of quantities for a typical Australian detached house, as demonstrated in Stephan [47]. The only exception is the number of doors which depends heavily on the spatial layout of the house and its open plan nature. In addition to the validation conducted in Stephan [47], ten random houses with varying floor areas were selected from the website of one of Australia's major developers. For each of these houses, the area of outer and inner walls were derived from floor plans and compared to those produced by the software for a house of the same floor area. The estimated quantities were within ±5% of the actual areas, further validating the estimation. However, estimating material quantities with an algorithm might produce figures that diverge from actual quantities in real buildings, as discussed in Section 5.3.

The quantity of materials is obtained by multiplying the quantity of each assembly by the quantity of materials per functional unit of that assembly. For example, the first house variation (10 m × 10 m) contains 150 m² of internal walls. Each 1 m² of internal walls contains the required ties, bolts, studs, proportion of bottom and top plate, noggins, bracing, plasterboard and water-based paint. The total quantity for each material is equal to 150 × the quantity of this material per m² of internal wall. In addition, defining whole assemblies in the software allows a detailed representation of the construction technology used and does not discard minor elements and materials as is often the case in building-related life cycle assessment studies. The bill of material quantities the first house variation (10 m × 10 m) is provided in Appendix A as an example. The next section describes how material quantities are converted to embodied energy figures.

3.3 Quantifying embodied energy

Embodied energy represents the sum of all energy inputs for the production of building materials across their supply chains, as well as energy for non-material inputs, such as services supporting material production. Embodied energy can be broken down into two components: initial and recurrent embodied energy. The first represents the total embodied energy of the house as-built, prior to its occupation. The second takes into account the embodied energy associated with the replacement of building materials across the life of the house (50 years in this study).

To date, the most comprehensive technique for quantifying embodied energy is hybrid analysis, combining industrial process data (based on the energy intensity of manufacturing processes) and economic input-output data at the sectorial level (e.g. the average energy intensity of the steel industry in GJ/currency unit). The input-output-based hybrid analysis developed by Treloar [51] and validated by Crawford [52] combines these two datasets in the most sophisticated manner, by avoiding double counting, based on a comprehensive system boundary and using the most reliable data where possible. Studies [24, 53-55] have shown that relying on hybrid analysis can produce embodied energy intensities that are two to four times higher compared to using process data alone, which is the most common, e.g. [39, 40].

This paper relies on the comprehensive input-output-based hybrid analysis to quantify embodied energy. The quantities of materials in each house size variation (see Section 3.2) are multiplied by embodied energy coefficients compiled by Treloar and Crawford [56]. An additional amount of energy is then added to the total to account for the energy associated with non-material inputs, such as insurance and advertising. Materials are replaced according to average service life values which are based on Ding [57] and NAHB and Bank of America [58]. The recurrent embodied energy associated with each material replacement is calculated by multiplying the quantity of materials replaced by the respective material embodied energy coefficient and adding the energy associated with the non-material inputs for the particular material. The life cycle embodied energy for each house size is quantified as per Equation 8.

$$\begin{aligned} LCEE_h = {} & \sum_{m=1}^{M}\left(Q_{m,h} \times EC_m\right) + \left(TERRBS - \sum_{m=1}^{M} TER_m\right) \times C_h \\ & + \sum_{m=1}^{M}\left[\left[\frac{POA}{SL_m} - 1\right] \times \left[\left(Q_{m,h} \times EC_m\right) + \left(TERRBS - TER_m - NATER_m\right) \times C_{m,h}\right]\right] \end{aligned} \tag{8}$$

Where: $LCEE_h$ is the life cycle embodied energy of the house in GJ; M is the total number of materials in the building; $Q_{m,h}$ is the quantity of material *m* in the house *h* (e.g. tons of steel); EC_m is the hybrid energy coefficient of material *m* in GJ per functional unit; *TERRBS* is the total energy requirement of the residential building sector, in GJ/AUD; TER_m is the total energy requirement of the input-output pathway representing material *m*, in GJ/AUD; and C_h is the cost of the house *h* in AUD; *POA* is the period of analysis, in years; SL_m is the service life of the material *m,* in years; $NATER_m$ is the total energy requirement of all input-output pathways not associated with the installation or production process of material *m* being replaced, in GJ/AUD, e.g. pathways representing concrete production when replacing aluminium frames; and $C_{m,h}$ is the cost of the material *m* in AUD in the house *h*.

3.4 Quantifying operational energy

The energy used by occupants to maintain indoor thermal comfort, for lighting, cooking, hot water and appliances is known as a building's operational energy. In this study, thermal energy is quantified using the heat transfer coefficient of envelope elements, ventilation rates and heating/cooling degree hours. The model described in Stephan [47] uses steady-state thermodynamic equations and relies on indoor comfort temperatures of 20°C and 26°C for heating and cooling, respectively. The degree hours calculated for Melbourne's climate (21 919 K·h for heating and 2 170 K·h for cooling) take into account solar and free internal gains by adapting the balance temperature. While using dynamic thermal modelling through a third party software tool (e.g. EnergyPlus), that takes into account thermal mass among other aspects, could generate more accurate results, the steady-state approach is sufficient within the scope of this paper and "[…] *is generally known to reliably predict heating loads* […]" [59] which is what is needed in the heating-dominated climate of Melbourne . Indeed, since this study aims to understand the relationship between house size and life cycle energy use, the consistency of the quantification approach for all variations is the most important aspect (rather than the accuracy of the energy demand estimation). In addition, using advanced simulation software does not systematically result in a more accurate quantification of thermal energy use, as demonstrated by a number of studies, such as Williamson *et al.* [60].

Energy for cooking and appliances is modelled using average intensities that are derived from DEWHA [46]. The hot water energy demand is based on a daily hot water use of 70 L/capita and an average annual temperature difference between mains water and final hot water of 47°C. This produces results that are consistent with the averages reported in [46] for Victoria, Australia. Energy for lighting is calculated based on the floor area of the house while energy for hot water, appliances and cooking are calculated based on the number of occupants. This is in line with the findings of Cuéllar-Franca and

Azapagic [61] that show that heating and lighting depend mainly on the house characteristics while energy use for hot water and appliances is related to the number of occupants.

The annual operational energy demand is assumed to be constant over the 50 year period of analysis. The life cycle operational energy demand is calculated as per Equation 9, by converting each energy use to primary energy terms, by considering the efficiency of the system and the energy source, summing all operational energy demands and multiplying the total by the period of analysis. Primary energy conversion factors of 3.4 for electricity and 1.4 for gas are used and are based on Treloar [62].

$$LCOPE_h = POA \times \sum_{e=1}^{E} \frac{OPE_{e,h}}{\eta_{e,h}} \times PEF_{e,h} \qquad (9)$$

Where: $LCOPE_h$ = Life cycle primary operational energy of the house h in GJ; POA = Period of analysis in years; $OPE_{e,h}$ = Annual final operational energy demand of the end-use e in GJ; $\eta_{e,h}$ = Average efficiency of the system used for end-use e; and $PEF_{e,h}$ = Primary energy conversion factor of the end-use e based on the energy source in $GJ_{primary}/GJ_{delivered}$.

3.5 Quantifying life cycle energy

The life cycle energy demand of each house variation (LCE_h) is the sum of its life cycle embodied energy ($LCEE_h$) and its life cycle operational energy ($LCOPE_h$) over the period of analysis (50 years).

4 Results

This section presents the results of the study. The relationship between house size and life cycle energy demand is first described before assessing the significance of the functional unit and embodied energy. Finally, a sensitivity analysis of the results to uncertainty in the data used is conducted.

4.1 The effect of house size on their life cycle energy demand

Figure 2 depicts the life cycle energy demand of each end-use (embodied and operational), for each house size variation. Only heating, cooling and lighting operational energy demands are represented as energy use for hot water, appliances and cooking are assumed to be solely determined by the number of occupants. The noise in the graph is due to the different material quantities for houses with different proportions but similar gross floor area. The 'Other' category includes all non-material embodied energy inputs, the so-called 'remainder' in input-output-based analysis (see Crawford [24] for more details). Note that the total increase in floor area is indicated in brackets at the end of the abscissa axis.

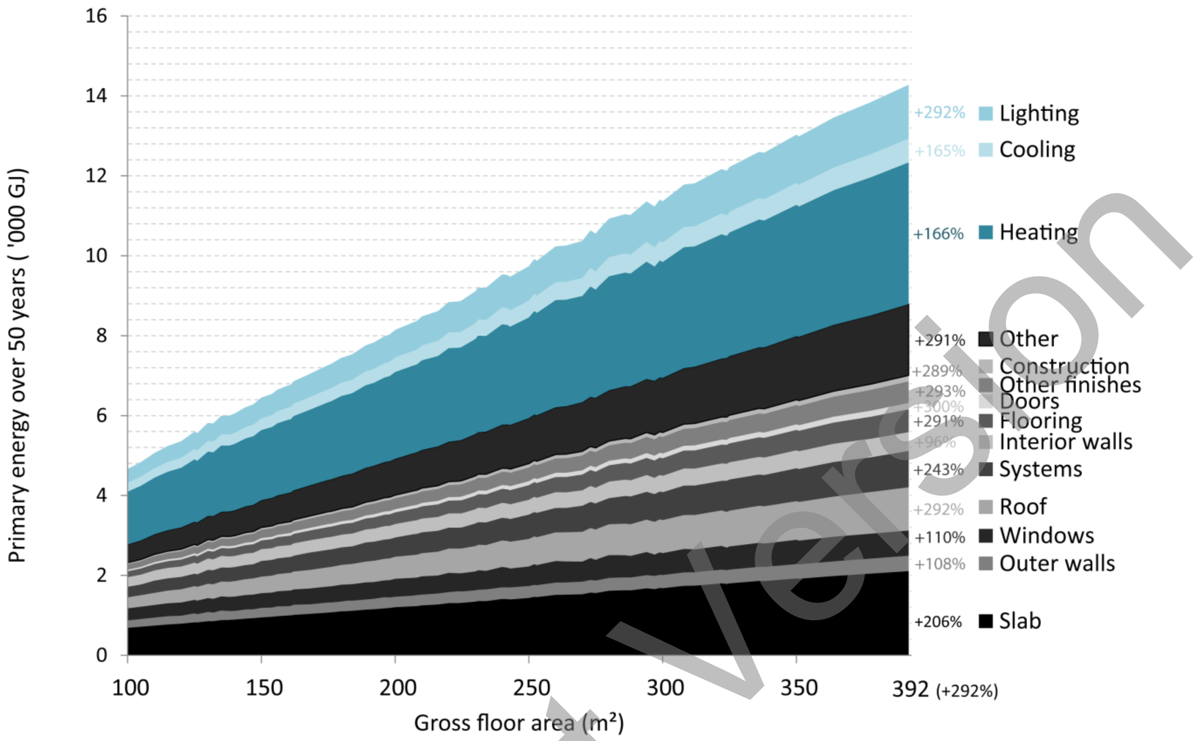

Figure 2: Effect of size on the life cycle primary energy demand of the house over 50 years, by use.

The life cycle energy demand of the largest variation (392 m²) is 14 440 GJ, compared to 4 702 GJ for the 100 m² variation. The increase in life cycle energy demand is therefore +207% compared to +292% in floor area. This shows that life cycle energy demand tends to be sublinearly correlated with house size. This implies that using a per square metre functional unit produces flawed results, as discussed in depth below. The life cycle embodied energy increases by 218% (in a similar manner for both initial and recurrent embodied energy) and thermal and lighting operational energy by 185% for an increase of 292% in floor area. This reveals that embodied energy becomes more significant as houses increase in size in comparison to operational energy.

However, the increase in embodied energy is different for each assembly type. As a general trend, the embodied energy of horizontal assemblies seems to be almost linearly correlated with house size, e.g. flooring (+293%) and roof (+292%). In contrast, the embodied energy of vertical assemblies, e.g. outer walls, interior walls and windows increases by ~110%. This is due to the fact that the material intensity for different house sizes is not the same and larger houses require less vertical assemblies as room areas become larger, as shown in. Mithraratne *et al.* [63]. In other words, horizontal assemblies contribute more than vertical assemblies to the life cycle energy demand of larger houses compared to smaller houses using the exact same assemblies. The choice of horizontal assemblies, their constituting materials and the detail of their construction becomes more critical for larger houses. Building designers need to take this into account in order to help reduce embodied energy for a fixed house size. Note that the 'other finishes', 'construction' and 'other' embodied energy categories are calculated on a per square metre basis and are therefore linearly correlated with floor area.

The heating and cooling demands increase by 166% and 165% for an increase in house size from 100 to 392 m², respectively. This is because the heat transfer area is not a direct function of the floor area but also depends on the compactness of the building or its external surface area to volume ratio (as can be deduced from Equations 2-5). This means that heating and cooling increase at around 57% the rate of the floor area of the case study house. Australian building energy efficiency regulations take this into account with the use of a so-called 'area adjustment factor' of ~40% between a 100 and a 400 m² house [64]. Even, this factor seems to be slightly underestimating the effect of size. However, regulations or certifications that do not correct for house size could be systemically favouring larger houses by artificially making them achieve a better operational energy performance because they have a lower heating and cooling demand per square metre. This is of concern as a significant number of large detached houses are being built in many parts of the world, including Europe, and certified as Passive Houses or low-energy houses. For example, out of 149 detached passive houses in French Speaking Belgium (including Brussels and Wallonia), 68 (46%) have a floor area larger than 200 m² and detached houses represent 34% of all certified passive house buildings, including apartment buildings, schools and others [65]. It is easier for larger houses to get certified while also requiring more energy for heating, cooling and lighting than smaller houses built with the same assemblies. Also, these larger houses require a significant amount of additional embodied energy, notably for the additional insulation, as shown in Dahlstrøm *et al.* [66] and Stephan *et al.* [27]. Including house size as a factor in all energy efficiency regulations is therefore critical to ensure that net energy reductions do occur.

This section has assessed the relationship between house size and life cycle energy demand in detail. The next section focuses on the significance of the functional unit used when comparing houses of different sizes.

4.2 The importance of the functional unit

Figures 3 and 4 show the effect of house size on total life cycle energy demand (including all operational energy end-uses) per square metre and per capita, respectively. The values of life cycle energy demand of the smallest and largest houses are indicated, as well as the percentage increase/decrease. Three main observations can be made.

Firstly, while the energy intensity per capita increases with house size at the same rate as the absolute energy demand, it decreases when expressed on a per square metre basis. This trend is aligned with the findings of Khajehzadeh and Vale [41] who also show that larger houses are less energy intensive on a per m^2 basis. As noted by Heinonen and Junnila [67] "[using a spatial functional unit] *omits users entirely, and while it has significant value in many other applications, it may lead to biased estimations of the actual energy consumption in a certain building due to varying occupancy rates and user behaviour".* Using a spatial functional unit also fails to consider the size of the house and tends to favour larger houses (See Section 4.1 for more details).

Secondly, because house size increases faster than energy demand, relying on a spatial functional unit blurs the difference between the different houses. For instance, the difference between the life cycle energy demand of a 100 m^2 house with two or five occupants is 43% (107 GJ/m^2 compared to 75 GJ/m^2) while the difference between two houses of 392 m^2 with the same number of occupants is only 17% (52 GJ/m^2 compared to 44 GJ/m^2). For increasing house sizes, using a spatial functional unit without any correction does not seem to be reliable.

Thirdly, Figure 4 reveals the importance of lifestyle. For example, it shows the significant difference in life cycle energy demand per capita between a household of two people in a 100 m^2 house (2 140 GJ/capita) or a 392 m^2 house (8 570 GJ/capita; +300%). This trend is aligned with the results of Khajehzadeh and Vale [41] who found that a household living in a house with 6 additional rooms, required 170% more energy over 50 years. Another lifestyle comparison shows that two occupants living in a 160 m^2 house (point A) use a similar amount of energy (~5 100 GJ) over 50 years as three occupants living in a 260 m^2 house (point B) or four occupants living in a 392 m^2 house (point C) and confirms the observations of Wright [68]. Expressing results on a per capita basis relates energy use back to the occupants and enables a comparison of different lifestyles by capturing the floor area per capita. Figure 4 also enables the comparison of energy use for the same floor area per capita. For instance, two occupants living in a 100 m² house (50 m²/capita) require 4 009 GJ/capita while four occupants living in a 200 m² house (50 m²/capita) require 3 495 GJ/capita, revealing the increased efficiency of larger houses with a large number of occupants. Yet, since household size has been decreasing, large houses with large households are becoming less and less common.

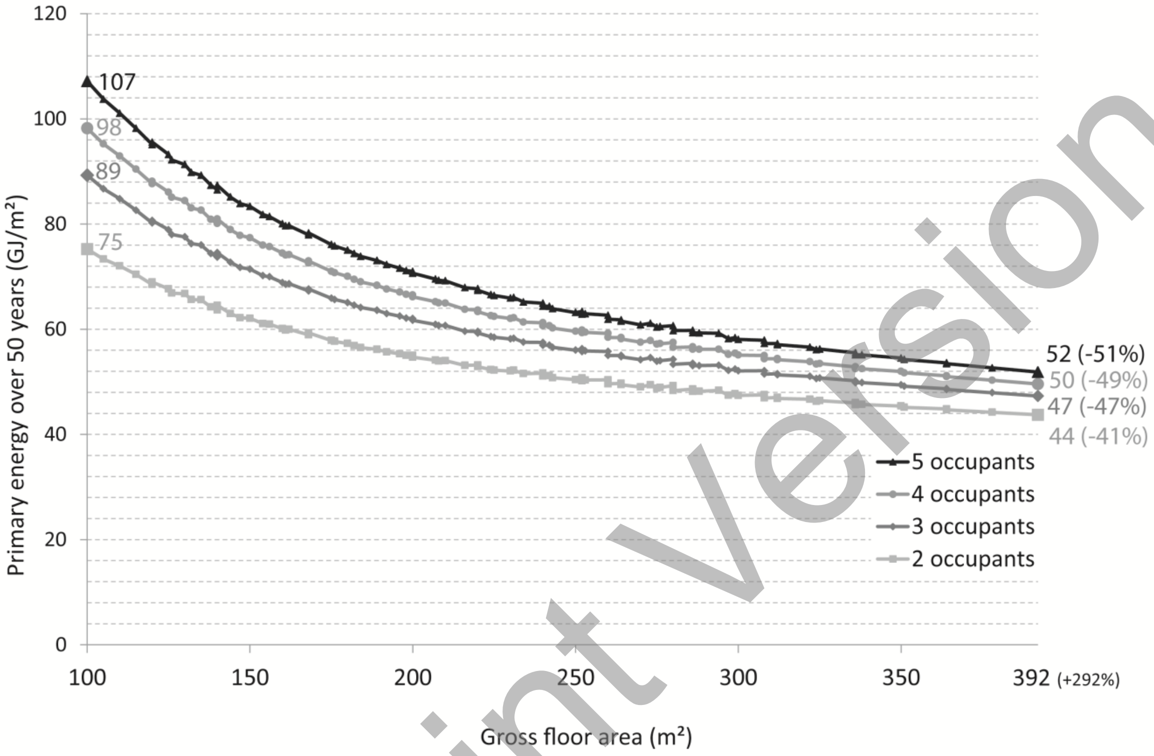

Figure 3: Effect of size and occupancy on the life cycle primary energy demand of the house over 50 years, per square metre.

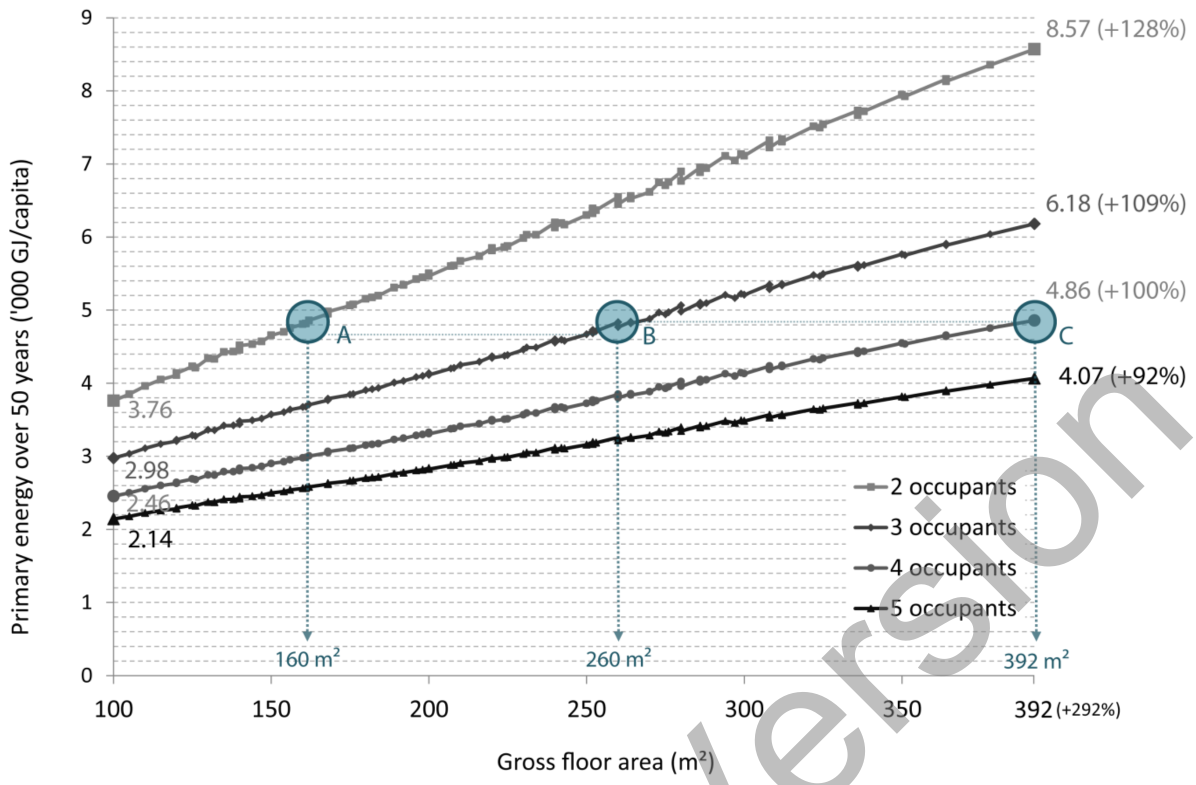

Figure 4: Effect of size and occupancy on the life cycle energy demand of the house over 50 years, per capita.

4.3 The significance of embodied energy

Figure 5 shows the contribution of initial and recurrent embodied energy as well as life cycle operational energy to the total life cycle energy demand of the house, for different house sizes and number of occupants. Overall, embodied energy represents 26-50% of the total life cycle energy demand. Note that for the 200 m² house with two occupants, which is very close to the average floor area per capita in Australia (100m²/capita ≈ 94 m²/capita, see Section 1), embodied energy represents 44% of the total. This is much higher than the average 10-20% reported in major reviews of life cycle energy demand in buildings and is due to the much wider system boundaries used in the quantification of embodied energy in this study.

A very important aspect to consider is the temporal significance of each energy demand. While recurrent embodied energy and operational energy use take place over 50 years in this study, the initial embodied energy demand occurs once. The environmental consequences of ongoing energy demands can be significantly reduced by relying on renewable energy sources and low embodied energy renewable materials. In parallel, the actual number of occupants in a house can fluctuate greatly over a building's life and the potential variability in operational energy demand is therefore significant. Conversely, the greenhouse gas emissions associated with initial embodied energy cannot be reduced once the house has been constructed. These have been highlighted by previous studies such as Säynäjoki *et al.* [69] who have dubbed them the 'carbon spike' in a building's life cycle. The environmental consequences of these emissions are also likely to be more significant presently than in the future, as demonstrated by Kendall *et al.* [70] and Schwietzke *et al.* [71]. With initial embodied energy representing a growing share of total life cycle energy demand as house size increases (up to 32%) and resulting in large quantities of greenhouse gas emissions, it is critical to ensure that the size of the house is optimised and building materials are chosen to reduce initial embodied energy as much as possible.

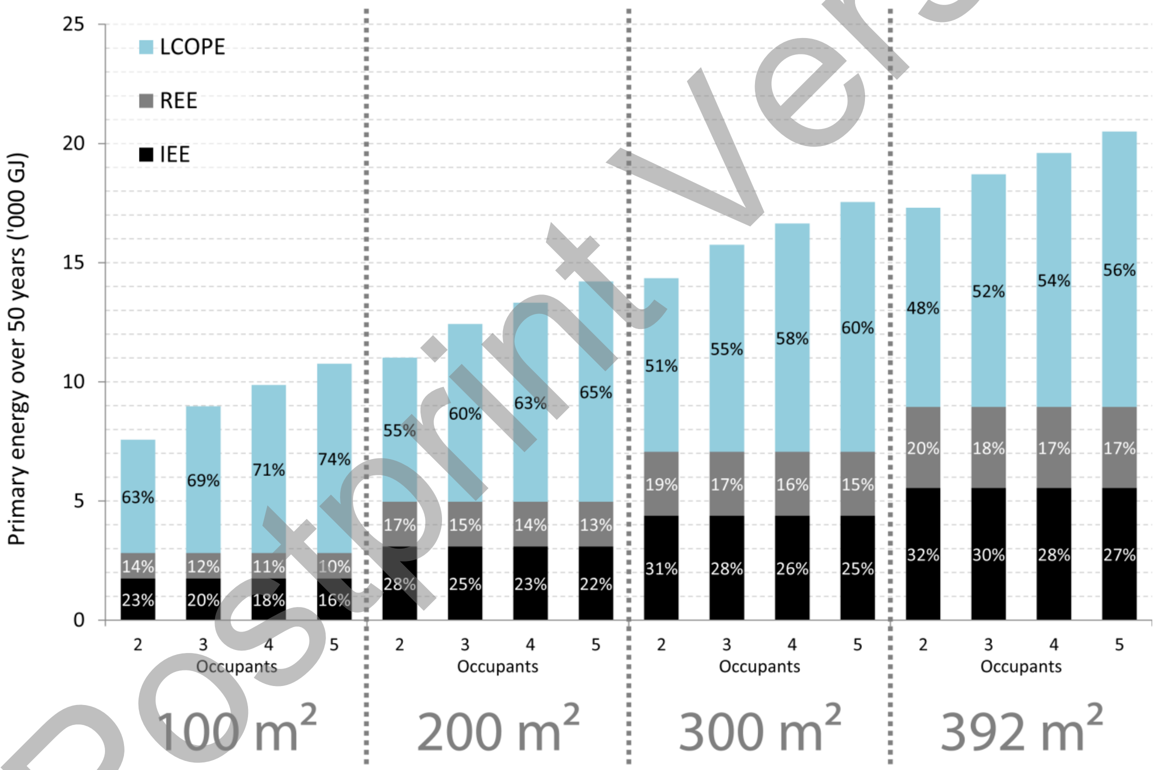

Figure 5: The contribution of embodied and operational energy to the life cycle primary energy demand of the house over 50 years, for selected house sizes and occupancy profiles. Note: IEE = initial embodied energy, REE = recurrent embodied energy and LCOPE = life cycle operational energy. Percentages may not sum due to rounding.

4.4 Sensitivity analysis

The comparative nature of this study makes it less prone to being influenced by uncertainty in the data as all variations are equally affected. The sensitivity analysis is therefore necessary only when absolute energy demands are being compared, such as the contribution of embodied energy and operational energy to the life cycle energy demand of each variation.

In order to evaluate to what extent uncertainty in the data affects the breakdown of the life cycle energy demand, a sensitivity analysis is performed by varying embodied and operational energy by a set potential error margin. The uncertainty for embodied energy is calculated using a margin of ±20% for process data and ±50% for input-output data as per Crawford [24]. This uncertainty is propagated throughout the model from the material embodied energy coefficients calculations. The overall resulting uncertainty margin for embodied energy is ±39.5%. For operational energy use, user behaviour as well as the assumption that the entire space is heated and cooled, regardless of the occupancy level, result in an uncertainty range of ±20%. This is based on previous studies on uncertainty and variability of operational energy use (e.g. [72, 73]).

Figure 6 shows the contribution of each of the life cycle embodied energy demand (dark) and the life cycle operational energy demand (light) to the total, for each house size, and for each combination of minimum and maximum uncertainty value. Note that the maximum operational energy figures are taken for a household size of five occupants. The sensitivity analysis shows that uncertainty in the data can significantly affect the contributions of each of the embodied and operational energy use. The life cycle embodied and operational energy demands can represent 15-65% and 35-85% of the total, respectively. These values should be seen as extreme boundaries with a relatively small likelihood of occurrence. The average values depicted in Figure 5 are representative of most cases. Regardless of uncertainty in the data, it should be noted that embodied energy, which is often thought to represent 10-20% of the life cycle energy demand over 50 years, represents at least 15% (in a 100 m^2 house with 5 occupants and considering the highest possible operational energy demand and the lowest possible embodied energy demand) and up to 65% of the demand. The high level of uncertainty when it comes to the contribution of each life cycle energy demand to the total is further discussed in Section 5.

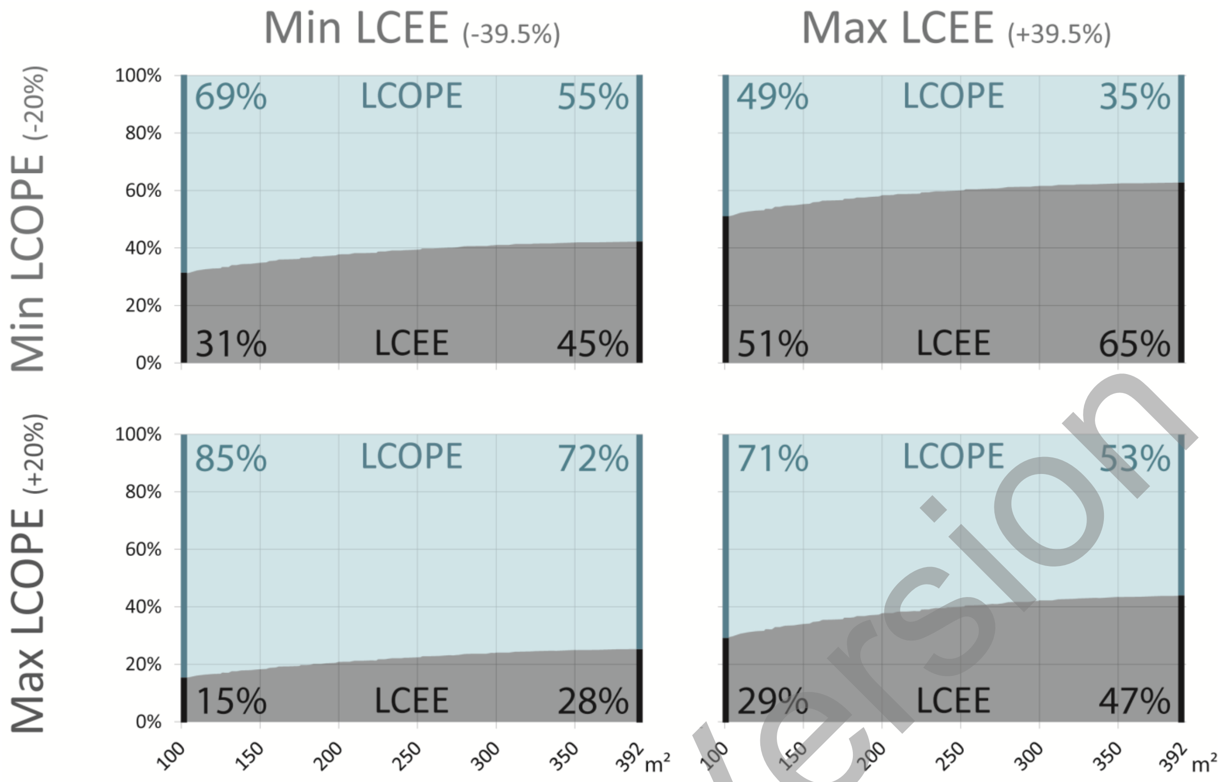

Figure 6: Sensitivity of the contribution of life cycle embodied and operational primary energy use to uncertainty in the data, by house size. Note: min = minimum, max = maximum, LCEE = life cycle embodied energy and LCOPE = life cycle operational energy.

5 Discussion

This paper has evaluated the relationship between house size and life cycle energy demand while using a systematic approach, comprehensive system boundaries for embodied energy and calculating primary operational energy use (thermal and non-thermal) over 50 years. Most previous studies on house size and energy use either focus on operational energy or do not consider a large sample of different house sizes (see Section 2 for details). Results show that larger house sizes tend to result in a higher overall life cycle energy demand through the increase of both operational and embodied energy (as in previous studies such as Wright [68], Calwell [22] or Nichols and Kockelman [39]) and that operational and embodied energy are sublinearly correlated with house size. The use of a spatial functional unit (e.g. MJ/m²) to express energy efficiency therefore favours larger houses, even for embodied energy. The latter was found to be significant and represents 26-50% of the total across all 360 variations. These results can inform future building energy efficiency regulations in Australia and in other parts of the world.

5.1 Recommendations for energy efficiency regulations for buildings

Including house size

Most existing building energy efficiency regulations do not take house size or floor area into account. This study has shown that house size is a critical factor affecting both embodied and operational life cycle energy use using a case study in Melbourne, Australia. Different life cycle energy efficiency levels can therefore be used for different house sizes with stricter limits for larger houses in order to favour more compact dwelling forms that use less materials. Also different limits can be used for particular assembly types depending on the house size as horizontal assemblies become more significant than vertical assemblies for an increasing floor area (see Figure 2 and [63]). These limits should however take into account the number of occupants the house is designed for. As shown in Figure 4, for the same floor area per capita, larger houses are more energy efficient. While, the floor area per capita could therefore be used as an indicator that can help inform financial incentives/disincentives for smaller/larger houses, it is very hard to measure this aspect at design. Indeed, the same house can be used in many different ways and by different households. One approach used in the UK relies on the number of bedrooms in a house in comparison to the household size to provide the latter with a subsidy for social housing [74]. However, using the number of bedrooms as a proxy for the number of occupants is not reliable to derive house size energy efficiency indicators as bedrooms can be converted to other uses and the size of the same household varies over time. More research is needed to help produce optimal forms of housing that are best tailored to the number of occupants that use them.

Including embodied energy

This study has shown that embodied energy can represent 26-52% of the life cycle energy use in an Australian context. This only confirms the findings of a number of previous studies (inter alia [8, 9, 75]) that show that embodied energy cannot be excluded from building energy efficiency regulations if these are to be most effective. With the increased operational energy efficiency of dwellings, embodied energy is set to become even more significant [27, 66].

Embodied energy should be calculated with the most comprehensive method available: currently input-output-based hybrid analysis. There is therefore a critical need to develop reliable, location-specific and open-access databases that allow practitioners to robustly conduct a life cycle energy analysis of a building. The current use of process data for most building life cycle assessments can significantly underestimate embodied energy [76], by up to 87% at the product level [52], and up to 77% at the whole building level [24, 53, 54]. Ideally, multi-regional input-output-based hybrid data should be compiled and made available more broadly on online platforms such as the Industrial Ecology Virtual Laboratory (IELab) in Australia [77].

Relying on different functional units

One of the major flaws of current building energy efficiency regulations around the world is their reliance on a single unit to measure efficiency: kWh/m² or MJ/m². However, this study has shown that both embodied and operational energy intensities cannot simply be used between different houses or buildings.

Different functional units are therefore needed to measure energy efficiency. As Calwell [22] indicated, having an absolute energy use indicator is the best way to measure the total associated environmental damage. This can be adjusted based on the size of the house and the number of occupants it is intended for. A spatial functional unit can also be used if it is corrected for size. The correction factors should be based on a broad analysis of existing buildings and their overall energy performance. Based on the findings of this study, correction factors for embodied energy should be based on both house size and material composition. A significant amount of work is needed in this area to produce reliable coefficients according to the dwelling type, size and material composition. Finally, a per capita functional unit would be ideal for post-occupancy monitoring. While post-occupancy monitoring can be too expensive to deploy for nationwide building energy efficiency regulation schemes, these can and should be an integral part of facultative certifications such as the PassivHaus certification. This would help determine whether occupants living in certified buildings actually use more energy than others living in standard buildings.

5.2 Beyond energy use

While this study has focused on energy use because it is often representative of broader environmental effects, there are a number of other flows that should be taken into account to ensure a broad assessment of the influence of house size on environmental performance. These include water, greenhouse gas emissions and material use. Since the software tool developed by Stephan [47] already generates these results, an indication of these broader environmental effects are provided below. For more information on the calculation of life cycle water use and greenhouse gas emissions, refer to Stephan and Crawford [78] and Stephan and Crawford [48], respectively.

Life cycle embodied water and greenhouse gas emissions are also sublinearly correlated with house size. They increase by 216% (from 5 881 kL to 18 584 kL) and 217% (from 166 096 kgCO_2-e to 526 601 kgCO_2-e) for a 292% increase in gross floor area, respectively. Since operational water is calculated on a per capita basis in the model, it is related strictly to household size and not to house size. It is also important to note that embodied water and greenhouse gas emissions represent 30-77% and 21-45% of the total. Operational greenhouse gas emissions associated with heating, cooling and lighting, increase by 198% (from 153 107 kgCO_2-e to 446 899 kgCO_2-e) for a 292% increase in gross floor area. The increase in quantities of aluminium, glass, timber and steel is 111% (from 361 kg to 762 kg), 141% (from 1 428 kg to 3 437 kg), 118% (from 73 071 kg to 159 293 kg) and 188% (from 4 854 kg to 13 965 kg), respectively. This preliminary analysis shows that for these other indicators, the findings of this study hold true: using a spatial functional unit favours larger houses and embodied resource and emissions requirements are significant.

5.3 Limitations and future research

As in any scientific study, a number of limitations can affect the results. Firstly, using a computer model to estimate bills of material quantities and calculate embodied and operational energy use can result in a significant level of uncertainty. This uncertainty could be further exacerbated by the assumption that house size does not significantly affect its design. Collecting actual bills of material quantities and post-occupancy operational energy figures would significantly improve the robustness of the results. This however would require a considerable amount of resources. Secondly, this research uses a case study house located in Melbourne, Australia and results are valid only for the studied house. While modifying the window to wall ratio to 20% or 60% only changes the life cycle energy demand by -3% and by +0.4%, respectively, other house types and building assemblies might affect the findings more significantly. Thirdly, this study has assumed that the height of the house remains constant across different sizes. However, Wilson and Boehland [13] state that larger houses tend to have a higher floor to ceiling height which entails more material and thermal energy use. Increasing the floor to ceiling height of the house from 2.4 m to 2.7 m for the 392 m² house increases its life cycle embodied energy by 3.3% and its life cycle operational energy by 3.4%. These same quantities still increase by 214%

(compared to 218% for 2.4 m of floor to ceiling height) and 188% (compared to 185% for 2.4 m of floor to ceiling height) for a 292% increase in house size, respectively. Therefore, the floor to ceiling height of the house seems to affect the findings only slightly, conversely to what is found in [13]. Fourthly, this study assumes that the energy demand associated with electrical appliances is proportional to the number of occupants. However, some studies (e.g. [14]) have shown that larger houses are also correlated with a higher electrical energy use, possibly for the same number of occupants. To test the influence of this assumption on the results, a power intensity of 5 W/m² (based on the maximum appliances heat losses for a living space throughout the day from [79]), operated year-round, is considered for each square metre above a floor area of 229 m². This is because the average appliances energy demand per capita used in this work is derived for a 229 m² floor area in [46]. Based on this assumption each additional 15 m² (equivalent to an average room size in this study) results in an extra 150 GJ of primary energy over 50 years. Despite this significant potential energy expenditure for larger houses with the same number of occupants, the findings are not affected. Indeed, the life cycle energy demand is still sublinearly correlated with house size and increases 105% instead of by 100% for a house size increase of 292% (considering 5 occupants). Fifthly, this study assumes that a higher occupancy density does not affect the service life of materials and their associated embodied energy. In reality, a higher number of occupants using a small space can result in increased wear. Although trying to forecast the service life of materials is difficult due to high levels of uncertainty [80-82], a worst case scenario is considered in an attempt to estimate the potential effect of this assumption on the findings. To this end, the recurrent embodied energy of finishes materials (paint, carpet and plasterboard, representing 44% of the total recurrent embodied energy) in the 100 m² house with five occupants is increased by 30%. This results in an additional recurrent embodied energy demand of 456 GJ or an increase in the life cycle energy demand of only 3%. Similarly, the contribution of embodied energy to the total shifts from 19% to 21.4%. This estimation justifies the assumption of not including additional wear for higher occupancy density as it does not affect the findings of this study. In addition to the above limitations, is also important to verify if the increased quantity of furniture in larger houses offsets the increased material efficiency. More research is needed in this regard. Finally, this study investigated the effect of house size on life cycle energy use, and while most findings should be applicable to other building types, a thorough investigation of the effect of floor area and building size on the life cycle resource requirements of different building types, including double-storey detached houses, would provide useful insights that can further inform broader environmental building regulations. Financial life cycle cost could also be considered as part of a future study to help identify potential stakeholder and policy incentives to reduce environmental effects [63, 83].

6 Conclusion

With an increasing global urban population, it is essential that future dwellings are designed and used with minimal environmental impacts. This study has quantified the relationship between life cycle energy demand and house size, for different household sizes. It has demonstrated that life cycle energy tends to be sublinearly correlated with house size and that embodied energy can represent up to 52% of the life cycle energy demand over 50 years. Based on these results, three main policy recommendations can be made. These are listed below (see Section 5.1 for details):

1. Take into account house size and the number of occupants when measuring energy efficiency in order to allow effective comparisons between houses. This could be done through the number of bedrooms in the house and its floor area, but more research is needed to develop effective metrics in this regard.
2. Include embodied energy requirements, both initial and recurrent, into building energy efficiency regulations, notably for larger houses which require significant amounts of materials. The use of the input-output-based hybrid life cycle energy technique is strongly recommended as it produces the most comprehensive embodied energy figures.
3. Use multiple functional units to measure energy efficiency, including absolute and specific units. Solely measuring energy efficiency per square metre of floor area tends to favour larger houses. Additional metrics, such total energy use and energy use per capita can better capture total environmental damage and lifestyle, respectively.

Failing to incorporate these three factors into building energy efficiency regulations could lead to a paradoxical increase in total life cycle energy use and associated environmental effects of houses.

Acknowledgements

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Appendix A Examples of bill of material quantities

This appendix provides a sample bill of material quantities in Table A.1 generated by the software tool used. These are originally generated in the comma-separated values format. Only quantities for the original house size of 100 m² (10 m × 10 m) are shown.

Table A.1: Bill of material quantities by assembly

Assembly subcategory	Material name	Material type	Measured quantity	Wastage coefficient	Delivered quantity	Unit
Foundations steel						
	Steel	Reinforcement	2.16	1.05	2.27	t
Foundations concrete						
	Concrete	25 MPa	21.60	1.10	23.76	m³
Ground floor slab						
	Plastics	Plastic membrane (1mm)	100.00	1.10	110.00	m²
	Sand and stone	Screenings	1.68	1.30	2.19	m³
	Steel	Reinforcement	2.00	1.05	2.10	t
	Plastics	UPVC pipe (100 mm)	50.51	1.05	53.03	m
	Concrete	25 MPa	20.00	1.10	22.00	m³
Outer wall						
	Sand and stone	Sand	11.93	1.10	13.12	m³
	Steel	Reinforcement	14.02	1.05	14.72	kg
	Timber	Softwood (framing)	0.90	1.02	0.92	m³
	Insulation	Fibreglass	8.25	1.10	9.07	m³
	Paint	Water-based	82.49	1.05	86.61	m²
	Plasterboard	(10 mm)	82.49	1.05	86.61	m²
	Aluminium	Reflective foil	82.49	1.10	90.74	m²
	Ceramics	Clay bricks (110 mm)	42.89	1.05	45.04	m²
Roof						
	Steel	Reinforcement	10.46	1.05	10.98	kg
	Concrete	Roof tile (20 mm)	115.03	1.10	126.53	m²
	Timber	Softwood (framing)	3.49	1.02	3.56	m³
	Steel	Gutter	24.50	1.05	25.73	kg
	Insulation	Fibreglass	20.91	1.10	23.01	m³
	Paint	Water-based	104.57	1.05	109.80	m²
	Plasterboard	(10 mm)	104.57	1.05	109.80	m²
Windows						
	Glass	Clear float (4 mm) window pane	57.60	1.03	59.33	m²
	Plastics	General (PVC)	2.88	1.05	3.02	kg

Assembly subcategory	Material name	Material type	Measured quantity	Wastage coefficient	Delivered quantity	Unit
	Aluminium	Frame	86.40	1.05	90.72	m
	Steel	Lintel	0.18	1.02	0.18	t
	Ceramics	Clay bricks (110 mm)	3.17	1.05	3.33	m²
Internal walls						
	Timber	Softwood (framing)	1.31	1.02	1.34	m³
	Steel	Reinforcement	12.00	1.05	12.60	kg
	Paint	Water-based	240.00	1.05	252.00	m²
	Plasterboard	(10 mm)	240.00	1.05	252.00	m²
Doors						
	Steel	Lintel	46.86	1.02	47.80	kg
	Timber	Softwood (framing)	0.10	1.02	0.10	m³
	Timber	MDF/particleboard	0.36	1.05	0.38	m³
	Aluminium	Door handle	6.00	1.05	6.30	no.
	Steel	Door accessories	2.40	1.05	2.52	kg
	Paint	Water-based	21.03	1.05	22.08	m²
Living rooms flooring						
	Ceramics	Tiles	40.50	1.05	42.53	m²
Bedrooms flooring						
	Carpet	Nylon	36.00	1.05	37.80	m²
Toilets and kitchen flooring						
	Ceramics	Tiles	13.50	1.05	14.18	m²
Pipes						
	Plastics	PVC water pipe (20 mm)	49.50	1.05	51.98	m
Wires						
	Plastics	Wire coating	2.11	1.03	2.17	kg
	Copper	Wire	2.70	1.03	2.79	kg
Heating						
	Other	Ducted heating generation	1.00	1.00	1.00	no.
Heating delivery						
	Other	Ducted heating delivery	5.00	1.00	5.00	no.
Cooling						
	Other	Split air Conditioning unit (700 AUD)	5.00	1.00	5.00	no.
Domestic hot water						
	Steel	Tank	63.00	1.03	64.89	kg
	Copper	Pipe	10.00	1.05	10.50	m
Other						
	Timber	MDF/particleboard	0.33	1.05	0.35	m³
	Glass	Clear float (4 mm) window pane	11.70	1.03	12.05	m²

Assembly subcategory	Material name	Material type	Measured quantity	Wastage coefficient	Delivered quantity	Unit
	Ceramics	Toilet suite	1.00	1.03	1.03	no.
	Ceramics	Basin	1.33	1.03	1.37	no.
	Timber	Squirting (20 x 1.8 cm)	72.00	1.10	79.20	m
	Steel	Stainless (sink)	0.33	1.00	0.33	no.
	Plastics	Bath (Acrylic)	0.67	1.00	0.67	no.