Evaluating the life cycle energy benefits of building energy efficiency regulations

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Abstract

Building energy efficiency regulations often focus solely on operational and thermal energy demands. Increasing building thermal energy efficiency is most often undertaken by increasing insulation thickness and installing high performance windows. These measures can result in a significant increase in embodied energy which is currently not considered in building energy regulations.

This study uses a case study house in Melbourne and Brisbane, Australia to investigate the life cycle primary energy repercussions of increasing building energy efficiency levels over 50 years. It uses the comprehensive hybrid approach and a dynamic software tool to quantify embodied and operational energy, respectively. It considers material and design-related changes in order to improve energy efficiency 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 supplementary insulation materials and efficient windows. The point at which supplementary insulation materials do not yield life cycle energy benefits is just above current minimum energy efficiency requirements in Australia. In order to reduce a building's life cycle energy demand, more comprehensive regulations are needed. These should combine embodied and operational energy and emphasise design strategies.

Keywords: Building energy regulations; Life cycle energy analysis; Insulation; Design; Climate; Australia

1 Introduction

With 2014 being the hottest year in modern record [1] and nine out of the ten warmest years having occurred since 2000 [2], the signs of global warming are becoming increasingly evident. The need for a robust response to curb greenhouse gas emissions from human activities and reduce global warming and climate change is one of the most critical challenges for humankind [3]. Buildings have a central role to play in this mitigation effort [4].

The operation of buildings alone represents 30-40% of the primary energy demand in most developed economies [5]. In 2004, residential buildings alone represented 22%, 28% and 26% of the final energy demand of the USA, the UK and the EU [6]. This makes buildings one of the most energy intensive sectors in developed economies.

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. Examples of such regulations are the Energy Performance of Buildings Directive (EPBD) [7] in Europe (implemented as a regulation at a national level in EU member states) and the 6 Star Standard in Australia [8]. These regulations focus on thermal operational energy requirements of buildings since these typically represent the largest contribution to their delivered energy demand [6]. Therefore, the most common approach of such regulations is to impose minimum requirements on insulation levels and glazing performance [9]. In some regions/countries, additional criteria on the annual heating and cooling final energy demand per m² must be met, e.g. 114 MJ/m²·a on thermal requirements for Melbourne, Australia [10]. While these regulations can undoubtedly 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 buildings materials.

The need to integrate embodied energy requirements into building energy efficiency regulations has been advocated for in many previous studies such as Garcia-Casals [11], Szalay [12], Dodoo et al. [13], Blengini and Di Carlo [14], Dahlstrøm et al. [15] and Stephan et al. [16]. This is because energy efficiency measures often require additional materials to be installed which leads to an increase in embodied energy demands [17]. It is therefore essential to ensure that reducing thermal energy

requirements results in net life cycle energy benefits. For instance, Stephan et al. [16] have shown that a house built to one of the most stringent thermal energy efficiency certifications in the world (the *PassivHaus* standard) can have the same life cycle energy use compared to a house built to minimum EPBD standards in Belgium, over 100 years.

Very few studies have evaluated the life cycle energy repercussions of increasing thermal energy efficiency levels in buildings (these are reviewed in detail in Section 2). This lack of research may be due to the common belief that embodied energy requirements represent only 10-20% of the life cycle energy of a building [18-21] and are therefore insignificant. However, the majority of existing studies rely on the 'process analysis' technique that can significantly underestimate embodied energy [22]. The use of a comprehensive hybrid analysis has revealed that embodied energy is often much higher. Studies by Crawford [17], Crawford and Stephan [23] and Stephan and Stephan [24] have shown that hybrid analysis can result in embodied energy figures at a whole building level 3.8, 4.4 and 3.9 times higher compared to process analysis, respectively. In other terms, the actual embodied energy requirements associated with increasing thermal operational energy efficiency might be higher than the operational energy savings they provide. It is therefore critical to quantify the embodied energy repercussions of increasing the thermal energy efficiency of dwellings in order to evaluate the net life cycle energy benefits.

1.1 Aim and scope

The aim of this research is to investigate the life cycle energy implications of increasing the thermal energy efficiency levels of residential buildings over 50 years. The study relies on a residential building located in two different climate zones in Australia and therefore uses the Australian building energy efficiency regulation [8] as an example.

The embodied energy of the building as well as the primary operational energy associated with heating and cooling are taken into consideration. Other operational energy end-uses, i.e. hot water, appliances, lighting and cooking are not considered. This is further discussed in Section 6. Figure 1 depicts the life cycle stages taken into account and the system boundaries of this study. The end of life stage is not taken into account because of the high level of uncertainty about the fate of the materials many decades into the future. In addition, Crowther [25] has found that the energy

associated with the end of life stage often represents less than 1% of the life cycle energy demand of a building and is therefore insignificant.

>>FIGURE 1 HERE

1.2 Structure

This paper starts by reviewing a number of existing studies on the life cycle benefits of building energy efficiency regulations in Section 2. Section 3 describes the approach; the case study buildings — and scenarios; the quantification techniques for embodied, thermal and life cycle energy requirements as well as the energy efficiency variations applied to the buildings. Results are presented in Section 4. Section 5 evaluates their sensitivity to the variation of key parameters and Section 6 discusses them before concluding in Section 7.

2 Studies on the life cycle benefits of building energy efficiency regulations

There is an increasing interest in assessing the life cycle energy demand and life cycle environmental effects of buildings in the scientific community. This is evidenced by the various recent reviews on the topic [18-20, 26] which have identified an increasing number of studies. Amongst these, few try to evaluate the life cycle benefits of building energy efficiency regulations.

Studies that evaluate the impact of improved building thermal energy efficiency can be categorised into two main groups: studies dealing with life cycle cost (LCC) and studies dealing with life cycle assessment (LCA), most commonly life cycle energy analysis (LCEA). While studies focusing on the LCC of energy efficiency measures (e.g Morrissey and Horne [27]) or insulation (e.g Hasan [28] or Ozel [29]) are important and can provide an insight into the effectiveness of building energy efficiency regulations from a monetary perspective, this is not the focus of this study. As stated in Section 1.1, this paper focuses on the life cycle energy implications of these regulations.

One of the most comprehensive reviews of the life cycle energy demand of standard and low energy buildings was conducted by Sartori and Hestnes [30] in 2007. In this study, they review 60 existing studies and conclude that low-energy houses always have a lower life cycle energy demand compared to standard houses. However, the studies they reviewed all rely on process analysis for the

quantification of embodied energy and can therefore underestimate its significance. Among the 60 buildings reviewed, 3 were assessed using a hybrid analysis, i.e those in Fay et al. [31] and Treloar et al. [32]. Yet, the significantly higher embodied energy in these cases put down to the variability of energy carriers from country to country while it is due to the broader system boundaries of the life cycle inventory. The findings from Sartori and Hestnes [30] cannot be considered as reliable as embodied energy could be significantly underestimated.

More recent studies have compared the energy use of low energy buildings, notably *PassivHaus* certified buildings, to standard buildings built to minimum standards. Dahlstrøm et al. [15] have conducted a full LCA of a conventional and *PassivHaus* building in Norway. They found that the low energy house requires additional initial embodied energy for insulation and systems but that this is quickly paid off in terms of operational energy savings. Another main finding was the significance of the heating system from a primary energy perspective. As in Gustavsson and Joelsson [33] they find that an electrically heated *PassivHaus* is comparable to a conventional house heated by a heat pump. Dadoo et al. [13] have undertaken a similar analysis in a Swedish context but have focused solely on energy use. Their comparison of dwellings built to the 1994 and 2009 Swedish regulation and to a *PassivHaus* standard reveal that the latter has the lowest life cycle energy demand over 50 years when the same heating energy source is used. They also found that the energy source for heating played a significant role in the primary energy demand and associated greenhouse gas emissions. A similar conclusion was also reached by Kneifel [34] in his comprehensive study on the LCC and life cycle greenhouse gas (GHG) emissions of new commercial buildings in the USA. He found that buildings located in states where electricity production was GHG intensive yielded more significant reductions in overall GHG emissions compared to those located in states with larger renewable energy shares in their electricity mix. He also finds that embodied GHG emissions are paid off rapidly by a decrease in operational emissions.

While these studies provide an insight on the life cycle energy demand and greenhouse gas emissions of conventional and more energy efficient buildings, they suffer from two drawbacks, most importantly the underestimation of embodied energy due to the method of assessment used and the limited scope of energy efficiency improvements and climates considered.

Indeed, apart from Kneifel [34] who relies on input-output analysis (which still underestimates embodied energy by a factor of up to 2 [17, 23]), all other studies rely on process analysis. While

Stephan et al. [16] have used hybrid analysis to assess the life cycle primary energy demand of a conventional and *PassivHaus* building in Belgium, their study only considers two levels of energy efficiency and does not consider different climates. The effect of climate can be critical and should also be evaluated.

This limitation is also present in the other studies which consider two to three levels of energy efficiency, often a base case, an intermediate level and a low energy level. Dahlstrøm et al. [15] and Stephan et al. [16] do investigate material and systems changes but they do not vary the thermal energy efficiency beyond their initial levels and for different climates.

There is therefore a need to comprehensively assess the life cycle energy benefits of building energy efficiency regulations at different thermal performance levels. The method used to undertake this assessment is described in the following section.

3 Quantifying the life cycle energy benefits of building energy efficiency regulations

This section details the method used to investigate the life cycle energy repercussions of increasing the energy efficiency of residential buildings. Background information on Australian building energy efficiency regulations is first given as well as the general research approach. This is followed by a description of the case study houses and the steps taken to improve their operational energy efficiency. The algorithms and software used to quantify embodied, operational and life cycle energy requirements are then described.

3.1 Approach

Australian residential building energy efficiency regulations are contained within the Building Code of Australia (BC) [8]. The BCA requires that a residential building meet minimum thermal performance levels under the 6 Star Standard. This minimum performance threshold of 6 Stars (out of a possible 10) defines a maximum heating and cooling demand in final energy terms, for a particular climate [10]. A 10 Star building is a near zero thermal operational energy building. Heating and cooling requirements can vary from 39 MJ/m²·a for the climatic zone of Sydney East, New South Wales (Mediterranean climate, *Cfb* in the Köppen climate classification) to 406 MJ/m²·a for Wyndham, Northern Territory (tropical wet and dry climate, *Aw* in the Köppen climate classification). The

disaggregation of thermal requirements into 69 climate zones across Australia makes the Australian energy efficiency regulations one of the most climate-specific, globally. In comparison, the USA relies on eight different climate zones, Spain on five, France on two and Germany on only one [9] in setting targets for their energy efficiency regulations. This precision, along with the refined scale of energy efficiency levels make Australian building energy efficiency regulations ideal as a basis for evaluating the life cycle energy implications of the implementation of energy efficiency regulations.

This paper uses a case study approach to evaluate the life cycle energy implications of increasing energy efficiency levels in an Australian context and for two different climates. Figure 2 depicts the general research approach used. The overall approach is to evaluate the life cycle energy (see Figure 1) of a 6 Star base case residential building before gradually improving its energy efficiency level to 7, 8 and 9 Stars and quantifying the associated life cycle energy repercussions. The improvements in energy efficiency are based either on additional materials (insulation and glazing) or on alterations to the building design. A combined scenario is then generated based on combinations of material and design strategies. Section 3.3 details the changes made for each improved scenario. The reductions in thermal operational energy requirements are compared to the additional embodied energy requirements and the net life cycle benefit is determined. This is undertaken for two different climates: Melbourne (Maritime temperate, *Csb* in the Köppen classification) and Brisbane (Warm temperate, *Cfa* in the Köppen classification).

>>FIGURE 2 HERE

3.2 Case study building and climates

A new typical suburban three-bedroom single family house was chosen as the case study. 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 [35]. Figure 3 shows the floor plan of the house.

203

204 >>FIGURE 3 HERE

205

206 As described in Section 3.1, the base case house meets the minimum 6 Star energy efficiency
207 standard for Melbourne. For Brisbane, some minor adaptations are made to the envelope assemblies
208 in order to achieve the minimum 6 Star requirement. Table 1 summarises the characteristics of the
209 base case house, for Melbourne and Brisbane.

210 >> TABLE 1 HERE

211

212 This section has described the original base case houses for both Melbourne and Brisbane. The
213 following section presents the material and design changes made to reach higher energy efficiency
214 levels.

215 **3.3 Energy efficiency improvements by material and design changes**

216 As mentioned in Section 3.1, the energy efficiency of the base case house is gradually improved to
217 meet 7, 8 and 9 Star ratings. The first approach to improving energy efficiency consists of changes to
218 the insulation levels and glazing type (double and triple glazing) which can have a significant effect on
219 embodied energy depending on the glazed area, the type of frames and argon/krypton filling used
220 (improvement by material). The second approach (improvement by design) attempts to make design
221 changes that require little, no or less embodied energy but that can yield significant operational
222 energy savings. These include exposing concrete floors (i.e. removing carpets); improving shading by
223 installing eaves, pergolas and exterior blinds; adding ceiling fans as well as reductions in the size of
224 windows. Changing the original brick veneer external walls to reverse brick veneer is also considered.
225 This change is included in the 'design changes' although it also involves minor changes to building
226 materials. This choice is made because the overall quantity of materials needed is approximately the
227 same and therefore this modification does not significantly effect embodied energy.

228 Improvement strategies are then combined to generate the highest possible star rating. A pragmatic
229 approach is adopted when selecting improvement strategies for the combined scenario. Uncommon
230 or unrealistic improvements are not considered eventhough they could contribute to an improved star

rating, e.g. insulated concrete wall construction, insulating the garage and significant design changes such as clerestory windows, skylights or floor plan changes. Instead, the final optimised version is kept within the realms of practical and typical construction materials and techniques used in Australia, and the overall floor plan/design and style of the house is kept the same. This shows what is practicably possible with a generic house design and strengthens the applicability of the results to a wider range of dwellings.

Tables 2 and 3 provide the changes made to the base case for the improved scenarios as well as the combined scenario in Melbourne and Brisbane, respectively. Houses reaching an 8 and 9 Star rating for Melbourne were impossible to achieve using the specified design improvement strategies. For this reason, only a 7 Star house is considered for the improvement by design changes' scenario for Melbourne.

>> TABLE 2 HERE

>> TABLE 3 HERE

3.4 Embodied energy requirements

The embodied energy of the base case scenario as well as all improved scenarios was quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar [36]. Treloar's approach combines bottom-up industrial data specific to manufacturing processes and economic top-down data that provide average energy intensities for sectors of the economy. This combination ensures that the most reliable data is used where available but also that energy use across the complete supply chain of the material is considered by evaluating upstream production stages and non-material inputs through average economic data. Crawford [22] has demonstrated that process analysis can omit up to 87% of the embodied energy of a particular product compared to a hybrid analysis. Lenzen [37] has shown that using input-output data in life cycle inventories is always better than not including it, regardless of the uncertainty arising from using national average energy intensities. Majeau-Bettez [38] and Dixit et al. [39] have demonstrated that hybrid analysis is the most comprehensive and reliable approach to assess the embodied energy of buildings.

Equation 1 is used to quantify the initial embodied energy of each house (IEE_h). The quantity of each material (Q_m) in each house (including wastage) is multiplied by a relevant material hybrid embodied energy coefficient (EC_m). These coefficients were compiled by Treloar and Crawford [40] to facilitate the use of hybrid analysis and comprise both industrial and economic data. The embodied energy of the house is the sum of the embodied energy of all its constituent materials. A so-called ‘input-output remainder’ covering all non-material processes (e.g. insurance, advertising, administration, etc.) is then added to this total to ensure that the complete supply chain supporting the construction of the house is taken into account. This remainder, which is not accounted for in studies relying on process analysis alone, is calculated by multiplying the price of the house in Australian Dollars (AUD) by the combined energy intensity of the input-output pathways representing the services within the entire supply chain of the house which are not accounted for with the use of material hybrid coefficients.

$$IEE_h = \sum_{m=1}^M (Q_m \times EC_m) + \left(TER_{rb} - \sum_{m=1}^M TER_m \right) \times C_h \quad (1)$$

Where: IEE_h = Initial embodied energy of the house in GJ; Q_m = Quantity of material m in the house (e.g. ton 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; and C_h = Cost of the house in AUD.

The initial embodied energy (IEE_h) is complemented by the recurrent embodied (REE_h) which accounts for the replacement of materials over the period of analysis. Studies by Fay et al. [31], Crawford [41], Stephan et al. [42], Stephan [43] and Rauf and Crawford [44], have shown that recurrent embodied energy can represent more than 60% of the initial embodied energy of a house over 50 years. The recurrent embodied energy was calculated as per Equation 2, by multiplying the quantity of each material (Q_m) by its embodied energy coefficient (EC_m) and adding the input-output remainder at the material level. This amount of energy is then multiplied by the number of material replacements over the period of analysis (POA). The average service live of materials is based on Ding [45] and NAHB [46].

$$REE_h = \sum_{m=1}^M \left[\left(\frac{POA}{SL_m} - 1 \right) \times \left[Q_m \times EC_m + TER_{rb} - TER_m - TER_{i \neq m} \times C_m \right] \right] \quad (2)$$

Where: REE_h = Recurrent embodied energy of the house h in GJ; POA = Period of analysis, in years;
 SL_m = service life of the material m , in years; $TER_{\neq m}$ = 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. All other variables are the same as in Equation 1.

The life cycle embodied energy of the house ($LCEE_h$) is obtained by summing the initial and
embodied energy requirements (i.e. $IEE_h + REE_h$)

3.5 Operational energy requirements

The 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). Heating and cooling 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. CHEENATH takes into account solar radiation, thermal mass
and natural ventilation and uses a time step of one hour. For all evaluated scenarios, the house was
assumed to be occupied as per the official guidelines of the Australian building energy efficiency
regulations: thermal comfort is maintained from 7 am to 12 am in living spaces (20°C for heating and
24°C for cooling) and from 4 pm to 9 am in sleeping spaces (18°C for heating from 4 pm to 12 am and
from 7 am to 9 am, 15°C for heating from 12 am to 7 am and 24°C for cooling at all times). The
internal heat gains comprise both sensible and latent heat and are given in Appendix A for the
different space types, per m² and per hour. The resulting 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
examples).

However, while dynamic energy simulation software can model building physics accurately, the
estimated energy demand still depends heavily on the occupancy of the building which is user-
dependant. A study by the Australian Greenhouse Office (AGO) [47] has shown that simulated energy
demands often overestimated the actual energy use in real-life buildings. This is confirmed in a study
by Williamson et al. [48] that showed significant discrepancies between measured and simulated

energy use. In particular, their study 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 [47] introduced so-called '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 for both locations [47]. The introduction of these factors can significantly affect the results and this is further discussed in Section 5.

Once corrected for occupancy, final energy requirements need to be converted to delivered and then to primary energy terms in order to take into account losses upstream in the energy supply chain [49]. Delivered energy takes into account losses due to the efficiency of the heating/cooling supply system. In this paper, cooling is assumed to be delivered by a split air conditioner with a cooling coefficient of performance (COP) of 2.5 based on AGO [47]. The heater system is a ducted gas heating with an efficiency of 0.7 based on the same source. These heating and cooling systems are the most commonly installed in Melbourne and Brisbane, Australia.

Primary energy is calculated using a primary energy conversion factor which is most often highest for electricity. This is due to distribution losses as well as high losses at the plant. For instance, Stephan and Stephan [24] have shown that the primary energy conversion factor for electricity can be as high as 3.8. This factor is 3.4 and 3.1 for Melbourne and Brisbane, respectively, based on Treloar [50]. The primary energy conversion factor for gas is taken as 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 4, by multiplying the final annual energy demand computed by FirstRate5 by the appropriate constraint factor, dividing the result by the efficiency of the heating or cooling system and multiplying the delivered energy by the relevant primary energy factor and the period of analysis. It is assumed that the energy demand remains constants over the life of the building. This is further discussed in Section 6.3.

$$LCTOPE_h = POA \times \left(PEF_{s=H} \times \frac{FHE_{FR5} \times CFH}{\eta_H} + PEF_{s=C} \times \frac{FCE_{FR5} \times CFC}{\eta_C} \right) \quad (3)$$

Where: $LCTOPE_h$ = Life cycle primary thermal operational energy of the house h in GJ; POA is the period of analysis, in years; $PEF_{s=H}$ and $PEF_{s=C}$ are the primary energy conversion factors for the source s used for heating H and cooling C , respectively, in GJ/GJ; FHE_{FR5} and FCE_{FR5} are the final

annual heating and cooling energy demands as calculated by FirstRate5, respectively, in GJ; CFH and CFC are the heating and cooling constraint factors; and η_H and η_C are the heating and cooling system efficiency.

3.6 Life cycle energy requirements

The total life cycle energy requirements (LCE_h) of the house are calculated by adding its life cycle embodied energy and its life cycle primary thermal operational energy as per Equation 4.

$$LCE_h = LCEE_h + LCTOPE_h \quad (4)$$

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. $LCE_h - LCE_{BC}$.

4 Results

This section presents the results of the study. It first compares the life cycle energy demands of houses with increasing thermal energy efficiency levels in Melbourne and Brisbane with the relevant base case house. The second part compares the contributions of embodied and thermal energy to the overall life cycle energy demand.

4.1 Net life cycle energy benefits of material and design improvements

Figures 4 and 5 compare all houses with a star rating equal to or higher than 7 to the base case 6 Star house in Melbourne and Brisbane, 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.

>>FIGURE 4 HERE

>>FIGURE 5 HERE

Three main findings can be observed. These are related to improvement by materials, improvement by design and the correlation between star rating and life cycle energy demand. These findings are described below.

Additional insulation and glazing only are not the solution

While scenarios that rely on improvements by material change result in significant reductions in thermal operational energy, they lead to insignificant life cycle energy savings and can even result in a higher life cycle energy demand because of an increase in embodied energy. In the case of Brisbane (see Figure 5), all three improved scenarios with a higher star rating than the base case (7, 8 and 9 Stars) paradoxically have a higher overall life cycle energy demand than the base case house. In the case of Melbourne, the largest reduction occurs for the 7 Stars house (-21 GJ) while the 9 Stars house saves the least (-9 GJ). In other words, the point at which simply increasing the thermal performance of a house's envelope (without considering broader design changes) does not yield anymore life cycle energy savings lies around the 6-7 Star mark for Melbourne and Brisbane. This result is in line with the findings of Stephan [43] and Crawford and Stephan [23] 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 cycle of the building.

Improvements by design can reduce both thermal and embodied energy demands

Conversely, improvements by design tend to yield the most benefit across the life cycle of the houses. For both Melbourne and Brisbane the scenario with the lowest life cycle energy requirement is a scenario with only design changes (7 Star in Melbourne (-145 GJ) and 9 Star in Brisbane (-303 GJ)). In these cases, the reduction in life cycle energy demand is associated with the choice of reverse brick veneer as the outer wall assembly as well as exposing the concrete slab. The reverse brick veneer increases the thermal mass which can yield significant final cooling energy demand savings [51, 52]. This is particularly visible in the 7 Star by design house in Melbourne, where the cooling demand is reduced more than the heating demand (see Figure 4). Exposing the slabs also increases the accessible thermal mass in the houses but as importantly reduces the quantity of carpet which results in reducing the recurrent embodied energy demand. For instance, the 9 Star by design house in Brisbane has a non-thermal-related recurrent embodied energy demand 309 GJ lower than in the base case scenario (see Figure 5), which represents 74% of all life cycle energy savings. This shows

that when attention is paid to the whole building, including finishes and not only to thermal performance, a well designed house can outperform standard practice in regards to both embodied and thermal operational energy demands.

The highest star rating does not guarantee the lowest life cycle energy demand, even if design changes are included

As depicted in Figures 4 and 5, scenarios that combine material and design changes, although achieving the highest star rating of all scenarios, do not result in the lowest life cycle energy demand. This is mainly due to the significant additional embodied energy associated with the higher thermal performance of the envelope. In the case of Melbourne, the combined scenario is the second best performer from a life cycle energy perspective, requiring 135 GJ less than the base case scenario. The additional embodied energy for insulation materials and high performance glazing (474 GJ) is paid off by the reduction in heating and cooling demand (507 GJ). However, in Brisbane, the additional thermal-related embodied energy (535 GJ) far outweighs the associated thermal energy savings (118 GJ). This demonstrates the need to consider embodied energy.

4.2 The significance of embodied energy

Figure 6 depicts the life cycle energy demands of the base case house in Melbourne and Brisbane, by energy demand. It shows that embodied energy requirements are more significant than for thermal primary energy. For the base case scenario, embodied energy requirements over 50 years represent 89% of the total for Melbourne (4 729 GJ) and 97% of the total for Brisbane (2 575 GJ). This demonstrates the significance of embodied energy and the need to consider it in building energy efficiency regulations, most importantly for energy efficient buildings where the space heating and cooling demands are reduced. Building energy regulations around the world are currently omitting this significant energy demand.

>>FIGURE 6 HERE

The high contribution of embodied energy is due to two main factors: the mild climates of Melbourne and Brisbane compared to parts of Europe and the USA where most previous studies have been conducted (e.g [14, 15, 33]) and the use of hybrid analysis for the quantification of embodied energy.

Indeed, the base case house in Melbourne and Brisbane need to have a maximum final annual thermal energy demand of 113.6 MJ/m²·a (31.5 kWh/m²·a) and 43 MJ/m²·a (12 kWh/m²·a) in order to meet the requirements of the Building Code of Australia [8] for a 6 Star rating. The minimum requirement for Melbourne is below the low energy house requirements of 60 kWh in most European countries (e.g. in Belgium [53]) and the minimum requirement in Brisbane is lower than for the *PassivHaus* standard [54]. In other words, all new houses in Brisbane require, in theory, less final thermal energy than some of the most energy efficient houses in Central and Northern Europe. The impact of climate explains why the scenarios with a higher star rating by material changes result in a significant increase in embodied energy for a relatively small reduction in thermal energy demand in Brisbane (see Figure 5). In addition to the climate factor, the use of hybrid analysis leads to a significant initial embodied energy intensity (19 GJ/m²) which is much higher than in previous studies relying on process analysis (e.g. 2.4 GJ/m² in Dadoo et al. [13]). This difference illustrates the significance of the quantification technique used and the need to use hybrid analysis in future building life cycle energy analysis studies.

5 Sensitivity analysis

Any model is a representation of reality and therefore will always suffer from a level of uncertainty. The model used to quantify embodied energy as well as the software and algorithm used to quantify primary thermal operational energy are no exception to this rule. The uncertainty affecting embodied energy results calculated using the hybrid approach is considered to be within the range of ±40% [17]. The thermal operational energy used within a house can vary greatly between households. For example, Steemers et al. [55] and Graham-Hansen [56] have shown that the same building can have energy bills that differ by a factor of 200% to 300% for different occupants. The variability resulting from user behaviour must be considered.

This section presents a sensitivity analysis on the life cycle energy demand of the improved and base case scenarios. The embodied energy of each house is varied by ±40% and the thermal operational energy is changed by modifying the constraint factors provided by the AGO [47] to 0.1 and 1.2 from their current values of 0.45 and 0.25 for heating in Melbourne and Brisbane, respectively and 0.4 for cooling in both locations. For example, the nominal specific heating demand of the base case scenario in Melbourne is 87 MJ/m²·a which is currently multiplied by 0.45 to obtain 40.89 MJ/m²·a. In

the sensitivity analysis, this factor would range from 0.1 to 1.2 and the resulting final heating energy demand will be 8.7-104.4 MJ/m²·a. This is then converted to primary energy terms. The values for the new constraint factors are based on the 2-3 times variability in operational energy observed by Steemers et al. [55] and Graham-Hansen [56]. The constraint factors for heating and cooling are assigned the same value as each other in the sensitivity analysis in order to identify the extreme cases of low and high operational energy use. This sensitivity analysis effectively considers a broader range of scenarios for the evaluation of the net benefits of increasing thermal energy efficiency of residential buildings.

Figures 7 and 8 show the sensitivity analysis of the life cycle energy benefits of all scenarios in Melbourne and Brisbane, respectively. The main result is that regardless of uncertainty and location, improvements by design always result in a reduction in life cycle energy demand. This confirms the findings of Section 4 and the importance of design in improving a building's life cycle energy performance compared to simply increasing envelope energy efficiency.

>>FIGURE 7 HERE

The sensitivity analysis also shows that improvements by material changes could result in significant benefits in Melbourne if embodied energy has been overestimated and thermal energy use has been underestimated. The potential energy savings are also more significant than potential increases in energy use. In comparison, Brisbane's milder climate results in a smaller variation in magnitude of life cycle energy demand potential improvements in the case of high data uncertainty (a maximum of 541 GJ variation compared to 1 508 GJ for Melbourne). This further confirms the impact of climate.

>>FIGURE 8 HERE

Overall, the level of potential uncertainty and variability in the data is concerning as the main findings of this paper could be quite different. More robust embodied energy databases and more accurate operational energy simulations are needed to better evaluate the life cycle energy benefits of higher energy efficiency levels.

Conducting the sensitivity analysis on the total energy use and not only the difference in energy use between the base case and improved scenarios confirms the significance of embodied energy. Even in the extreme case of overestimating actual embodied energy by 40% and underestimating actual thermal operational energy by a factor of 2.7, life cycle embodied energy would still represent more than 60% of the total energy demand.

6 Discussion

This section discusses the results of the study and contextualises them. It summarises the limitations of current building energy efficiency regulations and proposes amendments to better ensure that net energy benefits can be achieved. The limitations of this study are also discussed.

6.1 Current building energy efficiency regulations

This study has investigated the life cycle energy implications (over 50 years) of increasing thermal energy efficiency levels in residential buildings. It has demonstrated that simply adding insulation and high performance glazing can paradoxically result in an increase in life cycle energy demand, if no design changes are made. Figure 5 shows that increasing energy efficiency by simply relying on additional materials beyond the minimum 6 Star level in Brisbane's climate is detrimental to the aim of reducing life cycle energy demand. For Melbourne, there seems to be very small to almost no net benefit in improving efficiency by increasing the thermal performance of the building's envelope beyond 7 Stars. Thermal operational energy is reduced but this saving is then offset by an increase in embodied energy. For these reasons, current residential building energy efficiency policies do not necessarily lead to a net reduction in energy use.

Other avenues of energy efficiency improvement should be investigated, such as adopting a design approach. As can be seen in Figures 4, 5, 7 and 8, if building designers make small changes to their buildings in terms of material choice, solar access, thermal mass, carpet cover and other aspects, they can simultaneously improve the operational energy efficiency of the design and reduce its embodied energy for no or a small increase in the financial cost associated with materials. This is valid regardless of the high uncertainty in the data. However, this approach is currently not encouraged. This could be the result of the traditional focus on insulation in building energy efficiency regulations in Europe and the USA, which have, on average, much colder climates. The milder climate of Australia dictates a different approach to building energy efficiency.

Apart from these aspects, the scenarios combining design and material changes investigated in this study reveal that it might not be worthwhile pushing operational energy efficiency to an extreme level. Indeed, the scenarios 9★M&D and 10★M&D have a similar life cycle energy requirement compared to the base case (-2% for 9★M&D in Melbourne and +0.4% for 10★M&D in Brisbane). This result confirms the findings of Stephan et al. [16] who have shown that a *PassivHaus* in Belgium can have the same life cycle energy demand as a house meeting minimum energy efficiency standards. Instead of constantly increasing operational energy efficiency, future building energy efficiency regulations should also focus on regulating embodied energy.

6.2 Future building energy efficiency regulations

Including embodied energy in building energy efficiency regulations has been advocated by a number of previous studies [11, 12, 17, 42]. This study confirms this need by showing the significance of embodied energy in an Australian context. The fact that the embodied energy of houses does not significantly vary between climates (see Figure 6) is a further incentive to regulate embodied energy. However, this would only be possible and effective by adopting hybrid analysis as a common quantification approach, developing embodied energy databases for materials and enforcing environmental product declarations [57] for building materials. In light of the ever stricter building energy efficiency regulations, e.g. the EPBD that imposes nearly zero energy buildings from 2020 for new buildings in the EU [7], integrating embodied energy is and will become more critical as more materials are required to reduce operational energy use and to produce energy on-site.

The significance of embodied energy is further highlighted by the associated greenhouse gas emissions. Indeed, initial embodied energy represents 48-58% of the life cycle energy across all scenarios (see Figure 6). This initial embodied energy currently generates significant amounts of greenhouse gas emissions into the atmosphere as energy is mostly produced through the combustion of fossil fuels [58]. Operational energy and recurrent embodied energy are spread over the 50 years period of analysis during which significant reductions in greenhouse gas emission intensities are likely to occur. For this reason, the greenhouse gas emissions associated with the initial embodied energy of a house have been dubbed 'the carbon spike' in a study by Säynäjoki et al. [59]. In addition, as demonstrated by Kendal et al. [60] and Schwietzke et al. [61], greenhouse gases emitted in the coming ten years have a significantly higher global warming potential than future emissions. Initial

embodied energy is therefore critical to include in future building energy efficiency regulations. Recurrent embodied energy can be as significant but is harder to control as the replacement of building materials depends to a large extent on unpredictable factors such as the taste of the user, damage resulting from user behaviour, change in trends and other factors. Recurrent embodied energy is analysed in detail in Rauf and Crawford [44].

Favouring improvements by design is another major path that should be supported by future regulations. The fact that all improvements by design resulted in net life cycle energy benefits, regardless of the significant uncertainty in the data, demonstrates the relevance of favouring a design approach as compared to simply increasing the thermal performance of the building envelope. Improvements by design have the capacity to reduce both thermal operational and embodied energy requirements simultaneously (see Figures 4 and 5). The inclusion of embodied energy in future regulations might be a way to support design improvements in houses to enhance their life cycle energy performance.

Including other operational energy end-uses should also be a main focus of future building energy regulations. These include hot water, appliances, lighting and cooking. These end-uses should ideally be considered in final, delivered and primary energy terms. For instance, the current version of the European Energy Performance of Buildings Directive [7] covers space heating, space cooling, mechanical ventilation, domestic hot water and lighting in its scope. While this is a praiseworthy approach, it is critical to include all operational energy uses, notably appliances.

Figure 9 shows the life cycle energy breakdown of the Base case 6 Star house in Melbourne when considering all primary operational energy uses. Figures for hot water, appliances, lighting and cooking are based on averages from DEWHA [62] and on an occupancy of four users. These figures are averages and are used to demonstrate the significance of non-thermal operational energy.

>>FIGURE 9 HERE

When the non-thermal primary operational energy demand is considered, the life cycle operational energy demand becomes very significant accounting for more than 50% of the total over 50 years. The post-occupancy study of Crawford [63], which uses the actual energy bills of household, also finds that the total primary operational energy demand can account for up to 40% of the life cycle

energy demand of a 7 Star suburban house over 50 years. Figure 9 also shows the relatively small contribution of operational thermal energy requirements (6%) compared to non-thermal operational energy requirements (50%) and the need to take them into account. This small contribution of thermal energy is significantly different from the generally accepted average in Australia, i.e. 40% of the operational energy is associated with space heating and cooling [62] because a 6 Star house is much more efficient than the average building stock in Australia. With the increased operational energy efficiency of buildings, thermal requirements represent a smaller contribution and the focus should include the range of other demands, as shown by Blengini and Di Carlo [14].

Appliances represent the highest operational energy demand. The very high primary energy conversion factor for electricity in Victoria, Australia, due to the reliance on wet brown coal for electricity generation is partly responsible for this significant contribution. However, with the continuing proliferation of electronic devices, the operational energy associated with appliances is expected to continue to grow in the coming decades [62, 64]. Reducing the energy demand of appliances is therefore a critical aspect to consider in future energy policy.

6.3 Limitations

This study suffers from a number of limitations. Firstly, it considers only thermal operational energy and does not take into account non-thermal energy requirements which can be very significant (see Figure 9). 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). The results suffer from significant uncertainty and variability. While this point has been covered in Section 5, a more detailed sensitivity analysis targeting individual variables, should be undertaken. Despite these limitations, this study provides one of the most detailed life cycle energy analyses of current building energy efficiency regulations to date.

7 Conclusion

Improving the energy efficiency of buildings should not only focus on thermal requirements but should also include the embodied energy of buildings. Other non-thermal operational energy requirements should also be considered in primary energy terms. The significant contribution of embodied energy to the life cycle energy demand of buildings, regardless of the climate and the thermal energy performance of the building emphasises the need for more comprehensive 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 and elsewhere. More comprehensive building energy efficiency policies will ultimately help reduce energy use and associated greenhouse gas emissions.

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Appendix A: Internal heat gains for all investigated houses

This appendix details the internal heat gains, both sensible and latent, that are considered for all investigated houses. Each table provides the values used for a type of space, based on [65].

>>TABLE A1 HERE

>>TABLE A2 HERE

>>TABLE A3 HERE

Figure 1: System boundary of the current study

Figure 2: Flowchart diagram of the research approach

Figure 3: Floor plan of the case study house.

Figure 4: Difference between the life cycle energy demand of improved scenarios and the base case house in Melbourne over 50 years. Note: text is displayed on the right of the bars with values for improved readability, where applicable; Δ = difference, IEE = initial embodied energy, REE = recurrent embodied energy, M = improvement by material, D = improvement by design, M&D = improvement by a combination of material and design.

Figure 5: Difference between the life cycle energy demand of improved scenarios and the base case house in Brisbane over 50 years. Note: text is displayed on the right of the bars with value for improved readability, where applicable; Δ = difference, IEE = initial embodied energy, REE = recurrent embodied energy, M = improvement by material, D = improvement by design, M&D = improvement by a combination of material and design.

Figure 6: A comparison of embodied and thermal operational energy contributions to the life cycle energy demand over 50 years of the base case 6 Star house in Melbourne and Brisbane. Note: IEE = initial embodied energy, REE = recurrent embodied energy.

Figure 7: Sensitivity analysis of the difference between the life cycle energy demand of improved scenarios and the base case house in Melbourne over 50 years, due to variability and uncertainty in the data. Note: M = improvement by material, D = improvement by design, M&D = improvement by a combination of material and design.

Figure 8: Sensitivity analysis of the difference between the life cycle energy demand of improved scenarios and the base case house in Brisbane over 50 years, due to variability and uncertainty in the data. Note: M = improvement by material, D = improvement by design, M&D = improvement by a combination of material and design.

Figure 9: Life cycle primary energy demand breakdown of the base case 6 Star house in Melbourne over 50 years, including non-thermal operational energy, by use. Note: figures may not sum due to rounding; LCEE = Life cycle embodied energy and LCOPE = Life cycle primary operational energy.

Figure 1
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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 <i>Csb</i> in the Köppen classification Zone 21 in the FirstRate5 ^a tool	Warm temperate <i>Cfa</i> in the Köppen classification Zone 10 in the FirstRate5 ^a tool
Orientation	Kitchen / Family to North (see Figure 3)	
Site	Suburban terrain	
Areas	135.4 m ² net conditioned floor area (NCFA) 9.8 m ² unconditioned utilities (bathroom and laundry) 38.9 m ² unconditioned Garage 36.68 m ² glazing	
Roof	Concrete tile attic-type roof with 160 mm fibreglass insulation batts (U-value=0.29 W/(m ² ·K)) and a 60 mm reflective blanket (U-value=0.77 W/(m ² ·K)) Metal deck roof to garage, no insulation	
External walls	Brick veneer walls with 90 mm fibreglass insulation batts (U-value=0.5 W/(m ² ·K)) plus single sided reflective foil Single brick walls to garage, no insulation	
Internal walls	Plasterboard on stud frame, 90 mm fibreglass insulation batts (U-value=0.5 W/(m ² ·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/(m ² ·K); g-value: 0.69	Timber framed, toned single glazing U-value = 5.7 W/(m ² ·K); g-value: 0.52
Heating energy demand (MJ/m ² ·a)	87 ^b	8 ^b
Cooling energy demand (MJ/m ² ·a)	25 ^b	33.9 ^b
Total final thermal energy (MJ/m ² ·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

Note: ^a FirstRate5 is a certified dynamic software tool used to calculate the thermal energy efficiency of buildings in Australia (see Section 3.4 for more details).

^b As calculated with FirstRate5.

^c Constraint factors correct estimated heating and cooling demands to account for actual occupancy (see Section 3.5 for more details).

Table 2

Table 2: Changes made to improved energy efficiency scenarios for Melbourne, Australia

Improvement type	Improvement by material			Improvement by design	Combination scenario
Star rating	7★	8★	9★	7★	9★
Roof	Replace insulation with 275 mm fibreglass batts (U-value=0.16 W/(m ² ·K))	Replace insulation with 365 mm fibreglass batts (U-value=0.125 W/(m ² ·K)) and a 100 mm reflective blanket (U-value=0.44 W/(m ² ·K))	See previous column	-	Replace insulation with 365 mm fibreglass batts (U-value=0.125 W/(m ² ·K)) and a 100 mm reflective blanket (U-value=0.44 W/(m ² ·K))
External walls	Replace insulation with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K)) and a 20 mm reflective insulation board (U-value=2 W/(m ² ·K))	See previous column Replace foil with a 30 mm reflective insulation board (U-value=0.71 W/(m ² ·K))	See previous column	Reverse Brick Veneer	Reverse Brick Veneer Replace insulation with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K)) and a 30 mm reflective insulation board (U-value=0.71 W/(m ² ·K))
Internal walls	-	Replace insulation in walls to unconditioned utility with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K))	See previous column	-	Replace insulation in exposed walls to unconditioned utility with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K))
Floors	-	Install insulation below slab (U-value=0.5 W/(m ² ·K)) except under garage	See previous column	Exposed concrete to living and dining rooms	Install insulation below slab (U-value=0.5 W/(m ² ·K)) except under garage Exposed concrete to living and dining rooms

Improvement type	Improvement by material			Improvement by design	Combination scenario
Star rating	7★	8★	9★	7★	9★
Windows	Replace single glazing in living areas with double clear glazing (U-value=3.58 W/(m²·K); g-value=0.62) Opaque glass in entry	Replace all single glazing with double clear glazing (U-value=2.84 W/(m²·K); g-value=0.64) Opaque glass in entry	Replace all single glazing with triple low-emissivity glazing (U-value=1.21 W/(m²·K); g-value=0.45)	-	Replace all single glazing with double low-emissivity glazing (U-value=1.21 W/(m²·K); g-value=0.45)
External shading	-	-	-	North pergola (Summer/Winter transparency 20%/80%) 1.5 m External blinds to habitable windows	North pergola (Summer/Winter transparency 20%/80%) 1.5 m External blinds to habitable windows
Ceiling fans	-	-	-	To all living rooms and bedrooms	To all living rooms and bedrooms
Glazed area	-	-	-	Reduce by 35.8%	Reduce by 35.8%

Table 3

Table 3: Changes made to improved energy efficiency scenarios for Brisbane, Australia

Improvement type	Improvement by material			Improvement by design			Combination scenario
Star rating	7★	8★	9★	7★	8★	9★	9★
Roof	Replace insulation with 275 mm fibreglass batts (U-value=0.16 W/(m ² ·K))	Replace insulation with 365 mm fibreglass batts (U-value=0.125 W/(m ² ·K)) and a 100 mm reflective blanket (U-value=0.44 W/(m ² ·K))	See previous column	-	-	-	Replace insulation with 365 mm fibreglass batts (U-value=0.125 W/(m ² ·K)) and a 100 mm reflective blanket (U-value=0.44 W/(m ² ·K))
External walls	Replace insulation with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K)) and a 20 mm reflective insulation board (U-value=2 W/(m ² ·K))	See previous column Replace foil with a 30 mm reflective insulation board (U-value=0.71 W/(m ² ·K))	See previous column	Reverse Brick Veneer	See previous column	See previous column	Reverse Brick Veneer Replace insulation with 200 mm fibreglass batts (U-value=0.4 W/(m ² ·K)) and a 30 mm reflective insulation board (U-value=0.71 W/(m ² ·K))
Floors	-	Install insulation below slab (U-value=0.5 W/(m ² ·K)) except under garage	See previous column	Exposed concrete to living and dining rooms	See previous column	Exposed concrete in all rooms	Install insulation below slab (U-value=0.5 W/(m ² ·K)) except under garage

Improvement type	Improvement by material			Improvement by design			Combination scenario
Star rating	7★	8★	9★	7★	8★	9★	9★
Windows	Replace single glazing in living areas with double toned glazing (U-value=3.55 W/(m²·K); g-value=0.44) Opaque glass in entry	Replace all single glazing with double toned glazing (U-value=2.9 W/(m²·K); g-value=0.38) Opaque glass in entry	Replace all single glazing with triple low-emissivity toned glazing (U-value=1.4 W/(m²·K); g-value=0.29) Opaque glass in entry	-	-	-	Replace all single glazing with double low-emissivity glazing (U-value=1.21 W/(m²·K); g-value=0.45)
Eaves	-	-	-	-	-	1.2 m eaves	1.2 m eaves
External shading	-	-	-	-	External blinds to all windows (excluding garage)	See <i>previous column</i>	External blinds to all windows (excluding garage)
Other	-	-	-	Light roof and wall colours	See <i>previous column</i>	See <i>previous column</i>	Light roof and wall colours

Table A1: Internal heat gains used in all investigated houses, for living spaces, including kitchens, per hour.

Time	Appliances and cooking (W/m ²)	Lighting (W/m ²)	People (W/m ²)	Total (W/m ²)	Latent heat gains (W/m ²)
1:00 AM	1.25	0	0	1.25	0
2:00 AM	1.25	0	0	1.25	0
3:00 AM	1.25	0	0	1.25	0
4:00 AM	1.25	0	0	1.25	0
5:00 AM	1.25	0	0	1.25	0
6:00 AM	1.25	0	0	1.25	0
7:00 AM	1.25	0	0	1.25	0
8:00 AM	5	2.25	3.5	10.75	5
9:00 AM	1.25	2.25	3.5	7	2.5
10:00 AM	1.25	0	1.75	3	1.25
11:00 AM	1.25	0	1.75	3	1.25
Noon	1.25	0	1.75	3	1.25
1:00 PM	1.25	0	1.75	3	1.25
2:00 PM	1.25	0	1.75	3	1.25
3:00 PM	1.25	0	1.75	3	1.25
4:00 PM	1.25	0	1.75	3	1.25
5:00 PM	1.25	0	1.75	3	1.25
6:00 PM	1.25	3.75	2.625	3	1.875
7:00 PM	13.75	3.75	2.625	20.125	9.375
8:00 PM	3.125	3.75	2.625	9.5	1.875
9:00 PM	3.125	3.75	2.625	9.5	1.875
10:00 PM	3.125	3.75	2.625	9.5	1.875
11:00 PM	1.25	0	0	1.25	0
Midnight	1.25	0	0	1.25	0

Source: Based on [65]

Table A2: Internal heat gains used in all investigated houses, for living spaces that do not include a kitchen, per hour.

Time	Appliances and cooking (W/m ²)	Lighting (W/m ²)	People (W/m ²)	Total (W/m ²)	Latent heat gains (W/m ²)
1:00 AM	0	0	0	0	0
2:00 AM	0	0	0	0	0
3:00 AM	0	0	0	0	0
4:00 AM	0	0	0	0	0
5:00 AM	0	0	0	0	0
6:00 AM	0	0	0	0	0
7:00 AM	0	0	0	0	0
8:00 AM	0	2.25	3.5	5.75	1.75
9:00 AM	0	2.25	3.5	5.75	1.75
10:00 AM	0	0	1.75	1.75	0.875
11:00 AM	0	0	1.75	1.75	0.875
Noon	0	0	1.75	1.75	0.875
1:00 PM	0	0	1.75	1.75	0.875
2:00 PM	0	0	1.75	1.75	0.875
3:00 PM	0	0	1.75	1.75	0.875
4:00 PM	0	0	1.75	1.75	0.875
5:00 PM	0	0	1.75	1.75	0.875
6:00 PM	0	3.75	2.625	6.375	1.3125
7:00 PM	0	3.75	2.625	6.375	1.3125
8:00 PM	0	3.75	2.625	6.375	1.3125
9:00 PM	0	3.75	2.625	6.375	1.3125
10:00 PM	0	3.75	2.625	6.375	1.3125
11:00 PM	0	0	0	0	0
Midnight	0	0	0	0	0

Source: Based on [65]

Table A3: Internal heat gains used in all investigated houses, for bedrooms, per hour

Time	Lighting (W/m²)	People (W/m²)	Total (W/m²)	Latent heat gains (W/m²)
1:00 AM	0	2.5	2.5	1.25
2:00 AM	0	2.5	2.5	1.25
3:00 AM	0	2.5	2.5	1.25
4:00 AM	0	2.5	2.5	1.25
5:00 AM	0	2.5	2.5	1.25
6:00 AM	0	2.5	2.5	1.25
7:00 AM	0	2.5	2.5	1.25
8:00 AM	0	0	0	0
9:00 AM	0	0	0	0
10:00 AM	0	0	0	0
11:00 AM	0	0	0	0
Noon	0	0	0	0
1:00 PM	0	0	0	0
2:00 PM	0	0	0	0
3:00 PM	0	0	0	0
4:00 PM	0	0	0	0
5:00 PM	0	0	0	0
6:00 PM	0	0	0	0
7:00 PM	0	0	0	0
8:00 PM	1.25	0	1.25	0
9:00 PM	1.25	0	1.25	0
10:00 PM	1.25	0	1.25	0
11:00 PM	1.25	2.5	3.75	1.25
Midnight	0	2.5	2.5	1.25

Source: Based on [65]

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