



Energy-efficient dwellings – Can embodied energy spoil the story?

How energy-efficient homes make up for the energy embodied in their building materials ... for now.



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In one page

Energy-efficient homes reduce their operating energy costs and carbon emissions, and new design principles and technologies are making them ever more efficient. Yet some of the materials used to build them are themselves energy- and emissions-intensive to make. Does that matter? Many believe that the gains from lower operating energy far outweigh the embodied energy in even the most energy-intensive materials. To date, analysis on the question has been relatively rare. The market is uncertain as to how much attention should be given to the resource- and emissions-intensity of quality materials used in sustainable design.

Edge Environment has used life cycle assessment (LCA) to review the energy and emissions performance of a typical Australian freestanding home. This analysis considered the location and use of homes, their construction and their end-of-life decommissioning. We have drawn on both the existing LCA literature and our own work on the energy-efficient CSR House, built in 2013. By analysing and benchmarking different building and appliance options for CSR House, we were also able to answer questions left open by previous research. The conclusions from this research were consistent and clear.

Investments to reduce operational energy, including sustainable design using emissions-intensive materials, remain well worth it. Investing in an energy-efficient home pays off environmentally and financially. The energy drawn for the home's typical domestic use (operational energy) still dominates total lifecycle energy use. Each of the occupier's behavioural choices can dramatically reduce it, by smart and efficient appliances, and by sustainable design and choices of building materials. These savings comfortably outweigh additional emissions, if any, embodied in the materials used in sustainable design. As the cost premiums of non-'standard' materials continue to fall and energy prices continue to rise, sustainable design will also continue to be financially attractive.

However, more attention should be paid to embodied emissions, as they are already significant and are becoming more so. Even so, embodied emissions cannot be ignored. While most lifecycle emissions are due to the building's use, the building's materials account for at least 10-20%. As the buildings become more energy-efficient, that proportion is rising and embodied energy is almost matching operational energy in the most efficient designs. Moreover, as designers can influence but not control occupant behaviour, their choice of building material may account for up to half of the lifecycle emissions that they can control.

These findings have clear implications for home users, for design and construction businesses, and for their material suppliers. Designers and builders should continue to focus on the designs and materials that will reduce operational energy, including by influencing low-emission appliances and behaviour, but start to demand materials that minimise lifecycle emissions. Suppliers should continue to meet that demand with resource-efficient and low-emission production, both to reduce their operating costs and to maximise their market access and sales. Homeowners and users should seek out sustainably designed homes: with it, their own appliance and behavioural choices will save much in energy costs; without it, those choices will reward them less.

Lifecycle energy and carbon performance: the story to date

Focusing on carbon, not overall environmental performance

In debates on ‘sustainable housing’, at least three interdependent outcomes are often mistakenly boiled down to one: environmental performance, energy efficiency, and greenhouse gas or ‘carbon’ emissions. Some studies use carbon emissions as the primary environmental metric: a proxy for broad environmental consequences of energy use, and as a driver for climate change. However, that proxy may be misleading. A house with lower lifecycle carbon emissions (LCE) could very well have higher water consumption, energy consumption or other environmental impacts. The environmental metric that matters most depends on where you are. In a land with plentiful water and costly energy supplies, predominantly from fossil fuels, low energy use may be the priority. In a land with little water and plenty of cheap solar energy, water efficiency may be paramount. In a land with plenty of water and energy, yet overloaded waste infrastructure, all parties may be seeking waste minimisation. Then, there are regional contributions to global environmental impacts to consider.

The key environmental outcomes of emissions, resource use and biodiversity are related, though quite distinct. Energy resources and emissions are more closely intertwined, however, with carbon performance typically dependent on both the energy used, and the emissions intensity of that energy. In our assessments for this article, we considered only carbon performance, defined as:

$$\begin{aligned}
 \text{Carbon performance} &= \frac{\text{Carbon emissions (kg CO}_2\text{e)}}{\text{Area of floor space (m}^2\text{)}} \\
 &= \frac{\text{Energy/Material} \times \text{emissions intensity of energy/material}}{\text{Area of floor space (m}^2\text{)}}
 \end{aligned}$$

Lifecycle assessment

Life cycle assessment (LCA) is the accepted method to calculate the emissions of a building or of any component material or process in its making. LCA scientifically measures emissions (or other impacts) from “cradle to grave”: from the extraction of raw materials, through manufacturing, use and maintenance, to final disposal. To compare buildings using cradle-to-grave LCA, four important equivalences must be considered:

1. **Location equivalence.** The thermal properties and performance of a building will depend on its climate and location, as well as the orientation on the site, and its geographic surroundings (parklands, asphalt, neighbourhood buildings etc). The emission intensity of grid electricity also varies significantly between regions in Australia, with Tasmania being served by a large portion of hydro-electric power, and the eastern seaboard predominantly by coal-powered electricity with very high emissions intensity. An LCA comparison must consider location-specific variables and climatic conditions.
2. **Functional equivalence.** An LCA comparison must also be made between dwellings with the same demographics, lifestyle and behavioural assumptions. There is little point in comparing the inner city apartment of 2 ‘dinks’ (double-income-no-kids) with a freestanding home for a family of 5 in a new sub-division 30km from the CBD. There may be other economic, aesthetic, community and sustainability drivers of housing choices within a city, but the LCA must consider comparable building choices for a house designed for the same purpose in the same location.

The LCA can then determine variances in environmental performance as the purpose or occupancy assumptions change.

3. **Appliance and fixture equivalence.** The LCA should start by assuming that the homes have comparable assumptions for their appliances (electronics, lighting, water, heating, cooking, cleaners etc.) and fixtures (claddings, cupboards etc.). Again, variances in environmental performance are revealed as these assumptions change
4. **Operational life equivalence.** Whatever a house's intended life, it may last longer if well maintained, or be demolished prematurely when fashions change [2]. The assessment life must be reasonable and standardised. Comparative LCA studies in Australia and internationally use 50–75 years as a dwelling's life span^{1 2}.

Our analysis of CSR House's life cycle produced findings that are consistent with most other findings in the professional literature on LCAs of our domestic buildings.

Deconstructing lifecycle emissions

In considering the lifecycle emissions of a building, we isolate four contributing factors to total emissions: materials, construction, operations (use and maintenance), and decommissioning. Operational emissions may in turn be divided into four elements, and the lower the better for each one:

1. **Thermal load.** Thermal load represents the gap between the desired comfort levels of a building, and the levels achieved by the building itself, without air-conditioning, heating or other artificial ventilation. It includes both the heating load in winter and the cooling load in summer, given its location. For example, if the ambient outdoor temperature is 10°C at the site, the thermal performance of the building lifts it to 15°C inside, and the desired indoor temperature is 21°C, then at that time the thermal load is the missing 6°C. As the thermal performance of the building increases, the remaining thermal load is reduced. Accredited software can determine a building's thermal performance, its corresponding NatHERS rating and whether it meets a State's regulatory requirements.
2. **Home appliances.** These are the appliances generally built into the home: the heating, ventilation and air-conditioning (HVAC plant), stoves, hot water and lighting. Each item must deliver a defined level of comfort for the occupier. However, the appliances vary in their energy use and emissions in meeting those levels. For example, a gas or wood combustion heater will generally be more carbon efficient than an electric heater. Decisions on home appliances are made in construction and relatively rarely afterwards.
3. **Occupier appliances.** These are all the 'plug-in' items, from fridges to TVs to iPads to toothbrushes, which come and go with the occupier.
4. **Behaviour.** Whatever the technical limits of the thermal load and appliances, actual energy use and emissions are dependent on the occupier's behaviour. This can be influenced by the home's design and appliances, but not controlled. Whether a window is open or closed matters more than what it is made of.

¹ 50 years used by [2] [4] [7] [9], 60 years used by [6] [8], and 75 years used by [5].

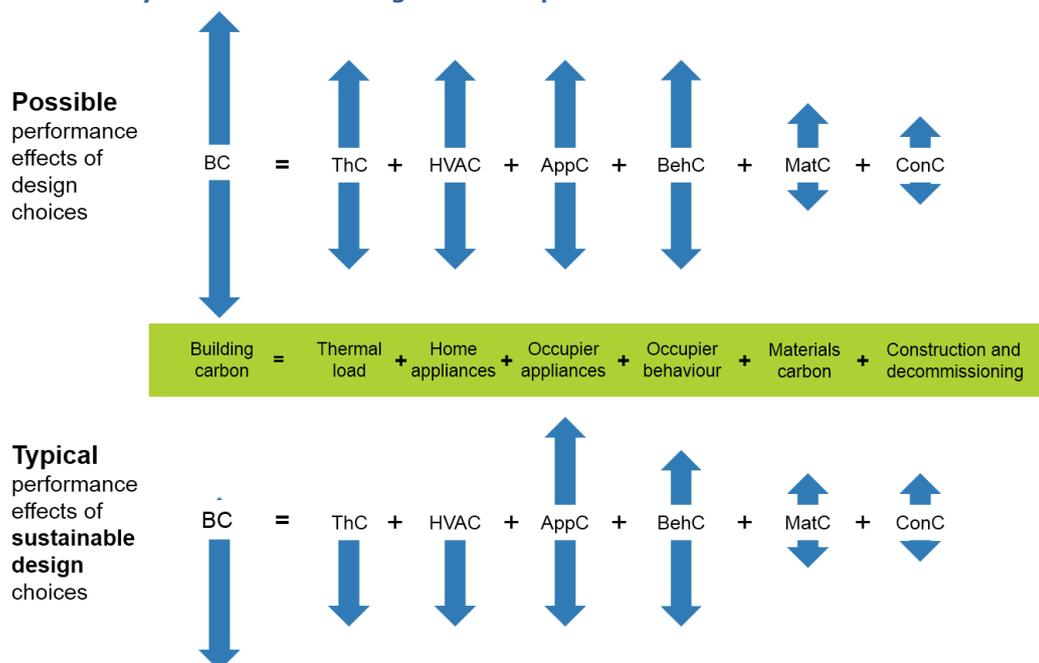
² However building stock assessments in New Zealand have estimated significant longer life span between 90 – 110 years [1].

In essence, the thermal load and home appliances are owner/designer/builder-driven, and the last two elements are occupier-driven. Note that as well, the thermal load is a function of both the layout and the building materials chosen. Putting all these elements together delivers the following summary equations:

$$\begin{aligned}
 \text{Building carbon (BC)} &= \text{Materials} + \text{Construction} + \text{Operations} + \text{Decommissioning} \\
 &= \text{Operations} + \text{Materials} + (\text{Construction} + \text{Decommissioning}) \\
 &= (\text{Thermal load} + \text{Home appliances} + \text{Occupier appliances and behaviour}) + \text{Materials} + (\text{C} + \text{D}) \\
 &= \text{ThC} + \text{HVAC} + \text{AppC} + \text{BehC} + \text{MatC} + \text{ConC}
 \end{aligned}$$

The relative impacts of these elements of BC are depicted in Figure 1 below. As we will see, operational emissions of the building (due to design, appliances and behaviour) still typically dominate overall emissions. However, operational emissions are falling rapidly, due to better thermal design and more efficient HVAC appliances. With growing energy and carbon awareness, emissions from occupier appliances and behaviours are also falling. As total operational emissions fall, the source and emissions-intensity of building materials are becoming increasingly significant at the domestic level. They are already and will become more significant to total emissions of the construction sector and of the economy.

Figure 1: Variability in domestic building emissions performance



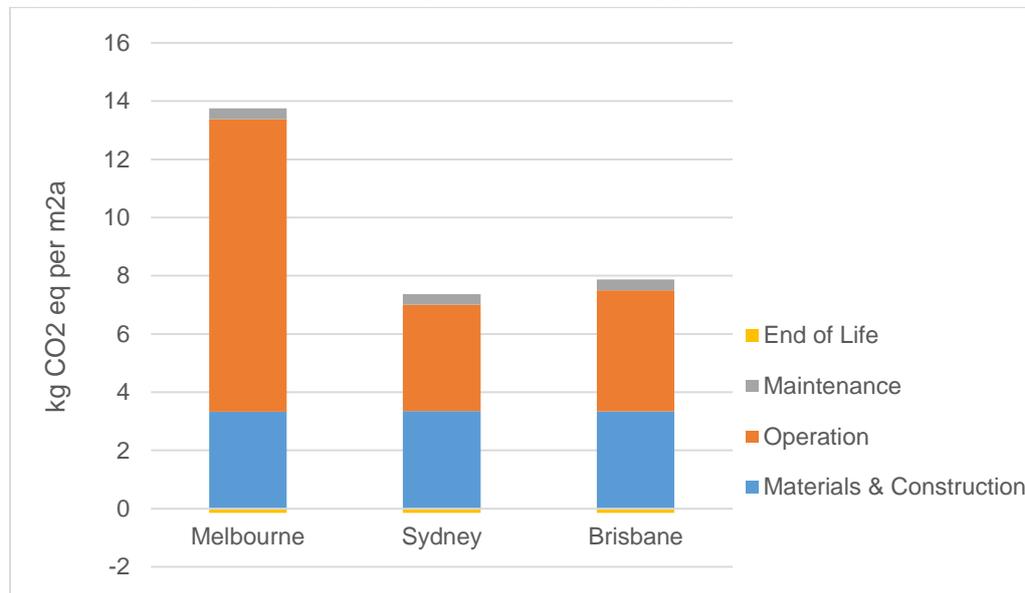
Current literature on lifecycle emissions

Recent reviews by two Australian building materials industries, timber and brick, have confirmed that operational energy accounts for the lion's share of total lifecycle emissions for dwellings. Forest & Wood Products Australia (FWPA) commissioned RMIT to review the international literature and to compare lifecycle emissions for a typical Australian house design constructed from alternative yet commonly used materials. The international literature was relatively consistent: finding that total operational energy contributes 76-92% of total lifecycle emissions. The more extreme the climate,

with greater heating and cooling loads, the more operational energy is needed. In their *Comparative Life Cycle Assessment of Alternative Constructions of a Typical Australian House Design*, all construction methods were set to achieve 5-star rating under the Nationwide House Energy Rating Scheme (NatHERS).

Figure 2 shows the carbon performance of the benchmark house in Sydney, Melbourne and Brisbane. Assessed over 50 year life spans, operations accounted for 74% of total lifecycle emissions in Melbourne, though only 51 to 54% in the milder Sydney and Brisbane. As the design of the house is improved to achieve a NatHERS 6-star rating, operational efficiency improves, so that materials and construction account for a higher portion of total lifecycle emissions. However, the published results did not identify the make-up of the operational share of emissions: how much was due to thermal load and the HVAC appliances needed to meet it, and how much was due to occupier choices in behaviour and plug-in appliances.

Figure 2: Life cycle impact drivers per m², 5 Star energy performance



adapted from FWPA study [2], House (d)).

Rather than compare different buildings, Think Brick Australia's *Life Cycle Analysis of Brick Products* took a more detailed look at the energy performance of an insulated brick veneer house. It examined different floor plans, climatic zones, orientations and construction materials to determine the balance between the energy embodied in materials and the energy consumed when the house is occupied. Over a 50-year life, total operational energy accounted for 90% of total lifecycle emissions: plug-in appliances being responsible for nearly 50% of all energy use, followed by lighting (14%), domestic hot water (14%) and HVAC (12%). Embodied emissions in the house's materials accounted for just 10% of total emissions. However, embodied carbon make up the majority of the lifecycle emissions directly influenced by the home's designers and builders: 45-59% compared to 35-50% for the core HVAC operations, and just 5% for construction and deconstruction.

Looked at this way, the environmental impacts embodied in our building materials cannot be ignored when taking a holistic life cycle perspective of our dwellings. In moderate climates such as Sydney and Brisbane, embodied carbon verges on being half of all emissions able to be directly influenced by designers and builders. And, as we will see, that share is rising.

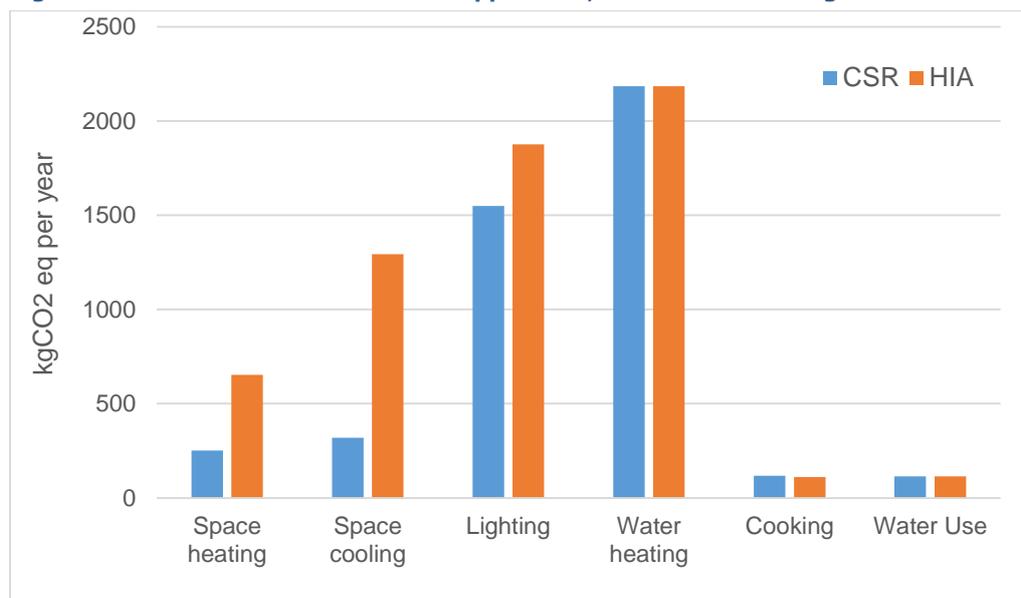
Reducing lifecycle emissions: the CSR House story

Edge Environment had the opportunity to test the relative impact of embodied and operational emissions, when it was commissioned to do an LCA of the CSR House. Launched in November 2012 in western Sydney, the CSR House is an energy-efficient display home that doubles as a working research and development facility to test house comfort, aesthetics and energy efficiency. Its designer and builder, CSR, is a leading building products company in Australia and New Zealand that is continually innovating to develop low-emission solutions, as are many of its competitors.

Our LCA compared the energy and environmental performance of CSR House across 23 climate zones in Australia, and benchmarked it against the Housing Industry of Australia's (HIA) reference building of similar size. While the HIA house was designed to achieve a NatHERS rating of 6 stars, the CSR House was designed to achieve 7.2–8.4 stars across the 23 zones. Both houses used high-efficiency gas for heating, water and cooking, 6-star rated air conditioning, and average-efficiency lighting.

Figure 3 shows the difference in annual heating and cooling emissions that the 2 extra NatHERS stars of stronger thermal performance delivers: a 61% reduction in heating emissions, and a 75% reduction in cooling emissions. Greater access to natural light also reduced lighting emissions by about 18%.

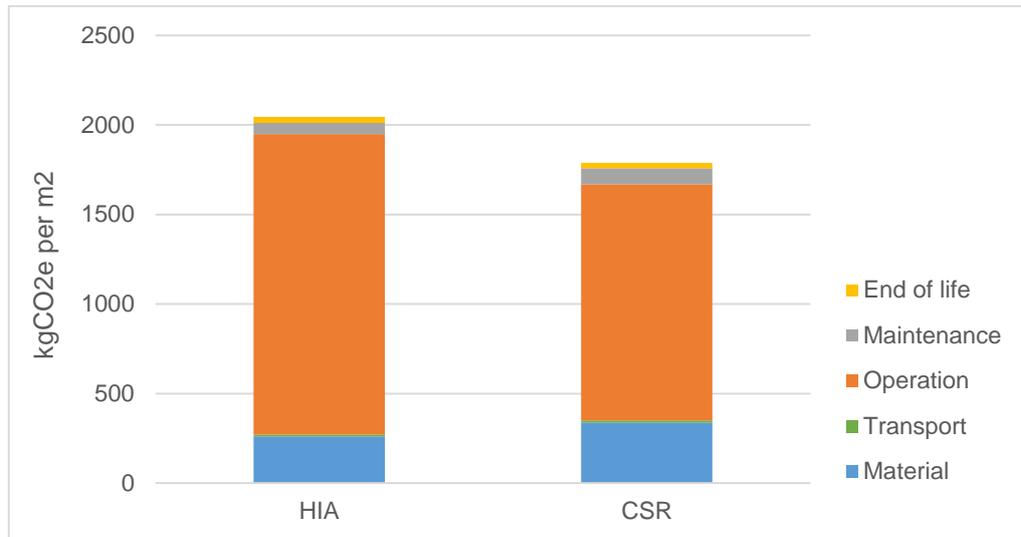
Figure 3: Annual emissions for home appliances, CSR House as designed vs HIA house



Over a 70-year life in the north-western Sydney climate with standard appliances, operational energy to meet the thermal load and other home appliances made up 77% of BC for the HIA house and 70% for the CSR house, see Figure 4. Overall, the CSR House had 19% lower BC than the HIA house. This was achieved despite the design using materials that themselves had higher embodied energy. The lower emissions from operational energy more than made up for the slightly higher emissions for the building materials. So lowering operational emissions remains key to lowering BC. This is before taking into account more energy-efficient occupier appliances and behaviour.

If operational energy is the dominant component of lifecycle emissions, how do we reduce it? There are three major levers: sustainable design and materials, energy-efficiency appliances and energy-aware behaviour. Arguably, all three are equally powerful.

Figure 4: 70-year lifecycle emissions for HIA and CSR houses with standard appliances

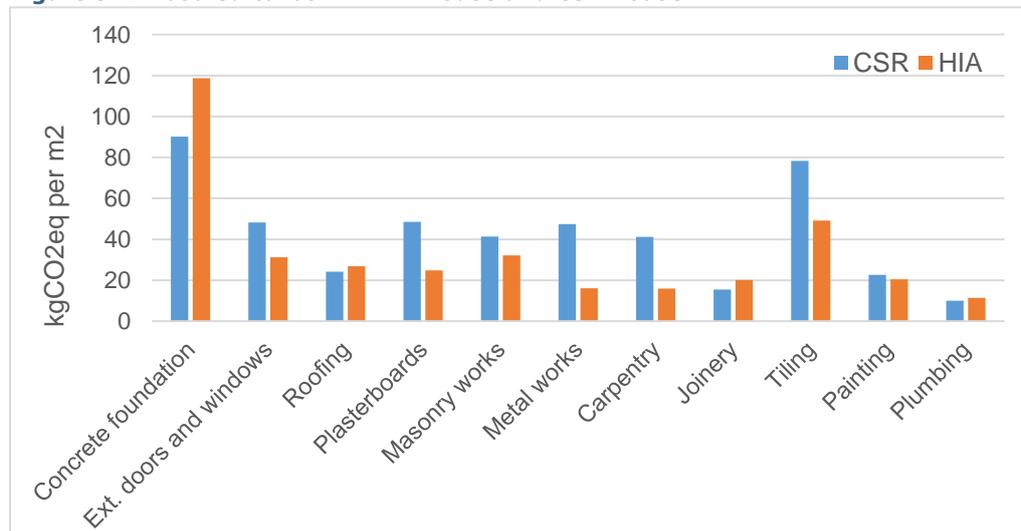


Sustainable design and materials

Our study of the CSR house readily shows the impact of sustainable design. Going back to Figure 4, we see that overall lifecycle emissions for the CSR house were 13% lower than for the benchmark HIA house with the same appliances. The embodied carbon (i.e. all non-operational carbon) in the CSR house (468kg CO₂eq/m²) was about 100kg CO₂eq/m², about 27.5% higher than that in the HIA standard house (367kg CO₂eq/m²). However, the effect of using those materials and the optimised design was to reduce operational carbon emissions by about 358kg CO₂eq/m², so that lifecycle emissions were reduced by 257kg CO₂eq/m², or over 100,000kg in total over 70 years' use.

In fact, the CSR house example exaggerates the additional embodied carbon needed to achieve lower operational energy. Some CSR house elements were chosen for their energy-efficiency: emission-intensive double-glazed windows were used to improve thermal performance. However, most of the increase in embodied carbon was due to aesthetic or functionality choices: metal works, carpentry, plasterboards and tiles. Figure 5 below shows how the non-operational embodied carbon for the CSR House compared with that of the HIA reference house. The additional tiling impact, for example, was due to the CSR house having 116m² in tiled areas, compared with 85m² in the HIA house, with the tiling assumed to be replaced every 20 years over the building's life.

Figure 5: Embodied carbon in HIA house and CSR house

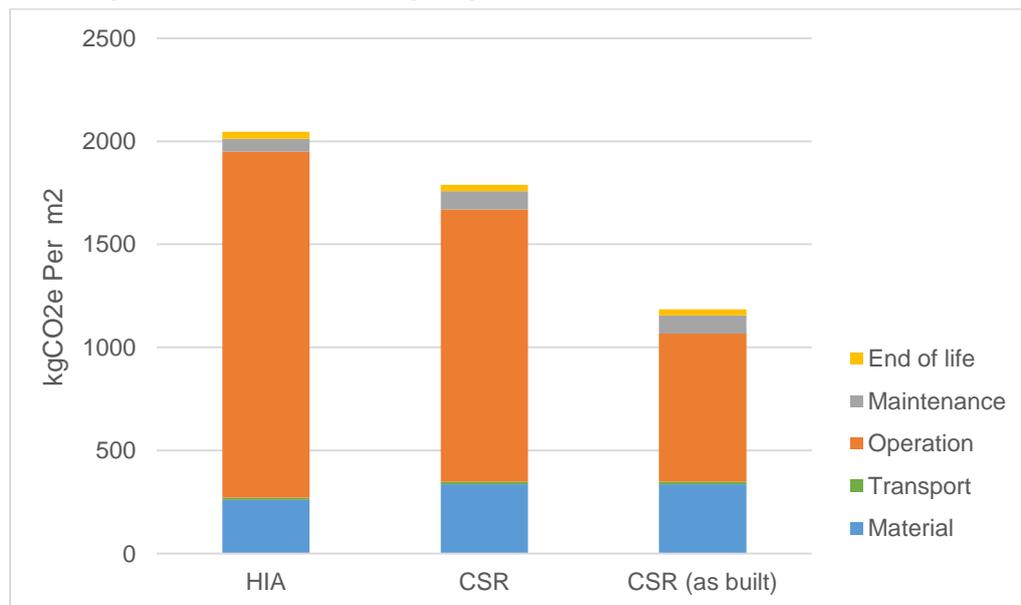


Energy-efficient home appliances

Although the exact measures vary, the RMIT, Think Brick and CSR House research is consistent in confirming the impact of energy-efficient home appliances. In the Think Brick example, home appliances accounted for nearly 50% of all energy use in a home, and 45% of total LCE over the home's 50-year life. The extent to which this energy use can be reduced is shown in Figure 6. The first two columns are the same as Figure 4: the HIA and CSR benchmark houses with standard appliances. The third column reflects the impact of the energy-efficient, low-emission appliances, lighting and hot water that were actually installed in the 'as built' CSR house. Operational energy is reduced by 46% compared to the standard CSR house, and total lifecycle emissions are reduced by 33%.

When these efficiencies are put in place, emissions embedded in the materials of the house become much more significant as a proportion of total emissions. Operational energy still accounts for 61% of total BC, but initial embedded emissions – not accounting for maintenance, replacements and end of life disposal – are now 29% of the total. The designers and owners who are investing to push down operational emissions are therefore starting to take a closer look at the initial embedded emissions that make the operational savings possible.

Figure 6: Life cycle carbon comparison of the standard 5 Star HIA house and the 8 Star CSR house over 70 years in north-western Sydney.



Occupant behaviour

Whatever the original design, the home's occupants will have a major effect on total BC. Occupiers determine whether the building's envelope is used effectively to store and release heat, how the installed home appliances are used, how many plug-in appliances there are and how efficient those plug-ins are. These choices can overwhelm, positively or negatively, the intentions of the original designers, builders and owners. We have not quantified the effects of occupant behaviour in our analysis of the CSR House. It is always worth stressing, however, that ease-of-use functionality does support the occupant's use of technical innovation to reduce energy use in the home.

Implications for sustainable design

Operational energy for our dwellings accounts for approximately 10% of Australia's total emissions, and we approach twice that if we include embedded emissions. We therefore need to continue to reduce direct and indirect residential emissions to meet any national emission target. The need to avoid rising energy costs means that homeowners and occupiers are increasingly curious of the thermal performance of their homes. Homes with poor performance risk losing value, or selling for less.

To date, the builders' equation has been one of cost and compliance: how little can we spend to meet the regulated standards or market demands for thermal performance, so that operational emissions are reduced to the policymaker's or home owner's satisfaction? This equation has been successful in ratcheting down operational emissions, and so life cycle emissions. It is also a virtuous cost circle. The demand for building materials that improve thermal performance has allowed their suppliers to innovate and increase scale, and so reduce their production cost. As their premium to 'standard' materials disappears, they are becoming the standard materials.

What then will distinguish between suppliers of these low-emission standard materials? The market will continue to value high thermal performance at low cost. However, as operational emissions fall, these materials are accounting for a far greater proportion of lifecycle emissions than previously. Increasingly, they are significant on their own terms, already often half of lifecycle emissions, and not just a side-issue to reduced operational emissions. As international and national reduction targets begin to bite, energy and emissions embodied in housing materials will stand out as an opportunity too obvious to avoid.

Focus through the value chain

The emerging exposure of embodied emissions to market and compliance scrutiny has implications for all parties in the residential value chain: investors, designers, builders, owners and suppliers.

Build-and-sell investors are not responsible for future operating costs, and so have the least immediate financial incentive to overspend on sustainable design. Yet the greater a home's thermal performance, the less they cost their owner/occupiers. In theory, these high performing homes should be valued more than a less thermally efficient one, all else being equal. This has not yet proven to be the case in Australia. Most investors commissioning new projects have an eye only to meeting regulated standards at least cost.

Intending owner-occupiers have a more obvious need to consider their home's current and potential energy costs. If they have an influence over the design and build, they have a strong incentive to balance the falling additional costs of sustainable design against the rising per-unit costs of energy - and to insist on off-grid energy solutions for their home. If the right investments aren't made in building, the owner-occupier will be paying for a long time. They should therefore insist on their architects and builders being able to estimate those costs, in both financial and emissions metrics. Equally, a buyer of an existing home must be aware of its energy assets and liabilities, and negotiate on them.

To the extent owner-occupiers are driving the market, designers need to be able to answer their needs. Occupiers and long-term investors are expecting solutions that are cost-effective yet deliver quality living and low operating costs. Fortunately, new building innovations are continually being brought to market to answer that challenge. The best commissions will fall to those designers able to assess the new solutions, and incorporate the best of them.

Builders have an equal part to play if they are to win contracts from the designers and long-term investors who can assess the net present value of sustainable design. Quality architects and builders learn from each other in a collaborative partnership. An innovation that looks good on paper may cause unintended problems on site. Builders will need to be aware of options. They will also need to know if there are major differences in the embodied performance of the same materials from different suppliers. Suppliers who have invested in low-emission production are able to reduce emissions by 1-2% annually. It doesn't take long before they can be streets ahead of their competitors, able to offer builders and designers reduced emissions for the same building performance, with little cost differential.

Project builders, substantial firms who are building thousands of dwellings a year, are in a different category. They will be looking at ways to gain priority access to scarce land, partnering with investors, local councils and state governments that are setting their own emissions targets. They also have the purchasing power to give scale advantages to suppliers with low-emission, quality product, all else being equal. Project builders are increasingly demanding standardised environmental reports (e.g. Environmental Product Declarations and ecolabels) that demonstrate the environmental performance of their suppliers.

Finally, project builders have the most immediate and largest incentive to reduce their per-unit emissions than anyone in this market. While individual dwellings have their own energy and emissions profile, suppliers are manufacturing the input for thousands of homes. What may be a marginal reduction in embodied emissions for one home, becomes a sector-significant reduction for a major supplier. The reduction in energy costs has an immediate financial benefit, which any pricing of carbon in the economy will magnify. As developers meet investors' increasing demand for low-emission construction, suppliers who can deliver low-emission, quality materials will be in the box seat. Without over-investing in those possibilities, there remains a lot of scope for reductions yet.

* * *

Our investigations of CSR House and HIA House adds to the existing research on the impact of embodied energy and emissions on the lifecycle emissions of our homes. Investing in an energy-efficient home continues to pay off environmentally and financially. While occupier choices continue to dominate life cycle emissions, good design and its communication will influence those choices. As technology-driven emissions continue to fall, more attention should be paid to embodied emissions. They are already a significant proportion of lifecycle emissions, and are becoming more so. The sector has come a long way in a short time in reducing those emissions, and they've only just begun.

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