Life cycle assessment and carbon footprint of multi-storey timber buildings compared with steel and concrete buildings

Andrew Buchanan, Stephen John and Simon Love

Abstract

Life cycle assessments are used to compare the environmental effects of energy and global warming potential or carbon footprint of a three-storey timber building with alternative concrete, steel and low-energy timber buildings. The environmental effects are assessed with reference to greenhouse gas emissions, leading to global warming potential. Differences from previous studies are explored. A material carbon footprint calculation is proposed for possible inclusion in green building rating schemes, to compare the environmental impacts of building materials.

Introduction

This article summarises the environmental effects of energy and global warming potential or carbon footprint from a comparative life cycle assessment study following the design and construction of a three-storey timber building in Nelson. A calculation method is proposed for inclusion in green building rating schemes, to compare the environmental effects of building materials.

The main features of the proposal are –

- The calculation method requires a set of coefficients for the production and disposal of all major building materials
- The coefficients will give typical New Zealand values for global warming potential, in tonnes of carbon dioxide equivalent per tonne of material, for manufacture and disposal of materials. These can be multiplied by the mass of material in any building to give a total effect for the building, then divided by floor area to give a carbon footprint.
- The coefficients must be derived from consistent life cycle assessment studies using rules and system boundaries agreed by all the major material manufacturers and in consultation with life cycle assessment experts.
- This proposal is only for global warming potential, but the same principles can be used for any other environmental effects
- The proposal is for only two parts of the building's life cycle – the production and eventual disposal of the building materials.

Operational energy of the building is not included because it is not heavily material-dependent, and it is assessed separately using established protocols. Transport of materials, construction of the building and eventual demolition activities are not included as the figures are small compared with production and disposal.

Case study building

The case study building is the three-storey timber Arts and Media building at the Nelson Marlborough Institute of Technology. In addition to the real timber building, a similar steel and a similar concrete building were designed and investigated. A fourth building was a special low-energy version of the timber building called the TimberLow building.

This article results from a collaborative research programme led by the University of Canterbury for the Ministry of Agriculture and Forestry in 2010 and 2011. Appendix D of that report is a life cycle assessment study from ScionResearch, carried out by Simon Love. That study includes a full description of the system under analysis, the functional unit, system boundaries and data quality. The system boundaries applied in this study were 'cradle to grave'.

System expansion has been employed to take into account the benefits of any recycling of metals and concrete, and energy from wood. Upstream processes, such as the production of diesel used in transport as well as the emissions of the transport vehicles, have been taken into account including all related environmental effects. This also applies to the provision of natural gas for heating and electricity.

The designers of the timber building, ISJ Architects and Aurecon Group engineers, were commissioned to design the concrete and steel alternatives, with equivalency between the different building designs. This enabled objective and in-depth comparison across a number of criteria including life cycle assessment.

The life cycle inventory data used in this study for most building materials is from Nebel et al [2], except that data on laminated veneer lumber are from Love [3]. Data for other materials is from a life cycle assessment software package GaBi 4.3 based on European industry data [4]. Global warming potentials for New Zealand energy sources – mainly electricity, natural gas and diesel – are based on recent life cycle calculations from AgriLink [5]. Energy figures for the actual construction and demolition of the building are not included because they are considered to be negligible [6].

The initial life cycle assessment analysis is carried out over the anticipated full 60-year life of the buildings. An additional 100-year life was also investigated in the original report, but is not reported here as no significant or unexpected differences arose from the longer life. The two categories considered are primary energy, as an indicator for resource consumption, and greenhouse gas emissions. A more extensive study could have included categories such as water use, ozone depletion and emission of volatile organic carbon gases. However, global warming potential is the main topic of this article.

Components of energy and resulting emissions

The components of energy and resulting carbon dioxide emissions for all buildings are from these life cycle stages –

1. Manufacturing the building materials cradle to gate
2. Delivering the building materials to the building site
3. Construction of the building
4. Lifetime operation of the building
5. Manufacturing the materials needed for routine maintenance
6. Deconstruction
7. Final disposal of the materials at the end-of-life of the building

All of these items can be assessed initially in terms of energy. The fossil fuel component of that energy results in the emission of carbon dioxide into the atmosphere. Additional emissions of greenhouse gases include carbon dioxide emissions from the manufacture of cement and of methane from anaerobic decay in landfills. In addition, carbon dioxide uptake by trees in the growth phase is included within the manufacture of building materials. These are all included. Greenhouse gas emissions are quantified in tonnes of carbon dioxide equivalent, which is the standard unit for the impact category of global warming potential.

Of the components listed above, operational energy which averages 85 per cent for all study buildings, and operational emissions, also averaging 85 per cent during the life of the building, are by far the largest component of energy use and emissions. For a typical building, operational energy consists mainly of energy for heating and cooling at 63 per cent, energy for lighting 16 per cent, hot water 15 per cent and six per cent for electrical appliances.

Operational energy for heating and cooling of buildings is reducing worldwide as new building designs become more efficient. Therefore, the embodied energy of the materials will become an increasingly higher proportion of total lifetime energy use. In this study, the calculated total annual operational energy consumption for the timber, concrete and steel buildings is very similar at 132 megawatt hours a year to 135 megawatt hours a year. The TimberLow building has a significantly reduced operational energy of 114 megawatt hours a year.

The other components combined make up the embodied energy and embodied emissions**.** The term embodied energy is often used only for manufacturing the building materials, but a full life cycle analysis needs to include all the steps listed above except operation. For this reason, the term embodied is not used further in this article because of confusion as to which parts of the building's life cycle it refers to.

This study concentrates on items one and seven in the above list – manufacturing of the building materials, and eventual disposal. The construction energy has been ignored in this study because it is very small and the same applies to deconstruction. The items for delivery and maintenance are small and uniform from building to building. They are discussed briefly below.

Material quantities

The material quantities for each building component of each building type, in tonnes, are presented in the Research Report [1], as estimated by Davis Langdon Quantity Surveyors. The total quantities, in tonnes, of the main building materials are summarised in Table 1. All of the analysis in this article is building by building, where for each building design, all the materials in the building are assessed and the results are aggregated to a building total.

Table 1: Total building material quantities for each building design in tonnes

Material tonnes	Concrete	Steel	Timber	TimberLow
Concrete	1,633	996	961	961
Reinforcing steel New Zealand	136	78	78	78
Structural steel imported	39	123	2.6	2.6
Sheet steel NZ	9.3	23.9	9.3	9.3
Glass	27.5	27.5	27.5	27.5
Timber	72.3	38.5	37.0	37.0
LVL	0	0	163	163
Plywood/MDF	29.8	29.0	30.0	30.0
Aluminium	3.7	3.7	3.7	1.1
Plasterboard	14.0	16.8	14.0	14.0
Paint	0.8	0.8	0.8	0.8
Glass wool insulation	16.2	16.2	16.2	17.6
Expanded polystyrene	0	0	0.2	0.3
PVC	0	0	0	1.3
Building paper	0	0.1	0.1	0.1
Total	1,982	1,353	1,344	1,344

Table 2: Summary of the end-of-life assumptions for the main structural materials

	Current end-of-life scenario	Future end-of-life scenario
Timber	All wood is sent to landfill. 82 per cent of wood is stored in perpetuity, 18 per cent is decomposed. From the decomposed wood, 50 per cent of the carbon is released as carbon dioxide, 50 per cent as methane 58 per cent of the methane is emitted to air, 42 per cent is captured. 43 per cent of the captured methane is burned for heat energy and converted to carbon dioxide, 57 per cent is burned and converted to carbon dioxide. The heat is used to avoid fossil fuel combustion, giving an energy credit.	All wood is burned for energy recovery. All wood is burned in a co-generation plant, with 98 per cent efficiency; 29 per cent of energy as electricity, 71 per cent as heat. Electricity and heat are used to avoid fossil fuel combustion, giving an energy credit. All carbon is released as carbon dioxide to the atmosphere.
Steel	85 per cent of structural steel and reinforcing steel is recycled. Energy credit from re-use of the 85 per cent of steel recycled used in place of virgin steel.	All structural steel and reinforcing steel is recycled. Energy credit from 100 per cent recycled steel replacing virgin steel.
Concrete	All concrete is sent to clean landfill after it is broken up to remove reinforcing steel, of which 85 per cent is recovered. Energy to crush concrete is not included.	All concrete is broken up for use as recycled aggregate in concrete made from new cement. It is assumed that the energy to crush concrete is the same as that required to make new aggregate, and that crushed concrete replaces aggregate production.
Aluminium	No recycling, hence no energy credits.	100 per cent recycling. Energy credit from recycled aluminium replacing virgin aluminium.

End-of-life scenarios

Two end-of-life scenarios are presented and discussed. The current scenario is based on disposal methods available today, with the future scenario considering a much higher level of recycling. The latter is a prediction for 60 years' time when current buildings will be at the end of their lives and new technologies are likely to have been implemented. The current scenario assumes waste disposal practices available now in New Zealand where most timber will be sent to landfill at the end of a building's life, 85 per cent of steel will be recycled, and all concrete will go to clean-fill.

Primary energy

Primary energy is contained in raw fuels and any other forms of energy which has not been subjected to any conversion or transformation process. Primary energies are transformed in conversion processes to more convenient forms such as electricity and cleaner fuels. The transformation includes losses in generation, transmission and distribution.

Figures 1 to 4 show primary energy for the construction of the four buildings. The term primary energy should strictly include all energy, including solar energy used in the production of growing trees, for a complete energy balance. However, the figures exclude photosynthetic solar energy. The life cycle assessment data for building materials is from Nebel et al [2] for New Zealand produced materials or from the GaBi database for others.

Energy used and returned

Figures 1a and 1b show the primary energy used for the full life cycle of each building for two end-of-life scenarios. It can be seen that the operational energy over the 60-year life of the buildings is by far the largest proportion, followed by the energy for production of the building materials. This energy use is roughly similar for all four buildings, except that the operational energy is lower for the TimberLow building.

The negative end-of-life energy for the two timber buildings is the energy obtained from burning the methane captured after the wood products are stored in a landfill for the current scenario, or the energy recovered from combustion of waste wood for the future scenario, minus all energy required to go through the end-of-life phase. That is, the deconstruction, transport to landfill, maintenance of landfill and the process for the capture of methane.

Improvements with timber

For the steel building, the negative end-of-life energy represents the avoidance of energy needed to manufacture new virgin steel because 85 per cent of the steel in the building is assumed to be recycled at end-of-life. The negative end-of-life energy for the concrete building is from the same source, mainly for the steel reinforcing bars. After subtracting these negative values from the positive values, the net primary energy for the first three buildings is almost identical.

For each of the four buildings, the bottom black boxes in Figure 1a and Figure 1b are similar, representing the energy for the production of all materials in each building. Figure 2 shows the proportion of renewable and non-renewable energy in each of these boxes. The renewable energy in Figure 2 includes energy from wood waste burned as fuel, and energy from the proportion of electricity generated by hydro-power or wind. Much of

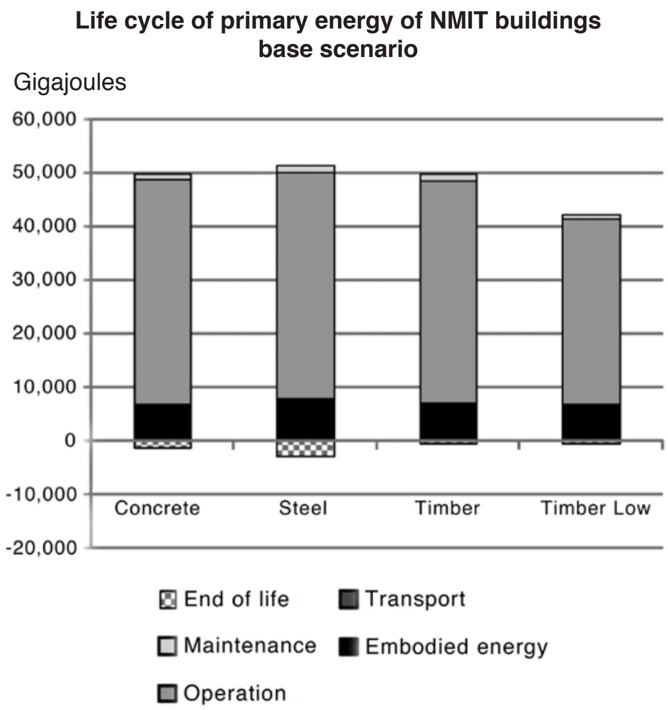

Fig 1a. Primary energy for each building, for 60-year life, for current end-of-life scenario

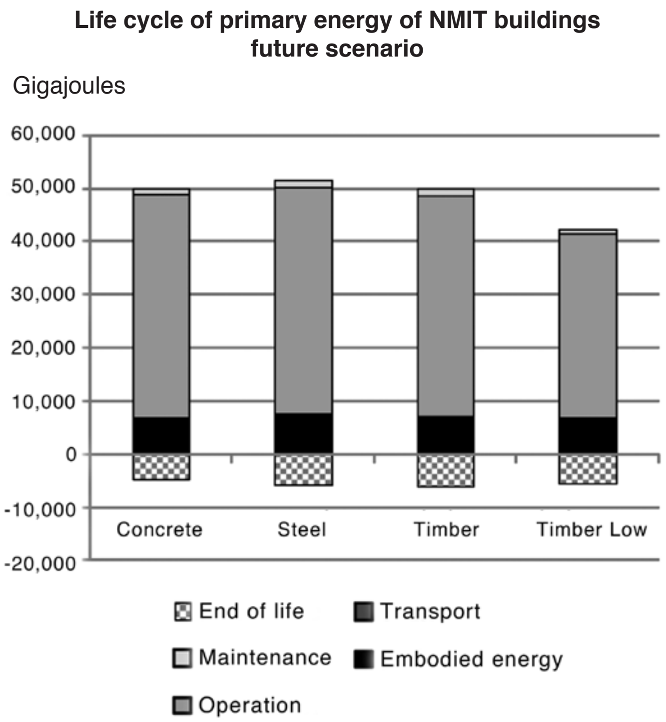

Fig 1b. Primary energy for each building, for 60-year life, for future end-of-life scenario

the energy required in the wood processing industries is obtained from burning of wood waste materials on-site, all of which is renewable. Only the non-renewable or fossil fuel part of energy contributes to carbon dioxide emissions and global warming potential.

The timber buildings show the biggest improvement because the current landfill scenario produces limited

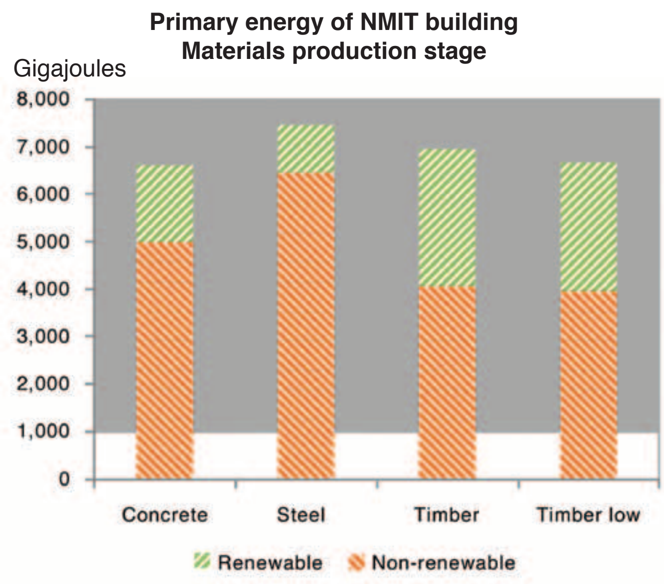

Fig 2. Renewable and non-renewable components of energy for materials production

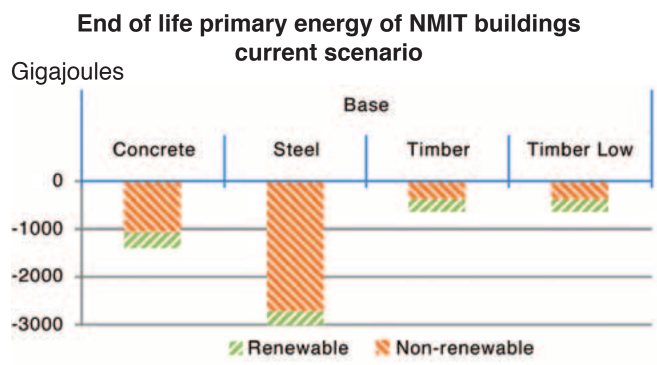

Figure 3a: Renewable and non-renewable components of energy for materials disposal for current end-of-life scenario

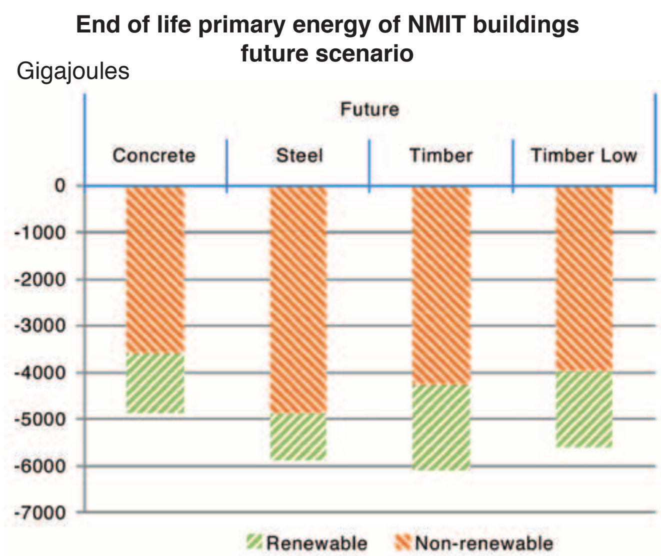

Figure 3b: Renewable and non-renewable components of energy for materials disposal for future end-of-life scenario

useful energy, whereas the future co-generation scenario produces a large amount of useful energy. The split between renewable and non-renewable energy is specific to New Zealand because of the high percentage of electric energy produced from hydro-generation. This split would be very different in a country such as Australia where most electricity is generated by fossil fuels.

Figure 4a and Figure 4b show the net primary energy for whole life cycle excluding operational energy for both end-of-life scenarios. In Figure 4a, current end-of-life, it can be seen that while the timber building overall requires the use of more primary energy than the others, it requires less non-renewable energy, and therefore has the highest proportion of renewable energy. The figures are much less for the future end-of-life scenario, especially for the two timber options, where it is significant that the net non-renewable energy is less than half of that for the concrete or steel buildings.

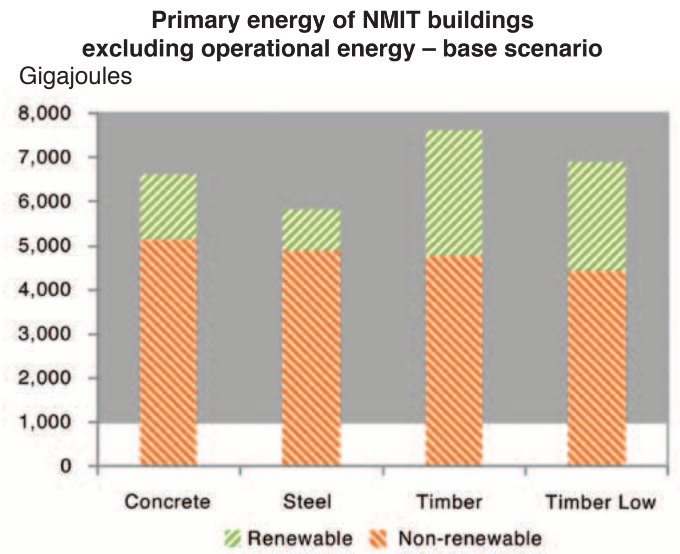

Figure 4a. Primary energy for whole life cycle, excluding operational energy, for current end-of-life

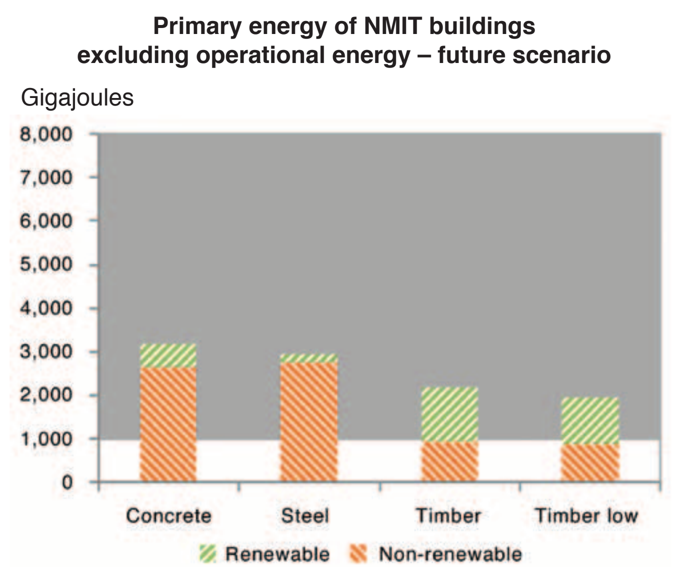

Figure 4b. Primary energy for whole life cycle, excluding operational energy, for future end-of-life

Global warming potential

Global warming potential is an expression of the contribution of a product or service to potential warming of the atmosphere, possibly leading to climate change. This report uses the most recent figures for carbon dioxide equivalents for greenhouse gas emissions published by the Inter-governmental Panel for Climate Change (IPCC, 2007 [7]).

The global warming potential figures for each life cycle stage for each building are shown in Table 3, plotted in Figures 5a and 5b. Much of this global warming potential is from the non-renewable component of the primary energy.

Table 3a: Global warming potential in tonnes of carbon dioxide equivalent for each building, by life cycle stage, for current end-of-life scenario – material carbon footprint is tonnes of carbon dioxide equivalent per square metre of floor area

	Concrete	Steel	Timber	TimberLow
Materials production	382	496	33	16
Transport	27	20	17	17
Operation	2,376	2,419	2,347	1,868
Maintenance	77	76	76	51
End-of-life	33	-128	178	178
Total	2,895	2,884	2,651	2,129
Total without operation	519	464	304	261
Material carbon footprint	0.262	0.234	0.154	0.132

Table 3b: Global warming potential in tonnes of carbon dioxide equivalent for each building, by life cycle stage, for future end-of-life scenario – material carbon footprint is tonnes of carbon dioxide equivalent per square metre of floor area

	Concrete	Steel	Timber	TimberLow
Materials production	382	496	33	16
Transport	27	20	17	17
Operation	2,376	2,419	2,347	1,868
Maintenance	77	76	76	51
End-of-life	-69	-236	101	129
Total	2,793	2,775	2,574	2,081
Total without operation	417	356	227	213
Material carbon footprint	0.211	0.180	0.115	0.108

Discussion of global warming potential

All the figures in Table 3a are in the original report. Some of the figures in Table 3b have been calculated subsequently. The production figures in row one come from the emissions due to non-renewable energy shown

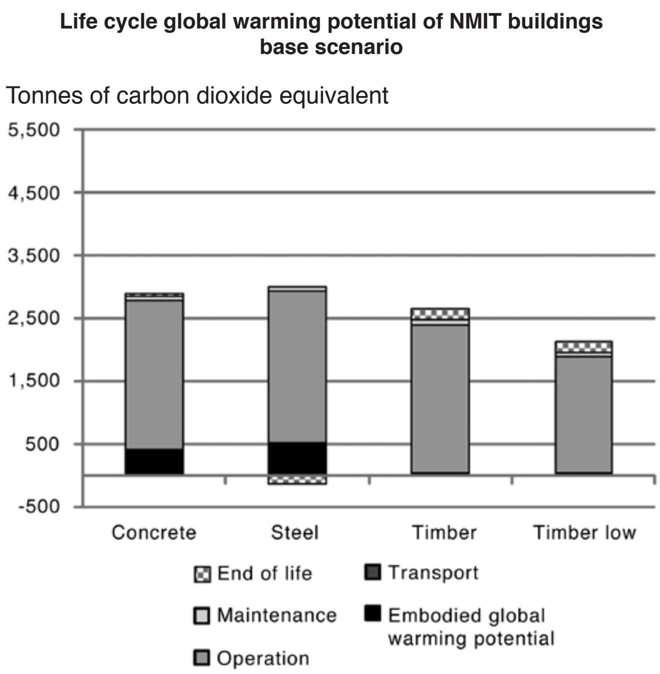

Figure 5a: Global warming potential for each building, by life cycle stage, for whole life cycle including operational energy – current end-of-life scenario

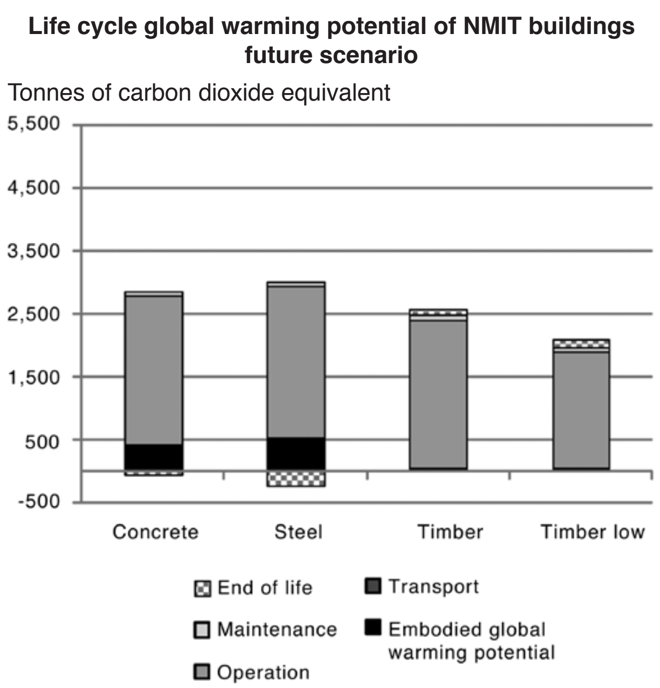

Figure 5b: Global warming potential for each building, by life cycle stage, for whole life cycle including operational energy – future end-of-life scenario

in Figure 2, along with other sources such as carbon dioxide emissions from manufacturing of cement. The timber and TimberLow figures are much lower than the steel and concrete figures because they include the sequestered carbon in the wood which offsets carbon dioxide emissions from production of other materials.

The transport figures in row two are the calculated figures for transport to Nelson from the most likely locations of materials production. It was assumed that structural steel would be imported from Australia or Asia, with most other materials made in New Zealand. These figures for other buildings will depend on the location. Emission factors for truck transport are taken from Love [3]. Emission factors for ocean transport come from United Kingdom figures [8], and are converted into energy figures using data from Barber [5].

The operational figures in row three come from the energy predictions in a PhD thesis by Nicolas Perez [9], converted into global warming potential using a life cycle inventory for New Zealand. This takes into account the typical energy mix for the generation of electricity. It can be seen that the global warming potential figures are all very similar, except for the TimberLow building, which was specially designed to have lower energy for heating. These figures are only included to show the magnitude of operational energy effects compared with material energy effects.

Maintenance and end-of-life

The maintenance figures in row four come from a maintenance schedule for each building based on life cycle costing data from BRANZ (Appendix C [1]). The replacement or refurbishment lifetimes of specific building materials are presented in Appendix B of the ScionResearch report. It was assumed that structural components and insulation would last the entire lifespan of the building. It was also assumed that any replacements required would be with an identical material to the original. The two biggest maintenance items over the 60-year life of the building are 7.4 tonnes of paint and replacement of 23.5 tonnes of window glass.

The end-of-life figures in row five come from a life cycle assessment study using the assumptions shown in Table 2. It is important to note that the figure for each building is the total combined figure for all the different materials in the building. The effect of end-of-life for each material separately is not given in this article. The negative figures for concrete and steel buildings come about mainly because of the energy benefit when virgin steel for future new buildings is replaced by the 85 per cent of the steel from these buildings, which will be recycled. This includes both structural steel and reinforcing steel.

The figure of 178 tonnes of carbon dioxide equivalent for timber and TimberLow buildings arises mainly from the methane, a much more potent greenhouse gas than carbon dioxide, which escapes to the air from landfills without being burned. Smaller portions of this 178 tonnes are from carbon dioxide emitted in burning methane from the landfill, and some from direct release of carbon dioxide from the landfill. Most of the carbon in wood products remains sequestered permanently in the landfill, as shown in Table 2.

Future end-of-life

For the future end-of-life for the timber building, 178 tonnes changes to 101 tonnes. This difference of 77 tonnes is mostly due to the increase in recycling of aluminium and steel, and a decrease in methane emissions from landfill operations. This is because the net greenhouse gas emissions of the incinerator, which releases the sequestered carbon in timber back into the atmosphere, balanced against the fossil fuel offset and the current landfill scenario are almost equal. A further benefit of burning timber for the production of useful energy is the simple avoidance of filling up landfill.

For the future end-of-life for the steel building, minus 128 tonnes changes to minus 236 tonnes. This larger reduction of 108 tonnes of global warming potential is mainly because of the energy credit from an additional 15 per cent of steel being recycled – up from 85 per cent to 100 per cent in this scenario. The production of recycled steel rather than virgin steel results in a large reduction of fossil fuel energy use as all current steel production is assumed to use 100 per cent fossil fuel energy.

Row six in Table 3 is the sum of the rows one to five. For both end-of-life scenarios, the timber building's lifetime global warming potential is 92 per cent of that for the steel or concrete buildings, an eight per cent reduction. Row seven is the total, modified to exclude operational energy effects, to show the differences in emissions from production, transport, maintenance and end-of-life. Looking at these figures only, the timber building's global warming potential is 59 per cent of that for the concrete building, or 66 per cent of that for the steel building for current end-of-life. For future end-of-life these figures become 54 per cent and 64 per cent, respectively.

Row eight shows the totals in row seven divided by the gross floor area of the building of 1,980 square metres. This gives a material carbon footprint in tonnes of carbon dioxide equivalent per square metre of floor area.

Global warming potential of NMIT buildings materials production stage

Tonnes of carbon dioxide equivalent

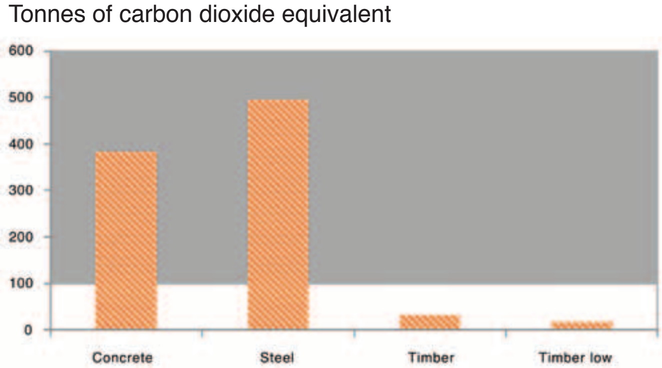

Figure 6: Global warming potential for materials production

When the figures up to row six are plotted as a graph, they give Figure 5a and Figure 5b. The figures from row one for materials production give Figure 6. The figures in row five for end-of-life give Figure 7, and the figures in row seven give Figure 8.

End of life global warming potential of NMIT buildings base scenario

Tonnes of carbon dioxide equivalent

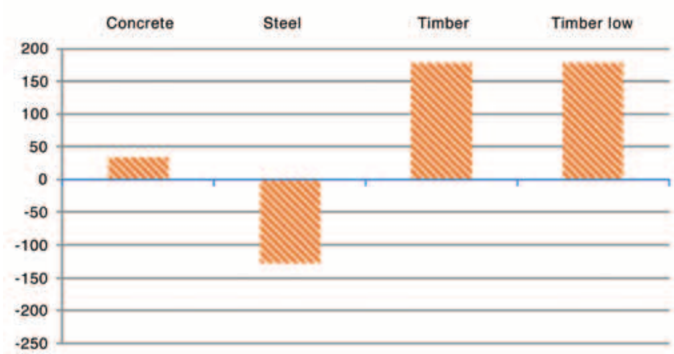

Figure 7a: Global warming potential for materials disposal for current end-of-life scenario

End of life global warming potential of NMIT buildings future scenario

Tonnes of carbon dioxide equivalent

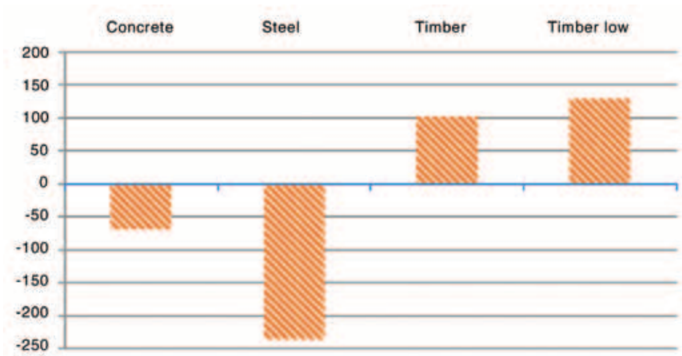

Figure 7b: Global warming potential for materials disposal for future end-of-life scenario

Discussion of remaining graphs

Figure 5a shows the global warming potential for the full life cycle arising from emissions of greenhouse gases, mainly carbon dioxide and methane, from all sources, over the 60-year life of the buildings. They include manufacture of materials and all the other fossil fuel components of the energy use shown in Figure 1.

All four buildings again have similar global warming potential arising from operational energy, except the lower value for the TimberLow building. The next biggest component is the global warming potential for the steel and concrete buildings, representing the emissions from fossil fuel energy used in manufacture of the materials. Transport and maintenance values are very small for all four buildings.

Figure 6 shows the global warming potential for material production. It can be seen that the timber building is carbon neutral for materials production. This is because the carbon sequestered in the wood products for the life of the building approximately offsets all the carbon dioxide emissions from the production of all other materials in the building.

Figure 7a and Figure 7b show the global warming potential for material disposal for the two end-of-life scenarios. It can be seen that the offset of virgin steel manufacturing is a significant factor for reduction of greenhouse gases. It can also be seen that the carbon which was sequestered in the timber buildings during their lifespan is released at the end-of-life.

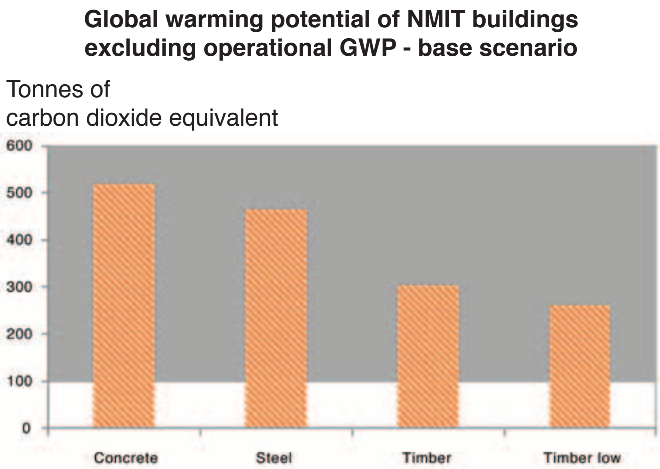

Figure 8a. Global warming potential for whole life cycle, excluding operational energy, for current end-of-life

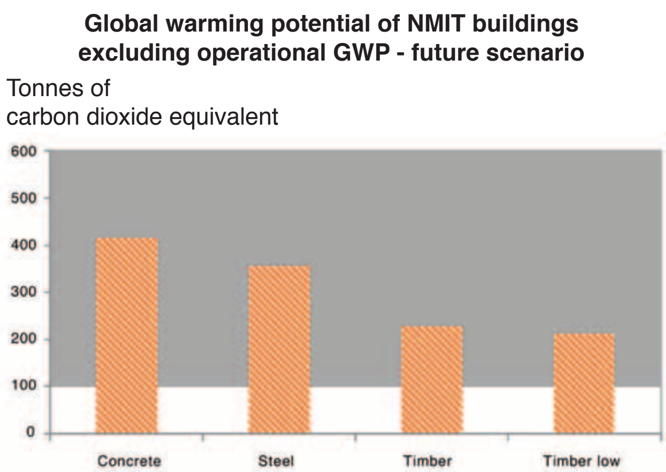

Figure 8b. Global warming potential for whole life cycle, excluding operational energy, for future end-of-life

Figure 8a and Figure 8b show the global warming potential for whole life cycle excluding operational energy, for the two end-of-life scenarios. It can be seen that the future end-of-life scenarios lower the life cycle global warming potential of all buildings. In addition, the net global warming potential values for the timber and TimberLow buildings are lower than those of the concrete and steel buildings, in both current and future scenarios. This indicates that while the operational stage is the largest contributor to energy use and global warming potential in the life cycle of the buildings, material choices can also have a significant effect on the final figures.

The future

This article has so far described a life cycle assessment based comparison of four different buildings. Many of the differences in global warming potential have been explained but some details are buried in the models. Therefore there is insufficient information in this article or the original report to have an informed discussion of all the results.

Green building rating schemes

Green building rating schemes such as GreenStar encourage design for low operational energy, but do not include a quantitative assessment of the environmental impact of materials. The method in this article uses calculation based on life cycle assessment for estimating the global warming potential associated with production, transport and disposal of all the materials in a building. Operational energy does not need to be included because there are already methods in green building rating schemes for assessing operational energy efficiency.

To make a comparison of the effects for every new building, a full life cycle assessment study could be conducted for each building, similar to the one described here, but this would take considerable time and cost. To allow building practitioners to make their own approximate calculations from a schedule of quantities, it would be preferable to have coefficients for each life cycle phase of each material.

In the new simple calculation method, green building points should be assigned for a low, medium or high material carbon footprint according to an agreed schedule. In addition to global warming potential, other environmental effects could be included in a similar way, with coefficients being derived for each material from a life cycle assessment analysis. Global warming potential is considered the most important effect to address because of global concern about the contribution of the building industry to climate change.

To use life cycle assessment-based methods to compare building materials it is necessary to have –

- Participation by all major material manufacturers
- Agreement on the system boundaries
- Derivation of material effects, given as coefficients, by life cycle assessment experts
- Adoption of simple methods by green building rating schemes.

Material coefficients

To calculate a lifetime material carbon footprint of a building all you need is a schedule of quantities from the quantity surveyor, and life cycle assessment-based global warming potential coefficients for production and disposal of each building material. These approximate coefficients need to be derived from a full life cycle assessment analysis for each material. Coefficients could be presented in a simple table such as Table 4.

This would allow building designers to use the coefficients separately or combined to make carbon footprint calculations. The coefficients would be combined with the total mass of each material in the building, as shown in Table 1, to calculate the total global warming potential. This would be divided by the gross floor area to give the carbon footprint in tonnes of carbon dioxide equivalent per square metre of floor area.

In Table 4 the most easily obtained figures are those for production of materials in a cradle-to-gate analysis because they have already been published. A complete life cycle analysis by definition must consider end-of-life in a full cradle-to-grave analysis.

Table 4: Suggested simple tabular presentation of global warming potential coefficients for building materials.

	Production	Transport	Maintenance	Disposal	TOTAL
Concrete					
Steel					
Glass					
Timber					
Aluminium					
Others					

Many of the coefficients for production are already available from for New Zealand materials. The other categories are more difficult, but they can be obtained following agreed life cycle assessment methods. All these figures will be different for countries other than New Zealand.

Figures for transport and maintenance will always be building-specific. However, they generally have lower environmental effects than other stages in the life cycle. They have been included in this article, but their inclusion in a rating scheme is open for debate. For transport, some average New Zealand specific transport figures can be derived, such as for a typical distance of 500 kilometres from the port of arrival or the point of manufacture, to be modified on a case-by-case basis for each job.

For maintenance, it is difficult to obtain coefficients per tonne of material because it is necessary to know where – and how – in the building the material is used and the expected lifespan of the material in that application. Inclusion of maintenance is likely to be much more trouble than it is worth because the numbers are low anyway. Because the transport and maintenance figures are low, and similar for most materials, it would be simpler to leave them out, further simplifying Table 4.

End-of-life is the most difficult to assess, and debate is needed as to whether to include it at all. However, to follow recognised life cycle assessment protocols and to ensure a fair comparison of materials, it is proposed that end-of-life be included in the new calculation method as described above for the NMIT building, but using simple coefficients in a table.

End-of-life

This case study has shown that the inclusion of end-of-life raises a number of questions about likely, or unlikely, future scenarios. It is difficult to predict future new technologies for managing materials in 60 years' time as the world changes and environmental pressures increase. On these grounds alone, a strong case could be made for leaving the end-of-life option out of the carbon footprint calculation. However, if end-of-life is left out of the rating scheme, then the stored carbon in the wood should not all be included.

If the system boundary ends at the gate then wood would receive credit for indefinite carbon storage. However, in fact it is limited to the life of the building or the life of recycled uses of the wood products. Some way of working out the benefit of 60 years of carbon storage, and using that as the credit, would give a fairer comparison. Possible future levels of re-use and recycling should also be included.

The same conclusion might be arrived at by consideration of discounted cash flow. In this case the present cost of future maintenance or environmental remediation is far less than the cost of the initial construction or of immediate environmental effects. Despite this, the authors of this article recommend the inclusion of end-of-life in the calculation method.

Conclusion

The operation of buildings, rather than production and disposal of materials or building maintenance, is the dominant contributor to both lifetime energy consumption and global warming potential. However, this is reducing as modern buildings become increasingly energy efficient.

Operational energy and maintenance energy are almost independent of structural materials for well-designed conventional buildings. An end-of-life scenario including disposal or re-use of materials must be included in the full life cycle assessment for a building. For a typical current end-of-life scenario and a possible future end-of-life scenario, the increased amount of timber in the timber building displacing concrete and steel, led to eight per cent lower global warming potential than for either the concrete or steel buildings for the full life cycle including operational energy.

Material production global warming potential emissions are almost zero for timber buildings. That is, the carbon dioxide emitted in production of all building materials is almost completely balanced by the carbon stored in the wood products. For the timber building, material production and disposal results in a half to two-thirds of the carbon dioxide equivalent emissions of the concrete or steel building, similar for both end-of-life scenarios.

Global warming potential coefficients for production, transport and disposal of specific building materials can be extracted from high-quality life cycle assessment studies. These coefficients can be aggregated with quantities from a quantity surveyor to provide a carbon footprint for this aspect of the whole building.

A carbon footprint calculation is proposed for incorporation into green building rating schemes such as GreenStar. This calculation should concentrate on global warming potential of material production and disposal because this is not included in current green building assessment.

With current New Zealand landfill management practice, it is not a good idea to send wood to landfill. Even though most of the wood never decays in the landfill, the methane emissions from the small amount of anaerobic decay creates more global warming potential than burning all the wood. Burning the wood in a co-generation plant for energy production is a much better end use because of the useful energy produced.

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Andrew Buchanan is Professor of Timber Design and Stephen John is Sustainability Researcher at the Department of Civil and Natural Resources Engineering, University of Canterbury in New Zealand. Simon Love is based at Leiden University in The Netherlands.