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Life Cycle Potential of Strawbale and Timber for Carbon Sequestration in House Construction

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ABSTRACT

Some construction materials can sequester carbon, balancing emissions from other materials and operating energy. This paper shows the ability for house design and construction to reduce CO_2 emissions towards net zero, by using biomaterials (strawbale and timber), and emission-reducing technologies. A life cycle analysis of different house designs was used to compare the effectiveness of biomaterials with CO_2-minimising technologies. End-of-life scenarios for materials are discussed. Strawbale and timber are ranked with other materials, energy-producing technologies, and efficient appliances, to compare CO_2 reductions. A limit to benefits from conventional insulation is identified; while strawbale is shown to continue providing thermal and CO_2 sequestration benefits as R-values increase. Strawbale and timber for house construction are as effective at reducing CO_2-e emissions (by about half) as solar hot water, photovoltaics, efficient appliances, and efficient lighting, combined. In combination, strawbale, timber, and emission-reducing technologies can potentially make houses net-absorbers of CO_2.

INTRODUCTION

This study aimed to discover how a house could be designed, built and operated, using emissions-reducing strategies, to achieve the lowest net carbon dioxide equivalent (CO_2-e) emissions practicable. Some construction materials or technologies have apparently 'green' credentials, while others are thought to be environmentally detrimental. Without a careful analysis, however, the relative contribution of different materials or technologies remains unknown. Timber is a familiar construction material with carbon sequestration benefits. Strawbale, a chemically similar plant waste material, has more recently been used for building construction and insulation. If these bio-materials are maximised in the construction of a house, can they make a useful contribution towards reducing life-time CO_2-e emissions, and compete with emission-reducing technologies?

A life cycle analysis was used to compare the effectiveness of using carbon-sequestering bio-materials (strawbale and timber) with emission-minimising technologies (solar hot water, photovoltaics, efficient appliances, efficient lighting, and wind generation). A typical New Zealand (NZ) house conforming to current building regulations was modelled, against which variations could be assessed. Different construction methods, for floor, walls, roof, insulation, windows, and operating energy sources, were compared to show their contribution to reducing emissions. Thermal analyses for four performance levels were used, to discover the relative benefits of increased insulation. The energy and emissions for individual materials, energy technologies, and operating energy were compared to rank their contributions. All energy values were calculated in primary energy terms. To make different CO_2-e emissions and absorptions easily comparable, a method of evaluating each contributing emission/absorption was developed. To account for end-of-life emissions, carbon emission rates for landfilled bio-materials were determined.

After a brief description of the methodology, the standard house and variations to be tested against it are outlined. The effects of increased conventional, and strawbale, insulation are described. Options for using more timber and the consequent reductions in CO_2-e emissions are discussed. Relative contributions and options for using different emission-reducing technologies are discussed. Finally, CO_2-e reductions from all interventions are ranked. Any unreferenced figures were derived from analysis in a PhD thesis by Alcorn (2010).

METHODOLOGY

Eighteen 200m^2 houses were analysed for embodied energy and embodied CO2-e in their materials. The houses included 4 representative of typical NZ construction practice for the 1970s and 2000s (Johnstone, 2001). A further 14 houses represented projected construction practice for houses in the decades from 2010 and 2020. The 1970s houses were typical of the average construction of the NZ housing stock up to 2000. The principal difference in the houses beyond 2000 was a greater use of insulation. Insulation levels of up to R10 for the 2020 houses were modelled with different insulation materials, and thicker framing to accommodate it, as appropriate.

Materials quantities were calculated from: overall house dimensions; wall lengths and heights; roof pitch, eaves and verges; window area; NZ building code framing sizes; insulation thickness; painted area; and life expectancy of individual materials. Values were calculated for: overall house dimensions; framing and fasteners; insulation; windows and doors; paint; life expectancy of materials; operating energy and emissions; and landfilled materials carbon loss or retention. Plumbing, wiring, floor coverings, furniture and landscaping were not included in the analysis.

For each material input, the embodied energy and CO_2-e emissions of the initial-build were calculated, using the hybrid analysis method developed by Alcorn (1995, 2003) but using updated values. (These values included NZ grid electricity emission factors, accounting for all line losses, fugitive emissions, hydro emissions, power plant efficiencies, local fuel types, and all other relevant detail.) Materials emitting or absorbing CO_2-e were treated separately, so that totals for emissions and absorptions could be calculated.

Annualised Lifetimes. Maintenance was according to typical lifetimes of materials. Houses were analysed with lifetimes of 50, 100, and 150 years. The results for each of these lifetimes were compared to annualised results. For the annualised results, each material or building component was assigned a lifetime according to typical NZ practice. Aluminium window frames, for example, were assigned a lifetime of 35 years (Bennet, 2008). The glass in the frames was thus also assigned a 35 year lifetime, since it would be replaced along with the frames. The embodied energy and CO2-e emissions for a complete window were thus divided by 35 to give an annualised figure.

Construction Variations. Most of the 18 houses were modelled with lightweight timber framing, common in NZ. For comparison, two heavyweight houses, using concrete and earth walls, were modelled. For all other houses, the cladding was timber weatherboard. Floor variations were concrete slab-on-grade, or suspended timber. Roof variations were zinc/aluminium coated corrugated steel, concrete tile, and timber shingles. For the timber framed houses, linings were of painted gypsum plaster board or timber, or unpainted earth plaster. Windows and doors were modelled as either aluminium or timber frames. Glazing varied from single for the 1970s houses to triple for the 2020 houses. Insulation variations included glass fibre, expanded or extruded polystyrene, and strawbale. Roof dimensions followed the wall thickness, according to insulation levels, and extra eaves and verges for rain protection over earth or strawbale walls.

End-of-Life. The typical end-of-life scenario for NZ houses is demolition and land-filling of materials. Carbon loss rates for the long-term sequestration of land-filled straw and timber materials were calculated from two important studies: Ximenes et al. (2008) and Micales and Skog (1997). Ximenes et al. based their concluding results on a single sample, although other samples were conducted, while Micales and Skog's calculations included arithmetical errors. Careful re-working of the calculations, however, shows that the carbon loss rate from both studies is between 5 and 6%. Micales and Skog analysed results for straw, which show a carbon loss rate of 7%, consistent with straw's lower resistance to decomposition.

Ximenes et al. note that low soil moisture content contributes to low decomposition of landfilled bio-materials, and that sound wood samples were recovered from a 100 year old landfill. In carefully managed landfills very low carbon loss rates seem attainable for the long-term; to be conservative, however, the carbon loss rate used for calculating annualised CO_2 absorption for the houses modelled in this study was 5.7% for timber and 7.0% for straw. These carbon loss rates translate into CO_2 retained in the long-term, or sequestered, at a rate of 70% for timber and 63%, for straw. This may, however, understate actual sequestration of carbon in bio-based building materials in landfills, especially in dry sites.

Operating Energy. Household types and their energy use patterns were analysed for: average NZ families of 2.7 people (Statistics NZ, 2008a; 2008b); households on benefit incomes; a retired couple; and a working, single person. Average operating energy data, except for heating, was taken from a national survey (Isaacs et al., 2006). This was modified by using specific heating data from the thermal analyses. Emissions for the different NZ energy types were applied pro-rata.

Electricity is the main energy source in NZ for housing construction and operation. Although it is ~60% hydro, it accounts for over 90% of house operating emissions. This percentage is based on *average* NZ grid emissions; if a *marginal* emission rate is used, grid electricity accounts for approximately 97% of house emissions. Accordingly, three technologies were modelled to reduce grid electricity demand: solar hot water; photovoltaic (PV) panels; and a wind generator.

Efficient lighting, appliances, and refrigeration, were modelled to reduce operating electricity demand. Increased insulation was modelled to reduce heating (and therefore electricity) demand. All of the technologies to reduce grid electricity use were also modelled on an annualised basis, including maintenance.

RESULTS

The Standard House. The 1970s house analysed, representing typical existing NZ housing stock, used 46.5GJ total annual energy, including embodied energy of construction and maintenance, and operating energy. Total annual CO_2-e emissions were 2,287 kg. The 2000s house, representing current construction practice, used 41.7GJ total annual energy, and had CO_2-e emissions of 2,197 kg. This was the base case against which changes in insulation, materials, and energy technologies were assessed. Table 1 shows the energy and CO_2-e totals for a 1970s house poor insulation), two 2000s houses using current code insulation levels, a 2010 house with better-practice-than-code insulation, and five 2020 'best practice' houses.

Not all figures sum, due to rounding. Care should be exercised interpreting particular values, which derive from spreadsheet calculations and may excessively suggest precision.

Table 1. Total Annual Energy and Net CO_2-e Emissions for NZ Houses

	Annual Energy (GJ)	Annual CO_2-e (kg)
'Poor' insulation, timber frame, concrete floor	46.5	2,287
'Current code' insulation, timber frame, concrete floor (**Standard house**)	**41.7**	**2,197**
'Current code' insulation, timber frame, suspended timber floor	42.6	2,151
'Better practice' insulation, timber frame, concrete floor	38.5	2,115
'Best practice' insulation, timber frame, concrete floor	41.3	2,252
'Best practice' insulation, timber frame, suspended timber floor	41.7	2,198
'Best practice' insulation, concrete walls, concrete floor	42.1	2,584
'Best practice', strawbale, timber frame, concrete floor	37.9	1,903
'Best practice', strawbale, timber frame, suspended timber floor	36.9	1,707

Table 1 shows that at current code or 'best practice' insulation levels, the thermal mass of concrete floors reduces total energy use. A suspended timber floor house, however, has lower CO_2-e emissions, because the CO_2-e absorbed in the timber floor exceeds the reduced heating emissions due to the high mass floor. For the 'best practice' house with high insulation levels, the total energy use and CO_2-e emissions are greater than for the 'better practice' house, with less insulation, because of the high energy and emissions associated with the thick polystyrene insulation. In the NZ climate, insulation of approximately R5 gives the lowest total net energy and CO_2-e emissions. More insulation, beyond R5 *increases* total net energy use, and emissions.

Strawbale Insulation. Table 1 shows the advantage of greater insulation in reducing heating energy. Choosing bio-based insulation rather than glass fibre, polystyrene, or other synthetic materials, however, provides advantages in reducing heating energy, plus reducing CO_2-e emissions. Table 2 shows the total CO_2-e emissions for a highly insulated 'best practice' house with suspended timber floor. Polystyrene insulation, used to minimise insulation thickness, was substituted with strawbale (SB) insulation, for the floor, walls, ceiling, or the whole house. The R value for polystyrene and strawbale were identical in the model. The total emissions show the effects of CO_2 sequestration in the straw. Strawbale is thus able to reduce heating demand and emissions through high R values, as well as sequestering CO_2. Total CO_2-e reductions from strawbale insulation may be as high as 560kg if a lower carbon loss rate from landfilled demolition straw is assumed.

Straw is highly sensitive to deterioration in the presence of water (Alcorn et al, 1999). If kept dry, however, straw can last the life of the wall. A lifetime of 100 years for strawbale was adopted for this study. When a shorter lifetime was adopted, the effect was for more CO_2 to be sequestered by the replacement strawbale, assuming the removed straw was landfilled. The calculated strawbale absorption figures in this study are therefore conservative.

Table 2. Total Annual CO_2-e Emissions and Reductions: Strawbale Insulation

	Annual CO_2-e emissions (kg)	CO_2-e reduction (kg)	CO_2-e reduction (%)
Suspended timber floor, all polystyrene insulation	2,200	0	0.0
SB *ceiling* insulation, floor and walls polystyrene	2,060	135	6.5
SB *wall* insulation, floor and ceiling polystyrene	1,990	213	11
SB floor insulation, walls and ceiling polystyrene	2,060	143	7.0
All strawbale insulation	1,710	491	29

Timber. Like strawbale, timber sequesters CO_2, and extra timber framing increases sequestration. More timber may be used to accommodate thicker insulation, wider eaves and verges, or a suspended timber floor. Timber linings, window frames, and roof shingles, are other CO_2-sequestering opportunities. Table 3 shows the CO_2-e reductions from using timber for some building elements. Percentage CO_2-e reductions are from the 'best practice' suspended timber floor lightweight house.

Table 3. Total Annual CO_2-e Reductions: Bio-Materials

Use:	CO_2-e reduction (kg)	CO_2-e reduction (%)
Wider eaves and verges (1 m)	9	0.4
Timber floor v concrete slab	54	2.5
Timber linings v gypsum board	77	3.5
Timber roof shingles v steel	110	5.0
Timber window frames v aluminium	139	6.3
Lightweight wall v concrete masonry	350	16
Strawbale insulation	491	29
Totals	*1,230*	*62.7*

The largest reduction from using timber is to replace concrete masonry walls. Other wall materials, such as steel frame or fired clay brick masonry were not modelled; both these materials, like concrete, have high embodied energy and CO_2-e.

The second largest emissions reduction available from timber, for use as window frames, is largely due to the elimination of high embodied CO_2-e aluminium frames. The modest CO_2-e reduction from wider eaves (as may be used with earth walls or for solar control) is amplified if combined with timber roof shingles, to 15kg, or 0.7%. The CO_2-e reductions by using timber linings include CO_2 sequestration and the avoidance of emissions from gypsum plasterboard linings. Both were modelled with the same painting regime; further reductions could be achieved by using unpainted or oiled timber linings. The CO_2-e reductions from a suspended timber floor assume polystyrene insulation; a greater reduction is available by using strawbale insulation for the floor.

Other Materials. A selection of other materials was analysed for potential reduction of annual net whole-house CO_2-e emissions, and is shown in Table 4.

Table 4. Total Annual CO_2-e Reductions: Selected Materials

	CO_2-e reduction (kg)	CO_2-e reduction (%)
Fired clay roof tiles v corrugated steel	31	1.4
Concrete roof tiles v corrugated steel	40	1.8
Earth walls v timber frame	40	1.8
Unpainted materials v painted	69	3.1

Concrete roof tiles in place of painted corrugated zinc/aluminium coated steel gave a modest emissions reduction, due to the CO_2 sequestered in the extra roof framing for the heavy roof, and the avoided emissions from the steel and its required painting maintenance. Fired clay roof tiles also have some of these benefits, although their higher embodied CO_2-e decreases the advantage.

Earth walls are often lauded for their environmental credentials. From an energy and CO_2-e perspective, however, in the NZ climate, they offer only modest reductions (a net 40kg). They were modelled with the same insulation as the equivalent concrete slab floor house, so suffered no R value penalty. Their high thermal mass made only a small contribution to CO_2-e reductions (9kg). Not needing to paint earth walls reduced CO_2-e by 41kg. The earth walls were modelled as straw-stabilised adobe, sequestering a small amount of CO_2 in the straw. Compared to timber frame and cladding, however, they sequestered much less CO_2 (64kg versus 128kg). More concrete was also required for foundations, further increasing CO_2-e emissions.

Paint can have a large impact, compared to its apparently small physical presence, as shown in Table 4. The repainting interval of 8-9 years is related to the average length of house ownership in NZ. Non-paintable materials are able to significantly contribute to reduced CO_2-e emissions.

Energy Technologies. To compare the contribution of reducing grid electricity demand towards lowering total annual CO_2-e emissions, six technologies were modelled, as shown in Table 5. All the emissions reductions from the energy technologies are from CO_2-e emissions avoided by lowering grid electricity use.

Table 5. Total Annual CO_2-e Reductions: Selected Technologies

	CO_2-e reduction (kg)	CO_2-e reduction (%)
Efficient appliances	90	4.1
Efficient lighting	110	5.0
Efficient refrigeration	170	7.8
Photovoltaic panels	435	20
Solar hot water heater	472	22
Wind generator	1031	47

The wind generator modelled had a rated output of 1kw. The actual output was based on average wind speed at NZ sites (EECA, 1995). Not all sites are suitable for wind generation, but for those that are, this option provides by far the single biggest reduction in emissions. Like the other technologies that reduce grid electricity use, this is because of the avoided emissions from average NZ electricity production. If a marginal emission factor was applied, which equates to coal and gas fired thermal generation, the mass of avoided emissions was approximately three times higher. Separate replacement rates were used to reflect the longevity of generator, tower, and copper cabling.

Isaacs et al. found that in NZ 75% of hot water is heated with electricity. Hot water heating releases more than twice the CO_2-e of any other domestic energy use in NZ, as shown in Figure 1.

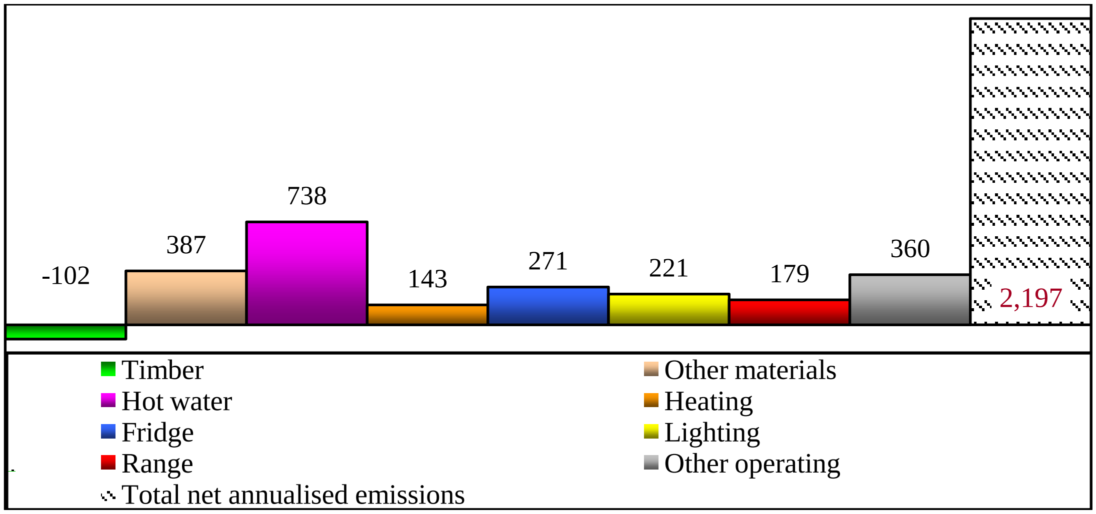

Figure 1. Total Annual CO_2-e flux: Current Code Construction and Operation

A solar hot water heater, with a panel area of 3.75m^2, the current average for a three bedroom NZ house, gave a CO_2-e reduction of over 470kg. A panel area of 4.3m^2 achieved a 75% water heating energy reduction, while 5.75m^2 heated virtually all hot water for a NZ house, using average figures (EECA, 2006). In this case, the total annual CO_2-e reductions for the whole house were over 720kg, or $^1/_3$ of total emissions.

The emissions reductions from PV panels were also dependent on panel area. With 10m^2 of panels, using multi-crystalline silicon cells, the CO_2-e reductions approached those from solar hot water. With larger 25m^2 panels, the CO_2-e reductions exceeded those from a wind generator. Cost, however, remains an even greater barrier to large panel installations than for solar hot water. Modelling modest sized PV panels was therefore more realistic. The PV systems modelled included panels, balance-of-system installation, and replacement at a 25 year interval (Alsema, 2000).

Refrigeration is second to hot water in operating energy use. The most efficient fridge currently on the NZ market, compared to the average-performing fridge currently sold, reduced annual CO_2-e emissions by 15kg. When comparing emissions reductions of the most efficient fridge versus currently-used refrigeration, which includes old second-fridges (the ‘beer’ fridge in the garage), the CO_2-e reductions available became significant (170kg) (Isaacs et al, 2006; Consumer, 2009).

Efficient appliances, not including refrigeration, provided a 25% reduction in total appliance energy use, according to a study of local appliance efficiency (University of Otago, 2008). Allowing for variation between households, the emissions reductions available from efficient appliances were approximately equivalent to those from efficient lighting. The CO_2-e reductions from efficient lighting provided a total 50% reduction over current usage, by using compact fluorescents where possible (Consumer, 2008).

CONCLUSION

Table 6. Total Annual CO_2-e Reductions: All Strategies

	CO_2-e reduction (kg)	CO_2-e reduction (%)
Wind generator	1,031	47
Aggregate of timber strategies	*739*	*34*
Strawbale insulation	491	29
Solar hot water heater	472	22
PV panels	435	20
Lightweight timber wall v concrete masonry	350	16
Efficient refrigeration	170	7. 8
Timber window frames	139	6.3
Efficient lighting	110	5.0
Roof shingles	110	5.0
Efficient appliances	90	4.1
Timber linings	77	3.5
Unpainted materials v painted	69	3.1
Timber suspended floor v concrete slab	54	2.5
Wider eaves and verges (1 m)	9	0.4

Table 6 shows all the discussed options for CO_2-e reduction from Tables 2-5, ranked. Wind generation has the greatest potential to reduce total net emissions, but has the practical disadvantage of not being suitable for all sites. After wind, timber and strawbale construction offer the greatest potential to reduce total net CO_2-e.

The second most important individual strategy after wind generation is to use strawbale insulation, with a net reduction of 500kg, including wider eaves and verges to provide weather protection. Super insulation (beyond R5) using conventional insulation materials is often assumed to reduce total energy use, but (at least in the NZ climate) this is incorrect. Strawbale insulation, however, does provide increased CO_2 benefits as more is used.

Another common misconception is that earth walls provide an important greenhouse gas benefit. Their contribution is only modest, principally because of the concrete commonly used for their substantial foundations. Cement stabilisation of earth walls would further reduce any benefits they have. They remain preferable to concrete walls, however, because of their low embodied CO_2, especially when stabilised with straw.

The use of timber materials in place of: masonry for walls and floor; steel for roofing; plasterboard for linings; and aluminium for window frames, provides a total CO_2-e reduction potential of sizeable 730kg. Straw and timber as CO_2 absorbing materials therefore total an annual CO_2-e reduction potential of about 1,230kg. This rises to 1,280kg if Micales and Skog's carbon loss rate is used for calculations. Even if carbon loss rates are greater than calculated from Ximenes et al. and Micales and Skog, by 20%, strawbale and timber absorptions still total 1,180kg.

Strawbale and timber absorptions (1,230 kg) were almost the same as the total emission-reductions from applied energy-minimising technologies (1,277kg), excluding site-specific wind generation. This is about half of total emissions from a standard house. The CO_2-e reductions from using strawbale and timber represent actual sequestration. The CO_2-e reductions from reduced operating energy, however, only represent avoided emissions from the national grid. These avoided emissions may be less if emissions-intensity in the national grid is reduced, by greater use of renewable energy. However, the ongoing sequestration of CO_2 from using strawbale and timber remains.

Strawbale and timber therefore represent a major opportunity to reduce annual CO_2-e emissions from housing construction and operation. Their use should be considered, as sustainable materials, at the forefront of attempts to reduce construction and maintenance CO_2-e emissions, and at least on a par with strategies to reduce operating emissions. By using strawbale and timber to sequester CO_2, in combination with technologies to reduce the use of grid energy, houses can be made to be net absorbers of CO_2, achieving an essential feature of sustainability.

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