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House size and future building energy efficiency regulations in Australia

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Abstract: The size of houses in Australia has significantly increased over the last decades. New houses have higher embodied and operational energy requirements due to their increased use of materials and larger area. Yet, current building energy efficiency regulations fail to adequately capture the effect of house size because of their omission of embodied energy and their sole use of a spatial functional unit for operational energy (e.g. MJ/m²). This study quantifies the effect of house size on life cycle energy demand in order to inform future building energy efficiency regulations. It uses a parametric model of a typical suburban house in Melbourne, Australia and varies its floor area from 100 to 392 m² for different household sizes. Both initial and recurrent embodied energy requirements are quantified using hybrid analysis and all operational energy end-uses (thermal and non-thermal) are calculated in primary energy terms over 50 years. Results show that larger houses appear to be more energy efficient per m² than smaller houses while actually having a much higher life cycle energy demand. Also, embodied energy represents 26-50% of the energy demand across all 360 variations. Guidelines are provided to improve current building energy efficiency regulations.

Keywords: House size; life cycle energy analysis; embodied energy; functional unit.

1. Introduction

There is an urgent need to reduce greenhouse gas emissions from human activities in order to prevent major disruptions to the Earth's ecosystems and climate. Reducing energy use in buildings is a key to reducing greenhouse gas emissions (IPCC, 2014). However, most existing building energy efficiency regulations focus on reducing operational energy only (ABCB, 2011), not considering embodied energy requirements. This narrow focus fails to capture the significant amount of additional materials needed in the ever larger new Australian houses (ABS, 2013b). Also, the use of a spatial functional unit to express energy efficiency (e.g. MJ/m²) does not systematically capture house size in the assessment. In the Australian case, an area adjustment factor is introduced to penalise houses with a conditioned floor area larger than 200 m² and favour smaller houses.

Clune *et al.* (2012) and Wilson and Boehland (2005) evaluated the relationship between house size and operational energy use and greenhouse gas emissions in Australia and the USA, respectively. They both found that large energy efficient houses can use more energy than smaller conventional houses and result in a more significant effect on the environment.

The lack of consideration of embodied energy in current building energy efficiency regulations has been widely discussed (García-Casals, 2006; Anderson *et al.*, 2015). Excluding embodied energy could be due to the fact that many previous studies found that it represents only 10-20% of the life cycle energy demand over 50 years, e.g. Chau *et al.* (2015). However, this low figure comes from the systematic underestimation of embodied energy due to the use of process analysis for its quantification (Majeau-Bettez *et al.*, 2011). Embodied energy can actually represent 30-70% of the life cycle energy demand of houses over 50 years (Stephan and Crawford, 2014a), depending on a range of factors, such as energy efficiency and size.

These flaws in energy efficiency regulations are particularly important in Australia where houses are among the largest in the world with an average of 241.1 m^2 of gross floor area (ABS, 2013a). Given that the average household size has also been declining in Australia over the last few decades (ABS, 2007), the floor area per capita has risen dramatically from ~57 m^2/capita in 1984 to ~94 m^2/capita in 2012. Since larger houses require more materials and associated embodied energy, as demonstrated by Fuller and Treloar (2004) and Fuller and Crawford (2011), the increase in floor area per capita results in a very high energy intensity per capita for housing. Considering an average initial embodied energy intensity of 14.1 GJ/m^2 as in Fay *et al.* (2000), this increase in floor area results in ~522 GJ of extra primary energy per capita. This is enough to drive around Australia ~11 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).

House size is therefore a determinant variable that significantly affects the life cycle energy demand of dwellings but is not accounted for in most existing building energy efficiency regulations. Existing studies that have evaluated the effect of house size on its life cycle energy demand either use a small sample of house sizes (e.g. Fuller and Treloar (2004) and Fuller and Crawford (2011)) or focus on operational energy only (e.g. Wilson and Boehland (2005) and Clune *et al.* (2012)). It is therefore critical to better understand how size affects the overall life cycle energy profile of a house.

1.1. Aim and scope

The aim of this paper is to quantify the effect of house size on the life cycle energy demand in order to inform future building energy efficiency regulations that can effectively reduce total energy use. The focus is on energy because it is a good proxy for building environmental impacts (Oregi *et al.*, 2015).

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. This study quantifies the embodied energy of all building materials 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. Method

This section describes the modelling approach and the quantification algorithms used. These are based on Stephan and Crawford (2014b) and quantify embodied and operational energy over the building's life cycle. The user-transport energy demand which is also considered in Stephan and Crawford (2014b) is not taken into consideration in this study.

2.1. Modelling approach

In order to evaluate the effect of house size on life cycle energy demand, a large sample of house and household sizes is needed. Collecting detailed data on existing houses (e.g. bill of material quantities) can be a prohibitive and time consuming task. Using a computer model can streamline the process.

A hypothetical house is modelled using the advanced software tool developed by Stephan (2013) and described in Stephan and Crawford (2014b). The tool modifies the house size, generates the associated bill of material quantities and calculates its life cycle energy demand over 50 years for different occupancy levels. While the tool is able to model multi-storey houses and apartment buildings, this was considered to be outside the scope of this paper. The total number of variations includes 9 widths × 10 depths × 4 household sizes (=360 variations). These 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 last census (ABS, 2013b). Lone person households were not considered as these typically reside in apartments based on the same census data.

Certain combinations of width and depth result in the same floor area (e.g. 12 × 10 m and 10 × 12 m). These pairs of combinations have both been evaluated because they result in different material quantities. The characteristics of the house are listed in Table 1. Note that the thermal performance of the house in terms of envelope heat transfer as well as the efficiency of building systems is kept constant across all sizes. This allows a better comparability of results and negates the effect of particular variables on the outcome (e.g. the ventilation rate).

Table 1: Characteristics of studied houses.

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
Location	Melbourne, Victoria, Australia
Period of analysis (years)	50
Structure type	Timber-framed
Façade	Brick veneer wall; 100 mm of fibreglass insulation; Double glazed aluminium-framed windows (30% window to wall ratio)
Roof	Concrete tiles; 200 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 (ach^{-1})	3
Operational energy sources	Gas heating (eff.: 70%) and cooking (eff.: 90%), Electrical cooling (COP: 2.5)

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

The study uses the climate of Melbourne, Victoria for which the assemblies used are designed (notably in terms of thermal performance). This is not only because Victoria has the largest houses in Australia (and therefore in the world) 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 set to increase its housing stock in the coming decades (Victorian Government, 2014). This section has described the modeling approach. The next two sections describe the quantification of embodied and operational energy, respectively.

2.2. Quantifying embodied energy

Embodied energy represents the sum of all energy inputs for the production of building materials across their supply chains. Initial embodied energy represents the embodied energy of the building as-built while recurrent embodied energy is the energy required to produce and replace building materials throughout the period of analysis. This paper relies on the comprehensive input-output-based hybrid analysis developed by Treloar (1997) to quantify embodied energy. This approach takes into account entire supply chains and does not underestimate embodied energy, as is commonly the case in existing building life cycle energy analysis studies (Crawford and Stephan, 2013). The quantities of materials in each size variation are multiplied by embodied energy coefficients compiled by Treloar and Crawford (2010). An additional amount of energy is then added to the total to account for non-material processes, such as insurance and advertising. The replacement rates of building materials, which determine recurrent embodied energy, are based on Ding (2004). The life cycle embodied energy for each house size is quantified as per Equation 1.

$$LCEE_h = \sum_{m=1}^{M}\left(Q_m \times EC_m\right) + \left(TER_{rb} - \sum_{m=1}^{M} TER_m\right) \times C_h + \sum_{m=1}^{M}\left[\left\lfloor \frac{POA}{SL_m} - 1 \right\rfloor \times \left[\left(Q_m \times EC_m\right) + \left(TER_{rb} - TER_m - TER_{i \neq m}\right) \times C_m\right]\right] \quad (1)$$

Where: $LCEE_h$ = Life cycle embodied energy of house *h,* in GJ; Q_m = Quantity of material *m* in the house, in t, m³, m or another functional unit; EC_m = Hybrid energy coefficient of material *m,* in GJ per functional unit; TER_{rb} = Total energy requirements of the residential building sector *rb,* in GJ per AUD; TER_m = Total energy requirements of the input-output pathways representing the material production processes for which process data is available, in GJ per AUD; C_h = Cost of the house *h* in AUD; *POA* = Period of analysis, in years; SL_m = Average service life of the material *m,* in years; $TER_{i \neq m}$ = Total energy requirements of all input-output pathways not associated with the installation or production process of material *m*, in GJ per AUD; and C_m = Cost of the material *m* in AUD.

2.3. Quantifying operational energy

Operational energy can be divided into thermal and non-thermal energy. Thermal energy is quantified using the heat transfer coefficient of envelope elements, ventilation rates and heating degree hours. The steady-state thermodynamic equations used rely on indoor comfort temperatures of 20°C and 26°C for heating and cooling, respectively. The degree hours calculated factor in solar gains and free internal gains by adapting the balance temperature. While using dynamic thermal modelling through a third party software tool (e.g. EnergyPlus) could generate more accurate results, the steady-state approach is sufficient within the scope of this study. Indeed, since this paper aims to compare houses with different sizes, 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 a dynamic simulation software does not systematically result in a more accurate estimation of energy use, as demonstrated by a number of studies, such as Williamson *et al.* (2010).

Non-thermal energy is modelled using average intensities that are derived from DEWHA (2008). Lighting is calculated based on the floor area of the house while hot water, appliances and cooking are calculated based on the number of occupants.

The annual operational energy demand is assumed constant over time. The life cycle operational energy demand is calculated as per Equation 2, by converting each energy use to primary energy terms, 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 (1998).

$$LCOPE_h = POA \times \sum_{e=1}^{E} \left(\frac{OPE_e}{\eta_e} \times PEF_e \right) \quad (2)$$

Where: $LCOPE_b$ = Life cycle primary operational energy of the house h in GJ; POA = Period of analysis in years; OPE_e = Annual final operational energy demand of the end-use e in GJ; η_e = Average efficiency of the system used for end-use e; and PEF_e = Primary energy conversion factor of the end-use e based on the energy source.

2.4. Quantifying life cycle energy

The life cycle energy demand of each house (LCE_h) is simply 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).

3. Results

This section presents the results of the study. The significance of current issues in building energy efficiency regulations is first evaluated. This is followed by a detailed analysis of the influence of size on the life cycle energy demand of the studied house.

3.1. The significance of the functional unit

Figure 1 shows the total life cycle energy demand per capita (upper part) and per m² (lower part) for all studied house sizes. Two main observations can be made.

Firstly, while the life cycle energy demand per capita increases with house size, it decreases when expressed on a per m² basis. Using a spatial functional unit fails to consider the size of the house by favouring larger houses. This is because the life cycle energy demand is sublinearly correlated with house size, meaning that the percentage increase in house size is larger than the associated increase in energy use (see Section 3.3. for more details). This means that building energy efficiency regulations need to correct energy use for house size in order to avoid artificially decreasing the energy intensity per m² of larger houses and making them look efficient while they result in a higher life cycle energy demand.

Secondly, Figure 1 reveals the importance of lifestyle. Indeed, two occupants living in a 160 m² house (point A) use a similar amount of energy over 50 years as three occupants living in a 260 m² house (point B) or four occupants living in a 392 m² house (point C). 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.

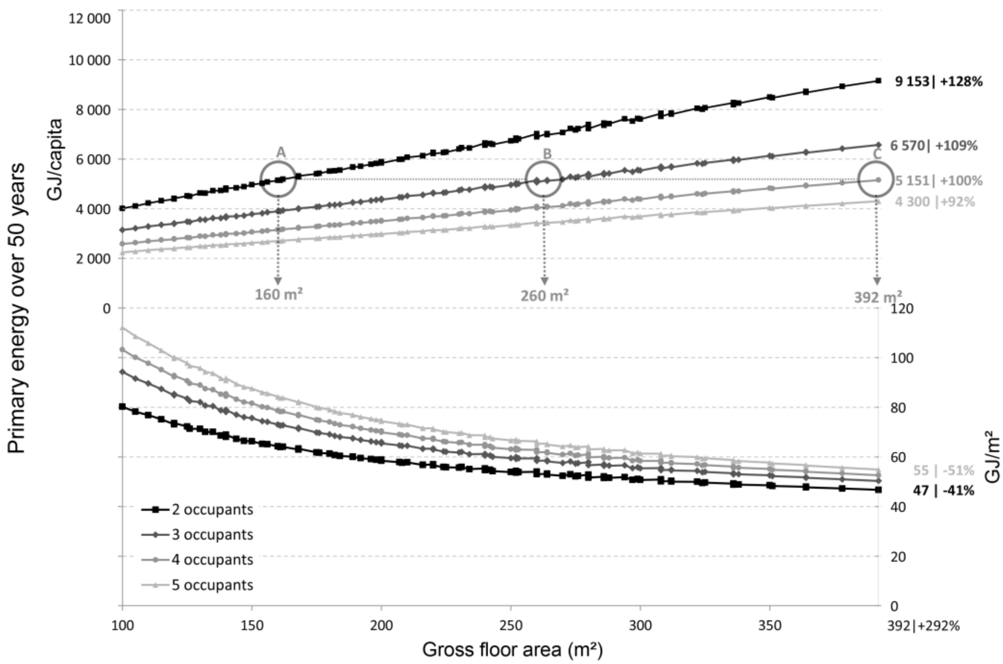

Figure 1: Effect of gross floor area and occupancy on the life cycle energy demand of the house over 50 years, per capita and per square metre.

3.2. The significance of embodied energy

Regardless of the house or household size, embodied energy represents a significant share of the life cycle energy demand over 50 years. As shown in Figure 2, even in the case of a 100 m² house with 5 occupants, embodied energy still represents 26% of the total. On average, initial embodied energy represented 61% of the life cycle embodied energy over 50 years (across all 90 house sizes).

More importantly, for the largest house size, embodied energy represents a significant share of the life cycle energy demand, representing up to 50% of the total for a household size of two occupants. Even if five occupants live in that same house, the share of embodied energy is still 43%. This high contribution of embodied energy is due to the use of the comprehensive input-output-based hybrid analysis for the quantification of embodied energy and the relatively higher than usual thermal energy efficiency of the house (achieving a 7 Star rating under the current Australian building energy efficiency regulation). Since new houses have a reduced operational energy demand, enforced by current building energy efficiency regulations, embodied energy becomes increasingly significant and should be considered. It is also important to underline that in this study, operational energy includes all non-thermal end-uses and is expressed in primary energy terms, capturing all losses across the energy supply chain. A more detailed analysis of the influence of size on the life cycle energy demand is provided in the following section.

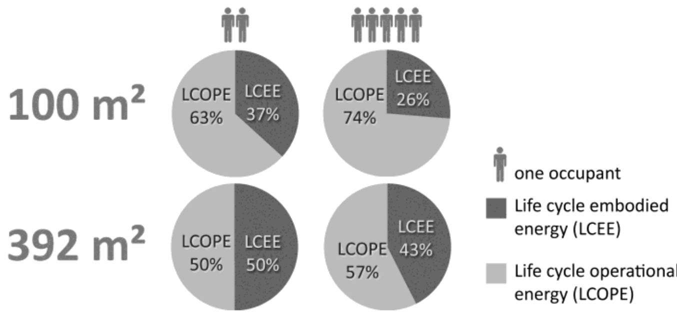

Figure 2: Contribution of embodied and operational energy for different house and household sizes.

3.3. The influence of size on the life cycle energy profile of houses

Figure 3 depicts the life cycle embodied and operational energy demand of all studied house sizes, by floor area and reveals a more significant increase in embodied energy with house size compared to the operational energy demand. It intentionally omits hot water, appliances and cooking energy demands as these are assumed to be affected solely by the number of occupants in this study.

For the largest house (392 m²), the life cycle energy demand (excluding hot water, appliances and cooking energy) is 15 443 GJ compared to 5 156 GJ for the 100 m² house. That is an increase of 200% compared to the 292% increase in house size. The life cycle energy demand seems to be sublinearly correlated with house size. This is why using a per m² functional unit tends to favour larger houses.

The embodied energy of assemblies varies differently with house size depending on the assembly type. As a general observation, the embodied energy of horizontal assemblies increases to a similar extent, e.g. flooring (+293%), the roof (+292%) and the slab (+206%). In comparison, the embodied energy of vertical assemblies, such as outer walls, interior walls and windows increases by ~110% (note that the window to wall ratio has been kept constant at 30% in all variations). This is because the amount of walls needed per m² is not the same for all house sizes. Horizontal assemblies are therefore likely to contribute more to the life cycle energy demand of large houses compared to smaller ones. The 'other finishes', 'construction' and 'other' are calculated on a per m² basis and are therefore directly correlated with floor area. Overall, the life cycle embodied energy increases by 193% and is therefore sublinearly correlated with house size as well.

The heating and cooling demands increase by 166% and 165%, respectively. This is because the heat exchange area is not a direct function of the floor area but also depends on the level of compactness of the building. In other words, heating and cooling increase at around 57% the rate of the floor area of the case study house. The Australian building energy efficiency scheme takes this into account and uses an area adjustment factor of ~40% between a 100 and a 400 m² house (Delsante, 2005). 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 allowing larger houses to achieve a better rating because they have a lower heating and cooling demand per m². This is the case of the passive house certification.

This study shows that in reality larger houses result in significantly higher embodied and operational energy use and associated environmental impacts.

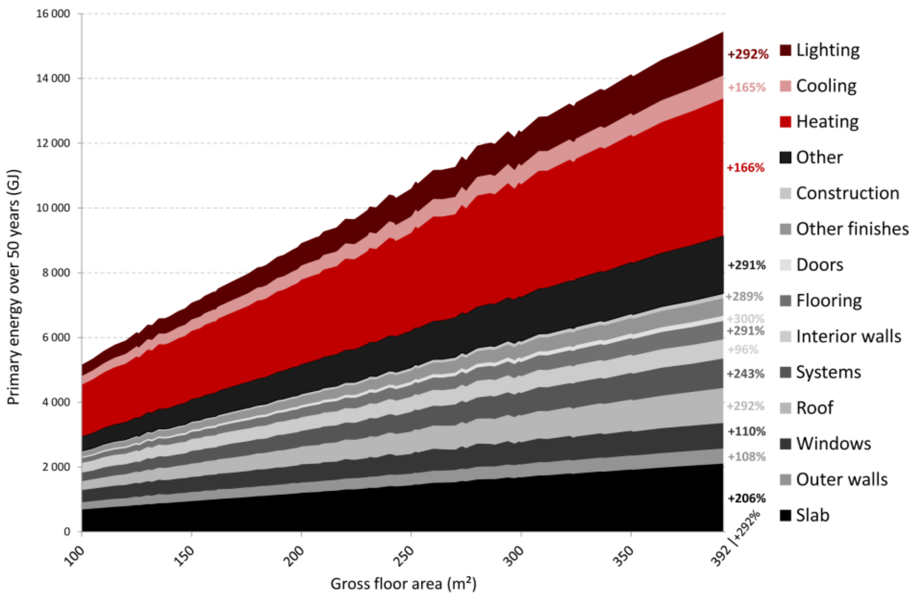

Figure 3: Effect of gross floor area on the life cycle energy demand of the house over 50 years, by use.

4. Discussion

This section describes the contribution of this study and provides guidelines regarding the improvement of current building energy efficiency regulations. Limitations of this study are then highlighted.

4.1. Contribution

This study has quantified for the first time the relationship between house size and life cycle energy demand while using a comprehensive embodied energy quantification approach. Results show that larger house sizes result in a higher life cycle energy demand, notably through the increase in embodied energy. Also, it was found that both operational and embodied energy are sublinearly correlated with house size. Hence, the use of a spatial functional unit (e.g. MJ/m²) to express energy efficiency tends to favour larger houses, even for embodied energy. These results can inform future building energy efficiency regulations in Australia and in other countries. The USA is particularly relevant because it also has a residential building stock with a high share of large houses (U.S. Census Bureau, 2013).

In order to actually reduce the overall energy use, current building energy efficiency regulations need to be revised. The main amendments proposed include:

- Incorporating embodied energy into the energy efficiency assessment;
- Developing standards for measuring embodied energy using the most comprehensive forms of analysis;

- Using overall and per capita energy use in addition to the current per m² measure; and
- Including efficiency requirements for primary energy and not only final thermal energy.

Implementing these changes in current building energy efficiency regulations would help ensure that net energy reductions are achieved and that additional environmental effects associated with larger houses are considered.

4.2. Limitations

This study suffers from a number of limitations. Firstly, using a computer model to estimate bills of material quantities and operational energy demand can result in a significant level of uncertainty. 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 significant amount of resources. Secondly, the operational energy use of a particular household can differ significantly from that of another. There is therefore a significant amount of variability in operational energy use and presented values should be considered as averages. Similarly, there can be a large level of uncertainty in embodied energy figures (±~40%). Because all houses in this study have the same materials, the uncertainty affects all houses equally and does not therefore influence the findings. However, the contributions of each of the embodied and operational energy can be significantly altered by uncertainty and variability. Finally, this paper uses a case study house and results are valid only for the studied house. Other house types and building materials might result in different findings.

5. Conclusion

With a forecasted increase in the global population and notably in urban population, it is essential that large houses with small households are avoided in order to minimise effects on the environment. This study has quantified the life cycle energy demand associated with house and household size. It shows that future building energy efficiency regulations should take embodied energy and house size into account in order to ensure actual reductions in the life cycle energy demand. Failing to incorporate embodied energy and house size into building energy efficiency regulations can lead to a paradoxical increase in life cycle energy use when building so-called ‘energy efficient’ large suburban houses.

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References

ABCB (2011) *Building Code of Australia (BCA) 2011*, Australian Building Codes Board, Australia.

ABS (2007) *Article: Larger dwellings, smaller households*,Australian Social Trends 2007, Australian Bureau of Statistics, Canberra, 10.

ABS (2013a) *8752.0-Feature article: average floor area of new residential buildings*, Australian Bureau of Statistics, Canberra.

ABS (2013b) *T14 Dwelling Structure by Household Composition and Family Composition*, Canberra.

Anderson, J. E., Wulfhorst, G. and Lang, W. (2015) Energy analysis of the built environment—A review and outlook, *Renewable and Sustainable Energy Reviews*, 44(0), 149-158.

Chau, C. K., Leung, T. M. and Ng, W. Y. (2015) A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings, *Applied Energy*, 143(0), 395-413.

Clune, S., Morrissey, J. and Moore, T. (2012) Size matters: House size and thermal efficiency as policy strategies to reduce net emissions of new developments, *Energy Policy*, 48(0), 657-667.

Crawford, R. and Stephan, A. (2013) The significance of embodied energy in certified passive houses, *ICCBM 2013: International Conference on Construction and Building Materials*, Copenhagen, 13-14 June, 473-479.

Delsante, A. (2005) Is the new generation of building energy rating software up to the task? - a review of accurate, *ABCB Conference 'Building Australia's Future 2005'*, Surfers Paradise, 11-15 September.

DEWHA (2008) *Energy use in the Australian residential sector 1986-2020*, Department of the Environment, Water, Heritage and the Arts, Canberra.

Ding, G. (2004) *The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities*, Ph.D. thesis, School of the Built Environment, University of Technology, Sydney.

Fay, R., Treloar, G. and Iyer-Raniga, U. (2000) Life-cycle energy analysis of buildings: a case study, *Building Research and Information*, 28(1), 31-41.

Fuller, R. and Crawford, R. (2011) Impact of past and future residential housing development patterns on energy demand and related emissions, *Journal of Housing and the Built Environment*, 26(2), 165-183.

Fuller, R. and Treloar, G. J. (2004) The Influence of Housing Size, Style and Location on Energy and Greenhouse Gas Emissions, *Proceedings Solar 2004: Life, The Universe and Renewables*, Australia.

García-Casals, X. (2006) Analysis of building energy regulation and certification in Europe: their role, limitations and differences, *Energy and Buildings*, 38(5), 381-392.

IPCC (2014) *Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*, in O. Edenhofer, R. Pichs-Madruga, Y. Sokona, J. C. Minx, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. v. Stechow and T. Zwickel (eds.), Cambridge University Press, Cambridge.

Majeau-Bettez, G., Strømman, A. H. and Hertwich, E. G. (2011) Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues, *Environmental Science & Technology*, 45(23), 10170-10177.

Oregi, X., Hernandez, P., Gazulla, C. and Isasa, M. (2015) Integrating Simplified and Full Life Cycle Approaches in Decision Making for Building Energy Refurbishment: Benefits and Barriers, *Buildings*, 5(2), 354-380.

Stephan, A. (2013) *Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework*, Ph.D. thesis, ULB-BATir - Building, Architecture and Town planning and UoM-ABP - Architecture, Building and Planning, Université Libre de Bruxelles and The University of Melbourne, Brussels.

Stephan, A. and Crawford, R. H. (2014a) A comparison of the life cycle energy profile of residential buildings in different countries, *World Sustainable Building Congress 2014: Are we moving as fast as we should?*, Barcelona, 8.

Stephan, A. and Crawford, R. H. (2014b) A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings, *Architectural Science Review*, 57(1), 39-48.

Treloar, G. J. (1997) Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method, *Economic Systems Research*, 9(4), 375-391.

Treloar, G. J. (1998) *A comprehensive embodied energy analysis framework*, Ph.D. Thesis, School of Architecture and Building, Deakin University, Geelong.

Treloar, G. J. and Crawford, R. H. (2010) *Database of embodied energy and water values for materials*, The University of Melbourne, Melbourne.

U.S. Census Bureau (2013) *American housing survey for the United States: 2013*, United States Census Bureau, Washington.

Victorian Government (2014) *Victoria in future. Population and household projections to 2051*, Victorian government, Melbourne, 16.

Williamson, T., Soebarto, V. and Radford, A. (2010) Comfort and energy use in five Australian award-winning houses: regulated, measured and perceived, *Building Research & Information*, 38(5), 509-529.

Wilson, A. and Boehland, J. (2005) Small is Beautiful U.S. House Size, Resource Use, and the Environment, *Journal of Industrial Ecology*, 9(1-2), 277-287.