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Does current policy on building energy efficiency reduce a building's life cycle energy demand?

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Abstract: Building energy efficiency regulations often focus solely on thermal energy demands. Increasing the thermal performance of the building envelope through additional insulation and efficient windows is the typical approach to increasing building thermal energy efficiency. This can result in a significant increase in embodied energy which is currently not considered in building energy regulations. A case study house in Melbourne and Brisbane, Australia is used to investigate the life cycle primary energy repercussions of increasing building energy efficiency levels over 50 years. Embodied and operational energy are quantified using the comprehensive hybrid approach and a dynamic software tool, respectively. Energy efficiency is improved by material or design changes as well as a combination of both. Results show that while increasing the envelope thermal energy performance yields thermal operational energy savings, these can be offset by the additional embodied energy required for additional insulation materials and more efficient windows. The point at which increasing the thermal performance of the envelope does not yield life cycle energy benefits is just above current minimum energy efficiency standards in Australia. In order to reduce a building's life cycle energy demand, a more comprehensive approach that includes embodied energy and emphasises design changes is needed.

Keywords: Building energy efficiency regulations; life cycle energy analysis; residential; Australia.

1. Introduction

The operation of buildings alone represents 30-40% of the primary energy demand in most developed economies (IEA, 2014). In 2012, buildings represented 20% of the final energy demand in Australia, of which 60% was associated with residential buildings (BREE, 2012). This makes buildings one of the most important areas to target in order to reduce energy use and greenhouse gas emissions (IPCC, 2014).

The considerable energy use associated with the operation of buildings has led to the development of building energy efficiency regulations. These regulations impose a minimum level of energy efficiency for all new buildings and in some cases retrofitted buildings. An example of such regulations is the Australian 6 Star Standard (ABCB, 2011). These regulations focus on thermal operational energy requirements of buildings since these typically represent the largest contribution to their delivered energy demand (Perez-Lombard *et al.*, 2008). In Australia, maximum levels of annual heating and cooling final energy demand per m² must be met, e.g. 114 MJ/m²·a for Melbourne, Australia (NatHERS, 2003). While such regulations can lead to a reduction in thermal energy use, improved thermal comfort and healthier buildings, it is critical to ensure that they do not result in an increased energy demand at other stages of a building's life cycle, notably for the production and manufacture of building materials.

The need to integrate embodied energy requirements into building energy efficiency regulations has been advocated for in many previous studies such as García-Casals (2006). This is because energy efficiency measures often require additional materials to be installed which leads to an increase in embodied energy demands (Stephan *et al.*, 2012). It is therefore essential to ensure that reducing thermal energy requirements results in net life cycle energy benefits. For instance, Stephan *et al.* (2013) have shown that a Passive house, meeting one of the most stringent thermal energy efficiency certifications in the world, can have the same life cycle energy use as a house built to minimum requirements in Belgium, over 100 years.

Over time, building energy efficiency regulations tend to become more stringent. However, very few studies have evaluated the life cycle repercussions of increasing thermal energy efficiency levels in buildings. Those that do, often focus on life cycle cost, such as Morrissey and Horne (2011) and Hasan (1999). Almost all of those that focus on life cycle energy demand underestimate embodied energy by relying on a process analysis approach (e.g. Sartori and Hestnes (2007) and Dahlstrøm (2011)). There is therefore a need to quantify the life cycle energy benefits of increasing thermal energy efficiency in buildings in order to inform effective building energy efficiency regulations.

The aim of this study is to quantify the life cycle energy repercussions of an increasing stringency in building energy efficiency policy in Australia. The study uses a representative case study house in Melbourne and Brisbane.

Section 2 describes the case study house and the approach used to quantify the embodied and operational energy. Section 3 presents the results, which are discussed in Section 4.

2. Method

This section describes the research approach and the case study building and its characteristics. The input-output-based hybrid analysis technique used to quantify embodied energy is described as well as FirsRate5, the dynamic software tool used to quantify heating and cooling energy requirements.

2.1. Research approach

In order to evaluate the net life cycle energy benefits of the current building energy efficiency regulation in Australia, different energy efficiency levels were investigated. A case study house (described in Section 2.2) was modified from a base case scenario (meeting the compulsory 6 Star standard out of a possible 10 Stars (equivalent to zero or near zero energy demand for heating and cooling)) to meet increasing energy efficiency levels and higher associated star ratings. These modifications were performed using two approaches: improvement by material and improvement by design. The first follows a business as usual approach and gradually increases the amount of insulation and the glazing thermal performance. The second uses design changes to achieve a higher star rating. These include exposing the thermal mass of the house (by removing carpets, using reverse brick veneer outer walls and installing shading devices). Lastly, for each location, a single scenario that combines both improvements by material and design was investigated. This scenario meets the highest star rating possible, considering the range of modifications investigated in this study.

The net life cycle energy difference between each of the aforementioned scenarios and the base case house was calculated. This reveals the net benefits of increasing thermal energy efficiency by material, by design and by a combination of both.

2.2. Case study house

A three-bedroom single family house was chosen as the case study (Figure 1). This house was developed by the Housing Industry Association (HIA) as a representative sample of new Australian houses for costing purposes. The brick veneer house has a net conditioned floor area of 135.4 m² (when modelled according to the Australian Nationwide House Energy Rating Scheme technical guidelines and zoning protocols) and a gross floor area of 202 m². This house is representative of housing in Australia, where more than 74% of all dwellings are detached houses (ABS, 2013).

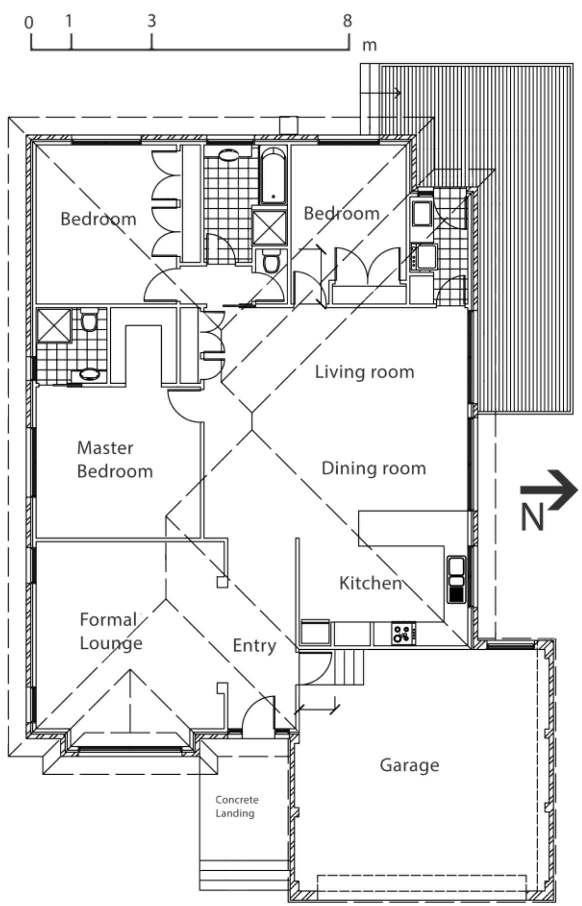

Figure 1: Floor plan of the case study house.

As described in Section 2.1, the base case house meets the minimum 6 Star energy efficiency standard for Melbourne. For Brisbane, some minor modifications were made to the envelope assemblies in order to achieve the minimum 6 Star requirement. Table 1 summarises the characteristics of the base case house, for Melbourne and Brisbane.

Table 1: Main characteristics of the case study house for Melbourne and Brisbane.

Characteristic	Melbourne	Brisbane
Period of analysis	50 years	
Number of occupants	4	
Climate zone	Maritime temperate *Cfb* in the Köppen classification Zone 21 in the FirstRate5[a] tool	Warm temperate *Cfa* in the Köppen classification Zone 10 in the FirstRate5[a] tool
Orientation	Kitchen / Family to North (see Figure 1)	
Site	Suburban terrain	
Areas	135.4 m² net conditioned floor area (NCFA), 38.9 m² unconditioned Garage, 9.8 m² unconditioned utilities (bathroom and laundry), 36.68 m² glazing	
Roof	Concrete tile attic-type roof with 160 mm fibreglass insulation batts (U-value=0.29 W/(m²·K)) and a 60 mm reflective blanket (U-value=0.77 W/(m²·K)) Metal deck roof to garage, no insulation	
External walls	Brick veneer walls with 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) plus single sided reflective foil, single brick walls to garage and no insulation	
Internal walls	Plasterboard on stud frame, 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) to unconditioned spaces	
Floors	Concrete slab on ground, no insulation, tiles in wet areas, carpet in other living spaces, concrete finish in garage	
Windows	Timber framed, clear single glazing U-value = 5.75 W/(m²·K), g-value: 0.69	Timber framed, toned single glazing U-value = 5.7 W/(m²·K), g-value: 0.52
Heating energy demand (MJ/m²·a)	87[b]	8[b]
Cooling energy demand (MJ/m²·a)	25[b]	33.9[b]
Total final thermal energy (MJ/m²·a)	112[b]	41.9[b]
Star rating	6[b]	6[b]
Constraint factor heating	0.45[c]	0.25[c]
Constraint factor cooling	0.4[c]	0.4[c]
Gas heater efficiency	0.7	
Electrical cooling COP	2.5	

Note: [a]FirstRate5 is a certified dynamic software tool used to calculate the thermal energy efficiency of buildings in Australia (see Section 2.4); [b]As calculated with FirstRate5; [c]Constraint factors correct estimated heating and cooling demands to account for actual occupancy (see Section 2.4).

2.3. Quantifying embodied energy

The embodied energy of a construction material is the sum of all energy inputs across its supply chain, including raw material extraction, material manufacture, processing, transport to site and construction, as well as the energy associated with the provision of services required to support each of these processes, such as banking and insurance. Embodied energy was quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar (1997) and validated by Crawford (2008). This technique combines industrial data with average economic data to produce comprehensive embodied energy coefficients for building materials. Most existing studies rely on the so-called 'process analysis' which underestimates embodied energy due to truncation of the supply chain.

The initial embodied energy of the house and the recurrent embodied energy associated with material replacement over 50 years were calculated. Average material service life values were used to calculate recurrent embodied energy. These are based on NAHB and Bank of America (2007). The sum of initial and recurrent embodied energy is the life cycle embodied energy and is given by Equation 1.

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

Where: Q_m = Quantity of material m in the house (e.g. t of steel); EC_m = Hybrid energy coefficient of material m in GJ per functional unit; TER_{rb} = Total energy requirement of the *Residential Building* sector rb in GJ/AUD; TER_m = Total energy requirement of the input-output pathway representing material m in GJ/AUD; C_h = Cost of the house in AUD; POA = Period of analysis in years; SL_m = service life of the material m in years; $TER_{i \neq m}$ = Total energy requirement of all input-output pathways not associated with the installation or production process of material m being replaced in GJ/AUD; and C_m = Cost of the material m in AUD.

2.4. Quantifying operational energy

Operational energy requirements comprise only heating and cooling demands in this study as these are the only demands considered by the Building Code of Australia (except for lighting which is considered only in a basic manner). They are also the focus of most similar regulations, globally. Annual specific final heating and cooling requirements are computed using FirstRate5 (FR5), one of the three accredited software tools that are used to evaluate the thermal energy efficiency of buildings in Australia. FR5 relies on the CHEENATH simulation engine which is a multi-zone dynamic energy simulation. It takes into account solar radiation, thermal mass and natural ventilation and uses a time step of one hour. The final heating and cooling demands are used in conjunction with the climate zone to determine the star rating of a building (see Table 1 for those of the base case house).

However, while dynamic energy simulation software can model building physics, the estimated energy demand still depends significantly on building users. A study by the Australian Greenhouse Office (AGO, 1999) has shown that simulated energy demands often overestimate the actual energy use in real-life buildings. This is confirmed in a study by Williamson *et al.* (2010) that showed that the heating and cooling energy demand estimated with FR5 was higher than measured energy use in 3 out of 4 houses. In order to correct for this overestimation, the AGO (1999) recommended the use of 'constraint factors' to account for occupancy patterns and zoning. The factors used in this study are 0.45 and 0.25 for heating in Melbourne and Brisbane, respectively, and 0.4 for cooling in both locations (AGO, 1999). These factors do not account for any other user-driven variability in operational energy use which can significantly affect the results. This is further discussed in Section 4.

The final heating and cooling energy requirements were converted to primary energy terms in order to account for all losses associated with energy production and distribution. This was done by dividing final energy figures by the efficiency of the heating/cooling system and multiplying the resulting delivered energy by a primary energy factor depending on the energy source. A factor of 3.4 and 3.1 were used for electricity in Melbourne and Brisbane, respectively, based on Treloar (1998). The primary energy conversion factor for gas was 1.4 based on the same source. The primary operational energy use of one house in a given location over the period of analysis is calculated as per Equation 2.

$$LCTOPE_h = POA \times \left(PEF_{s=H} \times \frac{FHE_{FR5} \times CFH}{\eta_H} + PEF_{s=C} \times \frac{FCE_{FR5} \times CFC}{\eta_C} \right) \quad (2)$$

Where: $LCTOPE_h$ = Life cycle primary thermal operational energy of the house h in GJ; POA = Period of analysis in years; $PEF_{s=H}$ and $PEF_{s=C}$ = Primary energy conversion factors for the source s used for heating H and cooling C in GJ/GJ; FHE_{FR5} and FCE_{FR5} = Final annual heating and cooling energy demands as calculated by FirstRate5 in GJ; CFH and CFC = Heating and cooling constraint factors; and η_H and η_C = Heating and cooling system efficiency.

2.5. Quantifying life cycle energy

The life cycle energy demand of a house (LCE_h) is simply the sum of its life cycle embodied energy ($LCEE_h$) and of its life cycle thermal operational energy ($LCTOPE_h$). The difference between the life cycle energy demand of a house scenario h and that of the relevant base case house (BC) in Melbourne or Brisbane (ΔLCE_{h-BC}) is the difference between the life cycle energy demand of a house scenario (LCE_h) and that of the base case house (LCE_{BC}), i.e. LCE_h-LCE_{BC}.

3. Results

Figure 2 compares all houses with an improved star rating to the base case 6 Star house, in Melbourne (top) and Brisbane (bottom), respectively. The embodied energy demand related to materials and assemblies associated with the thermal performance of the building envelope, namely insulation and windows, are grouped into the thermal embodied energy category. Non-thermal-related embodied energy covers all other materials in the buildings such as timber or carpet. Note that only a maximum of 7 Stars could be achieved for Melbourne with the chosen design changes.

Results show that simply increasing the thermal energy performance of the envelope can paradoxically result in an increased life cycle energy demand in Brisbane and negligible life cycle energy benefits in Melbourne. This is due to the increase in thermal-related life cycle embodied energy (+572 GJ and +422 GJ for the 9★M houses in Melbourne and Brisbane, respectively). This is a very significant result as current building energy efficiency regulations tend to focus solely on improving the thermal energy efficiency of the envelope, notably by specifying maximum heat transfer values for envelope elements, e.g. in different European regulations (Rodríguez-Soria *et al.*, 2014). This result is in line with the findings of Stephan (2013) and Crawford and Stephan (2013) who have shown that current building energy efficiency regulations, which do not consider embodied energy, can paradoxically lead to an increased energy demand over the life of a building.

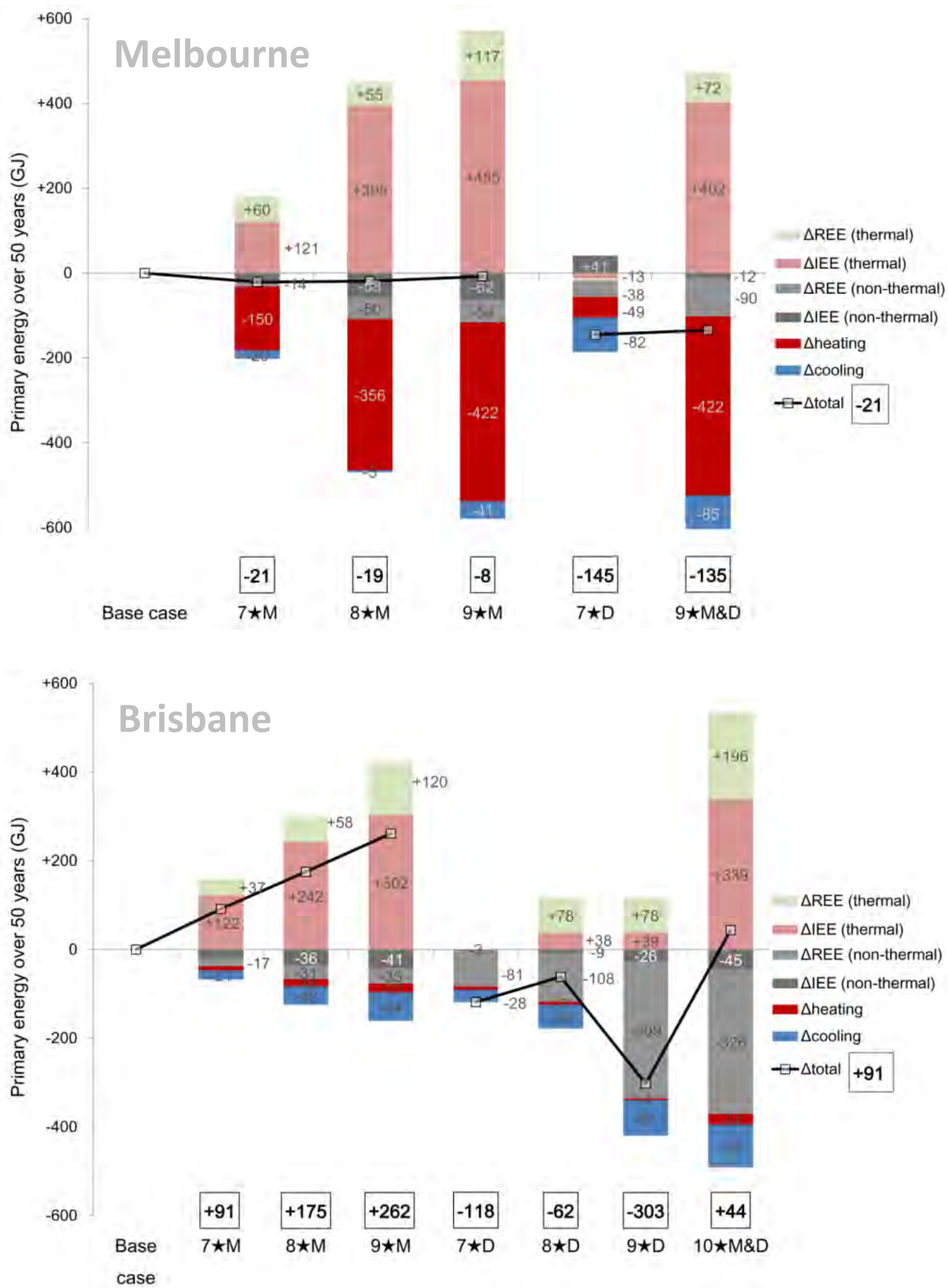

Figure 2: Difference between life cycle energy demand of improved scenarios and base case house in Melbourne and Brisbane over 50 years. Note: Δ= difference, IEE = initial embodied energy, REE = recurrent embodied energy, M = improvement by material, D = improvement by design, M&D = improvement by material and design.

In parallel, improvements by design tend to result in net reductions of both thermal operational energy and embodied energy. The 7★D house in Melbourne and the 9★D house in Brisbane save 145 GJ and 303 GJ over 50 years, respectively. Design changes such as exposing the concrete slab by removing the carpet (in the two aforementioned scenarios) can significantly reduce the cooling demand (see Figure 2) while simultaneously reducing the life cycle embodied energy requirements associated with installing and replacing the carpet. Current building energy efficiency regulations do not encourage changes by design.

In addition to the above, Figure 2 shows the star rating is not correlated with life cycle energy requirements. For instance, the 10★M&D house in Brisbane and the 9★M in Melbourne have a higher life cycle energy demand than the 7★D house in Brisbane and the 7★M house in Melbourne, respectively. This is because star ratings do not consider embodied energy at all even though it can be as significant as thermal operational energy. More inclusive building energy efficiency regulations that consider embodied energy in their ratings should be used to better measure and ensure net life cycle energy benefits.

4. Discussion

This section discusses the results and limitations of the study and proposes potential pathways to ensure that building energy efficiency regulations result in net reductions in life cycle energy.

4.1. Building energy efficiency regulations and life cycle energy

This study has demonstrated that current building energy efficiency regulations in Australia do not always result in net life cycle energy reductions over 50 years. Whether in Melbourne's marine temperate climate or Brisbane's warm temperate climate, increasing the thermal energy performance of the house by solely increasing the amount of insulation and using efficient windows does not result in notable life cycle energy savings and can even significantly increase them for Brisbane. This is because the embodied energy of the additional materials counterbalances the net reductions in thermal operational energy. The business as usual approach of increasing the thermal performance of the envelope seems to have reached its limits: star ratings higher than 6 and 7 in Melbourne and Brisbane, respectively, result in insignificant savings or dramatically increase life cycle energy demand. Conversely, houses with an improved thermal energy performance by design had the lowest life cycle energy demands. This is because design changes can reduce both operational and embodied energy requirements simultaneously, yielding significant savings.

If building energy regulations are to yield life cycle energy savings these should firstly take embodied energy into account, as advocated by a number of previous studies (García-Casals, 2006; Crawford and Stephan, 2013; Stephan *et al.*, 2013). However, this would require a significant amount of work before it can be implemented. Indeed, a common quantification technique for embodied energy should first be agreed upon in order to obtain consistent results, as advocated by Dixit *et al.* (2012). This technique should ideally rely on hybrid analysis in order to ensure that embodied energy is not underestimated.

Secondly, building energy efficiency regulations should encourage a design approach to energy performance as this is shown to yield significant benefits. Potentially, the benefits of particular design decisions for each climate could be evaluated and encouraged. For example, using reverse brick veneer walls significantly reduced thermal operational energy for the same embodied energy requirement as typical brick veneer walls. Such design measures could be explicitly favoured by the regulation.

4.2. Limitations

This study suffers from a number of limitations. Firstly, it considers only thermal operational energy and does take into account non-thermal operational energy requirements which can be very significant. Stephan and Crawford (2014) have shown that non-thermal operational energy can represent up to 67% of the total primary operational energy of an Australian house over 50 years. In addition, while care has been taken to choose a representative case study house, results are specific to this building only and variations to the type or design of the house may result in different findings. Thermal operational energy can vary widely based on user behaviour, the occupancy pattern of the building, orientation, nearby shading and other factors. It can also vary in time due to improved thermal performance, the installation of more energy efficient systems or a reliance on renewable energy sources (when considered in primary energy terms). Gram-Hanssen (2010) has shown that this variability can be up to 365% between two households living in identical dwellings in Copenhagen, Denmark. In addition, embodied energy figures can vary by up to 40% when hybrid analysis is used for its quantification (Crawford, 2011). Results therefore suffer from significant uncertainty and variability. A sensitivity analysis targeting individual variables should be undertaken to evaluate the robustness of the results. Despite these limitations, this study provides one of the most detailed life cycle energy analyses of building energy efficiency regulations to date.

5. Conclusion

Improving the energy efficiency of buildings should not only focus on thermal performance but should also include their embodied energy. The significant contribution of embodied energy to the life cycle energy demand of buildings emphasises the need for more comprehensive energy efficiency regulations. These will better ensure that net energy reductions do occur and that savings in thermal operational energy are not offset by an increase in embodied energy, as is currently the case in Australia. More comprehensive building energy efficiency policies will ultimately help reduce energy use and greenhouse gas emissions.

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