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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 392 m^2 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 m^2 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.

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

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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 m^2 in 2012 [17] compared to 167 m^2 in 1984. Houses in the USA have seen a similar increase in floor area over the same time period, rising from 163 m^2 in 1984 to 215 m^2 in 2012 (based on data from Refs. [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 m^2 in 1984 to 112 m^2 in 2013 (based on data from Refs. [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 m^2/capita in 1984 to ~94 m^2/capita in 2012 (+65%, based on [17,23]). This figure went from 33 m^2/capita to 44 m^2/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 Refs. [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 10 L/100 km, considering that the energy content of gasoline is 32.4 MJ/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 m^2 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 Ref. [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