The potential to reduce the embodied energy in construction through the use of renewable materials

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ABSTRACT: The threat of dangerous levels of global warming demand that we significantly reduce carbon emissions over the coming decades. Globally, carbon emissions from all energy end-uses in buildings in 2004 were estimated to be 8.6 Gt CO_2 or almost one quarter of total CO_2 emissions (IPCC 2007). In Australia, nearly ten per cent of greenhouse gases come from the residential sector (DCCEE 2012). However, it is not merely the operation of the buildings that contributes to their CO_2 emissions, but the energy used over their entire life cycle. Research has demonstrated that the embodied energy of the construction materials used in a building can sometimes equal the operational energy over the building's entire lifetime (Crawford 2011). Therefore the materials used in construction need to be carefully considered. Conventional building materials not only represent high levels of embodied energy but also use resources that are finite and are being depleted. Renewable building materials are those materials that can be regenerated quickly enough to remove the threat of depletion and in theory their production could be carbon-neutral. To assess the potential for renewable building materials to reduce the embodied energy content of residential construction, the embodied energy of a small residential building has been determined. Wherever possible, the conventional construction materials were then replaced by commercially-available renewable building materials. The embodied energy of the building was then recalculated. The analysis showed that the embodied energy of the building could be reduced from 7.5 GJ per m^2 to 5.4 GJ per m^2 i.e. by 28%. The commercial availability of renewable materials, however, was a limiting factor and indicated that the industry is not yet well positioned to embrace this strategy to reduce embodied energy of construction. While some conventional building materials could readily be replaced, in many instances a renewable substitute could not be found.

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INTRODUCTION

The energy used by commercial and residential buildings in Australia accounts for approximately 20% of the country's greenhouse gas emissions (DCCEE, 2012).These emissions need to be reduced to meet the challenges of global warming. The embodied energy of a product is a function of its creation, transportation and disposal. Conventional materials used by the construction industry are based on finite resources and generally represent large amounts of embodied energy. To reduce the amount of embodied energy and save these resources from becoming depleted, renewable materials need to be embraced by the industry. Renewable materials are those that are derived from living sources and have the ability to regenerate themselves. If harvested at a rate less than required for regeneration, there is no impact on the availability of these materials. Quantitative comparisons between a building using conventional and renewable materials are lacking in Australia. Although many buildings have had their embodied energy measured, a comparison of a building using standard materials with one that uses renewable materials could not be found. This paper describes research which investigated the potential of renewable building materials to reduce the embodied energy content of a small residential building. This paper begins with a review of previous research of residential building embodied energy and renewable building materials. The case study building is then described followed by the methodology used. The results are then presented and discussed. Finally, some conclusions are drawn about the potential to reduce the embodied energy in residential buildings.

1. BACKGROUND RESEARCH

1.1 Embodied energy of residential buildings

Monahan and Powell (2011) compared the embodied carbon in a low energy, affordable house constructed using an offsite panellised modular frame system with two other scenarios: one using a timber frame with a single brick skin and the other using traditional masonry construction. The aim of the study was to determine the embodied energy intensity of new housing and develop an understanding of areas that could be improved in order to reduce this intensity. The results concluded that the modular frame system embodied 5.7 GJ per m^2 of primary energy, the timber frame with single brick skin embodied 7.7 GJ per m^2 and the masonry construction had the highest primary embodied energy of 8.3 GJ per m^2. Monahan and Powell (2011) calculated that the panellised timber frame produced a 34% reduction in embodied carbon compared to traditional masonry construction. However, the data used to calculate the results are different to those used in Australia and so the results are of limited value.

In Australia, there have been a number of studies which have calculated the embodied energy in residential buildings. Treloar et al. (2000) found that a 123 m^2 double storey brick veneer house on a concrete slab in Melbourne had an embodied energy of 1441 GJ. Similar findings were made by Fay et al. (2000) who calculated the embodied energy of a 128 m^2 double storey brick veneer house to be 1803 GJ. Fuller et al. (2009) compared the energy and water use of houses typical of the 1950s and current (2009) eras. They found that although operational energy and annual water use had fallen over the time period, embodied energy and carbon emissions had risen, primarily due to the materials used and the growth in house size. For a floor area of 95 m^2, the 1950s house had an embodied energy of 874 GJ, whilst the 2009 house with a floor area of 233.5 m^2 had an embodied energy of 1860 GJ. In a subsequent study, Fuller and Crawford (2011) calculated the embodied energy of a 238 m^2 brick veneer house (including appliances) to have an embodied energy of 2967 GJ.

Crawford et al. (2002) compared the embodied energy of a small detached building, before and after refurbishment. The main purpose of the refurbishment was to reduce the building's operational energy, but also to minimise resource use and material wastage. The existing building was a 92 m^2 brick veneer structure with timber subfloor on concrete stumps. The floor area was increased to 116 m^2 through refurbishment, with a focus on sustainable design. This was achieved not only through structural alterations but also by the addition of a number of energy saving devices. The embodied energy of the original building was 16.3 GJ/m^2 and that of the refurbishment additions was 10.2 GJ/m^2.The authors found that there had been a 63% increase in embodied energy of the house as a result of the refurbishment. This study is relevant as it compares a building before and after changes are made although conventional building materials were used in both cases. In all of the cases mentioned, a hybrid approach was used to calculate the embodied energy of the buildings, combining process energy data for specific materials with national average energy data to fill any data gaps. Numerous other studies have been performed yet these have used less comprehensive approaches for calculating embodied energy, naturally resulting in an underestimation of the total energy embodied in the buildings studied.

1.2 Renewable building materials

Gelder (2002) identified many different types of renewable building materials that could theoretically be substituted for conventional building materials in construction. Using the matrix of renewable materials developed by Coulson and Fuller (2009) reviewed the commercial availability of renewable building materials for the construction industry. They found that whilst there are some materials and products available, a lack of available data makes it difficult for renewable materials to be a serious competitor with conventional (non-renewable) building materials. While there appears to be little (if any) research which systematically calculates the impact of RBM on the embodied energy of a residential building, some structures using these materials are being built and promoted as 'green'. The 2550 m^2 coffee and chocolate factory in Sibang Kaja in Bali is one example (Parkins, 2012). This is claimed to be the world's largest bamboo structure and as Bali's Green Building Benchmark. Other commercial buildings with a focus on using RBM include the S-House Project in Austria, which primarily uses straw, and the Stadthaus nine-storey apartment building in London, which uses load-bearing cross-laminated timber panels to replace traditional concrete panels. The Renewable House (2012) in the UK is an example of a residential building which has focussed on the use of RBM. A mixture of industrial hemp and lime mortar with emissions of 100 kg CO_2/m^2 is used for the walls. Other RBM include wool insulation and a timber frame. The carpets and roofing used have a high natural or recycled content.

2. CASE STUDY BUILDING

The potential of renewable building materials to reduce the embodied energy in residential construction has been investigated through an analysis of a small commercially-available cottage, sometimes referred to as a 'granny flat'. The cottage is designed to be an additional dwelling unit for a property with an existing primary residence. It consists of a bedroom, living area and bathroom (Figures 1 and 2). These dwellings use standard configurations and construction assemblies and can be built on any site.

Figure 1: Image of case study building
(source: VCG 2011)

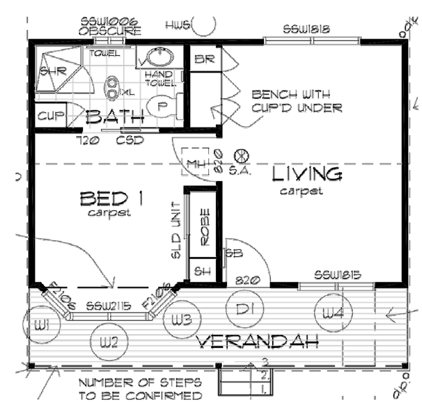

Figure 2: Ground floor plan of case study building
(source: VCG 2011)

The cottage has a floor area of 33.3 m^2 with a verandah area of 9.2 m^2, making a total of 42.5 m^2. The substructure consists of Cypress pine stumps, bearers, joists and structural flooring. Softwood timber frames are used for the walls, clad in fibre-cement sheet with internal plasterboard lining. Timber trusses are used to support the colorbond steel roof (Table 1).

Table 1: Materials used in case study building construction

Element	Materials
Substructure	100 x 100 Cypress pine stumps, steel ant caps, concrete pad footings, 130 x 35 LVL Bearers, 200 x 45 LVL joists, yellow tongue flooring. Substructure includes decking, stair stringers and stair treads for front deck
External walls	Softwood framing, painted fibre-cement sheet cladding, polyester batt insulation, thermal wrap
Roof	Standard softwood timber truss system, COLORBOND® steel decking, insulated with polyester batts and blanket foil roll
Windows	Aluminium-framed windows with 3 mm clear float glass
Internal walls	Softwood framing, polyester insulation
Floor finishes	Nylon carpet, ceramic tile, fibre-cement sheet base
Wall finishes	Painted 10 mm plasterboard, ceramic tiles
Ceiling finishes	Painted 10 mm plasterboard, cement cornice

3. METHODOLOGY

In order to assess the potential of renewable building materials to reduce the embodied energy of residential construction, this study has calculated the energy required to extract and manufacture all the materials used in the construction of the case study building. The calculated energy is then converted to greenhouse gas emissions. The extraction and manufacturing phases include transportation and the provision of capital equipment. The energy expended in construction, operation, maintenance, refurbishment, demolition, reuse and recycling is not included. Figure 3 indicates the system boundary chosen for the study.

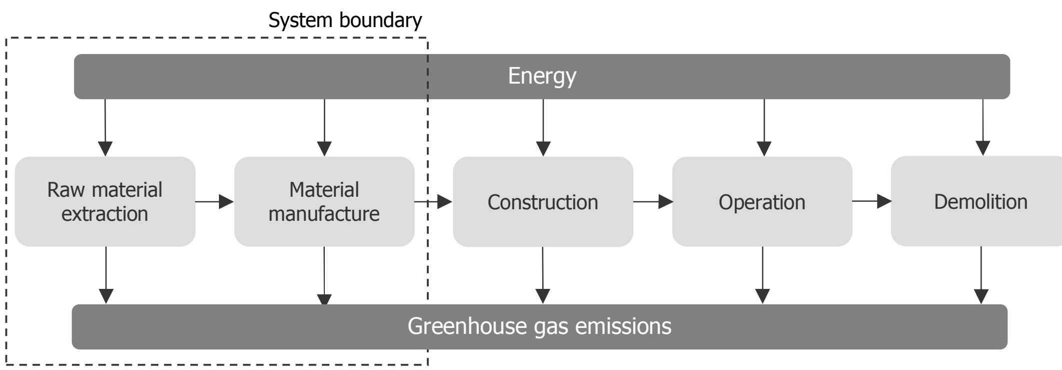

Figure 3: System boundary of case study
(source: adapted from Crawford 2011)

The building material quantities were first estimated from a bill of quantities provided by the manutacturer. The estimated quantities were then multiplied by their respective hybrid embodied energy coefficient (Table 2). The sum of these values represents the embodied energy for the conventional building, as defined above (see later Table 3).

Table 2: Embodied energy coefficients for selected building materials
(source: adapted from Crawford 2011)

Material	Unit	Hybrid Embodied Energy Coefficient (GJ/unit)
Aluminium	t	252.6
Cement sheet – 7.5 mm	m^2	0.36
COLORBOND® steel decking	m^2	0.993
Durra Strawboard Panel	m^2	0.0136
Glass – 3 mm	m^2	1.3
Insulation - Fiberglass	m^2	0.183
Insulation – sheep wool	m^3	0.054
Plasterboard – 10 mm	m^2	0.207
MDF/Particleboard	m^3	30.35
Timber – hardwood	m^3	21.33
Timber – softwood	m^3	10.93

4. RENEWABLE MATERIAL SUBSTITUTION

The renewable building materials substituted for the conventional non-renewable materials were selected, as far as possible, to replicate the appearance of the standard building materials that are used. However, in the event that this may not always be possible, the reduction in embodied energy is to remain the primary aim. The various building elements and their substitutions are discussed below and the actual replacement made is identified.

4.1. Colorbond steel decking

Colorbond steel decking is the single biggest contributor to the embodied energy of the cottage (see later Table 3). The decking is a durable product that lasts for years with little or no maintenance required. Gelder (2002) identified six different renewable materials suitable for roof cladding: bamboo, thatch, timber, seagrass, wool and hair. According to Coulson and Fuller (2009), the only available viable roofing materials available in Australia are timber shingles or thatching. Companies in Melbourne supply both hardwood shingles and alternative thatching products. If installed properly at an adequate angle the product can last between 15 and 20 years. Hardwood shakes are similar to shingles and from a distance, resemble traditional roofing materials. To determine the embodied energy of the replacement, the area of steel decking is replaced by an equivalent volume of hardwood. *Replacement renewable material: hardwood shakes.*

4.2. Steel battens

Timber battens are assumed to replace the steel battens. According to Gelder (2009), the only renewable alternatives for structural framing are timber and bamboo. As softwood timber is already used for the majority of framing it is a suitable choice for the replacement of steel mitred battens. As above, the area of steel is replaced by an equivalent volume of softwood timber to determine the embodied energy of the replacement. *Replacement renewable material: softwood.*

4.3. Glass

There is not a significant amount of glass in this building. However, it still contributes about 10% of the total embodied energy. There is no renewable alternative to glass, but some companies offer a product with a significant recycled glass content. Crawford (2011) states that recycled glass uses 75% of the energy used to create glass from virgin materials. Therefore the embodied energy of the glass used is reduced by 25% to represent the use of recycled glass. *Replacement renewable material:* N/A – *recycled glass used*.

4.4. Softwood structure

The majority of structural members used in construction of the cottage are made from softwood timber. While timber is considered a renewable material, it is important that the species used in construction is taken from sustainably harvested plantations that are specifically intended for the manufacture of building timber. The timber used for framing of walls, roof trusses and most flooring members is softwood pine, with joists and bearers made from LVL. Gelder (2002) lists the only alternatives for structural framing or flooring (including substructure) as timber and bamboo. Therefore no substitution was necessary. *Replacement renewable material: N/A.*

4.5. Particleboard structural flooring

Particleboard flooring is considered one of the most economical structural flooring materials in the building industry. It is manufactured from the timber left over during harvesting. The process of chipping the left-over wood and then mixing the flakes with resin, however, is very energy intensive, and therefore its embodied energy is high. According to Gelder (2002), the only alternatives for structural flooring again are timber and bamboo. Morris (2009), however, suggests that there are other materials that can be used to make composite panels similar to particleboard, but with less associated embodied energy. Hemp, for example, is a renewable material that can be used for many applications. Composite panels using hemp are produced in a similar manner to particle board but combine 'agricultural fibre residuals with bark and other wood fibre residuals in precise ratios to create a fibre blend with chemical properties that are optimized with resin systems'. Such composite board, however, cannot be found in Australia and would need to be sourced from overseas. Sourcing materials from overseas would unnecessarily increase the embodied energy and therefore it is assumed that the particleboard structural flooring will be replaced with hardwood timber floorboards. *Replacement renewable material: hardwood.*

4.6. Plasterboard

Plasterboard is not only used as an internal finish for the walls, but also on the ceiling of the conventional building. Plasterboard is made from gypsum plaster which is pressed between two sheets of thick paper. The process of creating the gypsum and placing it between the paper sheets to dry is energy intensive, hence the high level of embodied energy. Gelder (2002) lists wall coverings in the same category as wall boards and panels. The interior options for renewable wall cladding materials are more promising. Gelder identifies straw board and bamboo plywood as two available options. Compressed rice straw panels are suitable for internal applications (Ortech, 2010). The material can be used for both structural and finished applications, replacing the combination of stud wall and plasterboard. The embodied energy is therefore calculated by replacing internal walls, both softwood framing and plasterboard lining, with these panels. *Replacement renewable material: Compressed rice straw panels.*

4.7. Aluminium

Aluminium has the highest embodied energy coefficient of the materials used in the conventional building but only a small amount of aluminium is used overall, mainly in the windows. Timber is the only viable renewable alternative as a replacement for the window frames. *Replacement renewable material: Western red cedar (softwood).*

4.8. Carpet

The carpet specified in the cottage is nylon and represents a significant amount of embodied energy as it covers most of the floor of the building. Nylon is a petroleum-based product and is created using chemical processes that use oil and gas. Gelder (2002) identified ten different renewable materials suitable for floor coverings: rubber, turpentine, linseed oil, wool and hair, linoleum, cork, seagrass, timber, other vegetable and hemp. Couslon and Fuller (2009) believe that only natural rubber, wool carpets, cork, seagrass and sisal mats are realistically available. The replacement should also be similar in look and performance as the original, thus leaving wool carpet or sisal mats as the only options. Crawford (2011) lists the embodied energy coefficient of both nylon and wool carpet. Wool has a higher embodied energy than nylon, but as it is a renewable material, it is still subsituted. *Replacement renewable material: wool carpet.*

4.9. Paint

Paint is used inside and outside the cottage as all the materials used require internal finishing or weather protection. Paint uses pigments, binders and solvents that add to its embodied energy. The need for paint can either be eliminated through careful choice of cladding materials or a renewable option can be sourced. Gelder (2002) identifies 11 different renewable materials suitable for use as paint, resin or varnish, crambe oil, Japanese lacquer, linseed oil, shellac, soybean oil, tar, tung oil, turpentine, veronia oil, rubber and alcohol. According to Coulson and Fuller (2009), tung oil and linseed oil are available to coat timber, canauba wax and bees wax can be used for furniture polishing and also for internal timber lining. The rest of the renewable options for paint are either unavailable or used together with non-renewable materials to make a durable product. Natural paints are available but their focus is on low emissions of volatile organic compounds, rather than low embodied energy. As a consequence, no alternative material to conventional paint has been assumed. *Replacement renewable material: N/A.*

4.10. Insulation

Fibreglass insulation with an R2.0 rating is used in the walls of the conventional cottage. This is one of the main ways that has enabled the cottage to achieve a 5-star rating. Fibreglass insulation is made by melting glass and sand at high temperatures to make a liquid glass which is then spun rapidly to form fibres. The fibres are then coated with resin to bind them together prior to forming batts (Australian Government, 2011). Insulation can contain high amounts of embodied energy, thus illustrating how reducing operational energy can lead to an increase in embodied energy. Gelder (2002) identifies eight different alternative renewable materials suitable for thermal insulation: cotton, hemp, straw, agar, seagrass, cork, wool and hair. According to Coulson and Fuller (2009), the only products available in Australia are wool and seagrass. Although attempts to find a supplier of seagrass insulation were unsuccessful, wool insulation is a viable alternative in Australia and has an embodied energy of 54 MJ/m^3 (RAMS, 2011). *Replacement renewable material: sheep wool insulation.*

4.11. Fibre-cement sheet

Fibre cement sheet is sometimes used for external cladding of buildings and is known for its durability with little maintenance required over its lifetime. The HardiePlank™ weatherboard is made from cellulose fibre, Portland cement and sand, and is 7.5mm thick. Fibre cement sheet has a low embodied energy, but because it covers the entire exterior of the cottage, it makes a significant contribution to the total. The only renewable alternative for exterior cladding is hardwood timber, which is commonly used for weathboards. To recalculate the embodied energy, the area of fibre cement sheet is replaced by an equivalent volume of hardwood timber. *Replacement renewable material: hardwood timber weatherboards.*

4.12. Concrete

Concrete is used to support the timber stumps in the ground. It is made up of a mixture of cement, fly ash, slag cement, aggregate, water and chemical admixtures. Although concrete has a high embodied energy, only a small amount is used in the building of the cottage. Gelder (2002) lists rice hulls and nutshells as alternatives to cement or concrete. Coulson and Fuller (2009), however, were unable to find a supplier of a renewable substitute such as rice hulls. and furthermore state that currently there is no renewable replacement for concrete. Geopolymer concrete has much lower carbon emissions as well as other advantages. However, since the material is strictly not renewable and only small quantities are involved, no substitution has been made. *Replacement renewable material: N/A.*

5. RESULTS AND DISCUSSION

Table 3 and Figure 4 show the energy embodied in the individual materials used to construct the case study building, using either conventional or renewable materials. Steel was the highest initial contributor of embodied energy in the original building but after the substitution of renewable building materials, timber becomes the highest single contributor. Although the embodied energy contribution of timber is quite substantial, the use of timber, which is a renewable material, is more appropriate from a resource perspective than steel. The amount of steel used is reduced by 72%, while timber usage is almost doubled. These are the two most significant changes resulting from the replacement of non-renewable materials with renewable alternatives. In absolute terms, there are other significant changes. The use of timber, rather than aluminium, for the window frames represents over 25% of the total reduction. Similarly, the replacement of MDF/Particleboard with softwood timber combined with the use of wool instead of fibreglass for insulation together represent 38% of the total reduction. There is one increase in embodied energy resulting from the substitution of conventional materials with those that are renewable. Crawford (2011) indicates that the embodied energy needed to produce wool carpet is higher than that required to produce nylon carpet, and therefore there is a slight increase (9%) resulting from this replacement. Since it has been assumed that currently there is no viable replacement for plastics and ceramics, their embodied energy remains the same.

Table 3 shows that the total embodied energy of the case study building is 317 GJ or 7.5 GJ per m^2 of floor area. After replacing the conventional materials wherever possible with renewable materials, the embodied energy is reduced to 229 GJ or 5.4 GJ per m^2. The reduction of 88 GJ is the equivalent of 28% of the original embodied energy. The embodied energy of the cottage built with conventional materials is similar to estimates of other residential buildings e.g. Monahan and Powell (2009). Fuller et al. (2009) found a house built in 2009 with a floor area of 233.5m^2 had an embodied energy of 7.97 GJ per m^2 of embodied energy. However, higher estimates for the embodied energy of residential buildings have been calculated by other authors. Fay et al. (2000) calculated that a 128 m^2 double storey brick veneer house had an embodied energy of 14 GJ per m^2 and Treloar et al. (2000) estimated that a 123 m^2 double storey brick veneer house on a concrete slab house had an embodied energy of 11.7 GJ per m^2. These higher figures are most likely due to an embodied energy assessment based on a slightly more comprehensive system boundary.

Table 3: Embodied energy for the case study building using conventional and renewable building materials

Material	**Conventional Materials** (GJ)	**Renewable Replacement** (GJ)	**Reduction** (GJ)	**Percentage Reduction** (%)
Aluminium	29.64	5.17	24.5	83
Carpet	18.44	20.01	+1.6	+9
Concrete	2.66	2.66	0	0
Cement sheet	14.03	2.02	12.0	86
Ceramic	10.57	10.57	0	0
Durra Panel	0.00	2.51	+2.5	+251
Glass	33.84	25.38	8.5	25
Insulation	15.92	0.38	15.5	97
MDF/Particleboard	31.72	11.57	20.2	64
Paint	17.00	17.00	0	0
Plasterboard	25.86	18.99	6.9	27
Plastic	2.76	2.76	0	0
Steel	71.45	20.13	51.3	72
Timber	43.29	89.68	+46.39	+207
Total	**317**	**229**	**88**	**28**

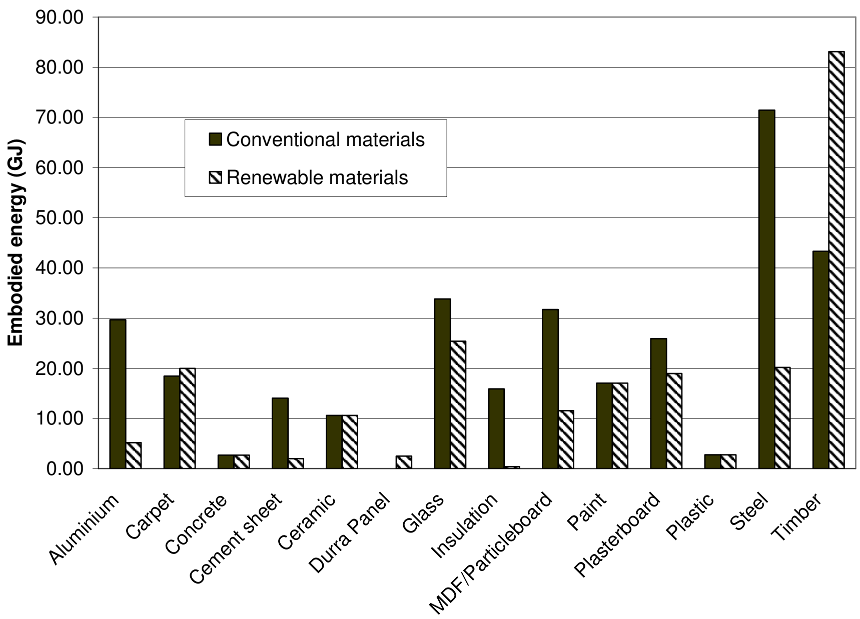

Figure 4: Comparative diagram of conventional and renewable building materials

Table 4 shows the breakdown of embodied energy calculations by building element, while Figure 5 shows the same data graphically. Originally, the highest contributing element to the total embodied energy was the steel roofing, and although this is still the case after the substitution with hardwood shakes, a reduction in embodied energy of approximately one third has been achieved. The second highest contributor to the building's original embodied energy were the wall materials, but once again a similar reduction (35%) has been achieved following substiution. The replacement of aluminium for timber frames and the substitution of recycled glass achieves an impressive 67% reduction. The embodied energy of the doors remains the same, since they are already largely constructed of timber, a renewable material. The embodied energy of the internal finishes increases slightly because of the substitution of wool carpet for nylon, the former having a higher embodied energy. In summary, the embodied energy of most of the building elements can be reduced through the substitution of renewable materials. Using the total embodied energy figures for the conventional and renewable versions, and an emission factor of 60 kg CO_2-e per GJ (Crawford 2011), the total embodied emissions were calculated. The calculated emissions for the original case study building and the building with renewable material substitutions were 19.03 t CO_2-e and 13.74 t CO_2-e respectively, representing a 28% reduction in carbon emissions.

Table 4: Embodied energy comparison by building element

Building Element	Conventional Materials (GJ)	Renewable Materials (GJ)	Reduction (GJ)	Percentage Reduction (%)
Substructure	43.09	37.44	5.65	13
Wall	64.31	41.6	22.71	35
Roofing	88.48	59.08	29.40	33
Windows	40.14	13.25	26.89	67
Doors	11.48	11.48	0	0
Internal Finishes	37.19	38.76	-1.57	-4
Internal Fit Out	32.70	27.88	4.82	15
Total	317	229	88	28

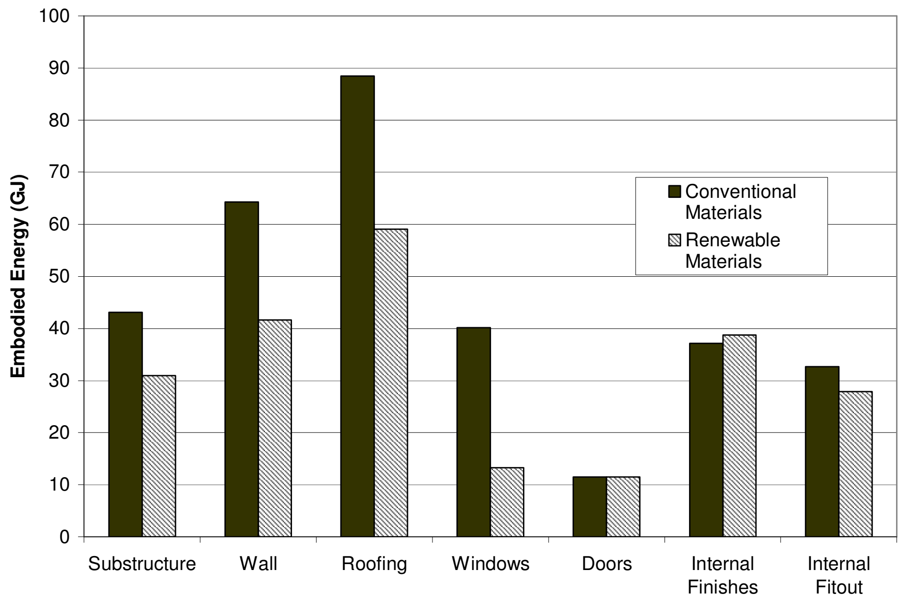

Figure 5: Embodied energy comparison by building element

CONCLUSIONS

Studies by Treloar (2000) and Crawford (2008) have demonstrated that the embodied energy of materials used in conventional building construction can sometimes equate to an entire lifetime of its operational energy. Renewable building materials have the potential to reduce this embodied energy because they are often useable in their natural form. Using renewable materials will also reduce the use of non-renewable materials which, by definition, are a finite resource. According to Crawford (2011) resources such as iron ore, used in the production of steel, may be depleted within the next 60 years.

The analysis showed that the case study building with conventional materials had an embodied energy of 7.5 GJ m^2. When renewable materials were substituted, wherever feasible, the embodied energy was reduced to 5.4 GJ m^2 i.e. 28% less. This saving is significant and, if a similar reduction could be achieved in a larger residential building, would be a good way to reduce the embodied energy and carbon in the residential construction sector. It is acknowledged, however, that some important disadvantages and advantages of renewable building materials, such as their durability and recyclabilty, would need to be considered for a more comprehensive analysis of their impact.

Previous research has identified a lack of some suitable renewable building materials within the construction industry (Gelder 2002; Coulson and Fuller 2009; and Morris 2009). This study found that the problem still exists. Even when renewable alternatives could be located, there was often insufficient information available to accurately calculate their embodied energy.

Overall, however, the study has shown that most of the materials in the case study building could be replaced with renewable alternatives. This option could be beneficial from a general resource perspective. Renewable materials, however, still require energy for processing and transportation. In Australia, this energy is predominantly sourced from fossil fuels. Therefore, the renewable materials still represent embodied carbon from this energy use. More widespread use of renewable energy in manufacturing and transportation would be required to reduce the embodied energy component of renewable building materials further.

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REFERENCES

Australian Greenhouse Office (1999), *Executive Summary Report – Australian Residential Building Sector Greenhouse Gas Emissions 1999-2010*, Commonwealth of Australia, Canberra.

Coulson, J.R. and Fuller, R.J. (2009) *Use of renewable building materials in residential construction – a review*, Proceedings: 43rd Annual Conference of the Australian and New Zealand Architectural Science Association, School of Architecture and Building Deakin University, Geelong.

Crawford, R.H. (2011) *Life Cycle Assessment in the Built Environment*, London: Taylor and Francis.

Crawford, R.H. (2009) Life Cycle Energy and Greenhouse Emissions of Building Construction Assemblies: Developing a Decision-Support Tool for Building Designers, *Sixth Australian Life Cycle Assessment Conference: Sustainability Tools for a New Climate*, Melbourne, February: 12p.

Crawford, R.H., Fuller, R.J., Treloar, G.J. and Ilozor, B.D. (2002) Embodied Energy Analysis of the Refurbishment of a Small Detached Building, *Proceedings: Australia and New Zealand Architectural Science Association Conference*, Geelong, November: 93-100.

Crawford, R.H. (2008) *Validation of a hybrid life cycle inventory analysis method*, Journal of Environmental Management, 88(3): 496-506.

DCCEE (2012). Buildings. Department of Climate Change and Energy Efficiency, Australian Government, Canberra. Available at < http://www.climatechange.gov.au/what-you-need-to-know/buildings.aspx> accessed 1st August 2012

Fay, R., Treloar, G. and Iyer-Raniga (2000). Life-cycle energy analysis of buildings: a case study. Building Research and Information, 28, 1, 31-41.

Fuller, R.J. and Crawford, R.H. (2011) Impact of past and future residential housing development patterns on energy demand and related emissions, *Journal of Housing and the Built Environment*, 26(2): 165-83.

Fuller, R.J., Crawford, R.H. and Leonard, D. (2009) What is wrong with a big house?, *Performative Ecologies in the Built Environment: Sustainable Research across Disciplines: Proceedings of the 43rd Annual Conference of the Australian and New Zealand Architectural Science Association ANZAScA*, Launceston, November.

Gelder, J. (1996). *Renewable resources: an introduction to materials.* Environment Design Guide, Pro 10, The Royal Australian Institute of Architects, August.

Gelder, J. (2002). *Renewable resources: a survey of materials*. Environment Design Guide, Pro 11, The Royal Australian Institute of Architects, November.

IPCC (2007). Chapter 6; Residential and commercial buildings. Climate Change 2007: Working Group III: Mitigation of Climate Change. International Panel on Climate Change. Geneva, Switzerland

Lippke, B., Wilson, J., Perez-Garcia, J., Bowyer, J., Meil, J. (2004) CORRIM: *Life-Cycle Environmental Performance of Renewable Building Materials,* In Forest Products Journal, 54, 6, Consortium of Research on Renewable Industrial Materials, Seattle.

Monahan, J. and Powell, J.C. (2009). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Buildings, 43, 179-188.

Morris, W. (2009). Sustainable building materials. Unpublished report, Master of Architecture, School of Architecture and Building, Deakin University, Waterfront Campus Geelong, Victoria 3217.

Ortech (2010). Durra panel. Available at: http://www.ortech.com.au/durra-panels/durra-panel. Accessed 14/08/2012.

Perez-Garcia, J., Lippke, B., Briggs, D., Wilson, J.B., Bowyer, J., Meil, J. (2005) *The environmental performance of renewable building materials in the context of residential construction*, in Wood and Fibre Science, 37 Corrim Special Issue, The Society of Wood Science and Technology, Monona.

Parkins, J. Bamboo buildings. Bali's green benchmark. Available at: http://designbuildsource.com.au/bamboo-buildings-bali%E2%80%99s-green-building-benchmark Accessed: 14/08/2012

RAMS (2011). Wool insulation: environmentally friendly. Available at: http://www.ramsinsulation.com.au/pdffiles/a-environmentally-friendly.pdf Accesse: 14/08/2012

The Renewable House (2012). Available at: http://www.renewable-house.co.uk/materials/ Accessed 14/08/2012

Treloar, G.J., Fay, R., Love, P.E.D. and Iyer-Raniga, U. (2000) Analysing the life cycle energy of an Australian residential building and its householders, *Building Research and Information*, 28(3): 184-95.

VGC (2011). Victorian Garden Cottages – (formerly) http://vgc.com.au. Now believed to be no longer trading