A life cycle assessment approach to improving the energy performance of housing: a case study

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Abstract: The aim of this study was to conduct a streamlined life cycle assessment (LCA) to identify the global warming potential (GWP) of a single-storey residential house (283 m² floor area) located in Melbourne, Australia. Evaluation of the initial design through a life cycle assessment approach was used to inform further improvements to the house across its initial construction, operation and maintenance stages with the aim of reducing its global warming impact. An input-output-based hybrid approach was used to calculate embodied energy of building materials and components based on a bill of quantities. IES-VE software was used to estimate operational energy demands of the house. Energy demand was converted into carbon dioxide equivalent (CO₂-e) using emissions factors to determine global warming potential. Based on the initial design, the total life cycle energy demand of the house was 18,758 GJ (66 GJ/m²) and the initial global warming potential a significant 1,474 t CO₂-e (5.2 t CO₂-e/m²). The operational stage contributed 83% to the total global warming potential of the house. The redesign of the house focused on improving passive thermal performance using materials and systems readily available in the construction industry. Total life cycle energy demand was reduced by 29% to 13,238 GJ (47 GJ/m²). The initial global warming potential decreased by 29%, down to 1,039 t CO₂-e (3.67 t CO₂-e/m²) for the redesigned house. The study highlights the potential for further improvements and the need for alternative construction materials and technologies in the local construction industry.

Keywords: Life cycle assessment; embodied energy; housing.

1. Introduction
Residential energy use in Australia is significant and continues to increase due to an expanding population. According to EPA Victoria (2008), housing and residential energy use represents 5% and 16% of Victoria’s ecological footprint, respectively. Therefore, selection of building materials and systems must consider how they affect the embodied energy and operational energy demands of a building. The aim of this study was to assess the global warming potential of a typical new detached residential building across its initial construction, operation and maintenance stages using a streamlined life cycle assessment approach. Life cycle assessment (LCA) is a tool used to identify and evaluate the loads and
impacts imposed on the environment by a particular product. This includes effects linked with processes upstream in the supply chain (Curran, 1993). LCA includes every stage of a product’s life cycle, from raw material extraction to its final demolition and disposal. Operational functions and building elements with the most significant energy demands were then identified and redesigned to minimise global warming potential using construction materials and systems readily available in the local market.

2. Case study house

The study analyses a single-storey, detached residential building located in Melbourne, Australia. The floor area is 283 m², similar to the national average size of 248 m² (ABS, 2010). The house has three bedrooms, a pergola and detached garage and is typical of new housing constructed in Australia.

Figure 1 shows a 3D visualisation of the house. Construction materials used are listed in Table 1.

3. Research Method

3.1. System boundary

Figure 2 indicates the stages included within the system boundary of the study. Energy demands for all stages of the building life cycle are included except for demolition as this has been shown to be an insignificant component of a building’s life cycle energy demand and most difficult to accurately determine. The operation stage includes energy for heating, cooling, lighting and appliances. Excluded from this study are the landscaping elements and fitout items such as cabinetry, sinks and plumbing.

Figure 2: System boundary of the study.
3.2. Life cycle embodied energy and emissions

An input-output-based hybrid approach developed by Treloar (1997) was used in this study to achieve a more comprehensive assessment of embodied energy as it accounts for data gaps that tend to exist in a traditional process analysis (Crawford, 2011).

Embodied energy was calculated based on a bill of quantities established from the set of working drawings. Published embodied energy coefficients from Crawford (2011) and Hammond and Jones (2011) were then multiplied by the quantity of materials to determine initial embodied and recurrent embodied energy. Recurrent embodied energy was calculated based on the average service life data for the materials contained within the house. The initial embodied energy of each material was multiplied by the number of replacements required during the 50 year period of the study. The sum of initial and recurrent embodied energy then results in total life cycle embodied energy over 50 years.

Direct energy for the construction process and a remainder value to account for data gaps associated with sideways truncation of the system boundary were then added to the above embodied energy values. Using input-output analysis, direct energy was calculated based on the cost of the house and the direct energy intensity of the Residential Building sector (ABS, 2001). A direct energy figure of 64 GJ was calculated.

The remainder value was determined by subtracting the total energy intensity of all pathways from the input-output model covered by the embodied energy coefficients from the total energy intensity of the Residential Building sector (10.633 GJ/A$1000) and multiplying the sum of remaining pathways by the estimated cost of the house ($183,950).

Total life cycle embodied energy was converted into greenhouse gas emissions to determine global warming potential. A conversion factor of 60 kg CO$_2$-e/GJ of embodied energy was used as per previous studies (e.g. Treloar, 2000), based on the average fuel mix and emissions intensity of Australian energy supply.

3.3. Operational energy and emissions

The IES-VE plug-in for SketchUp was used to determine the amount of energy required during the operational stage of the house over a period of 50 years. Primary energy values (GJ) were calculated using a conversion factor of 3.4 for electricity and 1.4 for natural gas (Treloar, 2008). As recommended for Victorian households (AGO, 1999), constraint factors of 0.45 and 0.4 were then applied to predicted heating and cooling energy loads, respectively, to reflect occupancy levels and zoning. Operational primary energy was then multiplied by emission factors (Department of Climate Change, 2008) and global warming potential factors (IPCC, 2007) to determine the total operational energy-related emissions and global warming potential.

3.4. House redesign

The findings of the initial life cycle energy analysis were used to inform the redesign of the house. An iterative design process was used to inform the redesign process in order to reduce the life cycle energy and global warming potential of the original house. A focus was placed on optimising passive thermal performance in conjunction with life cycle embodied energy. The redesign was based on the use of currently available materials and construction technology with consideration of a typical client’s demands and budget.
4. Results

4.1. Embodied energy and emissions of initial house

For a 50 year period, the initial house was found to have a life cycle embodied energy demand of 4,219 GJ resulting in an estimated 253 t CO₂-e emissions. Table 1 shows a breakdown of the embodied energy and related emissions of the house, by element.

<table>
<thead>
<tr>
<th>Element</th>
<th>Materials</th>
<th>Life cycle embodied energy (GJ)</th>
<th>Life cycle embodied emissions (t CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishes</td>
<td>Wool carpet, paint, plasterboard</td>
<td>964.90</td>
<td>57.89</td>
</tr>
<tr>
<td>Substructure</td>
<td>Reinforced concrete</td>
<td>842.00</td>
<td>50.52</td>
</tr>
<tr>
<td>Roof</td>
<td>Colourbond, softwood structure</td>
<td>828.70</td>
<td>49.72</td>
</tr>
<tr>
<td>Wall</td>
<td>Brick veneer</td>
<td>361.89</td>
<td>21.71</td>
</tr>
<tr>
<td>Windows</td>
<td>Single glazing</td>
<td>103.70</td>
<td>6.22</td>
</tr>
<tr>
<td>Doors</td>
<td>MDF, aluminium</td>
<td>91.74</td>
<td>5.50</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>Heating: Gas ducted system</td>
<td>123.60</td>
<td>7.41</td>
</tr>
<tr>
<td>Direct energy</td>
<td></td>
<td>64.00</td>
<td>3.80</td>
</tr>
<tr>
<td>Remainder value</td>
<td></td>
<td>838.44</td>
<td>50.00</td>
</tr>
<tr>
<td><strong>Life cycle embodied energy (GJ)/Emissions (t CO₂-e)</strong></td>
<td><strong>4,219.01</strong></td>
<td><strong>252.77</strong></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Breakdown of life cycle embodied energy, by material.

A further breakdown of the embodied energy of the house by material (Figure 3), indicates that the steel roof sheeting, steel reinforcement in the concrete slab and the carpet are the three most significant contributors to the life cycle embodied energy. Attempts to reduce the embodied energy of the house should therefore focus initially on these materials.
4.2 Operational energy and emissions of initial house

Throughout the 50 year life cycle of the house, an estimated 14,539 GJ of primary energy is required for its operation (Table 2), resulting in an estimated 1,221 t CO₂-e emissions (Table 3).

<table>
<thead>
<tr>
<th>Use</th>
<th>Delivered energy (GJ)</th>
<th>Primary energy (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (22%)</td>
<td>2,332.8</td>
<td>3,265.92</td>
</tr>
<tr>
<td>Ducted system (gas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling (0%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Air conditioning (electricity)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equipment (34%)</td>
<td>1,445.4</td>
<td>4,914.36</td>
</tr>
<tr>
<td>Various (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting (44%)</td>
<td>1,870.2</td>
<td>6,358.68</td>
</tr>
<tr>
<td>Fluorescent (electricity)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>5,648</td>
<td>14,539</td>
</tr>
</tbody>
</table>

Table 3: Life cycle operational emissions of the initial house, by use.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Primary energy (GJ)</th>
<th>GHG</th>
<th>Emissions factor (kg/GJ)</th>
<th>Global Warming Potential</th>
<th>GWP (kg CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>11,273.04</td>
<td>CO₂</td>
<td>92.7</td>
<td>1</td>
<td>1,045,011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₄</td>
<td>0.0048</td>
<td>25</td>
<td>1,353</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N₂O</td>
<td>0.0013</td>
<td>298</td>
<td>4,367</td>
</tr>
<tr>
<td>Natural gas</td>
<td>3265.92</td>
<td>CO₂</td>
<td>51.2</td>
<td>1</td>
<td>167,215</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₄</td>
<td>0.0048</td>
<td>25</td>
<td>392</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N₂O</td>
<td>0.0029</td>
<td>298</td>
<td>2822</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,221,160</td>
</tr>
</tbody>
</table>

4.3. Life cycle global warming potential of initial house

The life cycle global warming potential of the initial house over a period of 50 years was found to be 1,474 t CO₂-e (5.21 t CO₂-e/m²) with operational energy-related emissions accounting for 83% of this. Heating accounts for the largest share of operational energy demand, but the smallest share of operational energy-related emissions due to the use of natural gas, characterised by a smaller primary energy conversion factor and emissions intensity than brown coal-fired electricity.

Based on the assessment of the initial house design and the fact that the overwhelming majority of the global warming impact associated with the house is due to operational energy demands, the chosen improvement strategies focus on reducing operational energy demand whilst at the same time ensuring that embodied energy is not considerably increased.
4.4. Redesigned house

As operational energy demand was identified as the most significant contributor to energy demand and greenhouse gas emissions, the redesign of the house focuses on passive thermal strategies while also considering strategies for reducing embodied energy via alternative construction materials and systems.

The redesign of the house used the LCA approach described in Section 3 to select construction materials and systems that would help to minimise life cycle energy demand and emissions through an iterative design and assessment process. Several design iterations were compared to select a proposal resulting in the lowest life cycle energy. To ensure an objective comparison of embodied energy and operational energy between iterative design strategies, operational energy was simulated in IES-VE by incorporating a single iteration at a time using the initial house design energy data as a base case. To save time, the operational energy shown in this comparison is in the form of delivered energy. A sample of this exploration is demonstrated below for alternative wall designs (Figure 4). Although a reverse brick veneer construction system has a higher embodied energy due to additional fibre cement cladding, the R-value improves significantly, thus reducing operational energy by a greater amount than the increase in embodied energy.

![Figure 4: Comparison of life cycle energy for external wall design options.](image)

The redesigned house used reverse brick veneer construction for the external walls; roof tiles in place of Colourbond steel sheeting; increased insulation levels in the floor, roof and walls; fluorescent lighting replaced with LEDs; single glazing replaced with double glazing; and carpet, steel and aluminium with a higher recycled content. All changes to the original house design are highlighted in Table 4, showing the breakdown of life cycle embodied energy and emissions for the redesigned house.
Table 4: Life cycle embodied energy and emissions of the redesigned house, by element.

<table>
<thead>
<tr>
<th>Element</th>
<th>Materials</th>
<th>Life cycle embodied energy (GJ)</th>
<th>Life cycle embodied emissions (t CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishes</td>
<td>Recycled nylon carpet, paint, plasterboard, ceramic tiles</td>
<td>794.80</td>
<td>47.69</td>
</tr>
<tr>
<td>Substructure</td>
<td>Reinforced concrete, (50% recycled steel), R3.0 insulation</td>
<td>906.40</td>
<td>54.38</td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete tiles, softwood structure, R4.0 insulation</td>
<td>678.4</td>
<td>40.70</td>
</tr>
<tr>
<td>Wall</td>
<td>Reverse brick veneer with fibre cement sheet and R2.5 insulation</td>
<td>521.85</td>
<td>31.31</td>
</tr>
<tr>
<td>Windows</td>
<td>Double glazing</td>
<td>202.70</td>
<td>12.16</td>
</tr>
<tr>
<td>Doors</td>
<td>MDF core, aluminum-recycled</td>
<td>76.62</td>
<td>4.60</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>Heating: Gas ducted system</td>
<td>123.60</td>
<td>7.41</td>
</tr>
<tr>
<td>Direct energy</td>
<td>64.00</td>
<td>3.80</td>
<td></td>
</tr>
<tr>
<td>Remainder value</td>
<td>838.44</td>
<td>50.00</td>
<td></td>
</tr>
<tr>
<td><strong>Life cycle embodied energy (GJ)/Emissions (t CO₂-e)</strong></td>
<td><strong>4,206.81</strong></td>
<td><strong>252.05</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Life cycle operational energy of the redesigned house, by use.

<table>
<thead>
<tr>
<th>Use</th>
<th>Delivered Energy (GJ)</th>
<th>Primary Energy (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (15%)</td>
<td>948.06</td>
<td>1,327.28</td>
</tr>
<tr>
<td>Ducted system (gas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling (8%)</td>
<td>205.99</td>
<td>700.37</td>
</tr>
<tr>
<td>Air conditioning (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment (70%)</td>
<td>1,872.72</td>
<td>6,367.25</td>
</tr>
<tr>
<td>Various (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting (7%)</td>
<td>187.27</td>
<td>636.72</td>
</tr>
<tr>
<td>LED (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,214.04</strong></td>
<td><strong>9,031.62</strong></td>
</tr>
</tbody>
</table>

Improvements to the thermal performance of the building fabric reduced operational energy demand by a significant 38% and resulted in a reduction in life cycle embodied energy by 0.3%. Using the same approach for calculating the GWP associated with operational energy as in Table 3, the total life cycle greenhouse gas emissions/GWP of the redesigned house over 50 years is 1,039 t CO₂-e (3.67 t CO₂-e/m²). This is a 29% reduction compared to the initial house and enough emissions to fill the house 775 times. Figure 5 compares the life cycle GWP of the initial and redesigned house.
5. Discussion and Conclusion

This study has shown that the appropriate selection of construction materials and systems can result in a significant reduction in energy demand and global warming potential for a residential building. The life cycle analysis approach used enables a holistic assessment of the potential benefits of implementing a solution for improving building performance across every stage of the building life cycle. Both embodied and operational energy demand have been reduced through an iterative design approach. Simple strategies such as using building materials with higher recycled content (and thus lower embodied energy), improving the R-value of the building fabric and integrating more efficient lighting reduced the energy demand and GWP of the original house. These strategies are increasingly available with minimal cost implications as they are growing in popularity and are readily available in the market.
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The results of this study can be benchmarked against similar previous studies. Crawford (2011) calculated an initial embodied energy figure for a similar detached house of 13 GJ/m², which compares closely with the 11 GJ/m² in this study. The operational energy-related emissions from previous studies, such as 3.4 t CO₂-e/m² over 50 years from AGO (1999) also compare closely with the figures from this study. A figure of 1.57 t CO₂-e/m² for 50 years from Crawford (2011) is lower again, but for a much more operationally efficient house, indicating that even the redesigned house has potential for further reductions to operational energy (Figure 6).

As this study was conducted based on strategies that incorporate readily available alternatives in the construction industry, it is suggested that in order to achieve the ambitious goal of net zero energy and emissions buildings, alternate construction materials and technologies not commonly used currently, and a greater proportion of renewable energy in the national fuel mix are needed.

Based on this study, it can be deduced that alternative building materials with lower embodied energy must be explored to compensate for increased embodied energy as a result of the additional insulation and glazing required to reduce operational energy demands. Traditional building products with minimal heat and chemical processing are key to minimising embodied energy in a residential design. In many cases a dying trade, it is crucial for the industry to bring these products back into the market. For instance, lime wash and lime plasters are effective substitutes for paint and cement. Another popular product is compressed stabilized earth blocks (CSEB) with interlocking shapes, discarding the need for mortar. According to Auroville Earth Institute (2015), they are estimated to require four times less embodied energy compared to standard bricks. Compared to bricks which are strengthened by heat, compressed earth blocks contain less embodied energy as they are air dried.

Natural building techniques using resources from the site itself are an effective construction method to minimise energy for logistics and raw material extraction processes. Earth excavated from the site can be used to create adobe flooring and rammed earth walls. An adobe floor is estimated to contain up to 90% less embodied energy compared to a standard concrete slab (Racusin and McArleton, 2012). Rammed earth walls on the other hand have a lower R-value compared to brick veneer and therefore still require additional insulation materials in the Melbourne climate. Rammed earth walls are estimated to contain 16% less embodied energy in comparison to standard brick veneer (Treloar et al., 2001). Consideration must also be given to the longevity of these materials and their practicality for use in modern houses.

This study highlights the considerable potential that still exists to reduce the environmental effect of buildings on the natural environment. While considerable improvements have been made over recent years, there is still a long way to go to get close to the ambitious target of net zero, or even net positive, energy and emissions housing.

References


Hammond, G. and Jones, C. (2011) *Inventory of carbon and energy (ICE) version 2.0*, Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, UK.