Recycling of materials to reduce embodied energy consumption in the redevelopment of urban areas

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ABSTRACT: Whilst the size of many cities around the world is increasing, there is also an imperative for urban areas to minimise their environmental impact. One way to reconcile these opposing trends is by the densification of cities. Urban areas can be redeveloped into more compact configurations which accommodate a greater population and use existing infrastructure. New compact dwelling forms will also be more energy efficient thereby lowering energy consumption and greenhouse gas emissions. However, the redevelopment process uses additional energy by virtue of construction activities and the energy embodied in new building materials.

This paper describes future projections for the redevelopment of an existing suburb of Adelaide, Australia and models energy consumption including embodied energy. It shows that with certain demolition and redevelopment rates, embodied energy is significant and may negate energy savings made in new energy efficient dwellings. However, there is some potential for reducing this embodied energy by a much greater use of recycled materials from demolished buildings.

Keywords: Embodied energy, materials recycling, sustainable urban development.

INTRODUCTION

Much has been written about sustainable development since it was defined by Brundtland (1987) and this is a consequence of the substantial impact that towns, cities and their associated infrastructure have on the environment (Newman, 2006). Some of the indicators of this impact are energy consumption, greenhouse gas emissions, waste production, resource usage and loss of biodiversity. Since approximately two-thirds of OECD countries are classified as being 80 per cent or more dependent on fossil fuel consumption (DECC, 2008) and there is the link between greenhouse gas emissions and climate change (IPCC, 2007), it is not surprising that reduction in energy consumption has become a major focus for the design and operation of buildings and the built environment. Furthermore, the operation of buildings in the urban environment requires a substantial proportion of a nation’s energy usage and Steemers (2003) puts this proportion at over 50, 41 and 36 per cent for the UK, European Union and USA, respectively. However, this does not account for all of the energy used by buildings since they must also be constructed, maintained and renovated. A large portion of these inputs is the energy used to manufacture and supply the construction materials and components i.e. embodied energy. Hence, a more comprehensive analysis of energy consumption considers both embodied and operational energy of buildings.

The purpose of this paper is to initially highlight the importance of comprehensive energy analyses when considering the development and operation of the urban environment. This involves the consideration of both operational and embodied energy to ensure that the overall energy consumption of buildings is minimised. Previous research on the redevelopment of an existing suburb in Adelaide, Australia, which shows future projections of energy consumption due to urban redevelopment is summarised (Pullen, 2010). The embodied energy is found to be significant and may counterbalance energy savings resulting from new energy efficient dwellings, at least short to medium term. The paper then extends this research by presenting further scenarios whereby enhanced recycling of building materials generated from demolition (resulting from the redevelopment process) may compensate for the increased embodied energy. Comments are made with regard to recycling and re-use of building materials under these circumstances.

1. BACKGROUND

Since the analysis of energy consumption in buildings and the built environment often focuses on operational energy without consideration of embodied energy, this section provides some background to embodied energy consumption. Earlier work on the embodied energy analysis of buildings was carried out in various parts of the world in the 1970s and 1980s. A significant contribution was made by Stein et al (1976) who surveyed energy used in the U.S. construction industry. In the UK, Boustead and Hancock (1979) published a handbook which provided information on the amount of energy required to manufacture a wide range of industrial materials. In New Zealand, Baird and
Chan (1983) found that the construction industry consumed a substantial portion of national energy and this work has been substantially extended by Alcorn (2003). The methods for deriving embodied energy data were developed further by Treloar (1998) and Crawford (2005) in Australia and a database of embodied energy coefficients for building materials has been assembled by Hammond and Jones (2008) in the UK.

The significance of embodied energy compared with the operational energy of a building will vary according to many factors including the location, climate, operational energy efficiency, type of construction and the length of the life cycle of the building. In addition, embodied energy consists of an initial component corresponding to the materials in a newly constructed building and a recurrent component for the additional materials used for periodic maintenance and renovation. In a survey of research on 60 case studies from various countries, Sartori and Hestnes (2007) found that the embodied energy (initial and recurrent) varied significantly but was up to 38% of the total life cycle energy consumption (combined embodied and operational energy) of conventional buildings. The analysis of 20 schools by Ding (2007) in New South Wales, Australia and 30 residential, public, education and medical buildings in Melbourne, Australia by Langston and Langston (2007) indicated that initial and recurrent embodied energy varied from 24% to 39% of the life cycle energy usage. With a focus on low energy housing in Scandinavia, Thomark (2006) found that embodied energy amounted to as much as 40-60% of total energy use indicating the greater relative significance with more energy efficient buildings.

Hence, embodied energy can be a significant part of the overall energy consumption of buildings. This has been recognised in building rating schemes such as BREEAM (UK), LEED (US) and Green Star (Australia) whereby the specification of low embodied materials is rewarded in construction projects by scoring more ‘points’ as a contribution to the rating. However, the quantitative assessment and comparison of both operational energy and embodied energy of new buildings is not commonplace. This may become more frequent for new ‘green’ developments as it offers a mechanism for attempting to design, construct and operate buildings with a minimal life cycle emissions output as a contribution to more sustainable outcomes. Although the consideration of embodied energy has now become accepted and used in sustainable approaches to building design, further techniques are required to achieve better results at the larger scale of the suburb, neighbourhood or urban area.

2. ENERGY CONSUMPTION AT THE SCALE OF URBAN AREAS

In order that more informed decisions can be made about moderating the energy consumption of modern towns and cities a comprehensive understanding of energy usage is desirable. The representation of total energy consumption in the form of maps offers the potential for optimising built forms, tracking advances in energy efficiency and assisting in development decisions for urban renewal. This is even more important when the issue of urban densification is considered in an attempt to lower environmental impact. Despite a general acceptance of the advantages of higher urban densities there is still debate about the overall benefits, particularly with respect to energy consumption and greenhouse gas emissions. In a review of urban consolidation, Gray et al (2008) concluded that there had not been a definite assessment of the effects of densification in the context of full household emissions and energy demand. Hence, the mapping of energy consumption could also assist in analysing the benefits of compact urban areas.

The spatial representation of energy consumption in cities has been carried out by a number of researchers including Jones et al (2001) in Cardiff, Wales; Gupta (2005) in Oxford, England; Tornberg & Thuander (2005) in Goteborg, Sweden; Yamaguchi et al (2007) in Osaka, Japan and Heiple & Sailor (2008) in Houston, Texas. However, these mapping exercises, which are predominantly based on geographical information systems (GIS), display operational energy. A more comprehensive modelling of energy consumption including embodied energy has been undertaken by Matsumoto et al (2006) for the city of Toyohashi in Japan with anticipated changes in population through to 2053.

A method for displaying embodied energy of existing dwellings has been described using embodied energy theory, property register data and GIS software (Pullen, 2007). The method uses a model which is shown conceptually in Figure 1 and this is aimed at depicting the baseline embodied energy of the existing built environment. Operational energy can then be superimposed onto this enabling a more comprehensive energy analysis to be considered.

![Figure 1. Application of model for spatially representing embodied energy](image-url)
An example of the mapping of embodied energy is shown in Figure 2 for the suburb of Hawthorn in Adelaide, Australia showing the different levels of embodied energy of houses (in GJ) arising from different house sizes and construction materials. The embodied energy of the individual houses has been estimated from the quantities of materials used in construction and their embodied energy coefficients derived using hybrid input-output techniques. Typically, the embodied energy ranged from 6.7 GJ/m$^2$ to 8.6 GJ/m$^2$ of floor area depending on the age, construction methods and materials of the houses. The database underlying the maps contains information on house dimensions and construction materials such that it is possible to model the effects of retrofitting and redevelopment on the energy consumption of the suburb.

![Figure 2. Embodied energy of houses in the Hawthorn suburb](image)

### 3. ENERGY IMPLICATIONS FOR THE REDEVELOPMENT OF EXISTING SUBURBS

The model described in Figure 1 has been used to analyse the energy implications for the redevelopment of the established suburb of Hawthorn consisting of 938 property titles with houses of varying age (Pullen, 2010). Initially, a business as usual (BAU) projection was established which included operational energy and recurrent embodied energy (for periodic maintenance and renovation) over a 20 year period. Certain future energy projections over the same period were then estimated using the model's database and these included (a) the progressive retrofitting of a number of houses with additional insulation and solar hot water systems to improve energy efficiency and (b) the demolition and redevelopment of a small proportion of the housing stock into a greater number of energy efficient dwellings. The redevelopment projections took into account the lower operational energy for new redeveloped houses as well as their as-built and recurrent embodied energy. In addition, the embodied energy of retrofitted insulation and solar systems, and recurrent embodied energy was included for the majority of houses not subjected to redevelopment.

The redevelopment assumptions were for low, medium and high demolition rates of 0.9%, 1.4% and 3.0% per annum and an increase in the number of houses corresponding to 1.8 new dwellings for every house demolished which was...
based on historical trends (2002). The projections were generally in keeping with the concept of urban densification to accommodate more dwellings using existing infrastructure.

The results of this analysis are summarised and re-presented for this paper in Figure 3 which shows the operational, embodied and combined energy consumptions for the four projections. At the low demolition rate of 0.9%, the combined energy consumption is similar to BAU due to the lower operational energy which is compensated by the higher embodied energy arising from the construction of new houses. The 1.4% and 3.0% demolition rates progressively show increases in combined energy consumption even though the operational energy is lower and this is also due to higher embodied energy. Hence, over the relatively short period of 20 years, the effect of progressively improving the energy efficiency and increasing the density of housing in the suburb is to increase energy consumption when higher demolition rates are used.

4. EXTENSION OF THE RESEARCH TO INCLUDE THE RECYCLING OF CONSTRUCTION MATERIALS

4.1 Context
The reduction of embodied energy of materials used in the construction of new buildings and urban infrastructure can be achieved in a number of ways. These include more energy efficient manufacturing processes, the incorporation of more recycled content in products and the re-use of existing materials. Increasing recycled content and direct re-use of materials has advantages in reducing the exploitation of resources and minimising landfill. It would also moderate energy consumption and associated greenhouse gas emissions arising from the manufacture of new materials used in buildings. The re-use and recycling of the fabric of the built form can provide energy credits for new developments by recovering at least some of the embodied energy already expended. This is part of the cradle to cradle or cyclical flow concept and implies a stewardship approach to the management of building and infrastructure stock (Bringezu, 2003; Kohler and Chini, 2005; Schiller, 2007; Tanikawa and Hashimoto, 2009).

In Australia in 2007, the construction and demolition sector contributed 38% of the 43.8 million tonnes of waste that was generated nationally (ABS, 2010). Furthermore, approximately 43% of this construction and demolition waste ended up as landfill. Not surprisingly, recycling rates in Australia are considerably lower than in other OECD countries (Productivity Commission, 2006). Hence there are some very good reasons why increased recycling of construction materials should be encouraged.

4.2 Purpose
The analysis previously described raises the question of whether the recycling and re-use of materials arising from demolition can compensate, either wholly or partially, for the additional combined energy arising from increased embodied energy. This is because recycled or re-used materials can be considered as having a very low embodied energy depending on the amount of re-work that they require. Indeed, in life cycle energy accounting, a construction component which is directly re-used with no modification, preparation or transportation, would have an embodied energy of zero and this would contribute to a new building with lower combined energy. Recycled or re-used materials may act as substitutes for new materials thereby avoiding further embodied energy consumption (from the
manufacture of new materials and components) in either the building project where they are generated or in other
construction projects.

4.3 Method
Despite there being some data available on the quantities of building materials either going to landfill or being
diverted (Oke et al, 2008), there is less information based on the study of demolition sites which details the
proportions of each material which are re-used or recycled. In Australia, the re-use of building materials has not been
modelled extensively due to the paucity of data. However, future recycling scenarios for materials from all building
types have been proposed by RMIT (2006a; 2006b) using a baseline for 2005 and levels of recycling shown in
Table 1.

The embodied energy of these proportions of recycled materials was then estimated based on lists of the materials
used in typical houses in the Hawthorn suburb along with their embodied energy coefficients. Compared with the
initial embodied energy of a typical house, the energy embodied by the recycled materials amounted to 23% using
the baseline (2005) data, 37% for advanced recycling and 52% for the future separation technology scenario.

<table>
<thead>
<tr>
<th>Construction material</th>
<th>Baseline (2005)</th>
<th>Advanced recycling</th>
<th>Future separation technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>60</td>
<td>80</td>
<td>95</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>5</td>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>Concrete</td>
<td>75</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>Glass</td>
<td>10</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>Steel</td>
<td>90</td>
<td>95</td>
<td>98</td>
</tr>
<tr>
<td>Zinc coated steel</td>
<td>75</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>Steel sheet and reinforcing</td>
<td>75</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>5</td>
<td>20</td>
<td>95</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>5</td>
<td>20</td>
<td>95</td>
</tr>
<tr>
<td>Wood</td>
<td>20</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>Brick</td>
<td>50</td>
<td>75</td>
<td>95</td>
</tr>
<tr>
<td>Clay</td>
<td>50</td>
<td>80</td>
<td>95</td>
</tr>
</tbody>
</table>

Hence, on the assumption that these recycled materials could be used in the newly constructed houses, the saving in
embodied energy by avoiding the use of new materials could be included when estimating the combined energy for
new redeveloped dwellings. This is summarised in the equation:

\[ E_C = E_O + E_E - E_R \]

where

- \( E_C \) is the combined energy of the houses in the suburb
- \( E_O \) is the operational energy of all of the houses over the 20 year period
- \( E_E \) is the embodied energy consumption of all the houses within the 20 year period
- \( E_R \) is the embodied energy of recycled materials used over the 20 year period

Hence, the model used for estimating the energy implications of the redevelopment of the Hawthorn suburb was
modified to take into account the savings in embodied energy due to recycled materials and the combined energy
consumptions were then re-evaluated.

4.4 Results and Discussion
Figure 4 shows the effect of recycling rate (due to different recycling technologies) against the combined energy
consumption of redevelopment for different levels of demolition and re-building. Generally, it can be seen that
improved recycling rate (due to improved recycling technologies) causes a reduction in the combined energy
consumption of redevelopment. However, for the use of recycled materials to completely compensate for additional
embodied energy, the combined energy must be lower than the BAU case which is shown as the dotted horizontal
line in figure 4. This is possible for the 0.9% demolition rate scenario for all recycling rates.

It is also possible for the 1.4% demolition rate in combination with advanced recycling (37% of materials recycled) or
future separation technology (52% of materials recycled) but not for the baseline (2005) recycling rate (23% of
materials recycled). For the high 3.0% demolition rate, even recycling with future separation technology is not
sufficient to lower the combined energy to below the BAU case. Overall, this indicates that the use of materials
recycling to compensate for increased embodied energy in order to maintain the same level (BAU) of combined
energy of the redevelopment has some potential but is unlikely to provide a complete solution, particularly with high
demolition and redevelopment rates.
It is recognised that the example is specific and there are a number of variables including recycling rates of materials and the pace of redevelopment and densification which can change the results of the analysis. Furthermore, the dearth of quantitative information on the recycling of construction materials adds more uncertainty to modelling efforts. In this case, proportions of recycled materials from all building types have been used (RMIT, 2006a; RMIT, 2006b) and it may be the case that rates of recycling from the demolition of houses is very different from that of commercial buildings. In addition, in calculating the reduction of embodied energy due to recycling, no account was made of materials or components not listed in Table 1 such as fittings, finishes and services i.e. a zero % recycling rate for these items was used. Future improvements in recycling technologies of these items will affect energy analyses. On the other hand, if the estimates for future separation technologies (in Table 1) are overly optimistic and there are technical barriers which cannot be surpassed, then the indication that combined energy consumption can only be partially compensated by recycling is further substantiated. The graphs in Figure 4 would be truncated and reduced combined energy consumption could only occur at lower demolition and rebuilding rates.

A further discussion point is the period of analysis which at 20 years is short in terms of the life cycle of buildings. However, in the case of suburbs originally constructed over an extended period, the supply of older houses for demolition will continue with time and similar demolition and redevelopment rates would be possible into the future. Another issue that needs to be addressed is the down-cycling of building materials e.g. concrete into road-base, since this causes substitution of materials of lower embodied energy which reduces the potential for reducing embodied energy.

Clearly, the increased use of recycled construction materials can assist in reducing the embodied energy consumption in the redevelopment of urban areas. Apart from improvements in recycling technologies, this will also require the modification of building regulations to allow for recycled materials and in the approach of building designers and users in accepting old materials in new buildings.

CONCLUSION

The significance of embodied energy as part of the total energy consumption in the built environment has been emphasised in this paper. The inclusion of embodied energy is important to ensure that lower energy outcomes are achieved in the quest for sustainable development. The spatial nature of cities lends itself to the mapping of energy consumption and this is particularly useful for analysing the densification of urban areas and an example has been summarised for the Hawthorn suburb in Adelaide, Australia. This paper has extended that analysis and has considered the embodied energy of recycled materials to reduce the higher energy consumption arising from redevelopment activities.

The increased utilisation of construction materials arising from refurbishment and demolition represents a cyclical flow concept which offers a possible lowering of the environmental impact of new construction. The example
presented in this paper shows that there is potential for a reduction in total energy consumption to occur to some extent. Within the life cycle and geographical boundary of the example selected, the analysis indicates that this effect is unlikely to fully compensate for higher energy consumption arising from more rapid urban development rates. What has been presented in this paper is an initial analysis of the effect of utilising greater proportions of recycled materials on total energy consumption. It indicates that further investigation of this concept is well warranted and should be extended to include greenhouse gas emissions especially in the context of the densification of cities.

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