EMBODIED ENERGY ANALYSIS OF THE REFURBISHMENT OF A SMALL DETACHED BUILDING

Robert H. Crawford, Robert J. Fuller, Graham J. Treloar and Ben D. Ilozor
School of Architecture and Building, Deakin University, Geelong, 3217, Australia
Email: rhcrawfo@deakin.edu.au

SUMMARY

Energy efficient design principles and the minimisation of operational energy requirements have been demonstrated in the refurbishment of a small existing residential building. Significant thought has been given to these areas, together with an emphasis on the minimisation of resource consumption and material wastage. However, less consideration has been given to the embodied energy of the additional materials, components and systems required to meet these aims. The additional embodied energy may reduce the advantages of minimising the operational energy consumption by extending the energy payback period beyond the life of the building. In general, the embodied energy of buildings and their products has been found to be significant, when national average input-output data is used to fill gaps in traditional life-cycle assessment inventories. Through the use of an input-output-based hybrid embodied energy analysis, the embodied energy of this refurbished building has increased by 63% compared to the existing building, showing the impact that filling the gaps in traditional inventories can have on energy payback periods.

INTRODUCTION

There is now a considerable focus on new building design to ensure that new additions to the building stock minimise their use of life cycle energy, balancing operational and embodied energy demands. However, less attention has been given to the existing building stock. Refurbishment of these buildings to make them more energy efficient would generally appear to make sense on occupant comfort, financial and environmental grounds. While it is possible to reduce the operational energy requirements of a building to very low levels, the energy embodied in the materials and technologies used to achieve this outcome can be appreciable in the worst-case scenario. Energy efficiency features should generally pay back within the lifetime of the building. The gaps left in embodied energy inventories based on traditional energy assessment techniques can become a crucial factor in these payback periods. The energy payback period, based on traditional methods, may significantly increase above the expected life of the building, once the gaps in these traditional methods are filled. This paper describes the embodied energy evaluation of a small detached building that has been upgraded using active and passive solar technologies, as well as energy efficient design principles. The implications of the refurbishment on greenhouse gas emissions and their payback are also discussed.

BACKGROUND

Embodied energy analysis methods

The two main methods for embodied energy analysis are susceptible to different types of errors and have different benefits. The first method, input-output analysis, is unreliable due to assumptions regarding tariffs and the homogeneity and proportionality of sectors. But the results of input-output analyses are representative of the national average case, and the input-output system boundary is practically complete. The second energy analysis method, process analysis, can be significantly incomplete. This is primarily due to the complexity of the upstream requirements for goods and services (Lave et al., 1995). While the accuracy of the process analysis method can be high, it is only relevant to the particular system considered and can be subject to considerable variability (Tucker and Treloar, 1994).
Hybrid techniques attempt to combine the benefits of both methods, while minimising their respective limitations. Previous hybrid techniques, such as process-based hybrid analysis, also have problems, since they are almost exclusively based on incomplete process analysis data, suffering similar limitations to those outlined above for the two embodied energy analysis methods (Treloar, 1995). A key problem with hybrid analysis methods is that the input-output model is a 'black box'. An innovative input-output-based hybrid analysis method has recently been developed based on the disaggregation of the Leontief inverse data into embodied energy paths (Treloar, 1997; Treloar et al., 2000). Potentially, energy is consumed directly at each transaction node, and each upstream node requires goods and services from any sector of the economy. At each point, energy consumption occurs, leading to the coining of the term 'energy path', defined as a series of transactions leading to a direct energy requirement. Subsequently, process analysis data can be integrated into the input-output model without causing unwanted flow-on errors (i.e. a knock-on effect from the original change, for example, if data for road transport is added, it will affect all instances of road transport).

**Past embodied energy studies of residential buildings**

Embodied energy represents 20 to 50 times the annual operational energy of most Australian residential buildings (Harrington et al., 1999). This ratio depends on building design, fuel type, equipment type and operational efficiency, climate and the method of energy analysis used. Each year in Australia, the embodied energy used in new building construction is approximately equal to the annual operational energy of the built stock, and together they make up 30-40% of national energy use and greenhouse gas emissions (Harrington et al., 1999). An individual residential building embodies about 2000 GJ (Treloar, Love and Holt, 2001). Previous studies, now shown to be incomplete in system boundary, have shown lower values (for example, *inter alia*: Hill, 1978; Stein et al., 1981; Bekker, 1982; Baird and Chan, 1983; D’Cruz et al., 1990; Oppenheim and Treloar, 1994; Tucker et al., 1994; Viljoen, 1995; Lawson, 1996; Adalberth, 1997; Pullen, 2000; and Fay, Treloar and Iyer-Raniga, 2000).

Few studies have examined the embodied energy implications of an existing residential building that has been refurbished to lower building operational energy. This paper looks at such a building, and the implications, in the context of recent methodological developments that have improved system boundary completeness.

**METHODOLOGY**

The embodied energy evaluation of the existing building and the refurbishment involves the calculation of the initial embodied energy of the existing building as well as that of materials, components and equipment added by the refurbishment.

The study was performed on a single storey detached brick veneer house owned by Port Phillip Council and leased by a local environmental organisation. The house is located on the corner of the St. Kilda Botanical Gardens in Melbourne, Australia. The house has been refurbished to provide an example of a sustainable building and will be used as an educational tool as well as a meeting place for various environmental organisations. The aim of the project is to provide practical examples of ways that householders can improve the energy efficiency of their buildings, and to promote renewable and non-polluting technologies. The refurbishment therefore includes the installation of a number of energy saving devices, including photovoltaics, a solar hot water system and energy efficient appliances.

The house has been assessed in two stages. Firstly, prior to any improvements, based on its current use in order to determine its current embodied energy, based on existing conditions. Secondly, it has been assessed upon completion of the refurbishments to determine the impact that the refurbishment and inclusion of energy saving devices has had on the embodied energy of the building.

**Existing Building**

The area of the building is 92m², including a single car carport, with its long axis running north-south (see Figure 1). The existing substructure of the building is constructed of a timber subfloor on concrete stumps and the external walls are of brick veneer construction. The structural framing is a
traditional timber frame clad with plasterboard internally. Wall finishes include ceramic tiles in all wet areas and paint to all plasterboard. The structural framing of the roof is timber, clad with concrete roof tiles. The ceiling is insulated with R2.5 fibreglass batts, and the walls and roof have reflective foil, but there is no floor insulation. The windows are single glazed and are timber framed. The floor coverings in the kitchen, bathrooms and laundry are linoleum, and the rest of the house is carpeted. The appliances are those typically installed in a residential house, including a stove/oven, refrigerator, hot water system, gas central heating unit and a single cooling only air conditioner. A number of built-in cupboards and wardrobes, constructed of timber, are also part of the house. The house also included a number of external structures including a timber deck to the east of the house, a concrete porch and timber pergola to the west, a concrete driveway and paths as well as brick and timber fences.

Refurbished Building

The refurbished building includes a number of energy saving devices and structural alterations, increasing the floor area to 116m² (Figure 2). These include the removal of most of the internal timber and plasterboard walls and replacement with an environmentally friendly wall design system based on wheat and rice straw and recycled paper. These walls have then been finished with a number of coats of an environmentally friendly paint and wet areas have been finished with either ceramic tiles or marmoleum. All of the existing windows have been reused with an additional piece of glass attached to each to convert them to double-glazed units. The main structural addition has been the extension of the internal area to cover the existing carport to create two meeting rooms (M1 and M2), constructed with a timber subfloor on concrete stumps, recycled bricks, timber cladding and several double-glazed windows. A number of other alterations/additions have also been made;

- The carpet has been removed and the existing timber floors have been sanded and polished;
- The gutters and downpipes have been replaced and the existing toilets, basins, stove, electricals, plumbing and switchboard have been relocated;
- The floors of the two north facing rooms (Resource (R) and Demonstration (D) Rooms) have been covered in a 50mm concrete screed on a plastic membrane;
- R2.5 fibreglass batt insulation has been added to the underside of the entire floor;
- The existing gas hot water system has been replaced by a Solahart 151J Thermosiphon solar hot water system;
- Two Solartubes were installed above the new Bathroom (B) and Entry (E);
- 18 Solarex BP SX 80 multi-crystalline photovoltaic modules have been installed above the north façade of the house;
- The refrigerator has been replaced by a newer model;
- A timber Deck (D1) has been built along the extent of the east façade, from the south façade and along the path to the gardens;
- Two concrete water storage tanks have been installed (partially underground) on the north side of the house and surrounded by a timber paling fence;
- A new recycled timber pergola has been built along the extent of the west façade of the house;
- A timber external storage cabinet has been constructed on the south façade;
- New cabinets has been installed in various rooms of the house (e.g. Kitchen (K) and Office (OF));
- The north façade has been completely removed and replaced with recycled steel framed double-glazed windows;
- New brick and timber paling fences made from recycled materials have been erected;
- A water treatment system has been installed underground; and
- Stone steps and a gravel pathway have also been constructed.

Source: Ho, 2002.

Figure 2 Plan of refurbished building
Embodied Energy Analysis Method

In order to undertake the embodied energy analysis of the existing and refurbished building, the quantities of materials used in their construction were determined. Information regarding components, materials, masses, areas and volumes was obtained from the manufacturers of the various products, or through assumptions. All information was in the public domain.

The embodied energy values of the materials and components were derived using an input-output-based hybrid analysis method, as described by Treloar (1997), using input-output data for Australia from the financial year 1992-93. Various embodied energy data for major materials, which are based on process analysis, such as steel, were also integrated with the input-output data (Grant, 2000). The quantities of the materials used in the manufacture of each building element and component were multiplied by the respective embodied energy intensities. The sum of these results gave the total embodied energy for both existing and refurbished buildings. Using the method described by Treloar, Love and Holt (2001), the gaps in this method were filled using input-output data for the 'residential building construction', 'other electrical equipment' and 'household appliances' sectors. The energy embodied in maintenance and decommissioning was ignored in this study. A figure for the direct energy of construction, calculated using the direct energy intensity (GJ/$100) of the residential building construction sector from the 1992-93 input-output tables and based on an estimated price of $1150/m² of building area, was then added to this figure. For the refurbished building, the direct energy figure was calculated on a pro rata basis, based on the percentage of additional embodied energy in the refurbishment relative to the embodied energy of the existing building. These total embodied energy figures (existing and refurbished buildings) were then broken down into material groups and building elements. For this analysis, the specific materials contained in the building are allocated to material groups (Table 1).

The embodied energy figures of some of the energy systems that have been added to the existing building as part of the refurbishment, were taken from previous studies, which used the same input-output-based hybrid embodied energy analysis method as in this study. These included the solar hot water system (Crawford, 2000; and Crawford et al., 2002) and the photovoltaic modules (Crawford, Treloar and Bazilian, 2002).

<table>
<thead>
<tr>
<th>Material groups</th>
<th>List of included materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Sheet roofing, steel, stainless steel</td>
</tr>
<tr>
<td>Concrete</td>
<td>Cement, cement roof tiles, concrete various grades, fibre cement</td>
</tr>
<tr>
<td></td>
<td>sheet various thicknesses, granite, sand, screenings, bitumen</td>
</tr>
<tr>
<td>Other metals</td>
<td>Aluminium, copper, reflective foil</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Brick, tile, vitreous china</td>
</tr>
<tr>
<td>Carpet</td>
<td>Carpet</td>
</tr>
<tr>
<td>Glass</td>
<td>Clear float glass, toughened glass various thicknesses</td>
</tr>
<tr>
<td>Fibreglass batts</td>
<td>Fibreglass batt insulation</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>Plasterboard various thicknesses</td>
</tr>
<tr>
<td>Plastic</td>
<td>Laminate, membrane, plastic</td>
</tr>
<tr>
<td>Paint</td>
<td>Paint</td>
</tr>
<tr>
<td>Timber products</td>
<td>MDF/particleboard, MDF architrave, MDF skirting, timber</td>
</tr>
<tr>
<td>Household appliances</td>
<td>Household appliances</td>
</tr>
<tr>
<td>Additional items</td>
<td>Solar hot water system, photovoltaics</td>
</tr>
</tbody>
</table>

Table 1 Breakdown of material groups

RESULTS

The embodied energy of the existing and refurbished buildings is shown in Table 2. This figure for the existing building is broken down to show the total embodied energy for each material group (Figure 3) and for each building element (Figure 4). These material group and elemental figures also show the modified (process analysis) and remainder of unmodified (input-output) amounts, of the total embodied energy of the specific material groups and elements. The embodied energy added to the building through materials, components and equipment, as a result of the refurbishment was also
broken down into material groups (Figure 5) and building elements (Figure 6) with both modified and unmodified amounts shown.

<table>
<thead>
<tr>
<th>Embodied energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing building 16.3</td>
</tr>
<tr>
<td>Refurbishment additions 10.2</td>
</tr>
</tbody>
</table>

**Table 2 Embodied energy of existing building and refurbishments (GJ/m² of building area)**

**Figure 3** Existing building embodied energy, by material group (GJ/m² of building area)

**Figure 4** Existing building embodied energy, by building element (GJ/m² of building area)

**Figure 5** Building refurbishment embodied energy, by material group (GJ/m² of building area)

**Figure 6** Building refurbishment embodied energy, by building element (GJ/m² of building area)
DISCUSSION

Figure 3 shows that the embodied energy of the existing building is dominated by the steel materials group (25%) and other items (22%). The external items (26%) and other items (22%) dominate the embodied energy in terms of building elements (Figure 4). It has also been shown that for the existing building, the embodied energy added through the use of input-output data is quite significant (53%). For the refurbished building, the other items accounted for the largest portion of embodied energy (35%), followed again by both the steel materials group (24%) and the external items (26%) (Figure 5 and 6). The embodied energy value added through the use of input-output data accounted for 89% of the total embodied energy of the refurbished building. For both studies, the gap in traditional embodied energy methods, filled by the use of input-output data in this study, has been shown to be quite significant.

Part of the additional embodied energy added through the refurbishment will be offset through the savings in operational energy as a result of the use of the new equipment and systems. This reduction may justify a significant increase in embodied energy if there are long-term environmental benefits, such as a reduction in greenhouse gas emissions, and as long as the energy payback period does not extend past the reasonable life of the building. This can be determined by simulation, but is beyond the scope of this study, and is an area for further research. The embodied energy for the two main energy saving features in the refurbishment, the solar hot water and photovoltaic systems, are shown in Table 3.

<table>
<thead>
<tr>
<th>Building component</th>
<th>Embodied energy (GJ/m² of building area)</th>
<th>% of total embodied energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar hot water system</td>
<td>0.15</td>
<td>1.5</td>
</tr>
<tr>
<td>Photovoltaic modules</td>
<td>1.2</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3 Embodied energy of main energy efficiency features

CONCLUSIONS

This paper described the embodied energy evaluation of a small detached building that has been upgraded using active and passive solar technologies, as well as energy efficient design principles. It was shown that the additions to the house through the refurbishment led to a significant increase in the embodied energy of the building, in the order of 63%. Features such as the solar hot water system and photovoltaic modules, whilst contributing to a large portion of the additional embodied energy, in the future, due to predicted future increases in uptake and economies of scale, may reduce in embodied energy.

The embodied energy added through the use of input-output data has been shown to significantly increase the embodied energy of the building used in this study, compared to the use of traditional embodied energy analysis methods. The refurbishment of the existing building, whilst inevitably causing an increase in the building's embodied energy, will also result in a significant decrease in operational energy through the various energy saving devices installed. The increase in greenhouse gas emissions through the refurbishment may also be offset with future reductions in greenhouse gas emissions through savings in operational energy consumption in the future. While the energy payback period may end up being quite significant, eventual energy savings will be beneficial. Both of these are areas for further research.

REFERENCES


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