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Modelling the Role of Time in Carbon Footprints for Building Elements: Testing Different Methodologies

Sarah McLaren, Thomas Elliot, David Dowdell, Steve Wakelin, Hamed Kouchaki-Penchah and Peter Hall

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MODELLING THE ROLE OF TIME IN CARBON FOOTPRINTS FOR BUILDING ELEMENTS – TESTING DIFFERENT METHODOLOGIES –

ER83 [2024]: FINAL REPORT

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EXECUTIVE SUMMARY

Life cycle assessment (LCA) has been applied for many years in the construction sector globally, and there has been increasing focus, in particular, on the climate change impact of the construction sector due to concerns about climate change. Greenhouse gas (GHG) accounting guidelines have been developed and published in international and regional standards, and applied in Environmental Product Declaration (EPD) programmes. There are some differences between these guidelines, particularly for treatment of carbon storage and delayed carbon emissions. The latest version of EN15804 (EN15804:A2, CEN, 2019) requires that biogenic carbon stored in timber and engineered wood products is reported as released when it is landfilled, a change from the previous version where it could be modelled as continuing to be stored in this end-of-life scenario. This is particularly relevant for the New Zealand (NZ) context, as a substantial proportion of NZ's timber construction and demolition waste goes to landfill.

Furthermore, all the guidelines use static LCA. However, researchers are increasingly focusing on the use of dynamic LCA to assess long-lived products such as buildings. This research was commissioned by the New Zealand Ministry of Business, Innovation and Employment (MBIE), and the Building Research Association of New Zealand (BRANZ), to investigate the use of dynamic LCA in climate change impact studies of NZ residential dwellings.

In this study, both static and dynamic climate change impact analyses were undertaken of two alternative assemblies each for wall, ground floor and roof elements used in NZ residential dwellings, comprising different mixes of timber, engineered wood, concrete and steel materials. The functional unit was 1 m^2 of ground floor, wall, and horizontal ceiling projected up through the roof - for a building reference service life of 50 years. The life cycle extended from material production, through to element construction, operational use (including replacements), and final end-of-life treatment. Data were mostly obtained from climate change results reported in existing EPDs, and the case study assemblies were modelled in a typical New Zealand dwelling in a specific exposure zone. Sensitivity analyses were undertaken to examine the influence on the climate change results of using a 90 year service life, different exposure zones, two specific locations, and use of different parameters to model landfilling.

Using a static LCA approach, all the assemblies had higher climate change results when modelled excluding biogenic carbon storage in landfill (i.e. following EN15804:A2), although for the concrete floor the difference was very small as only a minor amount of timber was used in this assembly. This shows that a decision to include, or not, biogenic carbon storage in landfill is a significant determinant of the climate change results for the studied assemblies (except for the concrete floor).

When dynamic LCA modelling was used, accounting for biogenic carbon emissions and sequestration, the ranking of each pair of assemblies at year 50 remained the same as for the static LCA modelling. The dynamic results showed that the timber wall and timber floor, and steel wall (i.e. steel frame with timber cladding) from year 179 onwards, had negative cumulative radiative forcing results for varying periods of time in the modelled time period up to year 190 after construction. In other words, they were (at least) "net zero carbon" in the time period up to the year(s) in question.

The results show that a decision to include or exclude biogenic carbon storage in landfill is a significant determinant of the climate change results for all the assemblies except for the concrete floor, although this was not sufficient to alter the ranking between pairs of assemblies. The module D results were also significant determinants of the total climate change results for the assemblies that involved steel recycling. It may be questioned whether the inclusion of module D results calculated using the climate change impact of current technologies is appropriate for activities that will take place beyond 2050.

The sensitivity analyses of the static LCA results showed that choice of landfill parameters for modelling methane and carbon dioxide emissions from landfill are a significant determinant of the results, particularly for the assemblies containing larger quantities of timber products. Choice of a 90 (as opposed to 50) year reference service life more than doubles or halves the results for the concrete roof and steel wall respectively (and is related to the replacement schedules for different components); it makes a negligible difference to the concrete floor result which is not replaced during either time period. However, if the results are presented as "1 m^2·year" as opposed to "1 m^2 over the total lifetime", the concrete floor result for a 90 as opposed to 50 year reference service life is 45% smaller due to use of a larger denominator in the calculation. In contrast, the dynamic LCA results show that the concrete floor's cumulative contribution to radiative forcing increases from year 0 onwards i.e. at year 90 it is greater than at year 50.

To ensure a level playing field, we recommend that default values and modelling choices are specified for climate change impact calculation tools used to support decision-making regarding:

- Construction product characteristics: standardised product service lives, and data that account for different exposure zones (where relevant). These data are already available in BRANZ's module B4 datasheet.
- Future activities: proportions of different materials diverted from landfill, and specified technologies for future manufacturing activities (used in module D to model displaced activities due to recycling). Data on materials diverted from landfill are also already available in BRANZ's module A5 and module C1 datasheets. For future manufacturing activities, this requires further consideration.
- Heating/cooling requirements in Use phase (related to differences in construction R values and/or thermal mass): a standardised approach to energy simulation. Further research is required to define the most suitable approach, and work undertaken for this project provides a useful starting point.
- Forestry: assessment period for forest cultivation, and specification of sustainable or unsustainable forestry for both sourcing of timber products and displaced forestry cultivation (module D). For forest cultivation (module A1), we recommend use of stand-level assessment with forest cultivation beginning at year 0 for sustainably managed forests.
- Biogenic carbon calculations: the carbon content of different types of wood, and DOCf values and landfill gas recovery percentages to use for landfill modelling. For DOCf and landfill gas recovery, we recommend that values should be aligned with the Ministry for the Environment GHG accounting guidelines.

In conclusion, dynamic LCA provides additional insights to support climate change policymaking beyond those provided by static LCA, particularly where policy involves the use of time-specific carbon targets. However, due to the additional data requirements for dynamic LCA, a time-disaggregated presentation of static LCA results maybe more appropriate for use in climate change impact calculation tools. In addition, we recommend that timber products reaching landfill should be modelled to include ongoing biogenic carbon storage of the remaining carbon after degradation and release of methane and carbon dioxide. For consistency, recycled timber products could also be modelled as associated with ongoing biogenic carbon storage – although this requires further consideration due to methodological limitations. Default datasets and modelling choices should be specified for climate change impact calculation tools used to support decision-making with respect to the construction sector.

1 INTRODUCTION

1.1 LCA AND THE CONSTRUCTION SECTOR, INCLUDING CARBON FOOTPRINTING

In order to move towards a more sustainable future, the climate change impact (aka carbon footprint) of human activities must be significantly reduced. The operation of buildings contributes 30% and the manufacture of construction products 10% of global greenhouse gas (GHG) emissions (UN Environment and International Energy Agency, 2017), and in NZ nearly 9.4% of domestic GHG emissions were building-related in 2018 (MfE, 2022c, p.228). Therefore it is important for this sector to identify behavioural changes, activities, design strategies, materials and technologies that will both reduce its GHG emissions and mitigate remaining GHG emissions via carbon sequestration. Thus, information is required about the climate change impact of alternatives, and this requires assessment of both GHG emissions and carbon sequestration.

Life cycle assessment (LCA) has been applied for many years in the construction sector globally, and there has been increasing focus, in particular, on the climate change impact of the construction sector due to concerns about climate change. In New Zealand, the Ministry for Business, Innovation and Employment (MBIE) has initiated a Building for Climate Change (BfCC) programme in order to "reduce emissions from constructing and operating buildings, and to make sure our buildings are prepared for the future effects of climate change" (MBIE, 2023). BRANZ has initiated a Transition To a Zero Carbon Built Environment research programme[1] and the New Zealand Green Building Council (NZGBC) has increasingly incorporated recognition of LCA and carbon footprinting into its building environmental rating tools Green Star and Homestar.

Internationally, LCA studies (including those for buildings and construction products) follow the requirements in the ISO 14040 and 14044 LCA standards (ISO, 2006a, 2006b), and carbon footprint studies are additionally guided by ISO 14067 ("Greenhouse gases – carbon footprint of products – requirements and guidelines for quantification", ISO, 2018). LCAs of construction products and buildings may be guided by international and/or European standards, depending on the location in which they are carried out. For example, building LCAs carried out in North America are likely to be guided by ISO 21931–1 (ISO, 2022), and construction product LCAs will follow ISO 21930 (ISO, 2017). However, for construction products both the International EPD System and its regional partner EPD Australasia are additionally aligned with EN15804 ("Sustainability of construction works – environmental product declarations – core rules for the product category of construction products") (CEN, 2019).

In New Zealand, LCAs of buildings and construction products tend to follow EN15978 ("Sustainability of construction works – assessment of environmental performance of buildings – calculation method") (CEN, 2011) and EN15804 (CEN, 2019) respectively. As environmental product declarations (EPDs) are becoming more widely used, EN15804 is increasingly seen as a *de facto* international standard for construction product LCAs in New Zealand (and Australia); however, although it is aligned with ISO 14040 and 14044, it goes beyond them in providing some detailed methodological guidance on topics of ongoing research interest, in particular assessment of biogenic carbon storage.

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[1] https://www.branz.co.nz/environment-zero-carbon-research/

Meanwhile, in the LCA research community, there has been growing interest in addressing the role of time in assessment of carbon storage and delayed emissions of greenhouse gases, as originally proposed by Nebel and Cowell (2003), Clift and Brandão (2008), Müller-Wenk and Brandão (2010), and Courchesne et al. (2010). Levasseur et al. (2010) proposed a dynamic LCA approach to account for time in LCA, and elaborated a method for land use, land use change, and forestry (Levasseur et al., 2012). More recently, use of the dynamic LCA method has been discussed and applied in LCAs of construction products and buildings (e.g. Hoxha et al., 2020; Head et al., 2021).

Another recent development is the increasing use of time-defined climate change targets in policymaking. For example, in New Zealand the Climate Change Response Amendment Act 2019 requires the setting of emission budgets in order to meet a 2050 goal of net zero greenhouse gas (GHG) emissions (except for biogenic methane which is required to reduce to 24-47% less than 2017 emissions by 2050) (New Zealand Government, 2019). The emission budgets for the periods 2022-2025, 2026-2030, and 2031-2035 have been published by Ministry for the Environment (2022a).

Therefore, in light of (a) the different methodological approaches to addressing timing of GHG emissions and carbon storage in LCA, (b) the potential significance of the timing of GHG emissions and mitigation efforts in the context of climate change policy and associated climate targets, and (c) the important role of the construction sector in New Zealand's GHG emissions (Chandrakumar et al., 2020), this research set out to investigate the use of static versus dynamic LCA approaches in building LCA studies. The aim was to provide recommendations on a preferred approach regarding assessment of the potential contribution of carbon storage, and timing of carbon emissions, to mitigate the climate change impact of new buildings. The study involved assessing the climate change impact of case studies comprising two assemblies each for walls, ground floors and roof elements used in NZ stand-alone residential buildings, using alternative methodologies.

The research was funded by MBIE and the Building Research Levy, and took place between February and November 2023. It included three meetings with stakeholder representatives from Concrete NZ, EPD Australasia, Heavy Engineering Research Association (HERA), Ministry for Business, Innovation and Employment (MBIE), Ministry for the Environment (MfE), and the Wood Processors and Manufacturers Association of New Zealand (WPMA) to discuss the chosen assemblies, methods and results. In addition, the stakeholders also provided additional data to improve the accuracy of the case studies (as noted elsewhere in this report). Two international experts on dynamic LCA, Professor Annie Levasseur (École de Technologie Supérieure, Montréal, Canada) and Associate Professor Endrit Hoxha (Aalborg University, Copenhagen, Denmark) provided methodological guidance throughout the project, and reviewed the final draft report. The target audience for the report is those involved in developing policy and guidelines for climate change assessment of construction products and buildings.

It should be noted that the studied floor, wall and roof building assemblies are not intended to be representative of 'average' or 'typical' New Zealand building assemblies but are case studies to facilitate improved understanding of the strengths and weaknesses of different climate change assessment methods. Also, the terms static LCA (sLCA) and dynamic LCA (dLCA) have been used in this report although the specific application discussed here is the climate change impact category. Therefore the results should not be used in comparative assertions about the overall environmental performance of these different elements.

1.2 EN15804 AND TREATMENT OF BIOGENIC CARBON

As noted in Section 1.1, EN15804 ("Sustainability of construction works – environmental product declarations – core rules for the product category of construction products") is widely used in LCAs of construction products and activities in New Zealand, as well as Australia and Europe. Its latest version (2012+A2:2019, hereafter EN15804:A2) (CEN, 2019), which supersedes the EN15804:2012+A1:2013 (hereafter EN15804:A1) (CEN, 2013) version, includes additional details about the functional unit (Sections 6.3.1 to 6.3.4), impact assessment (Sections 6.5 and 7.2), reporting of data (Section 7.3), and assessment of biogenic carbon (Sections 6.3.5.5, 6.4.4, 7.2.5).

Regarding biogenic carbon, the new text in Section 5.4.3 states that "the effect of temporary carbon storage and delayed emissions … shall not be included in the calculation of the GWP. The effect of permanent biogenic carbon storage shall also not be included in the calculation of the GWP." This means that there is no net carbon credit associated with the removal of carbon dioxide from the atmosphere by trees and its subsequent storage in timber and engineered wood products (irrespective of the end-of-life treatment). Furthermore, the new text in Section 6.3.5.5 (Note 3) requires that degradation of biogenic carbon reaching a solid waste disposal site is to be modelled "without time limit" and that any remaining biogenic carbon is "treated as an emission of biogenic CO_2 from the technosphere to nature". This represents a significant change in modelling of biogenic carbon compared with the previous version of EN15804 where permanently stored biogenic carbon (including in landfill) could be modelled as a carbon credit. As discussed in Ouellet-Plamondon et al. (2023), different approaches to modelling of biogenic carbon storage are described as -1/+1, -1/+1*, -1/0, and 0/0 where the first and second digits represent the modelling approaches to biogenic carbon sequestration and carbon release at end-of-life respectively. The * represents a variant of the -1/+1 approach, where variable amounts of sequestered carbon dioxide may be considered as stored long-term in landfill at end-of-life. Thus, whilst the previous version of EN15804 was not prescriptive with respect to the approach taken and allowed for a -1/+1* approach, the latest version represents a mandatory -1/+1 approach (Section 6.3.5.5 and C.2.4) for biogenic carbon (excluding biomass from native forests), including when it is stored in a solid waste disposal site.

Additionally, the latest version states that sequestered carbon in products shall be declared separately in "kg C" for both the product and any packaging (unless it constitutes less than 5% of the mass of the product or packaging) (Sections 6.4.4 and 7.2.5).

In summary, there is no representation in the module A-C carbon footprint net result of biogenic carbon storage in construction products (and packaging) in LCA studies that follow the updated EN15804:A2 modelling requirements.

1.3 DYNAMIC LCA VERSUS STATIC LCA

In a static LCA, the climate change result comprises the summed contribution of all individual GHG emissions and removals associated with the system under analysis across all the life cycle stages,, and may or may not include the contribution of temporary carbon storage. However, in a dynamic LCA, the timing of GHG emissions and removals, and duration of temporary carbon storage, are regarded as relevant, and the climate change results are presented as disaggregated yearly impacts along timelines that are not truncated. This means that, in a dynamic LCA, the decision-maker can look at how the climate change impact of, for example, a building changes each year over its service life and beyond.

A second point of difference is that, in a static LCA, the GHG emissions and removals are (usually) assessed over a fixed 100 year time horizon from the point of emission/removal. Thus, for example, an emission of 1 kg CO_2 during building construction is assessed in static LCA as having a climate change impact equivalent to an emission of 1 kg CO_2 during building demolition in, say, 50 or 90 years' time. In other words, there is an inconsistency in the time boundaries used for the assessment of the GHG emissions. However, in a dynamic LCA there is no fixed time period under consideration. This means that the climate change impact of different GHG emissions and removals can be assessed over different time horizons according to the needs of decision-makers (Levasseur et al., 2010).

Lastly, in a static LCA, the climate change impact is usually assessed using global warming potentials (GWPs). These represent the radiative forcing of a GHG relative to 1 kg CO_2 over a fixed time period (usually 100 years, using GWP100 values), and are measured in "kg CO_2-eq" units. However, in a dynamic LCA the climate change impact is assessed as the radiative forcing caused by a GHG emission at time 0, during each successive year, and is measured in "Watts per m^2", and thus transparently represents the decay rate over time of different GHGs. These values can then be shown as instantaneous radiative forcing values for each year under consideration, or they can be summed over time as cumulative radiative forcing results.

Thus, dynamic LCA provides information about the timing of climate change impacts that is absent from static LCAs, and that is arguably becoming more relevant as countries increasingly adopt time-dependent climate change targets.

2 GOAL AND SCOPE

2.1 OVERVIEW OF THE STUDY

In this study, two assemblies each for external walls ("walls"), ground floors ("floors") and truss roof ("roofs") elements used in NZ stand-alone residential buildings, were assessed for their climate change impacts. Details of each construction are presented in Section 3.1.

For the floors, the unit of analysis was 1 m^2 of ground floor, with an area/perimeter ratio (A/P) of 2.5. For the walls, the unit of analysis was 1 m^2 of wall, assuming a clear wall construction[2]. For the roof, the unit of analysis was 1 m^2 of horizontal ceiling projected up through the roof. For all the assemblies, replacement of any materials with a service life shorter than the building reference service life of 50 year was included in the study if it was required. Maintenance was not included in any of the assemblies; repainting of the walls and ceiling takes place every few years but as this was common to both wall and both roof assemblies it was omitted.

Data for assemblies were adapted from the BRANZ CO_2RE tool (BRANZ, 2023). Data for processes such as electricity use, transportation, and landfilling, were sourced elsewhere and are documented in Section 3. As the study focused on different modelling approaches in dynamic versus static LCA, modelling decisions within each BRANZ CO_2RE dataset were not part of the study (e.g. detailed modelling of specific forestry or mining activities). Also, it should be noted that none of the datasets used in this study include the GHG emissions associated with an increased prevalence of natural disturbances and accidents as this is outside the remit of LCA (but could be considered in a separate

[2] A clear wall construction assumes no window or door openings, and no junctions with other building elements.

risk assessment) e.g. GHG emissions related to forestry timber displaced during heavy rainfall events, or mining accidents.

At impact assessment, the climate change impacts were assessed using the IPCC's GWP100 characterisation factors in the static LCA, and the dynamic characterisation factors provided by Levasseur et al. (2010) and updated by Myhre et al. (2013) for the dynamic LCA. For the dynamic LCA, results were calculated and presented for a time period of 190 years; this represents the longest service life modelled in the study plus 100 years. A longer time period was not presented in this report as it not relevant in the context of this study.

2.2 Modelling approach

The methodology guidelines in EN15804:A2 were followed in this study but with one exception for the baseline results: the biogenic carbon in timber products that entered landfill and did not degrade to carbon dioxide or methane within the 190 year timeframe of the study was regarded as being permanently stored. This method is aligned with EN15804:A1. The influence of this method on the final results was investigated by calculating another set of results that excluded biogenic carbon storage in landfill.

For clarity, biogenic carbon flows were modelled as follows for the baseline results:

1. Biogenic carbon in timber used in the assemblies (and in replacement activities) was reported separately in a "biogenic carbon" category together with other biogenic carbon emissions.[3]
2. Timber that was recycled/reused (for these case studies, a relatively small amount during construction, see Table 3) was modelled as crossing the system boundary with a biogenic carbon emission associated with it.[4] In addition, its recycling/reuse activity was represented in module D as discussed in Section 3.3.4.

Materials were modelled as having reached their "end-of-waste state" at the point they became waste at either the construction or the demolition site (following EN15804:A2, Section 6.4.3.3).

The potential benefit of recycling (module D) of materials was modelled as a range encompassing two extreme scenarios: displacement of equivalent primary material production using (a) current average technologies and (b) future zero carbon technologies. As the majority of these recycling activities will not occur for at least 20 years (Table 6), and alternative technologies are likely to be in place by that time, use of a range is considered appropriate. Section 3.3.4 provides more details.

3 Inventory Analysis

3.1 Description of assemblies

As introduced in Section 2, six stand-alone residential assemblies were selected for the study: two roof, wall and floor assemblies. The selected assemblies achieve (at least) updated minimum construction

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[3] These include GHG emissions from smaller quantities of biogenic carbon stored in timber that goes to landfill in modules A1 to A3, biogenic GHG emissions during electricity generation in module B6, and GHG emissions from landfilled timber (modules A5 and C4).

[4]Section C.2.4 of EN15804:A2 specifies that recycled timber is modelled as a "+1" emission as it crosses the system boundary, as does EN16485 (CEN, 2014, Figure 1, Figure 2).

R values from the 5th edition of H1/AS1 (MBIE, 2022a) in climate zones 1 (Auckland) and 5 (Christchurch), as follows:

- Roof: R6.6 in climate zones 1 to 6
- Wall: R2.0 in climate zones 1 to 6
- Floor: unheated concrete slab on ground R1.5 in climate zones 1 to 4, R1.6 in climate zone 5 and R1.7 in climate zone 6. Other floors (including suspended timber floors) R2.5 climate zones 1 to 3, R2.8 climate zone 4 and R3.0 climate zones 5 and 6.

For the baseline, embodied carbon is modelled across a 50 year building service life (MBIE, 2022b), including modules A1 – A3, A4, A5, B1[5], B4, C1 – C4 and D (as defined in EN15978:2011 (CEN, 2011). A sensitivity analysis is additionally included, which uses a 90 year building service life (Section 5).

An A/P ratio of 2.5 is used for the house in which these assemblies are located.

In some instances, where there are differences in thermal mass and/or construction R values between each of the roof, wall or floor assemblies, an energy simulation was carried out to account for additional energy demand due to heating and cooling in one assembly, compared to the other. The method used is described in Appendix A. Energy simulations were carried out using EnergyPlus v22.1.0[6], and are reported as module B6. Further information is provided in Section 3.3.2.3.

As part of the process of finalising the constructions comprising the assemblies, a list of materials for each construction was provided to the Project Stakeholder Group[7] to obtain any feedback. Adjustments were made to the assemblies based on feedback received.

3.1.1 Roof

The roof assemblies include a corrugated steel profile cladding and concrete tiles[8]. Indicative illustrations[9] are provided in Figure 1.

[5] Concrete carbonation during the Use phase.

[6] EnergyPlus is a free, open source, whole building energy simulation programme that can model energy consumption (heating, cooling, ventilation, lighting, plug and process loads). It is funded by the US Department of Energy's Building Technology Office and is updated twice annually. For further information, please see https://energyplus.net/.

[7] The National Association of Steel Framed Housing (NASH) https://nashnz.org.nz/ was additionally approached, and provided feedback, on the steel framed wall construction.

[8] A heavier roof that features concrete tiles can require additional bracing in other elements, notably bracing walls, to meet requirements in NZS3604:2011 (in which Tables 5.8, 5.9 and 5.10 of the standard provide bracing demands). The scope of this case study is the truss roof only, with any additional bracing in bracing walls (for example, use of a bracing plasterboard rather than standard plasterboard) required as a result of using concrete tiles, not included.

[9] These are indicative of the type of construction only. Actual assemblies modelled may differ slightly, for example, with respect to the amount of insulation included.

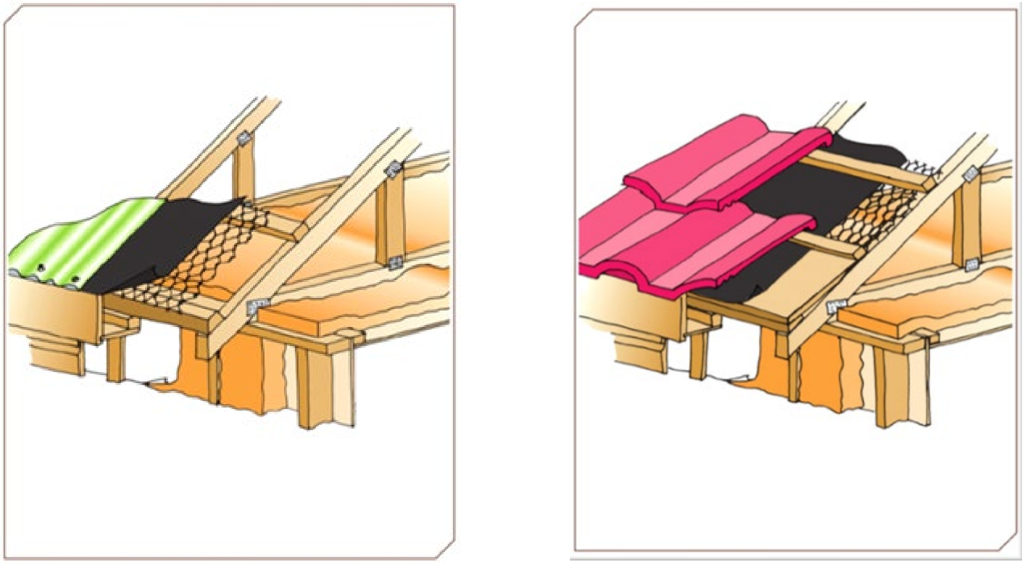

Figure 1 Truss roof assemblies with steel cladding or concrete tiles

Results for stand-alone houses from the BRANZ Materials and Characteristics Survey for consents taken out in 2021, show that sheet metal clad roofs comprise 70% of the New Zealand market (with a further 17% for metal tiles), and concrete tiles comprise 2%.

Both options have a 15° roof pitch with material quantities based on 1 m^2 of horizontal ceiling area. The baseline assessment assumes a location in exposure zone C[10], per NZS3604:2011 (Standards New Zealand, 2011), with sensitivity assessments that assume a location in exposure zones B and D (Section 5).

A description of the assemblies used in the baseline assessment is as follows, with a more detailed list of materials and quantities in Appendix B:

- Profiled (corrugate) zincalume steel cladding (represented using New Zealand Steel's ColorSteel® Endura® product, with a base metal thickness (BMT) of 0.4 mm) or concrete roof tiles
- Timber purlins at 900 mm centres
- Timber trussed structure at 900 mm centres
- Insulation
- Timber battens
- 13 mm plasterboard.

The construction features R7.0 Pink Batts glass wool insulation on top of the plasterboard ceiling between trusses and squashed into the perimeter (averaging R5.4 in the edge area due to some compression of the insulation). At an A/P ratio of 2.5, this should achieve a construction R value of around R6.8.

3.1.2 Wall

The external wall options include 90 mm timber frame and steel frame, both with a bevel backed timber weatherboard cladding. Indicative illustrations are provided in Figure 2.

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[10] The zones relate to the severity of exposure to wind-driven salt, with B being low risk, C medium risk and D high risk. For more information, see https://www.branz.co.nz/branz-maps-zones/.

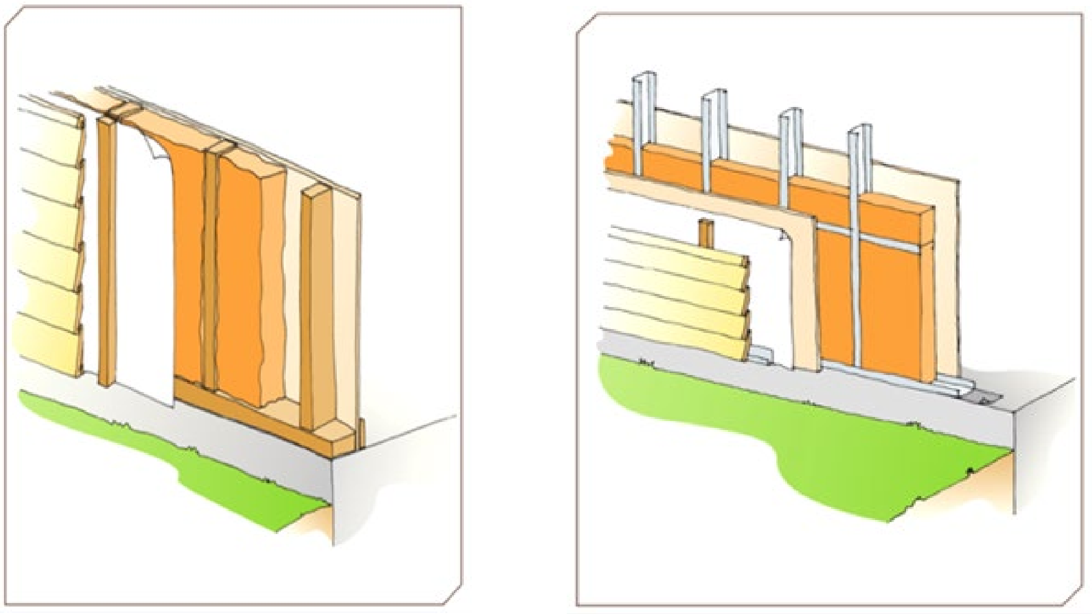

Figure 2 External wall assemblies with timber frame or steel frame

Results for stand-alone houses from the BRANZ Materials and Characteristics Survey for consents taken out in 2021, show that timber frame comprises 77% of the New Zealand market (with a further 6% for laminated veneer lumber (LVL) and 2.5% for solid wood), and steel frame comprises 2%. Timber weatherboards make up 20% of the New Zealand claddings market.

Both options have material quantities based on 1 m^2 of external "clear wall" area, with a framing ratio of 14% (in contrast to measured built framing of 34% caused by, for example, presence of window openings and junctions (Ryan *et al.*, 2019)). This was selected for the following reasons:

- The study focus is on how application of different carbon footprint methodologies impact on the calculated climate change impact associated with different assemblies.
- The study scope is at the construction level, rather than the building level.
- The timeframe for the study was short, and it was being conducted at a time when changes to H1 were coming into force. Whilst the required construction R value for external walls has hardly changed, it was important to maintain momentum, and not speculate on how an R2.0 construction R value would be achieved with a 34% framing ratio.

A description of the assemblies used in the baseline assessment follows, with a more detailed list of materials and quantities in Appendix B. The timber frame assembly is based on:

- A 2.4 m high wall, with 150 mm bevel backed timber weatherboards on a cavity and building wrap.
- 90 mm x 45 mm studs at 600 mm centres, dwangs at 800 mm centres (giving a 14% framing ratio)
- Damp proof course
- Insulation
- 10 mm plasterboard, stopped and painted
- Timber skirting and scotia.

The construction features R2.2 Pink Batts glass wool insulation between the framing, to achieve an R2.0 construction R value.

The steel frame assembly[11] is based on:

- A 2.4 m high wall, with 150 mm bevel backed timber weatherboards on a cavity and building wrap.
- 89 mm x 41 mm x 0.75 mm studs (Z275) at 600 mm centres, dwangs at 800 mm centres (giving a 14% framing ratio)
- All framing features external thermal break strips per NASH standards (NASH, 2019). In this study, a 75 mm x 10 mm extruded polystyrene (XPS)[12] thermal break strip was included.
- Damp proof course
- Insulation
- 10 mm plasterboard, stopped and painted
- Timber skirting and scotia.

The construction features R2.8 Pink Batts glass wool insulation between the framing, to achieve an R2.0 construction R value.

3.1.3 Floor

The ground floor options include an unheated concrete slab floor and a suspended timber floor. Figure 3 provides indicative illustrations.

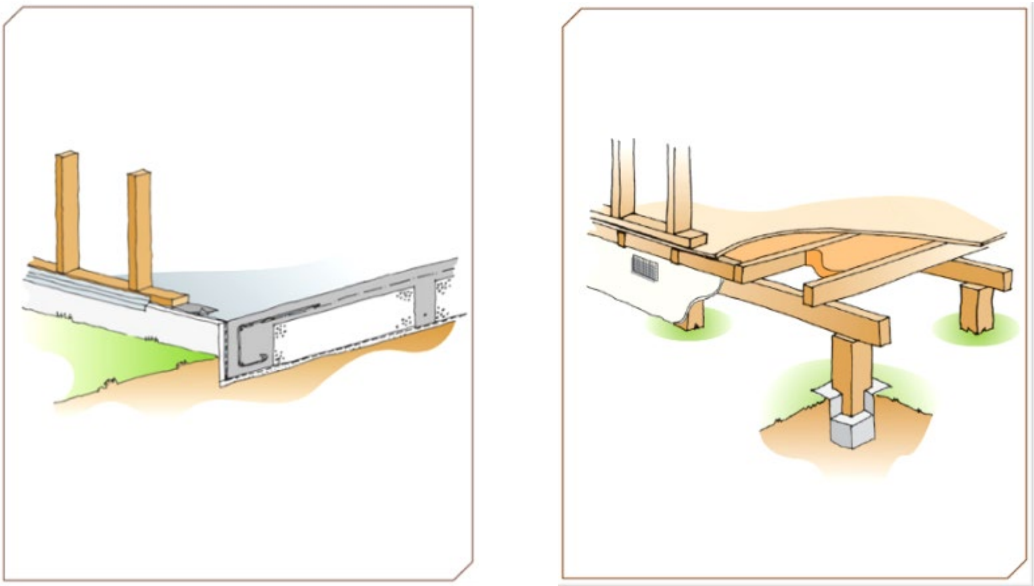

Figure 3 Ground floor assemblies using a concrete floor slab or suspended timber floor

Results for stand-alone houses from the BRANZ Materials and Characteristics Survey for consents taken out in 2021, show that concrete slab comprises 73% of the New Zealand market and suspended timber the other 27%.

Both options have material quantities based on 1 m^2 of floor area. In the suspended timber floor option, this includes materials below the floor level, including an enclosed sub-floor perimeter, timber piles and concrete pile bases. A description of the constructions (both of which assume a 90 mm deep

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[11] The study authors would like to acknowledge Nick Collins, General Manager of the National Association of Steel Framed Housing (NASH) https://nashnz.org.nz/ for support in co-ordinating feedback on the steel framed wall construction.

[12] The project team considered modelling the thermal break as an oriented strandboard (OSB) with graphite polystyrene foam and laminated synthetic building wrap. However, investigation of an Environmental Product Declaration (EPD) for the product showed that the proportion of wood in the OSB from certified sustainable forestry was uncertain.

wall frame) used in the baseline assessment is as follows, with a more detailed list of materials and quantities in Appendix B.

The concrete floor assembly comprises:

- 25 mm of sand blinding and wrap-up damp proof membrane
- 85 mm waffle slab with 665 Pacific Steel SEISMIC® mesh on 200 mm thick by 1100 mm by 1100 mm grade S expanded polystyrene (EPS) pods, separated by polypropylene spacers at 600 mm centres
- Concrete ribs at 1200 mm centres with 1 x HD12 reinforcing
- 300 mm x 220 mm concrete strip footing with 3 x HD12 reinforcing
- R1.0 extruded polystyrene (XPS) edge insulation
- Painted 7.5 mm glue-fixed fibre cement edge protection and Z flashing to base of cladding.

The construction achieves an R1.6 construction R value. It is worth noting that the achieved construction R value can vary with the A/P ratio. For example, if this construction is used in a house with a reasonably compact design (A/P ratio >2.8), it could achieve R1.7 (and thus comply in all six climate zones). However, with a less compact design (A/P ratio of <2.2), underslab insulation may also be needed. The baseline assessment includes the following:

- The concrete slab floor is exposed
- 20 MPa in-situ concrete is used[13].

Concrete used in the construction is assumed to contain Ordinary Portland Cement (OPC) supplied by Golden Bay Cement and contains no supplementary cementitious material (SCM) content. The SCM content of NZ cement is reported as 2% in binders in ready-mix concrete used in New Zealand (Concrete NZ, 2023, p.12).

The suspended timber floor (with enclosed sub-floor) construction includes:

- 20 mm particleboard floor, fixed with adhesive and steel screws
- 140 mm x 45 mm timber joists at 450 mm centres
- R3.2 insulation
- 900 mm long timber piles, with a clearance to underside of joists of 450 mm (to comply with the minimum specified in NZS3604:2011)
- 17.5 MPa in-situ concrete bases (made with OPC, and no SCMs) for timber piles.

This achieves a construction R value of R3.4.

As a sensitivity, both the concrete floor slab and suspended timber floor are additionally assessed when covered (Appendix F).

3.2 Materials used in case studies

A summary of the materials used in the assemblies is provided in Table 1. A list of the module A1-A3 carbon footprint values for materials used in each assembly is provided in Appendix B. Appendix C provides sources of manufacturing-related climate change impacts used in the study. Where required for the dynamic LCA, the climate change results were back-calculated to constituent GHGs using

[13] This construction may also use 17.5 MPa or 25 MPa concrete, depending on location.

emissions data in the ecoinvent 3.7 (cut-off) datasets for corresponding processes; this was required in order to represent the time-dependent decay rates of different GHGs.

Table 1 Different materials used in assemblies (kg per m²)

Material	Truss roof [1]				External wall [3]				Ground floor			
	Steel cladding	Notes	Concrete tiles	Notes	Timber frame	Notes	Steel frame	Notes	Suspended timber	Notes	Concrete slab	Notes
Timber / engineered wood	9.8		13.3		25.8	4	19.2	4	35.0	6	0.5	7
Steel	4.5		0.3		0.5		3.9		0.6		6.2	
Concrete (in-situ)	0.0		0.0		0.0		0.0		32.9		372.3	
Insulation	4.3		4.3		1.1		2.5	5	2.6		2.2	
Plasterboard	9.8		9.8		7.7		7.7		0.0		0.0	
Concrete tiles	0.0		52.5	2	0.0		0.0		0.0		0.0	
Other	0.1		0.2		0.3		0.3		4.2		374.3	8
Total	**28.5**		**80.4**		**35.3**		**33.6**		**75.3**		**755.5**	

Notes

1. Represents 1 m² of horizontal ceiling area
2. Includes underlay and battens
3. Based on a clear wall construction (14% framing ratio)
4. Includes bevel back weatherboard cladding
5. Includes XPS thermal break strips
6. Includes particleboard floor
7. Includes plywood formwork and pegs
8. Includes basecourse and sand blinding

The relative contributions of the different materials to the A1-A3 climate change impact of the assemblies is summarised in Appendix H.

3.2.1 Timber

The wood products in the assemblies include sawn and kiln-dried timber, plywood (formwork for the concrete floor) and particleboard (for the timber floor). Each of the six assemblies contains two or more of these products, varying in dimensions and level of preservative treatment. The full list of timber components is given in Appendix B, and sources of climate change data for different products in Appendix C.

Regarding biogenic carbon stock in the forest, carbon accumulates and is stored in a forest in three broad pools: soil, live biomass in trees and other plants, and dead organic matter on the forest floor or in standing dead trees. In a natural forest, these pools will all be present and may be fluctuating about a steady-state carbon stock. In a new plantation forest planted onto grassland, the carbon stock in live and dead biomass will build up from a low base level, but some initial loss of soil carbon is likely (Figure 4). At the time of harvest, some biomass leaves the forest as harvested logs and some is transferred to the dead organic matter pool as harvest residues, which then decay over time. While this decay takes place, the replanted forest accumulates carbon again in biomass.

In this study, net carbon storage in the forest takes into account the overall net change in these three forest pools. There are alternative methods for assessing this storage, including:

1. Stand-level, historic: forest carbon is tracked from the time a forest is established on non-forest land until the time of harvest (time = -28 to 0 years in Figure 4). A biogenic carbon credit is associated with this cultivation, and ongoing carbon storage in harvested timber.
2. Stand-level, replacement: forest carbon is tracked from the time of harvest until the carbon removed from the forest as logs has been recaptured in the re-established forest (time = 0 to 28 in Figure 4). A biogenic carbon credit is associated with this cultivation, and ongoing carbon storage in harvested timber.

3. Forest-level: this approach assumes that a forest under sustainable forest management is carbon neutral, with no net change in the carbon stored in the forest over longer timeframes (Figure 5). The amount harvested each year is equal to the growth increment in the rest of the forest that year. As an example of this approach, Figure 5 shows that the live biomass reaches a steady-state 'cycle' from the time of the first harvest, the soil reaches a steady-state 20 years after the first harvest (t=20), and the dead organic matter continues to accumulate (although at a very low rate) even after 100 years - although it very close to a steady-state cycle after the second harvest. Using this approach, no biogenic carbon credit is calculated for the forest plantation; however, the harvested timber is associated with a biogenic carbon credit for ongoing carbon storage.

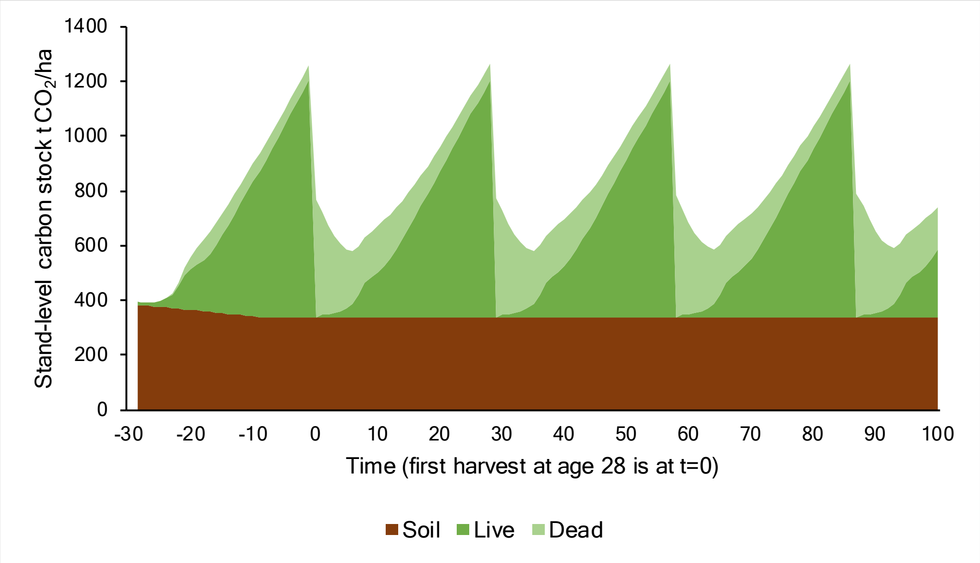

Figure 4 Carbon stocks in the soil, live biomass and dead organic matter in a plantation forest stand established in year -28 and first harvested in year 0

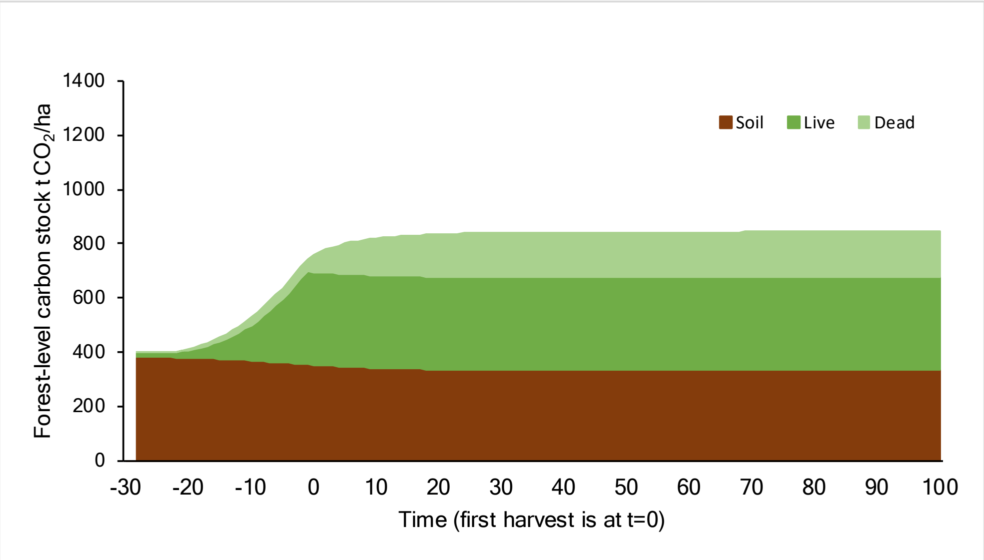

Figure 5 Carbon stocks in the soil, live biomass and dead organic matter in a plantation forest established annually from year -28 to year 0, and first harvested in year 0 (includes stock in soil and live biomass in pre-afforestation pasture as the plantation is established)

For this study, the second method was followed and it was assumed that the forest was in a longer-term steady state as regards soil carbon and dead organic matter. In other words, we modelled an established forest not in its first rotation (for background information on this choice see discussion in Hoxha et al., 2020). This is considered appropriate for New Zealand's moist temperate conditions where dead organic matter decay is relatively fast and soil carbon is not expected to accumulate under a constant land use (MfE, 2021).

The total amount of carbon stored in the timber used in the assemblies was taken from EPDs for different timber products (as listed in Appendix C). For the dynamic LCA (dLCA), carbon sequestration in the forest was then allocated across the different years in proportion to the sequestration rate for growing trees in a yield table published by MfE and used for greenhouse gas inventory reporting under the United Nations Framework Convention on Climate Change (MfE, 2022b). The yield table was derived from analysis of data from a representative sample of remeasured permanent plots located at 4 km grid intersections across post-1989 planted forests, established as part of New Zealand's National Forest Inventory (Beets et al., 2011).

If, instead, the first method was used and the timber products were sourced from a forest where there had previously been a change in land use, then any associated change in soil carbon levels and above-ground dead organic matter should be assessed and included in the analysis. For example, in New Zealand's GHG inventory (MfE, 2022b) afforestation of pasture results in a net loss of soil carbon, assumed to occur at a constant rate over twenty years. However, for clearfelled and replanted plantation forests, the long-term average carbon stock will be higher than in the former grassland and so there is a net biogenic carbon storage benefit compared with the previous land use.

3.2.2 Steel

The key steel materials included in the study were profiled zincalume steel cladding on the truss roof, galvanised steel framing in the steel frame wall and reinforcing steel in the concrete slab floor.

The underlying process for manufacture of steel for all three products is at New Zealand Steel's Glenbrook plant in Auckland, which is a primary manufacturing process. Further processing occurs at other sites as necessary (for example, steel billet from Glenbrook is reheated in a furnace at Pacific Steel's Ōtāhuhu site, to make reinforcing bar, coil, rod and wire and flat zincalume coil is transported to rollformers, where it is uncoiled and shaped into different profiles e.g. corrugate).

At the time of the study, New Zealand Steel and Pacific Steel were in the process of updating their published EPDs for ColorSteel® and Seismic® products respectively.

New Zealand Steel was approached for updated embodied carbon data for steel products and was able to supply figures for Axxis (steel framing) and Seismic (steel reinforcement) products. The updated (but unpublished at the time of writing) Seismic® figures for reinforcing steel were used in this study in preference to those reported in the (soon to be replaced) Seismic EPD (Pacific Steel (NZ) Ltd, 2018). Embodied carbon data for Axxis steel framing (to be published in a forthcoming New Zealand Steel EPD), was also used[14].

The process of updating embodied carbon figures for a new version of New Zealand Steel's ColorSteel® EPD was not sufficiently advanced for the updated data to be included in this study. Therefore, the

[14] The project team would like to thank Israel MacDonald of New Zealand Steel for provision of data used in this study. We would also like to thank Amir Shah Mohammadi of HERA for facilitating the use of these data.

study used embodied carbon data in the published New Zealand Steel EPD (2018, including Addendum with rollforming).

Upfront embodied carbon data for other minor steel materials included in assemblies (such as fixings, for example) were based on overseas manufacture.

3.2.3 Concrete

In-situ concrete is present in the concrete slab and suspended timber floors (in the latter case, in the timber pile bases). It is additionally present in a precast form in the concrete tile truss roof construction. Data for in-situ concrete production are based on cement made in New Zealand by Golden Bay Cement, located in Whangarei Harbour, Northland, and production of in-situ concrete at New Zealand batching plants. For this study, we did not consider use of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBS) and fly ash, as cement replacements, as their use in the specific assemblies considered in this study was assumed to be low.

Generic ecoinvent (version 3.1) data was used to represent manufacture of concrete roof tiles, adapted with Ordinary Portland Cement (OPC) made in Australia (using AusLCI[15] data).

3.2.4 Other materials

The other materials included in each construction, together with their quantities (excluding wastage during construction) and manufacturing climate change impacts, are provided in Appendix B.

A list of sources of manufacturing-related climate change impacts by material, is provided in Appendix C.

3.3 Modelling of Activities

3.3.1 Transport to the construction site and construction (modules A4 and A5)

3.3.1.1 Transport to the construction site (module A4)

Distances for transport of specific materials listed in Table 2 to a construction site were estimated based on general knowledge with all other materials assumed to be transported 100 km by truck. Transport emission factors were used from MfE (2022a), and the heavy truck emission factor for truck transport.

[15] AusLCI is the Australian National Life Cycle Inventory Database www.auslci.com.au/.

Table 2 Distance to construction site and mode of transport for different materials/products

Material/product	Distance to construction site	Mode of transport	Distances for sensitivity analyses
Sawn timber[i]	245	Truck	Auckland: 240 km
			Christchurch 250 km
Plywood	135	Truck	Auckland: 210 km
			Christchurch: 240 km[ii]
Particle board	250	Truck	Auckland: 110 km
			Christchurch: 800 km[ii]
Steel	560	Truck	Auckland: 60 km
			Christchurch: 1060
Concrete mix	30	Truck	Same
Concrete roof tiles	2500	Bulk carrier ship	Auckland: 2400 km shipping
			Christchurch: 2600 km shipping
	50	Truck	Same
All other materials	100	Truck	Same

Notes:

[i] Estimated average distance weighted by mill capacity for structural timber-focused mills

[ii] Mix of rail, ferry and truck transport for Christchurch but represented by truck transport in this study

3.3.1.2 Construction (module A5)

The following activities were included in the modelling for this life cycle stage: manufacture of materials that become waste during construction (e.g. offcuts of timber or plasterboard) and their subsequent end-of-life management. Construction waste was modelled as summarised in Table 3.

In general, construction activities were not modelled (e.g. use of power tools) based on expert opinion that they are unlikely to make a significant contribution to the overall results.[16] However, as site preparation for the floor options may be more significant,[16] it was included as follows:

- Concrete floor slab: a topsoil depth of 0.25 cm was assumed, meaning about 0.5 m^3 of material is removed per m^2. An estimate of emissions was derived using the ecoinvent 3.8 dataset called "RoW: excavation: hydraulic digger".
- Suspended timber floor: the same assumptions were used as for the concrete floor slab. In addition, excavation of pile holes (350 mm width x 350 mm length x 450 mm depth) at a rate of 0.39 piles/m^2 was included, using the same ecoinvent 3.8 "RoW: excavation: hydraulic digger" dataset.

[16] Richard Haynes of Cerclos https://cerclos.com/ and Tim Grant of life cycles www.lifecycles.com.au/ were contacted about their opinions on the significance of construction activities, and both confirmed that in their experience, these contribute relatively little. Richard and Tim are thanked for their input. Richard mentioned that site preparation may be more significant, so an estimate was calculated for the study. Richard also confirmed that a larger contribution is made by construction site workers commuting to a construction site, but this isn't typically included in the scope defined in EN15978:2011, and has not been included in this study.

Table 3 Construction site waste scenarios used in the study[17]

Life Cycle Stage	Timber	Steel	Concrete
Construction waste (module A5)	10% is wasted at construction site: 85% goes to landfill, and 15% is recycled (displacing primary timber production) (pers.comm., Annette Day, Naylor Love)	1% is wasted at construction site: 100% displaces primary steel production in a blast furnace	4% is wasted at construction site: 90% goes to landfill and 10% is washed and the aggregate recycled (displacing primary aggregate production)

3.3.2 Use (modules B1 to B7)

The following modules were included in the Use phase modelling:

- Carbonation of concrete (module B1)
- Replacement of materials during the building service life (module B4)
- Electricity use, due to a differential in heating and cooling energy when comparing assemblies (module B6). See Appendix A.

The following Use phase modules were excluded from the scope:

- Module B2 (maintenance): should be carried out in line with manufacturer instructions to ensure materials can continue to provide functional performance over their service life. The main maintenance activities excluded from the study but relevant to the assemblies are painting of the cladding and internal wall surfaces (external walls) and ceiling lining (roofs), as well as washing.
- Module B3 (repair): can be needed due to accidents or significant events e.g. storms, earthquakes. May also be required when materials are not maintained in line with manufacturer instructions.
- Module B5 (refurbishment): over the 50 year building service life, it is assumed there is no significant upgrade or change of use that would require refurbishment, over and above the replacements of elements that are allowed for in module B4.
- Module B7 (operational water use): covers water use by occupants for day to day activities such as cooking, washing and watering gardens.

Further information about each of the modules included in the study is provided in the following sections.

3.3.2.1 Carbonation (module B1, and also modules A5, B4 and C4)

The method used to estimate concrete carbonation follows Souto-Martinez et al. (2017, 2018). As well as carbonation in the Use stage (module B1), carbonation can also occur in module A5, beginning in

[17] Module A5 end-of-life scenarios based on BRANZ's module A5 datasheet available at www.branz.co.nz/environment-zero-carbon-research/framework/data/ with some simplification. This includes assuming that 100% of waste steel produced in construction is recycled. The proportion of timber waste from construction that is landfilled and recycled was also changed, following input from Annette Day of Naylor Love. Annette is thanked for her input to the project.

year 1 (if concrete material becomes waste during construction and is sent to landfill), module B4 (if replacement includes concrete both as a new installation or as a waste stream), and module C4 (beginning the year after service life ends if concrete is a waste stream going to landfill).

There are a number of approaches for estimating concrete carbonation. The usual approach in static LCA is to estimate CO_2 uptake as a percentage of CO_2 emitted during concrete production (Possan et al., 2017). In a UK report by MPA The Concrete Centre (2016), carbonation is estimated as a percentage of overall carbon footprint between the use stage (2.5% of production emissions) and end-of-life stage (5%); another method is published by BRE (BRE, 2023, Appendix C). However, these methods do not provide the temporal resolution required for a dynamic LCA. The method described by Souto-Martinez et al (2017, 2018) allows for the calculation of the depth of carbonation front over time, and thus the change in concrete carbonation each year. Furthermore, this method incorporates detail of exposure conditions based on Monteiro et al. (2012), allowing for the different rate of carbonation between waffle slab floor and roof tiles.

Carbonation depends on the exposure conditions, the type of concrete, surface area and volume of the concrete. Many such variables are selected based on the most representative situation for New Zealand. Other variables are chosen from literature. The equations and variables used to model carbonation are given below.

The following process is applied to each concrete element separately, to give consideration to the type, exposure, and geometry of each element. First, we calculate the carbonation potential (Cm).

Silica-rich supplementary cementitious materials (SCMs) can partially substitute ordinary Portland cement (OPC), which can reduce the environmental impacts of concrete (Souto-Martinez et al., 2017). Examples include fly ash and slag (Yang et al., 2015). We assume the concrete type is Type 1 (see Table 4), and that no SCMs are used, setting y equal to 0 (see Eq. 1).

Table 4 Cement types and their parameters for calculating carbonation (from Monteiro et al., 2012)

Cement Type	α	SCM	Average σ % SiO_2	β
Type I	0.165	Fly Ash (Class F)	0.5	0.55
Type II	0.163	Fly Ash (Class C)	0.25	0.27
Type III	0.166	Slag	0.35	0.38
Type IV	0.135	Silica Fume	0.9	0.99
Type V	0.161	Metakaolin	0.5	0.55

$$C_m = \alpha - \beta \cdot y \quad \text{(Eq. 1)}$$

$C_m =$ carbon sequestration potential, kg CO_2/kg cement

$y =$ 0, percent replacement of OPC by SCM, in decimal

$\alpha =$ carbon sequestration potential coefficients given in Table 1

$$\beta = 1.1 \cdot \sigma$$

From the carbonation potential we calculated the depth of the carbonation front (x, see Eq. 2). Exposure classes can be selected based on Table 5 (Monteiro et al., 2012). During the B1 module, exposure class XC4 is used for concrete roof tiles, while XC1 is used for all other concrete elements including pile bases. For concrete elements in a landfill, XC1 is used, based on the assumption that concrete will be used as clean fill and therefore unexposed. The exposure class determines the k_1 and n factors. Together with the environmental CO_2 concentration (c, we use 420 ppm), these variables determine the rate of change of the carbonation front. The carbonation front is the surface undergoing the carbonation reaction.

Table 5 Exposure classes and parameters used to calculate carbonation front (from Monteiro et al., 2012)

Class	Environment	Examples	k_1	n
XC1	Dry or permanently humid	Reinforced concrete inside buildings or structures, except areas of high humidity; Reinforced concrete permanently under non-aggressive water.	1	0
XC2	Humid, rarely dry	Reinforced concrete under non-aggressive soil; Reinforced concrete subjected to long periods of contact with non-aggressive water.	0.2	0.183
XC3	Moderately humid	Outer surfaces of reinforced concrete sheltered from wind-driven rain; Reinforced concrete inside structures with moderate to high air humidity.	0.77	0.02
XC4	Cyclically humid and dry	Reinforced concrete exposed to wetting/drying cycles; Outer surfaces of reinforced concrete exposed to rain or outside the scope of XC2.	0.41	0.085

$$x = \sqrt{\left(\frac{2 \cdot c \cdot t}{R}\right)} \cdot \left[\sqrt{k_0 k_1 k_2}\left(\frac{1}{t}\right)^n\right] \qquad \text{(Eq. 2)}$$

$c =$ 0.000814 environmental CO_2 concentration, $\mathrm{kg/m^3}$

$t =$ exposure time, years

$k_o =$ 3

$k_1 =$ given in **Table 5**

$k_2 =$ 1

$R =$ $0.0016 \cdot f_c^{3.106}$ carbonation resistance coefficient, kg year $/m^5$

$f_c =$ compressive strength (MPa)

$n =$ given in **Table 5**

The total carbonated volume (Eq. 3) at any finite point in time can be calculated by multiplying the total carbonation depth, x, by the total surface area of exposed concrete, from which the total mass of CO_2 stored in concrete is calculated (Eq. 4).

$$V_c = \begin{cases} SA \cdot x & if\ SA \cdot x \leq V \\ V & \text{the total volume of OPC}, if\ SA \cdot x > V \end{cases} \quad \text{(Eq. 3)}$$

$$\phi_c = \text{degree of carbonation}, \in (0, 1). \text{ Observed values } \in (0.40, 0.72)$$

$$C_s = \phi_c C_m \cdot [V_c \cdot m] \quad \text{(Eq. 4)}$$

3.3.2.2 Replacement of materials during the building service life (module B4)

Depending on the service life and the exposure zone[10], replacement in module B4 occurs for the timber cladding, steel roof cladding, and concrete roof tiles at various years over the life cycles. These replacement years are shown in Table 6.

Table 6 Timing of replacement of products in assemblies over 50 and 90 year service lives (year from year 0)

Service life (years)	Exposure zone	Wall (timber): timber cladding	Wall (steel): timber cladding	Roof(steel): steel cladding	Roof (concrete): concrete tiles	Floor (timber)	Floor (concrete)
50	B (inland)	-	-	-	-	-	-
	C (inland coastal)	-	-	30	-	-	-
	D (coastal)	-	-	20,40	-	-	-
90	B (inland)	60	60	45[18]	75	-	-
	C (inland coastal)	60	60	30,60	75	-	-
	D (coastal)	60	60	20,40,60,80	75	-	-

[18] For modelling purposes, and due to the conservative nature of material service life estimation, we do not model a replacement when a material is estimated to have a 45 year service life, as this is deemed as being sufficiently close to the 50 year building reference service life.

For the 50 year reference building service life, only the truss roof assembly with a steel roof cladding features a replacement. The baseline assessment assumes a location in exposure zone C where a ColorSteel® Endura® corrugate roof profile, with a base metal thickness (BMT) of 0.4 mm, is modelled. Using BRANZ's module B4 datasheet, this is estimated to have a service life of 30 years[19], and is therefore modelled as requiring one replacement (in year 30) during a 50 year building service life. The replacement includes:

- Manufacture of the steel cladding
- Transport to the building and installation (using construction wastage and diversion from landfill rates as set out in Table 3.
- Disposal of the old, replaced steel cladding, using the building end-of-life diversion from landfill rate in Table 8.

As shown in Table 6, more materials are replaced over a 90 year reference building service life. For any replacement in module B4, impacts are estimated in the year of replacement which include material manufacture (A1-A3), transportation to the building (A4), transportation to landfill (C2) and landfill (C4). If materials are recycled, this is separately calculated in module D. For concrete roof tiles in particular, any carbonation that occurs when they are replaced and landfilled is also accounted in module B4.

3.3.2.3 Operational energy use (module B6)

3.3.2.3.1 Estimating electricity demand from heating/cooling

A simulation of operational heating and cooling energy is required where there are differences in construction R value achieved by each of the two wall, roof and floor assemblies (in comparison with each other) and/or where there is likely to be a difference due to thermal mass.

This was necessary for the two floor assemblies, due to differences in construction R values between the concrete floor slab and suspended timber floor option, but also because of the thermal mass of the concrete floor slab. It was also necessary for the two external wall options, due to thermal mass of the timber frame.

The methodology that was used to undertake this energy simulation is set out in Appendix A. This was shared with the Project Stakeholder Group and updated based on comments received.

Operational energy use was modelled as the difference between simulated electricity use for each pair of assemblies that is required using baseline scenario defaults set out in Appendix A. This was calculated by subtracting the electricity use for the construction requiring less heating/cooling energy from the electricity use for the construction requiring more heating/cooling energy. Thus, only the additional electricity (as kWh low voltage electricity /m^2) required for heating/cooling by the construction requiring **more** heating/cooling energy was modelled. These values are shown in Table 7 (including additional requirements for the Auckland and Christchurch scenarios modelled in Section 5).

[19] Actual service life depends on several factors including exposure zone, local environment, thickness and quality of the aluminium/zinc alloy coating, design of the roof, standard of the build and whether maintenance is carried out, for example. This service life estimate is conservative.

Table 7 Additional Use electricity requirements for wall (steel) and floor (timber) - relative to wall (timber) and floor (concrete) – measured per m²/year for New Zealand (average), and Auckland and Christchurch

Location	Wall (steel) (kWh/m²/yr)	Floor (timber) (kWh/m²/yr)
New Zealand	0.28	1.56
Auckland	0.30	3.95
Christchurch	0.26	-0.33[20]

3.3.2.3.2 Estimating the greenhouse gas impact of the New Zealand grid into the future

The climate change impact of the New Zealand grid each year of the Use phase uses the life cycle method and model developed by Bullen (2020) and provided in the BRANZ module B6 datasheet[21]. The greenhouse gas impact of this electricity use each year was modelled as follows:

- Consequential impact factors were used (rather than attributional impact factors), as presented in the module B6 datasheet. The consequential impact factors attribute the impacts of constructing new electricity generation infrastructure to the year it is commissioned, rather than assigning a portion over the life of the asset. Therefore, no impacts are assigned to generating and transmission infrastructure that already exists, as the emissions have already occurred.
- There are five MBIE scenarios modelled, based on MBIE's Electricity Demand and Generation Scenarios report (2019). For the purposes of this study, the Reference scenario was used.
- The year of construction was assumed to be 2024. Therefore, the Use phase starts in 2025.
- The MBIE Reference scenario is only modelled to 2050. Thereafter, the 2050 emissions per kWh continue to be used for the rest of the building service life (i.e. the grid carbon impact factor per kWh remains the same for years after 2050).

It is worth noting that the life cycle-based impact factors calculated using this model are higher than those reported by, for example, the Ministry for the Environment (2022a). The module B6 datasheet provides reasons for this, such as inclusion of pre-combustion emissions for fossil fuels and embodied carbon of new infrastructure[22].

3.3.3 Building end of life (modules C1-C4)

For the three main material products assessed in this study (timber framing, cladding, floor and piles; steel roofing and framing; concrete floor, pile bases and roof tiles), end-of-life (EofL) was modelled at building demolition (after year 50 or 90). The EofL modelling assumptions are given in Table 8. Other products were modelled as 100% going to landfill.

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[20] The negative number means that for Christchurch, the concrete floor slab was modelled as requiring additional energy for heating/cooling in comparison with the suspended timber floor. So this should not be interpreted as the suspended timber floor requiring 0.33 kWh/m²/year less energy, but instead the concrete slab floor needing an additional 0.33 kWh/m²/year more energy. See Appendix F and Appendix G for further information.

[21] New Zealand grid environmental factors (module B6) datasheet is available at https://www.branz.co.nz/environment-zero-carbon-research/framework/data/.

[22] The module B6 datasheet shows a comparison of the calculated greenhouse gas impact factor for 2018, compared to the MfE Scope 2 and T& D impact factor for the same year, and showed an increase of 35%.

All waste was modelled as travelling 47.5 km to a landfill using the heavy truck emission factor in MfE (2022). For the Auckland and Christchurch scenarios, the distances were 30 and 65 km respectively.

Table 8 End of life modelling of building demolition waste[23]

Life cycle Stage	Timber	Steel	Concrete
End of service life	100% to landfill	85% recycled which displaces primary steel production in a blast furnace 15% landfilled	80% landfilled 20% recycled by crushing to create secondary aggregate (displaces primary aggregate production) and steel reinforcing sent to recycling (displacing primary steel production in a blast furnace)

For landfill emissions, we accounted for timber products (sawn timber, plywood, particleboard), as well as uptake due to carbonation of landfilled concrete products. Other landfilled materials were treated as insignificant from a climate change perspective in module C4 and not modelled. For landfilled timber, the approach for calculating landfill methane emissions in MfE (2022a) was followed using the MfE parameter values for timber in managed landfills (Table 9). A sensitivity analysis was undertaken for use of alternative Degradable Organic Carbon (DOCf) values (Section 5). The method used to model the fate of timber, and subsequent emissions, is explained in more detail in Appendix D. For the dLCA, methane emissions from timber decay in landfill were modelled following Eunomia (unpublished).

Table 9 Examples of parameters used to calculate landfill gas emissions from landfilled timber in various sources

	IPCC default values	NZ GHG Inventory (MfE, 2022) - managed landfill	NZ GHG Inventory (MfE, 2022) - non-municipal landfill	NZ EPDs (e.g. Abodo, 2020; Carter Holt Harvey, 2023a,b; Red Stag, 2022a,b; WPMA, 2019)
DOCf	0.1	0.14	0.5	0.001
Recovery efficiency, R	20%	68%	0%	40%

3.3.4 Module D

For recycling of materials at end-of-life, EN15804:A2 provides guidance on how to define an "end-of-waste state" (CEN, 2019, Section 6.3.5.5). Thereafter, the climate change impact of recycling activities is represented (in Module D) as the net result of recycling/recovery processes minus displaced

[23] BRANZ's Module C1 datasheet available at www.branz.co.nz/environment-zero-carbon-research/framework/data/ provides suggested default typical and best practice diversion rates from landfill for building end-of-life waste. In some cases, simplifying assumptions were used to ease the modelling for this study. For example, in this study, the timber at building EoL was modelled as going to landfill, and in the sensitivity analysis it was modelled as being incinerated and displacing heat from natural gas (Section 5). Alternative options for timber at EoL include reuse, recycling or incineration for use in specific industrial processes (such as cement production) but they were not modelled separately in this study. Another example is the concrete roof tiles. In this study, 80% was assumed to go to landfill, to align with other concrete modelling, compared to a Module C1 datasheet typical value of 50% for tiles (concrete) specifically.

equivalent primary material production using current average technologies/practices (CEN, 2019, Section 6.3.5.5, Note 3; Section 6.4.3.3).

As a simplification, in this study, materials were modelled as having reached their "end-of-waste state" without modelling processes that may be necessary (in module A5 or C3) to reach this point. For example, washing of uncured concrete (module A5) to recover aggregate, and crushing of cured concrete (module C3), were omitted from this analysis. These are activities with relatively small climate change impacts compared with other activities in the life cycle of concrete, and so their omission does not materially affect the conclusions of this study.

The module D results were modelled as a range encompassing two extreme scenarios: displacement of equivalent primary material production using (a) current average technologies and (b) future "zero carbon" technologies. The approaches used for scenario (a) were:

- Timber (only relevant for the small amount of timber recycled/reused from the construction site, see Table 3): the recycled/reused timber was modelled as a biogenic carbon emission in module A5 (following EN16485, 2014, Figure 1, Figure 2), and a net zero (or near to net zero) biogenic carbon saving in module D. The module D calculation assumes displaced sustainable forest which is offset by the biogenic carbon credit associated with the recycled timber being used in a subsequent system.
- Steel: recycled steel represented as displacement of blast furnace steel production plus recycling in an electric arc furnace (as commonly done in existing steel EPDs).
- Concrete: recycling into secondary aggregate represented as displacement of primary aggregate production (crushing of the EofL concrete to produce secondary aggregate omitted in this study due to its relative insignificance compared with other concrete-related activities).

The approach used for scenario (b) was to model the recycled materials as displacing activities with "zero carbon" emissions. As the majority of these recycling activities will not occur for at least 20 years (Table 6), and alternative technologies are likely to be in place by that time, use of a range is considered appropriate.

4 IMPACT ASSESSMENT RESULTS

The baseline results presented in Sections 4.1 and 4.2 are for the assemblies with a 50 year building reference service life, using average NZ transportation distances, and assuming an exposure zone C (inland coastal) location. The influence of changing these parameters is investigated in Section 5. For the figures and tables where single numbers represent the module D results, these represent the maximum displacement of emissions due to recycling activities (see Section 3.3.4). These maximum displacement values are used as the basis for the sensitivity analyses in Section 5 and discussion in Section 6. The breakdown of module A1-A3 climate change results by materials is given in Appendix H.

4.1 WHOLE-OF-LIFE CLIMATE CHANGE RESULTS INCLUDING BIOGENIC CARBON STORAGE

4.1.1 Static modelling (sLCA) based on EN15804:A1 (CEN, 2013)

The total results for the different GHGs and overall total are reported in Table 10. The concrete roof, timber wall, and timber floor have the lower baseline climate change results (out of each pair of assemblies) when using sLCA. However, it should be noted that the climate change results for the steel-containing assemblies, in particular, could be quite different if an alternative modelling approach for recycling steel was used (see Section 3.3.3). The biogenic contribution is also relatively large for all the assemblies apart from the concrete floor, due to the storage of biogenic carbon in the timber in these assemblies and subsequently in landfill (see Table 1).

Table 10 Whole-of-life climate change results (kg CO_2eq / m^2) by greenhouse gas for each assembly accounting for biogenic carbon storage and including module D (EN15804:A1 approach)

Assembly	Total net CO_2	Total net CH_4 (CO_2-eq)	Total net N_2O (CO_2-eq)	Total net climate change impact* (CO2-eq)	Total net biogenic contribution (CO_2 + CH_4) (CO_2-eq)	Module D contribution (CO_2-eq)	Net biogenic carbon storage (CO_2 only) (CO_2-eq)
Roof (steel)	16.11	6.52	0.26	22.89	-12.91	-8.21	-16.44
Roof (concrete)	-2.86	6.37	0.16	3.67	-17.20	-2.85	-21.98
Wall (timber)	-28.82	10.40	0.16	-18.26	-32.84	-0.12	-42.13
Wall (steel)	-9.45	8.87	0.22	-0.36	-24.69	-2.91	-31.64
Floor (timber)	-19.72	16.05	0.30	-3.36	-39.04	-1.40	-51.87
Floor (concrete)	68.74	6.42	0.42	75.58	-0.49	-8.96	-0.65

*Total net climate change impact includes both fossil and biogenic GHG emissions, biogenic carbon storage (from atmospheric CO_2), and module D.

The results are shown in Figure 6 as bar charts, highlighting the different life cycle stages that contribute to the respective climate change impacts. The total net impact is indicated with a black dot, which corresponds to the "Total GHGs" column in Table 10.

4.1.2 Static LCA modelling but disaggregated results for distinct time periods

Figure 7 shows the same results as those in Section 4.1.1 but disaggregated to identify the time period in which emissions occur. The negative biogenic carbon bar (coloured red) in years 1-28 for all the assemblies except the concrete floor is due to carbon sequestered in the growing forest (i.e. the source of the timber), and the smaller positive values from year 51 onwards are due to timber degradation in landfill.

Note that, for concrete that goes to landfill, there are carbonation climate change impacts from year 51 through to the point that maximum carbonation is reached or year 190 – whichever comes first - but the small values means they cannot be seen on all the graphs.

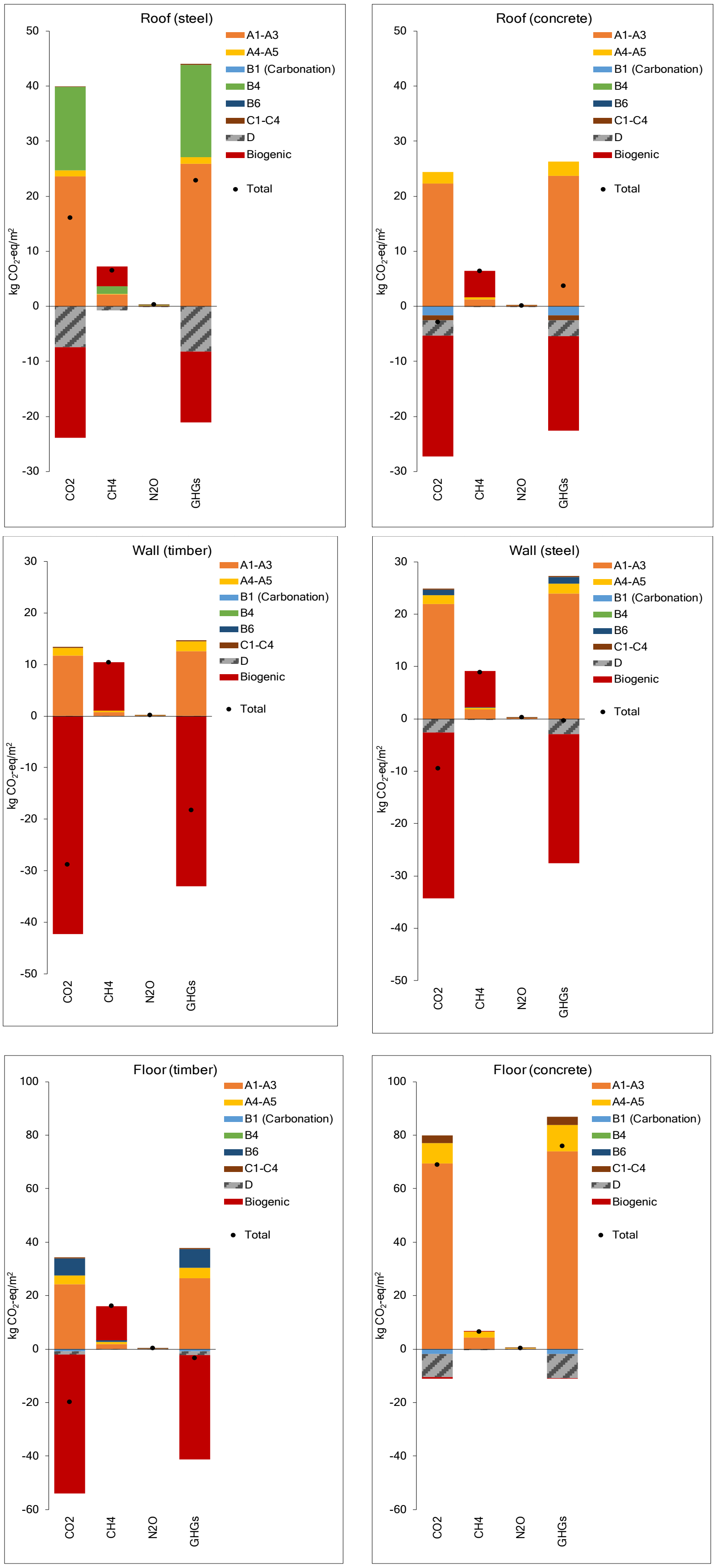

Figure 6 Contribution of life cycle stages and greenhouse gases to climate change impact, accounting for biogenic carbon storage (50 year building reference service life)

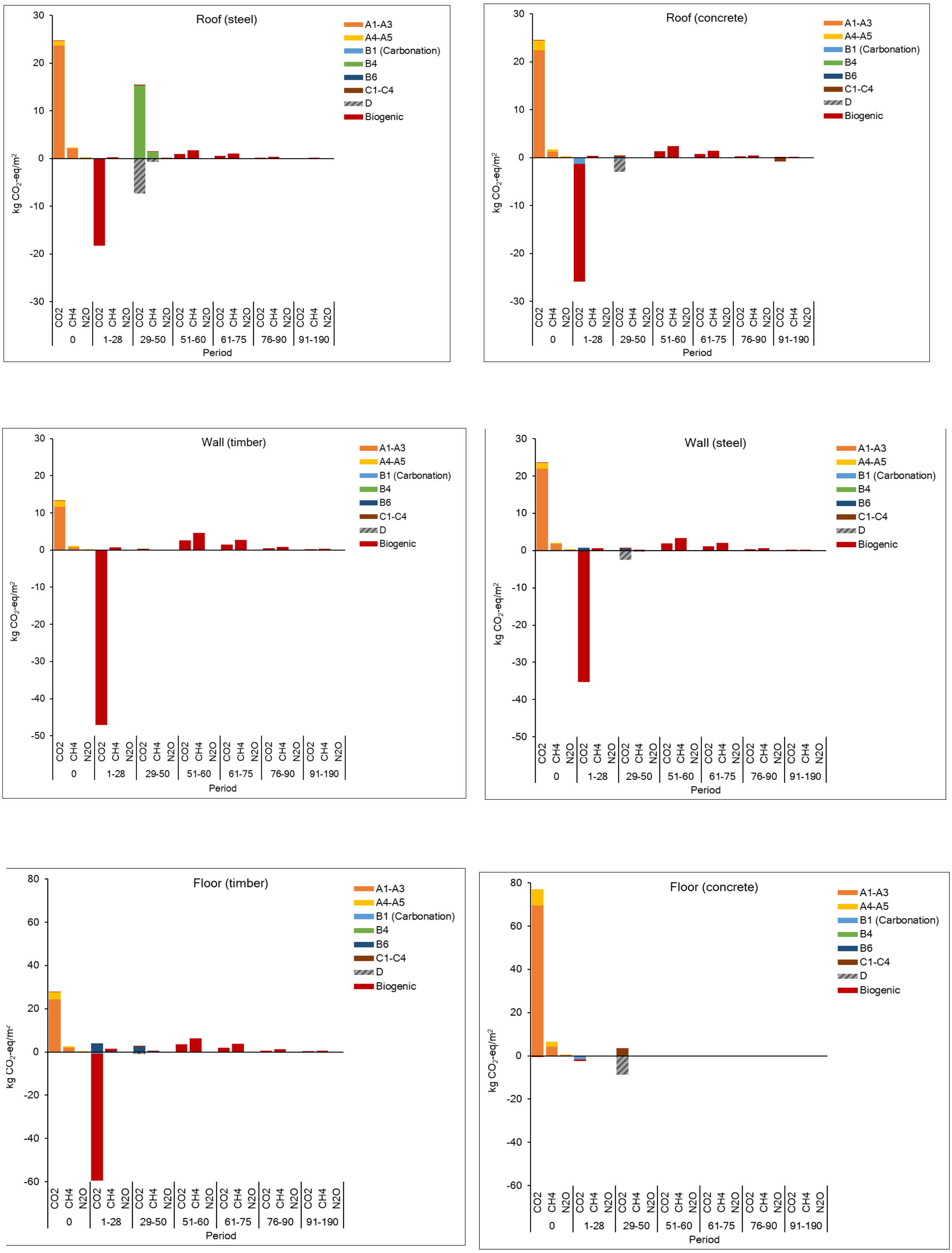

Figure 7 Climate change impact of each assembly showing greenhouse gas contribution by selected time periods (measured in years from assembly construction), accounting for biogenic carbon storage (50 year building reference service life)

4.1.3 Dynamic modelling (dLCA)

Dynamic LCA (dLCA) climate change results are measured in terms of radiative forcing (Watts per square metre, W/m^2), as opposed to static LCA (sLCA) climate change results which are measured in kg CO_2eq. The radiative forcing (RF) can be reported as instantaneous radiative forcing or a cumulative radiative forcing; instantaneous RF results represent RF over a one year period and cumulative RF results represent the sum of instantaneous RF forcing results in each year over a defined time period. While RF may be considered a more meaningful metric than GWP because it does not require subjective choice of a specific time horizon for the analysis, it is less commonplace than use of the GWP100 factors (provided in kg CO_2eq) required by building sustainability standards such as EN15804.

In Figure 8, Figure 9, and Figure 10, the instantaneous RF results show the change in RF associated with each pulse emission in each year up to year 190. As the majority of the GHG emissions happen in year 0 of the reference period, this is the largest instantaneous impact. The instantaneous graphs for all the assemblies show declines up to year 28 (at least), and this is due to the declining RF contributions of the GHGs over this time period, as well as forest sequestration due to regrowth of forests and carbonation for some of the assemblies.

The steel roof exhibits a small increase in instantaneous RF at year 30, which is the net impact of replacing the steel cladding, while no such increase occurs for the concrete roof. At year 50, both roof assemblies benefit from recycling, although this is more pronounced with the steel roof due to its higher recycling rate. After year 50, the instantaneous impact for both roof assemblies increases along a smooth curve which represents the release of methane from timber biodegradation in the landfill, and then decreases over time as the methane decays away.

The cumulative impact results show the overall effect of the instantaneous impacts and give a clearer comparison between equivalent assemblies. For example, the cumulative impact in Figure 10, in particular, highlights the different impacts of the timber and concrete floors on radiative forcing at different points in time.

In summary:

- The instantaneous impact curves show the additional radiative forcing relative to the previous year caused by the GHGs emitted in the years up to that point, taking into account their lifetime in the atmosphere.
- The cumulative impact curves show the additional radiative forcing relative to the start of year 0 caused by the GHGs emitted in all the years up to that point.
- All the instantaneous curves tend to a near-steady state at the end of the 190 year reference period due to the long lifetime of carbon dioxide in the atmosphere.
- The steel roof and concrete floor instantaneous curves tend to a positive value, indicating that the RF effect of the emissions exceeds the mitigation effect of storing biogenic carbon in landfill.

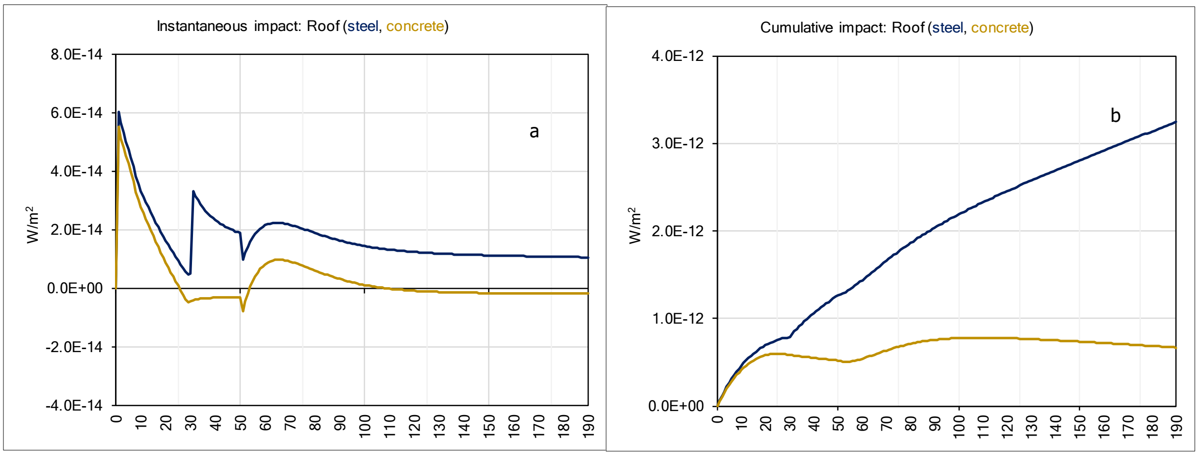

Figure 8 dLCA results for roof assemblies (instantaneous and cumulative) (50 year building reference service life, 1 m² of horizontal ceiling area), for years 0 to 190 (x axis)). Instantaneous graphs represent radiative forcing in one year (represented on x axis), and cumulative graphs represent the sum of radiative forcing results in each year up to the year represented on the x axis.

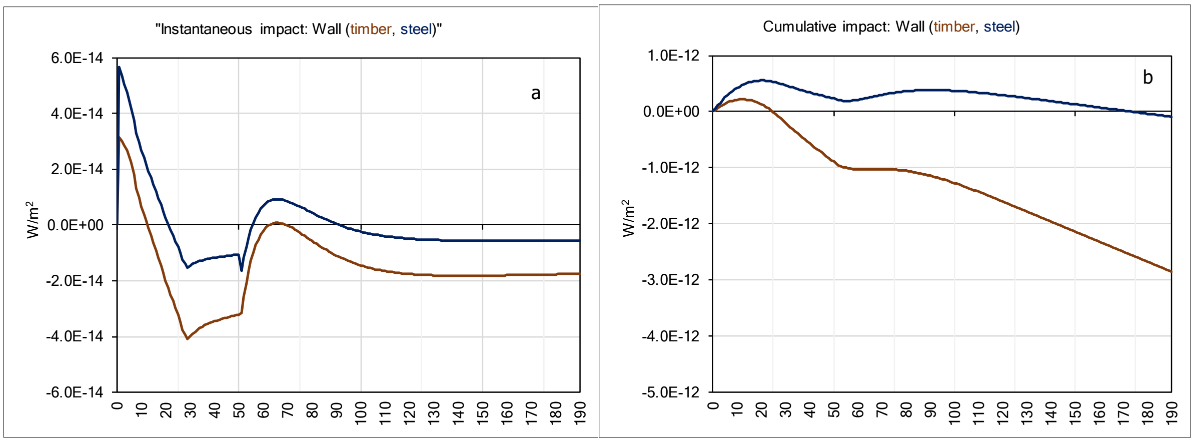

Figure 9 dLCA results for wall assemblies (instantaneous and cumulative) (50 year building reference service life, 1m² of wall area), for years 0 to 190 (x axis). . Instantaneous graphs represent radiative forcing in one year (represented on x axis), and cumulative graphs represent the sum of radiative forcing results in each year up to the year represented on the x axis.

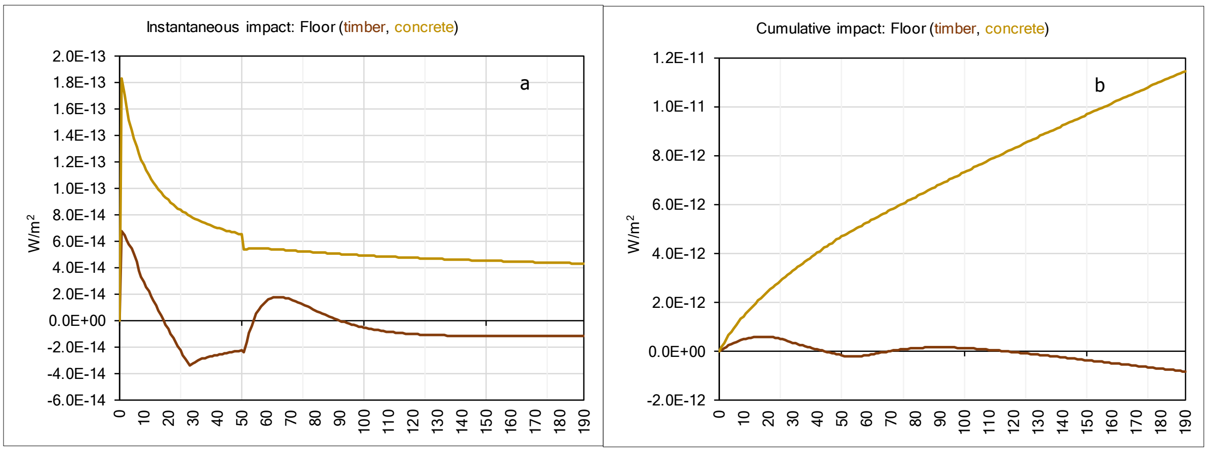

Figure 10 dLCA results for floor assemblies (instantaneous and cumulative) (50 year building reference service life, 1m² of floor area), for years 0 to 190 (x axis). Instantaneous graphs represent radiative forcing in one year (represented on x axis), and cumulative graphs represent the sum of radiative forcing results in each year up to the year represented on the x axis.

4.2 WHOLE-OF-LIFE CLIMATE CHANGE RESULTS EXCLUDING BIOGENIC CARBON STORAGE IN LANDFILL (EN15804:A2)

4.2.1 Static modelling (sLCA)

EN15804:A2 (CEN, 2019, Section 6.3.5.5, Note 3) states that emissions from biogenic carbon degradation in landfill are to be calculated "without time limit" and that any remaining biogenic carbon is treated "as an emission of biogenic CO_2 from the technosphere to nature". Additionally, Section C2.4 states that the so-called -1/+1 kg CO_2-eq approach is to be used, and Section 5.4.3 states that "the effect of temporary carbon storage and delayed emissions, i.e. the discounting of emissions and removals, shall not be included in the calculation of the GWP. The effect of permanent biogenic carbon storage shall also not be included in the calculation of the GWP." In summary, this means that no credit is to be given for storing biogenic carbon when calculating the total climate change result. However, the biogenic carbon content in a construction product (and packaging) shall be separately declared using the unit "kg carbon" (although this is not necessary if the mass of "biogenic carbon containing materials" in the product or packaging is less than 5% of the mass of the product or packaging (CEN, 2019, Section 6.4.4, Section 7.2.5)).

If this approach is used, the sLCA climate change results are shown in Table 11. Not surprisingly, they are all higher than the results presented in Section 4.1.1 (Table 10) (albeit the concrete floor is almost exactly the same), due to the absence of any biogenic carbon storage credits. The concrete roof, timber wall, and timber floor still have a lower calculated climate change impact than their alternatives; however, the results for any pair of assemblies are more similar.

The results show that the contribution of module D relative to the total climate change result is larger for whichever assembly in a pair contains more steel (i.e. steel roof, steel wall, concrete floor). However, it should be noted that the climate change results for the steel-containing assemblies could be quite different if an alternative modelling approach for recycling steel was used. The climate change impact (benefit) of carbonation of concrete is equivalent to 10.3%, 1.9% and 2.6% of the total A1-C4 modules climate change impact (excluding biogenic carbon storage) result for the concrete roof, timber floor, and concrete floor respectively (calculated from data in Appendix E).

Table 11 Climate change impact by greenhouse gas for each assembly excluding biogenic carbon storage (50 year building reference service life)

Case study	Total CO_2	Total CH_4 (CO_2-eq)	Total N_2O (CO_2-eq)	Total GHGs (CO_2-eq)	Module D contribution
Roof (steel)	32.55	6.52	0.26	39.33	-8.21
Roof (concrete)	19.13	6.37	0.16	25.65	-2.85
Wall (timber)	13.31	10.40	0.16	23.86	-0.12
Wall (steel)	22.19	8.87	0.22	31.28	-2.91
Floor (timber)	32.15	16.05	0.30	48.51	-1.40
Floor (concrete)	69.39	6.42	0.42	76.23	-8.96

4.2.2 Static LCA modelling but disaggregated results for distinct time periods

Figure 11 shows the same results as those in Section 4.2.1 but disaggregated to identify the time period in which emissions occur. These results are the same as those in Figure 7 except that there is a biogenic carbon emission at year 51 after the timber and engineered woods go to landfill.

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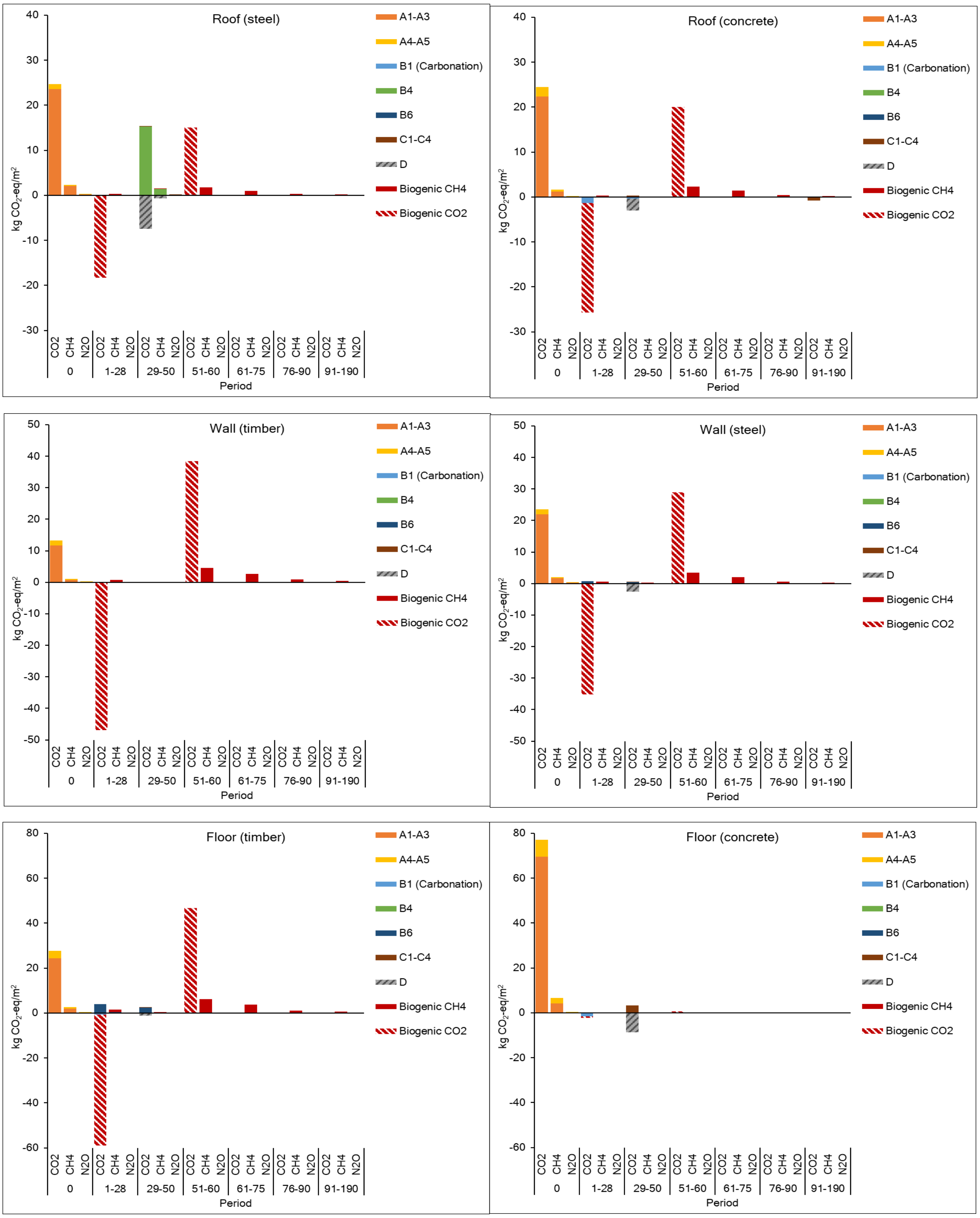

Figure 11 Climate change impact of each assembly, showing greenhouse gas contribution by selected time periods, excluding biogenic carbon storage in landfill (50 year building reference service life)

4.2.3 Dynamic modelling (dLCA)

Dynamic modelling was not undertaken for the assemblies excluding biogenic carbon storage because the results would not represent the time-dependent RF results associated with the different assemblies.

5 SENSITIVITY ANALYSES

Four sensitivity analyses were conducted to investigate the importance of parameters that may vary under different building contexts in New Zealand:

- SA1: 90 year reference service life
- SA2: exposure zones B (SA2.1) and D (SA2.2)
- SA3: Role of location - investigated by modelling different distances, Use energy, and landfill-specific characteristics for assemblies in Auckland (SA3.1) and Christchurch (SA3.2)
- SA4: End-of-life parameters: IPCC values used in landfilling calculations (SA4.1); NZ EPD values (SA4.2); direct release of landfill methane (SA4.3); non-municipal landfill (SA4.4); incineration instead of landfilling at timber end-of-life (including displaced heat from natural gas as per current NZ EPDs[24]) (SA4.5).

SA4.1 and SA4.2 investigate the influence of using IPCC and typical EPD[25] waste wood decay parameters (e.g. DOCf) respectively to the MfE parameters used in the baseline. SA4.3 shows the results assuming 100% direct release of GHGs from the landfill, compared to the baseline which assumed 68% landfill gas recovery. SA4.4 models the situation with a non-municipal landfill (using MfE parameters).

Each sensitivity analysis was undertaken independently by varying one or more parameters in the baseline results (i.e. the results including biogenic carbon storage), and the sLCA results are presented as the net climate change impact value (modules A-D total). The total climate change impact of each scenario is given in Table 12, and the distribution of results for each scenario is plotted per assembly in Figure 12. Full results for the sensitivity analyses are given in Appendix E.

In addition, we considered the sensitivity of the energy simulation results (which contribute to the module B6 impact in some of the assemblies) to several variables, including:

- ESS1: Use of more or less energy for heating/cooling, in comparison with baseline energy use.
- ESS2: Inclusion of linear heat losses at junctions between assemblies.
- ESS3: Inclusion of a floor covering (such as a carpet) over ground floor assemblies.

Results from these energy simulation sensitivity (ESS) analyses are provided in Appendix G.

Table 12 Sensitivity analysis results for each assembly (sLCA results including biogenic carbon)

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[24] Abodo, 2020; Carter Holt Harvey, 2023a,b; Red Stag, 2022a,b; WPMA, 2019.

[25] New Zealand timber EPDs commonly use a 0.001 (0.01%) DOCf (e.g. Abodo, 2020; Carter Holt Harvey, 2023a,b; Red Stag, 2022a,b; WPMA, 2019)

Sensitivity analysis	Wall (timber) (kg CO_2-eq)	Wall (steel) (kg CO_2eq)	Roof (steel) (kg CO_2eq)	Roof (concrete) (kg CO_2eq)	Floor (timber) (kg CO_2eq)	Floor (concrete) (kg CO_2eq)
Baseline	-18.3	-0.4	22.9	3.7	-3.4	75.6
SA 1 (90 year service life)	-34.3	-15.4	35.6	14.4	1.8	75.4
SA 2.1 (exposure zone B)	-18.3	-0.4	10.2	3.7	-3.4	75.6
SA 2.2 (explosure zone D)	-18.3	-0.4	35.6	3.7	-3.4	75.6
SA 3.1 (location Auckland)	-19.3	-1.5	21.9	2.5	5.3	73.0
SA 3.2 (location Christchurch)	-18.9	-1.0	23.0	3.1	-13.3	74.8
SA 4.1 (landfill IPCC values)	-15.4	1.8	24.0	5.2	0.6	75.6
SA 4.2 (NZ EPD values)	-32.6	-11.0	17.4	-3.7	-22.9	75.3
SA 4.3 (release of landfill methane)	-0.7	12.7	29.6	12.7	20.5	75.9
SA 4.4 (non-municipal landfill)	4.5	16.6	31.5	15.4	27.6	76.0
SA 4.5 (incineration at EofL)	-15.5	1.9	24.4	5.4	1.1	75.6

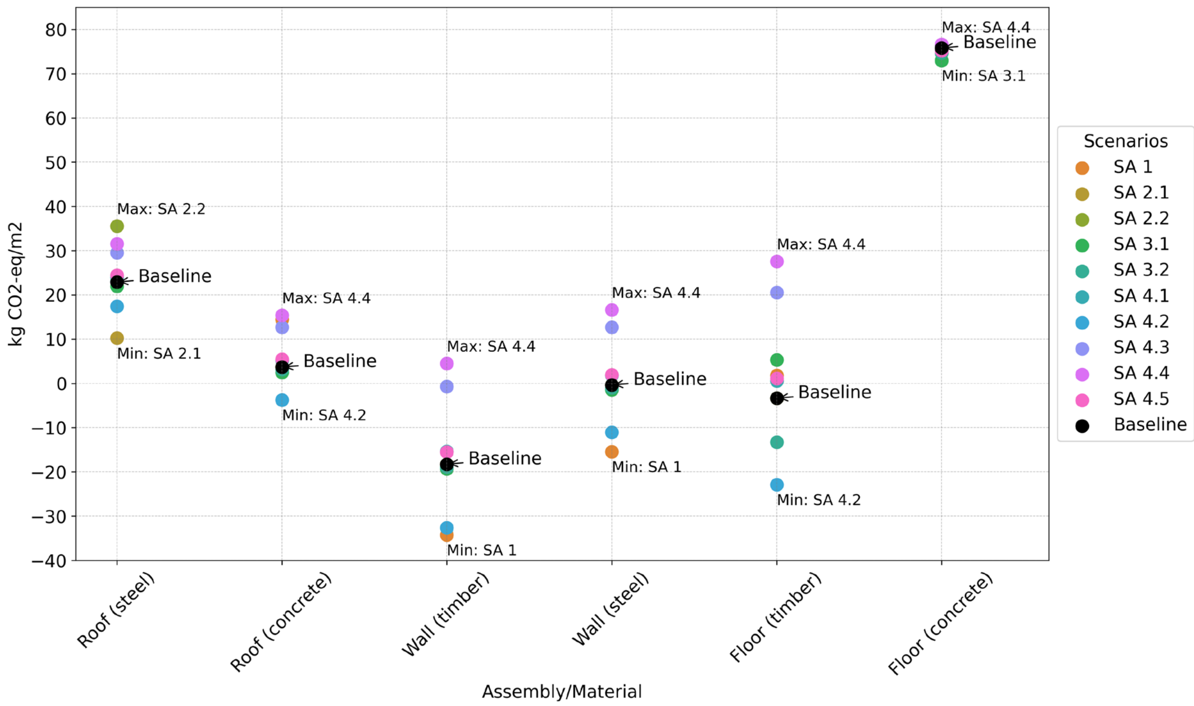

Figure 12 Sensitivity analysis results for each assembly (assessed for sLCA method), highest and lowest sensitivity analysis results individually labelled for each assembly

The concrete slab floor is insensitive to any changes in parameters. For the two wall assemblies and the timber floor - which all contain larger quantities of timber than the concrete floor - the results are highly sensitive to changes in the parameters used in landfill modelling. When the service life is increased to 90 years (SA1), the timber and steel clad walls have the lowest values out of all the assemblies for the same reason: the timber cladding is replaced at year 60, meaning a second forest growth-harvest cycle is modelled, doubling the carbon storage associated with the timber cladding.

Comparing landfill parameters, the results across all the sensitivity analyses and for any scenario are lowest when using the NZ EPD values (SA4.2), and highest when assuming a non-municipal landfill (SA4.4) (i.e. with no landfill gas capture/flaring) (with the exception of SA1 for both the walls and the concrete floor). Thus the results are highly sensitive to both the choice of DOCf value and the choice of landfill gas capture/flaring percentage. For example, the timber wall result drops 14 kg CO_2-eq/m^2 from the baseline (a decrease of 78% relative to the baseline) when the NZ EPD parameters are used, and increases by 23 kg CO_2-eq/m^2 (an increase of 125% relative to the baseline) when the non-municipal landfill parameters are used. The same trend appears with the two roof assemblies, both of which contain significant quantities of timber.

For the incineration scenario where incineration displaces landfilling of timber and engineered wood products (SA4.5), the results are similar to the baseline results for all the assemblies because the carbon dioxide released is offset by the displaced natural gas no longer required for heat generation. However, it is highly unlikely that natural gas will be the displaced heating fuel in 50 years' time. If a low carbon fuel is displaced instead, then incineration at end-of-life will be associated with higher net results for those assemblies containing timber and engineered wood products.

In general, smaller differences can be seen between the locations (Auckland and Christchurch, relative to New Zealand) across all assemblies. These differences are largely determined by the transport distances for timber (i.e. module A4 results), which are both further for Christchurch compared to Auckland or the New Zealand average, landfill characteristics (module C4 results), and Use energy (rmodule B6 results). [Note that for the Use energy, these results are relative to the Use energy for the baseline concrete floor i.e. difference in Use energy between the baseline and the studied scenario.] The only noticeable location-specific sensitivity occurs for the timber floor; that construction is carbon positive in Auckland (5.29 kg CO_2-eq/m^2) and carbon negative (-13.3 kg CO_2-eq/m^2) in Christchurch largely due to differences in Use energy (i.e. relative to the NZ average baseline Use energy).

6 DISCUSSION

6.1 STATIC LCA COMPARISON OF EN15804:A1 WITH EN15804:A2

Both EN15804:A1 and EN15804:A2 use a static approach, and require the use of GWP100 characterisation factors. However, a key difference between the two versions concerns how landfill of materials containing biogenic carbon is modelled (as described in Section 1.2). This is particularly relevant for modelling of timber and engineered wood products, as 100% of these materials are assumed to go to landfill at building end-of-life (as well as most of these materials that are wasted during construction).

Table 13 shows the total calculated climate change impacts for the different assemblies using EN15804:A1 and EN15804:A2.

Table 13 Comparison of assembly climate change results using EN15804:A1 and EN15804:A2, inclusive of biogenic carbon and module D

Method based on:	Assembly (total climate change impact, 50 year building service life, kg CO_2eq /m^2)					
	Roof (steel)	Roof (concrete)	Wall (timber)	Wall (steel)	Floor (timber)	Floor (concrete)
EN15804:A1	22.89	3.67	-18.26	-0.36	-3.36	75.58
EN15804:A2	39.33	25.65	23.86	31.28	48.51	76.23
Difference (A2 – A1)	+16.44	+21.98	+42.12	+31.64	+51.87	+0.65

Table 13 illustrates how the alternative methods for accounting for landfill based on EN15804:A1 and EN15804:A2 produce ***significantly different climate change results*** for all the assessed assemblies except for the concrete floor. This, unsurprisingly, is a function of the amount of timber and/or engineered woods in each assembly (see Table 1). The assemblies whose climate change results are most affected are those containing the most timber and/or engineered woods. The concrete floor has the least timber and therefore its climate change result is only marginally changed. However, the ***ranking order for each pair of assemblies does not change*** when using either EN15804 version i.e. the lower climate change result for each of the roofs, walls and floors is the concrete roof, timber wall and timber floor, respectively when using either EN15804:A1 or EN15804:A2.

Table 14 uses the same results presented in Table 13 but shows the differences between each pair of assemblies when using each of the EN15804 versions. As also noted in Section 4.2.1, the ***climate change results between the two options for each of the wall and floor assemblies become much smaller*** when using EN15804:A2. It is worth noting that this does not take into account, for example, different bracing requirements that may be necessary in walls for a heavy roof construction versus a light roof construction, and the carbon implications of this.

The results in Table 13 and Table 14 use the total climate change results including module D. If a different method was used to represent module D, both the ranking order and the magnitude of difference between alternatives in each pair of assemblies could change (see Section 6.3.3).

Table 14 Comparison of differences in climate change results between pairs of assemblies, based on alternative static LCA methodologies

Method based on:	Assembly (difference in climate change impact, 50 year building service life, kg CO_2eq /m^2)					
	Roof (steel)	Roof (concrete)	Wall (timber)	Wall (steel)	Floor (timber)	Floor (concrete)
EN15804:A1	+19.22	-	-	+17.90	-	+79.19
EN15804:A2	+13.68	-	-	+7.42	-	+27.88

From this assessment, then, it is obvious that a decision to include, or not, biogenic carbon storage in landfill is a significant determinant of the climate change results for the studied assemblies (except for the concrete floor). However, the EN15804:A2 approach to modelling landfill does not allow any carbon credit for biogenic carbon storage in landfill, Instead, it requires modelling any stored carbon as an emission of CO2 (CEN, 2019, Section 6.3.5.5, Note 3).

In reality, international research suggests that timber and engineered woods degrade slowly in landfills (Wang et al., 2011; Ximenes et al., 2019). For example, Ximenes et al. (2019) recommend use of a 1.4% carbon loss for wood in landfills in Australia concluding that, "disposal of wood in Australian landfills results in long-term storage of carbon, with only minimal release of carbon to atmosphere." In this study, using the modelling approach described in Appendix D, the methane and carbon dioxide emissions from the landfilled timber products decrease over time and are very small even 40 years after landfilling (Figure 7). Effectively, for the time periods likely to be relevant for climate change policy and associated applications, landfills may be regarded as providing ongoing storage of any remaining biogenic carbon after accounting for methane and carbon dioxide emissions in the first few decades.

At the same time, provision of a carbon credit for biogenic carbon storage in landfill could have several perverse outcomes such as:

- It might encourage building designers to utilise more timber products than strictly necessary in building elements. From a systems perspective, this would not be desirable because these materials should be used efficiently so that more of those materials are available for use in other applications.
- When recycling of timber products occurs, this is usually represented as a biogenic carbon emission in the analysis (following EN16485, 2014, Figure 1, Figure 2). Thus the A1-C4 climate change results for a timber product that is recycled at EofL will be higher than for landfilling the same product (under EN15804:A1) (when providing a carbon credit for biogenic carbon storage in landfill). This outcome is mitigated (to an extent) by accounting for the displaced **sustainable** forest cultivation in module D, provided that module D is included in the final "total GWP" result. In this case, manufacture of the displaced product (which enters a subsequent system with a "-1" carbon credit) and emissions from combustion of fossil fuels used in cultivation of the displaced forest, are avoided. However, if **unsustainable** forest cultivation is assumed as displaced, then there would also be a significant module D biogenic carbon credit associated with recycling of timber products (provided they were originally sourced from sustainably managed forests). NZ timber product EPDs currently assume sustainable forest cultivation in modules A1-A3 and D.

The first of these outcomes can be addressed by declaring the quantity of biogenic carbon in building elements as a separate indicator in a climate change impact assessment, as required in EN15804:A2 (CEN, 2019, Section 6.4.4).

The second outcome requires further consideration of how to account for recycling of timber products. One possible approach is to attach a "carbon neutral" status to timber that is recycled. The subsequent system using the recycled/reused timber product would then account for it as a carbon credit ("-1") but any subsequent biogenic carbon emissions (e.g. due to incineration of the product) would be assessed as contributing to climate change. Arguably this modelling is more aligned with an approach based on the physical relationships and flows between systems (as supported in both EN15804:A2 (CEN, 2019, Section 6.4.3.1, 6.4.3.2) and ISO 21930 (CEN, 2017, Section 7.2.4, 7.2.5.2)).

Recommendations:

- We recommend that use of the EN15804:A2 approach to modelling landfill emissions from biogenic carbon (CEN, 2019, Section 6.3.5.5, Note 3) in New Zealand should be reconsidered because it does not represent the situation in New Zealand (MfE currently recommends a DOCf of 14%, compared to EN15804:A2 which is, effectively, using a DOCf of 100% and instant decay). As landfilled timber continues to store carbon that was previously CO_2 in the atmosphere for prolonged periods of time, this storage should be included in the calculation of the final climate change result (assuming the timber comes from sustainably managed forests). [Of course, whilst beyond the remit of this study, other environmental impacts are associated with landfills and should be assessed alongside climate change when considering the environmental profile of alternative building elements.]

- Consistent calculation of biogenic carbon storage in landfill requires default values to be provided for key variables that contribute to the calculation of what is emitted and what is stored. These include: the carbon content of different types of wood, accounting for timber reuse/recycling/recovery at end-of-life, and choice of DOCf values and landfill gas recovery percentage in landfill (see also Section 6.3.2 recommendations). In addition, the type of analysis depends upon knowing that the timber comes from a sustainably managed forest (or not), and a modelling decision to use stand- or landscape-level assessment. Default values (based on "real life" practices at construction and demolition building sites) and default modelling choices should be developed and made mandatory for use in New Zealand building climate change impact studies, and provision of a simple tool or look-up tables could provide users with the figures that should be used.
- As already required in EN15804:A2 (CEN, 2019, Section 6.4.4) for building products, there could be merit in separately declaring sequestered carbon at the element or building level, when undertaking climate change impact studies. Appropriately interpreted, this can function to provide indicative ranges for carbon sequestration in different building typologies, which may help in understanding opportunities and, additionally, potential overuse to obtain an additional carbon credit.
- The method used to account for recycling timber products requires further consideration because currently it leads to perverse outcomes relative to landfilling the same products (when providing a carbon credit for biogenic carbon storage in landfills). An alternative approach that treats the biogenic carbon content of recycled timber products as "carbon neutral" may have merit, and should be further considered.

6.2 COMPARISON OF STATIC AND DYNAMIC LCA METHODS

This section summarises some key benefits of the dynamic approach which overcome limitations in a static LCA method. Here, we focus on the dLCA results presented in Section 4.1.3 given our recommendation to reconsider the landfill modelling method for biogenic carbon in EN15804:A2.

6.2.1 Timeframe

The EN15804 methodology is based on a static LCA approach. Using this approach, the climate change impact of a GHG emission over the 100 years[26] following an emission, is accounted in the life cycle module in which the emission occurs. Thus in Figure 6 it is not possible to see when these emissions occur unless one knows the timing of activities in each of the named modules. For example, by looking at the diagram it is not obvious that steel manufacturing emissions occur in years 0 and 30, and that steel recycling credits (part of module D) occur in years 30 and 50. Furthermore, as all emissions are assessed for their contributions to climate change over the 100 years following an emission, there are inconsistent timeframes in this type of analysis e.g. years 0 to 100 for steel manufacture, and years 50-150 for steel recycling at year 50. The representation of timeframes is improved in Figure 7 where emissions are disaggregated into distinct time periods; however, there is still inconsistency in the assessment timeframes.

[26] 100 years because EN15804 requires calculation of climate change impacts using GWP100 impact potentials.

In contrast to the static LCA approach, a dynamic LCA approach models how emissions of GHGs (and sequestration of atmospheric CO_2) contribute to changes in radiative forcing along timelines. Therefore, it has the potential to be more informative for policy setting, for example, as it enables an understanding of how GHG emissions or removals occurring at a specified point in time contribute to radiative forcing in any particular year (e.g. 2030, 2050) or over a specified time period (e.g. 2024 to 2050). Additionally, it provides insight into the likely longer-term contribution to radiative forcing as a result of strategies, policies or options implemented in the shorter term.

6.2.2 Achievement of net zero carbon?

A static approach (based on EN15804:A1) can provide an indication whether a construction achieves net zero carbon (which includes biogenic carbon and module D). This is when the climate change impact from GHG emissions is cancelled out by biogenic carbon storage and potential benefits from recycling or reuse of materials. An example is the sLCA results for the steel wall assembly in Figure 6 in which the dot shows that the net result is very close to zero. However, this static approach provides no indication when the construction in the assembly achieves "net zero".

Using a dynamic LCA method, however, net zero can be interpreted as being achieved when the cumulative radiative forcing line reaches zero. This means that there is no remaining net radiative forcing impact caused by construction, use and end-of-life of the assembly. Figure 9 shows the results for the steel wall assembly but using a dynamic LCA method. Here, we can also see that the construction achieves "net zero carbon", in this case, a negative cumulative radiative forcing value but that this is not achieved until about 170 years after construction. In contrast, the timber wall achieves net zero carbon approximately 25 years after construction (almost 150 years before the steel wall assembly). Thus, dynamic LCA can reveal how quickly assemblies can achieve "net zero carbon" in terms of no further contribution to radiative forcing (which is ultimately what is driving climate change). This is particularly important with a legislated net zero goal for 2050.

6.2.3 Additional insights

For the **roof assemblies**, Figure 8 summarises the instantaneous (graph a) and cumulative (graph b) radiative forcing (RF) due to carbon sequestration and GHG emissions. These graphs show:

1. *The accumulating benefit of carbon dioxide sequestration in sustainably managed forestry.* Both roof options include timber; the growth of new forest, which replaces harvested forest, occurs from years 1 to 28. In both roof options, the highest contribution to RF is in year 0, when all materials are manufactured and the next forest growth cycle has not started. Over the next 28 years, the instantaneous RF decreases year on year due to the atmospheric CO_2 sequestration in the growing forest. For the concrete roof, this yearly sequestration negates the RF impact of manufacture by the end of the growth cycle (year 28).
2. *The influence of service life.* In the steel roof option, there is a replacement of the steel cladding in year 30 whereas there is no replacement of the concrete tiles (as they are modelled as being more resilient to wind-driven salts). The manufacture of new steel cladding, displaced by the recycling of the replaced steel cladding, results in the increase in RF observed at this time (Figure 8a). The net effect is that there is still an instantaneous RF contribution between year 30 and year 50 for the steel roof. By contrast, there is no replacement modelled for the concrete tiles, meaning that the construction has a slight negative instantaneous RF between year 30 and year 50 (Figure 8a).
3. *The benefit of diverting waste from landfill to displace the use of new materials.* In year 50, at the building end-of-life, the steel roof shows a decrease in instantaneous RF due to recycling of the waste steel cladding (modelled as manufacture in an EAF minus manufacture in a blast furnace). In contrast, the concrete tile roof has a smaller RF reduction, due to more limited benefits associated with diversion of waste from landfill.

4. *The concrete and steel roof assemblies have fairly similar cumulative RFs up to year 25* (as shown by the different areas under the curves in the cumulative RF diagrams) but then diverge as the steel roof's cumulative RF continues to increase but the concrete roof's cumulative RF levels off (mainly due to the benefits of continued biogenic carbon stored in the landfilled timber).

For the **wall assemblies**, the shape of the instantaneous graph for the steel wall (Figure 9a) is similar to the steel roof (Figure 8a) except there is no replacement at year 30 and therefore no increase in RF at that point associated with the replaced steel manufacture. For both the walls, biogenic carbon stored in the timber materials in landfill means that the cumulative RF decreases below "net zero" before year 25 for the timber wall and year 174 for the steel wall, and continues to decrease over the modelled time period (Figure 9b).

For the **floor assemblies**, the shape of the instantaneous graph for the timber floor (Figure 10a) is similar to the timber wall (Figure 9a). For the concrete floor, the instantaneous curve decreases from year 0 to year 50 due to decaying methane emissions (emitted during manufacture of various materials), and carbonation; it then drops at year 50 mainly due to recycling of the reinforcing steel in the concrete (Figure 10a). The cumulative RF graphs for the timber and concrete floors (Figure 10b) are markedly different from each other (and also note the different scale compared with the roof and wall graphs). The timber floor is near to "net zero" RF from year 0 due to its large timber content; however, the concrete floor has a continuously increasing RF over the modelled time period mainly due to the CO_2 emissions from concrete and reinforcing steel manufacture that were released at year 0.

In Section 4.1, as well as presenting the sLCA results using the conventional aggregated approach (Section 4.1.1), we also present the sLCA results disaggregated into different time periods according to when the GHG emissions occur or carbon storage begins (Section 4.1.2). This shows that most emissions occur in years 0 to 28; smaller emission pulses occur in subsequent years and are associated with landfill emissions (for timber), differences in Use energy, and/or displaced materials due to recycling at end-of-life. An exception is the steel roof where there are substantial GHG emissions associated with replacement of the steel cladding and avoided GHG emissions associated with recycling the original steel cladding. Given the urgent need to mitigate climate change over the next few years (and definitely within 28 years i.e. by 2050), this suggests that the choice of materials with lower module A1-A3 climate change impact values for new roof, wall and floor assemblies has the most significant potential to contribute to climate change mitigation in the near future. Although the same conclusion can be reached by considering the aggregated sLCA results in Section 4.1.1 and the timing of emissions occurring in the different modules, the disaggregated results in Section 4.1.2 provide a clearer communication of this insight. The dynamic LCA results in Section 4.1.3 take this analysis further, showing the RF contribution over the modelled timeframe of 190 years. Perhaps the most useful graphs are the cumulative RF graphs which show how the RF contributions of the different assemblies accumulate over time. This facilitates an understanding of the net RF contributions of the different assemblies at points in time that may be aligned with time-defined climate change targets set in policymaking.

6.2.4 Risk of wrong conclusions when normalising

A further example is provided here to illustrate the additional insights gained from use of dLCA. For the building reference service life, the baseline results were modelled over 50 years of use. A sensitivity analysis was undertaken where the service life was extended to 90 years (SA1 in Figure 12, Section 5), and included at least one replacement of roof and wall products (Section 3.3.2.2) – as well as additional Use energy for the steel wall and timber floor.

Figure 13 shows the sLCA climate change results if the functional unit is standardised to 1 m^2·year for all the assemblies, for both the 50 and 90 year building reference service lives. For the concrete floor, presented this way, the 90 year building reference service life appears to have a climate change impact that is almost half the climate change impact for the 50 year building reference service life (not surprisingly, as the floor is assumed not to be replaced during the 90 year period). However, interestingly, the dLCA result for the concrete floor (Figure 10b) shows the opposite result: the cumulative RF is larger at year 90 than year 50, indicating the RF of the assembly will continue to increase over time, irrespective of the reference service life. This illustrates the additional perspective provided by use of dLCA: there is no "net zero" date for this construction, as long-lived GHGs (carbon dioxide in this case) that are not offset by any removals (e.g. carbon sequestration by forests for timber products) continue to contribute to RF for many years into the future.

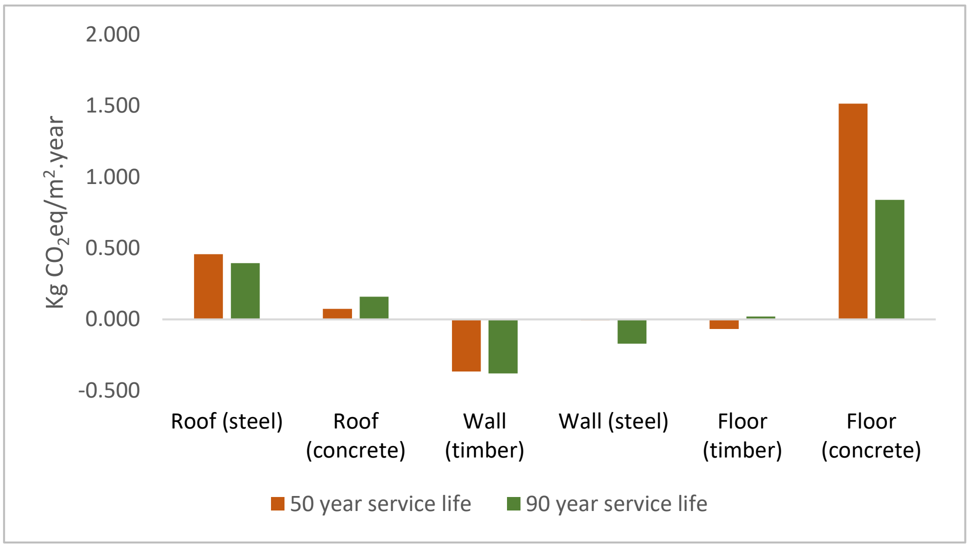

Figure 13 Climate change impact of assemblies for 50 and 90 year building reference service life measured in kg CO_2eq/m^2.year.

Recommendations: if the timing of GHG emissions and biogenic carbon storage is considered relevant in a decision situation, then the cumulative dLCA results should be presented alongside the sLCA results. At a minimum, the sLCA results can be shown disaggregated along relevant timelines (e.g. pre- and post-2050). For building LCAs carried out in accordance with MBIE's embodied carbon technical methodology (MBIE, 2022b), a sLCA approach is likely to be adequate; for government policymaking, use of both sLCA and dLCA is likely to be appropriate.

6.3 OTHER LEARNINGS FOR CONSIDERATION

6.3.1 Modelling of forestry

In the baseline, biogenic carbon storage in timber was modelled in year 0 to year 28 for the dLCA results presented in Section 4.1.3. An alternative approach is to model the biogenic carbon storage in the 28 years up to harvest and use in year 0 (as explained in Section 3.2.1) i.e. from year -28 to year 0. As an example, the instantaneous and cumulative RFs calculated using dLCA for these two approaches is shown in Figure 14 for the timber floor. Considering the cumulative RF results, it can be seen that, using the year -28 to year 0 timing (Figure 14b), the timber floor is "zero carbon", and remains below "zero carbon" for all the modelled years. Using the year 0 to year 28 timing, the timber floor contributes to RF at various points up to year 118. Thus, the choice of modelling approach for forestry leads to quite different dLCA results. However, the sLCA results would not change because they are calculated independently of the time period when biogenic carbon emissions and storage take place.

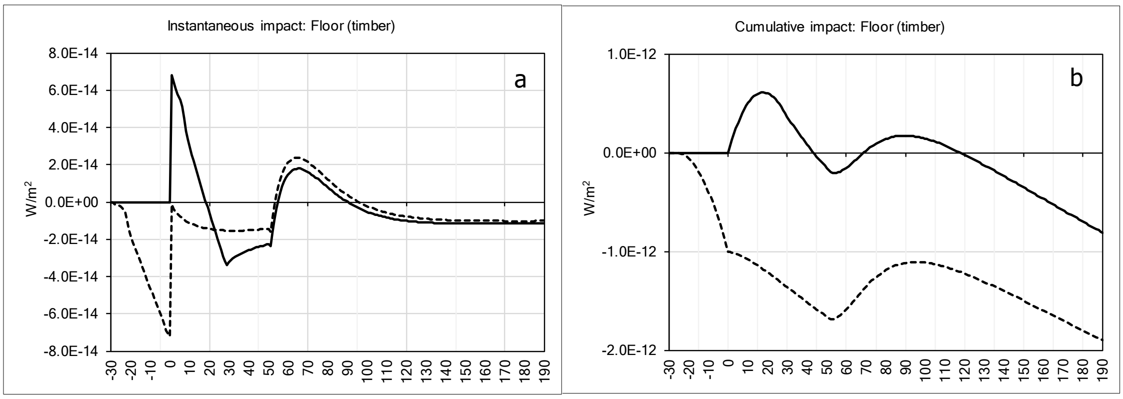

Figure 14 dLCA results for timber floor showing radiative forcing when biogenic carbon storage is modelled from year 0 (solid line), and from year -28 (dotted line)

Recommendations: for future dLCA studies, a consistent modelling method for forestry needs to be adopted. Following Hoxha et al. (2020), we recommend stand-level modelling of forestry from year 0 to 28 because it is more aligned with sustainable practices where there is an emphasis upon replacement of any harvested forest. Note that this is not a consideration when using an sLCA approach (unless forestry practices have changed in the recent past).

6.3.2 Modelling of methane emissions from landfilling timber

The static LCA results show that between 22 and 25% of the biogenic carbon credit for timber is offset by methane emissions in landfill across the assemblies. This proportion changes considerably when different assumptions are made about landfill emissions (Section 5). The timber wall and floor assemblies contain the largest quantities of timber, and the sensitivity analyses shows that different assumptions about methane generation from landfilled timber give results ranging from -32 to +5 kg CO_2eq/m^2 for the timber wall (compared to -18 kg CO_2eq/m^2 for the baseline), and -23 to +28 kg CO_2eq/m^2 for the timber floor (compared to -3 kg CO_2eq/m^2 for the baseline).

Recommendations: default values for parameters used to calculate methane emissions (e.g. in the annual MfE "Measuring emissions: a guide for organisations" publication), as well as other modelling choices for timber and engineered woods going to landfill, should be mandatory for use in New Zealand building climate change impact studies. Provision of a simple tool or look-up tables could provide users with the figures that should be used.

6.3.3 Modelling the future

Buildings are usually long-lived assets lasting many decades. During this long service life, materials in buildings may be replaced for technical or aesthetic reasons, and the materials that are removed will be disposed. The service lives for some materials may be shorter than the reference service life of the building, requiring them to be replaced. The service lives of some materials, such as steel claddings, may be impacted by exposure zones.

Typically (as with this study), modelling of future processes or activities is based on current data. Thus, end-of-life routes for disposed materials are based on current practice rather than future practice, in which we would hope that there is much more diversion from landfill. Despite this, modelling is normally conservative so future manufacturing processes are modelled using current manufacturing data to represent them.

In addition, module D can be very dependent on the underlying basis for the calculation. Steel is an example of a material that is sensitive to this, due to the high rate of recycling already attained and the significant climate change impact of current primary steel manufacture. Figure 6 shows that the assemblies containing most steel (steel roof, steel wall, and concrete floor) have potentially large module D values when steel recycling is modelled as displaced blast furnace steel manufacture (see Section 3.3.4). However, it is not unreasonable to expect that primary steel manufacture will have significantly lower emissions in 2050 as the steel industry decarbonises, and ultimately achieves "net zero" emissions. In such a situation, the module D benefit of recycling steel by substituting for primary steel production, will be zero or close to zero. Of course, other environmental impacts should also be assessed alongside climate change in this comparison in order to avoid burden-shifting.

The basis on which module D is calculated, and the use of current process data to represent future processes (up to 50 years in the future, by which time they should be "net zero" carbon or have significantly reduced climate change impacts[27]) can lead to an inflated module D benefit that is unlikely to be realised at the time this recycling will actually occur. Similarly, given the increasing focus on circularity, it is not unreasonable to expect that both landfill rates, and GHG emissions from landfills, should decline in the future.

Recommendations: standardisation is required for the methods used to account for future activities, including future manufacturing, the proportion of materials diverted from landfill, and the service life of materials. This could be in the form of look-up tables (for example), so those calculating building climate change impacts use the same defaults. This will help to ensure that different assumptions are not used across building climate change impact studies without good reason, and they can be updated as our understanding of what may happen in the future changes.

6.3.4 Location (exposure zones, Use energy)

The baseline results used average NZ transportation distances, and default parameters for energy simulations provided in Appendix A. The sensitivity analyses SA3.1 and 3.2 (Section 5) modelled Auckland and Christchurch-specific dwelling locations using location-specific estimates of transportation distances (Table 2) and accounting for use of different landfills and varying energy demand for heating and cooling in the Use phase (Section 3.3.2.3). The results in Figure 12 show that the different locations make very little difference to the results with one exception: the timber floor in Christchurch where the sLCA climate change result ranges from +5.3 kg CO_2eq/m^2 in Auckland to -13.3 kg CO_2eq/m^2 in Christchurch (compared with a baseline of -3.4 kg CO_2eq/m^2, which represents the reduced energy requirement for the baseline concrete floor compared with the timber floor). This difference is due to the differing heating/cooling energy requirements in the use phase for the timber and concrete floors (as discussed in Section 5).

[27] For example, Concrete NZ intends to produce net zero concrete by 2050 (Concrete NZ, 2023), and the NZ government recently announced plans to partner with NZ Steel to build an electric arc furnace which would reduce NZ's total annual emissions by 1% (NZ Government, 2023).

For the steel roof, the exposure zone is more important. For this construction, the sensitivity analysis (Section 5) showed that the total climate change result varied from 10.2 CO_2eq/m^2 to 35.6 CO_2eq/m^2 (compared with the baseline of 22.9 kg CO_2eq/m^2) for low (inland) and high (coastal) exposure zones, due to more or less frequent replacement rates for the steel cladding (and noting the approach to modelling future processes, set out in Section 6.3.3).

Recommendations:

- LCA requires that alternatives are evaluated based on the same functional unit. Thus, in studies that focus on specific assemblies, consideration of different heating/cooling requirements should be included due to differences in construction R values and/or thermal mass. There should be a standardised approach to energy simulation which reflects the diversity of ways that people live in their houses and provides consistency with respect to estimating energy use.
- At a building level, the connections between embodied carbon and operational carbon are important, and should be considered across the MBIE embodied and operational carbon frameworks.
- Standardised material service lives for use in building LCAs should be mandated, and include consideration of different exposure zones.

7 CONCLUSIONS

This study was undertaken to develop a better understanding of assessment methods for quantifying the climate change impact of alternative NZ residential roof, wall and floor assemblies. The aim was to provide recommendations about a preferred method for calculating climate change impacts that support decision-making for NZ residential dwellings. Potential application areas include MBIE's Building for Climate Change programme, the General Programme Requirements for EPD Australasia, and climate change impact calculation tools such as CO_2RE and LCAQuick produced by the Building Research Association of NZ (BRANZ).

The case studies showed that a life cycle perspective is important when considering the climate change impact of NZ residential dwellings because a majority of the climate change impact for roof, wall and floor assemblies is embodied in the upstream production of materials used in these assemblies, and in ongoing biogenic carbon storage in timber specifically. Recycling of end-of-life steel is also significant in some assemblies - although the magnitude of its contribution depends upon the chosen modelling approach.

The timing of emissions and carbon sequestration is an important consideration for long-lived products such as buildings. Future emissions may be "locked in" at the design stage and so should be considered as early as possible in the design process. For example, sustainably sourced timber stores biogenic carbon but may also represent a source of future GHG emissions at end-of-life e.g. methane emissions in landfill or CO_2 released during incineration of the timber. On the other hand, GHG emission reduction and carbon sequestration in forests in the near term may be regarded as important in order to "buy time" for development of new carbon mitigation technologies. At the same time, overuse and unnecessary use of timber in building designs should be avoided, as this has the potential to place significant pressure on supply chains. Both the dLCA method, and the disaggregated sLCA diagrams presented in this report, facilitate improved understanding of the timing of GHG emissions and carbon sequestration.

In order to calculate the climate change impact of alternative assemblies, various methodological issues must be addressed. In this research, we identified that choice of methods for assessing recycling of materials at end-of-life, biogenic carbon stored in timber (sequestered during forestry cultivation and permanently stored in landfill), and methane emissions in landfill, are particularly significant determinants of the final climate change results. For consistency, specific methods (and parameters where relevant) should be agreed and mandated for use in building climate change impact calculations to avoid arbitrary differences between study results, prioritising:

- Construction product characteristics: standardised product service lives, and data that account for different exposure zones (where relevant). These data are already available in BRANZ's Building materials replacement (module B4) datasheet[28].
- Future activities: proportions of different materials diverted from landfill, and specified technologies for future manufacturing activities (used in module D to model displaced activities due to recycling). Data on some materials diverted from landfill are available in BRANZ's Building end-of-life (module C1) datasheet[28]. For future manufacturing activities, this requires further consideration.
- Heating/cooling requirements in Use phase (related to differences in construction R values and/or thermal mass): a standardised approach to energy simulation. Further research is required to define the most suitable approach. The energy modelling method outlined in this report can provide a good basis for this.
- Forestry: assessment period for forest cultivation, and specification of sustainable or unsustainable forestry for both sourcing of timber products and displaced forestry cultivation (module D). For forest cultivation (module A1), we recommend use of stand-level assessment with forest cultivation beginning at year 0 for sustainably managed forests.
- Biogenic carbon: the carbon content of different types of wood, and DOCf values and landfill gas recovery percentages to use for landfill modelling. For DOCf and landfill gas recovery, we recommend that values should be aligned with the Ministry for the Environment GHG accounting guidelines.

Furthermore, we recommend that timber products reaching landfill in New Zealand should be modelled to include ongoing biogenic carbon storage of the remaining carbon after degradation and release of methane and carbon dioxide. For consistency, recycled timber products could also be modelled as associated with ongoing biogenic carbon storage - but an appropriate accounting method requires further consideration.

Dynamic LCA provides insights that are obscured by static LCA, such as how alternatives can impact on radiative forcing in any specific year or over a defined period e.g. from now to 2050. This makes it a useful additional tool for policy or strategy development. Static LCA is the approach enshrined in the ISO and EN standards on building sustainability, and should be sufficient for the purposes of setting building embodied carbon thresholds, and calculating building embodied carbon footprints. However, there may be merit in disaggregating calculated impacts into emissions today (year 0), emissions to 2050 (e.g. year 1 – 25 as an approximation), emissions for the rest of the building reference service life (e.g. year 26 – 50), and emissions beyond the building reference service life (e.g. year 51 onwards). This approach could facilitate recognition of earlier GHG savings over later GHG savings, that may or may not occur in the future.

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[28] Available at www.branz.co.nz/environment-zero-carbon-research/framework/data/.

The insights from this study can be used to inform further development of data, information and/or tools to support calculation of more consistent building carbon footprints in the construction sector. In addition, efforts should also be made to assess the other environmental impacts associated with this sector in order to provide more comprehensive environmental profiles of both buildings and construction products.

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APPENDIX A ENERGY SIMULATION METHOD

A simulation of operational heating and cooling energy is required where there are differences in construction R value achieved by each of the two wall, roof and floor assemblies (in comparison with each other) and/or where there is likely to be a difference due to thermal mass.

This was necessary for the two floor assemblies, due to differences in construction R values between the concrete floor slab and suspended timber floor option, but also because of the thermal mass of the concrete. It was also necessary for the two external wall options, due to thermal mass of the timber frame.

BRANZ used a house energy simulation model from its existing library, with the following characteristics:

- 4 bedroom single story house with a pitched roof.
- Internal floor area of ~156 m^2, or ~194 m^2 including the garage (garage not included in the thermal envelope).
- A window/wall ratio (WWR) of 20%.
- Two bathrooms, and both a lounge and an open living/kitchen area.

Overall this house is fairly typical of new houses being built today, which according to 2020 data (Jaques and Sullivan, 2023) have an average WWR of ~22%, ~3.4 - 4.4 bedrooms, and a floor area ~150 m^2. As a single storey house it is more representative of typical builds in regions such as Christchurch or Hamilton, while new houses in Auckland are more likely to be two-storey.

There are multiple parameters that can affect simulated heating and cooling energy. To cover these, the approach was to define a Low, Baseline and High energy use scenario, each of which are set out in Table 16. Parameters in the Low scenario are designed to produce a lower energy demand (and therefore electricity use) requirement, whereas those in the High scenario, produce a higher energy demand (and therefore electricity use).

Internal gains schedules were based on adjusted Household Energy End-use Project (HEEP[29]) data estimates for reasonable improvements in appliance energy efficiency that could be derived from publicly available information, as described in previous BRANZ work (Sullivan, Jaques, and Dowdell, 2021). This corresponds to 4.26 W/m^2 for the Baseline scenario, 3.98 W/m^2 for our Low heating use scenario, and 3.33 W/m^2 for the High heating use scenario.

Natural ventilation was modelled using EnergyPlus's Airflow Network (AFN), with openable windows assumed to have a maximum equivalent opening area of ~20%[30]. Baseline levels of infiltration and ventilation were assumed to be 3 ACH in the roofspace and 11.5 ACH in the subfloor (McNeil et al. 2015; Rupp and McNeil, 2018).To account for the thermal mass of the framing, the Combined Thermal Properties method was used (Mahattanatawe, Puvanant, and Mongkolsawat 2006; Gomes, de Souza, and Tribess 2013; Purdy and Beausoleil-Morrison, 2001). This involves taking the volumetric average of the mass properties of the framing and insulation to estimate the overall mass of the bridged layer.

[29] https://www.branz.co.nz/environment-zero-carbon-research/heep2/heep/

[30] Using the Discharge coefficient calculator here: https://www.gov.uk/government/publications/classvent-and-classcool-school-ventilation-design-tool

Suggested parameters were tested with the Project Stakeholder Group, and some updates made based on comments received[31].

The process of undertaking the energy simulation was as follows:

- Each construction was inserted into a house model (for example, the concrete slab floor, followed by suspended timber floor), keeping all other assemblies constant. Note this means that with the wall modelling *only* the external wall construction is changed. In reality, a steel framed house would also have steel framed internal walls, however the modelling here kept the internal walls as timber in order to keep the comparison focused.
- The parameters set out in the table below were run for each of New Zealand's six climate zones, to obtain electricity supply figures due to heating and cooling. This generated 18 electricity supply figures for each construction, being three scenarios in six climate zones.
- The total electricity supply figures were divided by the area of the assemblies being modelled, to derive a normalised electricity supply figures (in kWh low voltage electricity /m^2).
- A simple average of normalised electricity supply was calculated across the six climate zones for the Baseline scenario. Simple average electricity supply was also calculated for each of the Low and High scenarios.
- The average, normalised Baseline electricity supply for the construction with the lower figure was subtracted from the average, normalised Baseline electricity supply for the construction with the higher figure. Thus, the difference in average, normalised Baseline electricity supply is attributed to the construction requiring higher heating/cooling energy only.

Note on linear thermal transmittance through junctions

Different assemblies may have different heat losses due to differences in linear thermal transmittance.

This additional heat loss through linear thermal bridges (e.g. corners, wall junctions etc.) may be accounted for calculating the ψ-values for the additional heat loss through the junctions following ISO 10211, and applying this as an adjustment to the R-value of the wall construction (Morrison Hershfield, 2021). The challenge for this project is that while existing New Zealand work provides such details for timber framing (Quinn, 2022), the same is not true for light steel framing.

The key issue is if the linear thermal transmittances for steel framing are significantly different to those of timber framing. If they are not, then inclusion or exclusion does not meaningfully affect the comparison of those two assemblies in this study.

To conserve resources, the approach was to:

1. Compare the timber and steel framed walls without the linear thermal transmittances included.
2. From this, carry out sensitivity checks to see whether or not it is likely that our conclusions would be changed by any differences in linear thermal transmittances between the assemblies. For example, the steel framed wall model could be run having linear transmittances 50% higher or lower than those of the timber framed wall. In the event it is found that conclusions do not meaningfully change, then we would know that there is no need to model the steel framing details precisely.

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[31] The Project Team would like to thank MBIE for comments received on the energy simulation approach.

Junction ψ-values were taken from the PHINZ high performance details handbook (Quinn, 2022) using the closest match. The exception was the wall/slab junction, as the ISO 10211 method effectively assigns the slab edge to the junction, which would result in the slab edge losses being double-counted if applied to an EnergyPlus model. Hence, the wall/slab junction was calculated using THERM with the foundation heat loss calculated in line with the way it would be set up in Kiva in EnergyPlus. Similarly, the cladding and ventilated cavity are included as they are in the model, derated by 45% following New Zealand practice (NZS 4214). The resulting ψ-value is thus mostly adding the effect of the 2D bottom plate/slab interface, as well as the effect of a gap at the top of the edge insulation for a cladding drip edge. ψ = 0.144 for the exposed slab junction, reduced to ψ-0.089 with carpet[32].

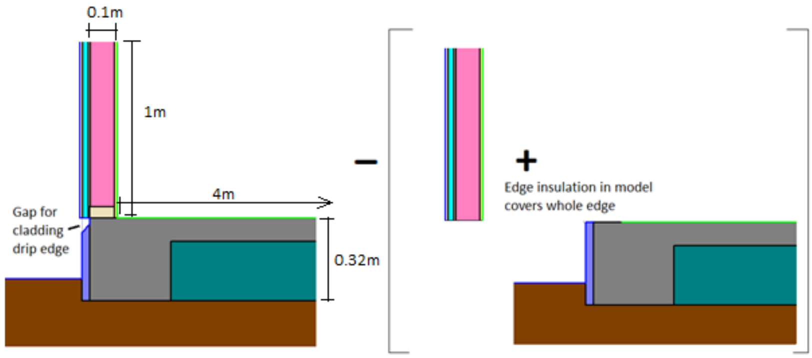

Figure 15 Edge insulation junction calculation. The heat loss of the individual wall and slab elements is subtracted from that of the complete junction to compute the ψ-value – the additional heat loss associated with that junction not already accounted for in the model

Table 15 ψ-values used for junctions

External corner	0.119
Internal corner	0.176
External/internal wall Intersection	0.156
Window-header	0.208
Window-sill	0.106
Window-jamb	0.172
Roof/wall junction	0.095
Floor (timber)	0.075
Floor (timber) + carpet	0.071
Slab with edge ins.	0.144
Slab with edge ins. + carpet	0.089

[32] This difference is exacerbated by the fact that adding carpet to the slab construction means that the Kiva slab foundation height, and thus slab edge, is also increased by 0.02m in the model which then needs to be accounted for in the ψ-value calculation.

A note about cooling energy

Cooling energy was included in the study. Up to 25°C, it was assumed that occupants open windows to achieve cooling. At 25°C, windows are closed and mechanical cooling commences, assuming a house has a heat pump with a COP of 3.75 for all scenarios (a typical value based on EECA observations).

In reality, people without a heat pump do not have the ability to mechanically cool, unless they have additional equipment e.g. portable air conditioner, fans. Most of the time, people open their windows to achieve cooling and, if this is insufficient, experience higher temperatures.

Table 16 Summary of parameters

	Low	Baseline	High
Heater	Heat pump (Coefficient of Performance (COP 3.75)	Basic electric heaters (COP 1)	Basic electric heaters (COP 1)
Cooling	Heat pump with COP 3.75	Heat pump with COP 3.75	Heat pump with COP 3.75
Heat recovery	On (assume 70%)	None	None
Baseline fresh air provision	0.35 ACH[33] to meet minimum NZS4303 requirements	0.35 ACH	0.35 ACH
Curtains	Used	Used	No curtains
Schedules	Morning/evening occupancy and conditioning. No conditioning in bedrooms overnight.	Spaces conditioned during occupied hours – daytime (7am-11pm) for living spaces, day and night for bedrooms.	Whole building conditioned 24/7 per PHPP (Passive House Planning Package)
Heating setpoint	18°C	18°C	22°C (to reflect needs of possible elderly occupants)
Cooling setpoint	25°C	25°C	25°C
Natural Ventilation	Windows gradually open between 22-24°C	Windows gradually open between 22-24°C	Windows gradually open between 22-24°C
Water table depth	10m	6m	2m
Soil properties	Conductivity = 1.2W/mK; heat capacity = 1.2×10^6 J/K as per old BRANZ measurements and NZS4214 clay soil	Conductivity = 2.0W/mK; heat capacity = 2.0×10^6 J/K as per H1/VM1	Conductivity = 2.0W/mK; heat capacity = 2.0×10^6 J/K as per H1/VM1
Occupancy	Full (5 people)	Full (5 people)	3 people (average house = 2.6)
Construction derating (reducing insulation performance to reflect real buildings performing less well than designed)	Good as-built fabric performance similar to PassiveHaus (Walls U-value +0.03, Roof U+0.04)	Typical as-built fabric performance observed in low energy homes (Walls U+0.07, Roof U+0.1)	Typical as-built fabric performance observed in low energy homes (Walls U+0.07, Roof U+0.1)

[33] Air changes per hour.

APPENDIX B ASSEMBLIES

This section contains a detailed listing of the following, for each of the assemblies:

- The construction or assembly.
- The material description.
- The quantity of material in 1 m^2 of the construction, and relevant units e.g. kg, m^2.
- The global warming potential (fossil fuels) or GWPF per unit of each material, used in the study.
- The global warming potential (biogenic) or GWPB per unit of each material, used in the study.

Quantities are based on calculation and presented to two decimal places, which should not be inferred as a level of accuracy.

B1 Truss roof

Table 17 Truss roof with profiled steel cladding

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
ProfiledSteelCladding	Roof Trusses	kg	6.16	0.14	-1.64
ProfiledSteelCladding	Galvanised Nailplates to trusses say 4/1.2 m	kg	0.17	1.00	0.00
ProfiledSteelCladding	Galvanised Wire Dogs	kg	0.01	1.00	0.00
ProfiledSteelCladding	L/L Galv strip brace & tensioner(30m)	kg	0.02	1.00	0.00
ProfiledSteelCladding	Galv Multigrips say	kg	0.00	1.00	0.00
ProfiledSteelCladding	70x 35 Rad Mch UT MG RL	kg	2.08	0.14	-1.64
ProfiledSteelCladding	70 x 45 Rad MSG8 H1.2 MG KD RL wet	kg	1.54	0.14	-1.64
ProfiledSteelCladding	Purlin screws - box of 250	kg	0.01	1.00	0.00
ProfiledSteelCladding	R7.0 Fibre Glass Batts (2.6 m2)	kg	4.33	0.96	0.00
ProfiledSteelCladding	Thermakraft Watergate plus 295 to roof	kg	0.13	2.57	0.00
ProfiledSteelCladding	Galv wire netting 75 (100 m2 roll)	kg	0.22	1.00	0.00
ProfiledSteelCladding	13 mm Gibraltar Board	kg	9.78	0.27	-0.09
ProfiledSteelCladding	100 x 4.0 JH BS 25 kg	kg	0.05	1.00	0.00
ProfiledSteelCladding	75 x 3.15 JH BS 25 kg	kg	0.03	1.00	0.00
ProfiledSteelCladding	40 x 2.8 Clts Galvanised 5 kg	kg	0.01	1.00	0.00
ProfiledSteelCladding	75 x 14 Batten screws (25)	kg	0.00	1.00	0.00
ProfiledSteelCladding	Misc fixings allowance timber roof constrn	kg	0.01	1.00	0.00
ProfiledSteelCladding	0.40 STEEL TO CORRUGATED ROOFING	kg	3.98	4.11	0.00
ProfiledSteelCladding	Ceilings	m2	1.00	0.37	0.00
ProfiledSteelCladding	Interior primer	m2	1.00	0.19	0.00

Table 18 Truss roof with concrete tile cladding

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
ConcreteTile	Roof Trusses	kg	6.16	0.14	-1.64
ConcreteTile	Galvanised Nailplates to trusses say 4/1.2 m	kg	0.03	1.00	0.00
ConcreteTile	Galvanised Wire Dogs	kg	0.01	1.00	0.00
ConcreteTile	L/L Galv strip brace & tensioner(30m)	kg	0.02	1.00	0.00
ConcreteTile	Galv Multigrips say	kg	0.00	1.00	0.00
ConcreteTile	70x 35 Rad Mch UT MG RL	kg	2.08	0.14	-1.64
ConcreteTile	50 x 50 Rad MSG8 H1.2 MG KD RL wet	kg	4.04	0.14	-1.64
ConcreteTile	90 x 45 Rad MSG8 H1.2 MG KD RL	kg	0.94	0.14	-1.64
ConcreteTile	70 x 45 Rad MSG8 H1.2 MG KD RL	kg	0.05	0.14	-1.64
ConcreteTile	R7.0 Fibre Glass Batts (2.6 m2)	kg	4.33	0.96	0.00
ConcreteTile	Thermakraft Watergate plus 295 to roof	kg	0.13	2.57	0.00
ConcreteTile	Galv wire netting 75 (100 m2 roll)	kg	0.22	1.00	0.00
ConcreteTile	13 mm Gibraltar Board	kg	9.78	0.27	-0.09
ConcreteTile	100 x 4.0 JH BS 25 kg	kg	0.05	1.00	0.00
ConcreteTile	75 x 3.15 JH BS 25 kg	kg	0.03	1.00	0.00
ConcreteTile	40 x 2.8 Clts Galvanised 5 kg	kg	0.01	1.00	0.00
ConcreteTile	75 x 14 Batten screws (25)	kg	0.00	1.00	0.00
ConcreteTile	Misc fixings allowance timber roof constrn	kg	0.01	1.00	0.00
ConcreteTile	Concrete tiles, underlay & battens	kg	52.53	0.26	0.00
ConcreteTile	Ceilings	m2	1.00	0.37	0.00
ConcreteTile	Interior primer	m2	1.00	0.19	0.00

B2 External wall

Table 19 Timber frame

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
90mmTimberFraming-R2.2Batts-14%FramingRatio	M12 x 100 Galv steel Ankascrews	kg	0.03	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	90 Dampcourse (20 m roll)	kg	0.07	0.81	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	90 x 45 Rad MSG8 H1.2 MG KD RL	kg	6.58	0.14	-1.64
90mmTimberFraming-R2.2Batts-14%FramingRatio	45 x 21 Rad Mch H3.1 D2F RL cavity batten	kg	0.84	0.16	-1.64
90mmTimberFraming-R2.2Batts-14%FramingRatio	L/Lock galv angle brace 3.6 m.	kg	0.01	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	R2.2 Fibre Glass Batts (13.9 m2)	kg	1.06	0.96	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Thermakraft Watergate plus 295 to walls	kg	0.12	2.57	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	DanBand Blue fixing strap 300mx19mm	kg	0.01	2.57	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Rapid Galv staples 140-06 2000s	kg	0.00	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Hardies PVC cavity vrnt strip 3.0m	kg	0.06	3.52	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	150x 25 bev. back H3 FJ P/P W/Bd	kg	18.13	0.32	-1.65
90mmTimberFraming-R2.2Batts-14%FramingRatio	Flat Soakers 150 mm Galvanised	kg	0.03	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	10 mm Gibraltar Board	kg	7.70	0.28	-0.12
90mmTimberFraming-R2.2Batts-14%FramingRatio	Cornice 40 mm bevelled (No 8)	kg	0.12	0.14	-1.64
90mmTimberFraming-R2.2Batts-14%FramingRatio	Skirt. 60x10 bevel 1 edge(No 20)	kg	0.09	0.18	-1.65
90mmTimberFraming-R2.2Batts-14%FramingRatio	100 x 4.0 JH BS 5 kg	kg	0.22	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	8T10 Nailplate connectors	kg	0.01	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	50 x 2.0 PP BS 500 g	kg	0.00	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	30 x 1.6 PP BS 500 g	kg	0.00	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	60 x 2.8 JH Galvanised 5 kg	kg	0.14	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	30 x 2.5 Clts Galvanised 5 kg	kg	0.01	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Misc fixings allowance stud wall constrn	kg	0.01	1.00	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Exterior walls	m2	1.04	0.43	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Exterior primer	m2	1.04	0.27	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Interior walls painted	m2	1.00	0.37	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Interior primer	m2	1.00	0.19	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Skirting & Cornice ne 150	m2	0.13	0.37	0.00
90mmTimberFraming-R2.2Batts-14%FramingRatio	Interior primer - Skirting	m2	0.13	0.19	0.00

Table 20 Steel frame

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
90mmSteelFraming-R2.8Batts-14%FramingRatio	M12 x 100 Galv steel Ankascrews	kg	0.03	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	90 Dampcourse (20 m roll)	kg	0.07	0.81	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	89 x 41 x 0.75 x 189 girth G275 steel framing	kg	3.52	2.88	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	89 x 41 x 0.75 x 189 girth G275 steel framing	kg	0.17	2.88	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	45 x 21 Rad Mch H3.1 D2F RL cavity batten	kg	0.84	0.16	-1.64
90mmSteelFraming-R2.8Batts-14%FramingRatio	90 x 70 x 10 Assumed thermal break packer	kg	0.00	2.91	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	75 x 10 mm XPS	kg	0.11	2.91	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Adhesive 375 ml. Sturdi-Bond	m	4.18	0.06	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	R2.8 Fibre Glass Batts (6.4 m2)	kg	2.43	0.96	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Thermakraft Watergate plus 295 to walls	kg	0.12	2.57	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	DanBand Blue fixing strap 300mx19mm	kg	0.01	2.57	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Rapid Galv staples 140-06 2000s	kg	0.00	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Hardies PVC cavity vrnt strip 3.0m	kg	0.06	3.52	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	150x 25 bev. back H3 FJ P/P W/Bd	kg	18.13	0.32	-1.65
90mmSteelFraming-R2.8Batts-14%FramingRatio	Flat Soakers 150 mm Galvanised	kg	0.03	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	10 mm Gibraltar Board	kg	7.70	0.28	-0.12
90mmSteelFraming-R2.8Batts-14%FramingRatio	Cornice 40 mm bevelled (No 8)	kg	0.12	0.14	-1.64
90mmSteelFraming-R2.8Batts-14%FramingRatio	Skirt. 60x10 bevel 1 edge(No 20)	kg	0.09	0.18	-1.65
90mmSteelFraming-R2.8Batts-14%FramingRatio	60 x 6 galvanised screws 1000	kg	0.01	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	10g - 19 mm Xdrive	kg	0.01	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	50 x 2.0 PP BS 500 g	kg	0.00	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	30 x 1.6 PP BS 500 g	kg	0.00	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	60 x 2.8 JH Galvanised 5 kg	kg	0.14	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	30 x 2.5 Clts Galvanised 5 kg	kg	0.01	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Misc fixings allowance (reduced for steel)	kg	0.01	1.00	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Exterior walls	m2	1.04	0.43	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Exterior primer	m2	1.04	0.27	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Interior walls painted	m2	1.00	0.37	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Interior primer	m2	1.00	0.19	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Skirting & Cornice ne 150	m2	0.13	0.37	0.00
90mmSteelFraming-R2.8Batts-14%FramingRatio	Interior primer - Skirting	m2	0.13	0.19	0.00

B3 Ground floor

Table 21 Suspended timber

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
SuspendedTimberFloorR3.2Batt	140 x 45 NZDF SG8 H1.2 MG SL	kg	9.13	0.14	-1.64
SuspendedTimberFloorR3.2Batt	Pynefloor 3600 x 1800 x 20 mm	kg	15.04	0.89	-1.42
SuspendedTimberFloorR3.2Batt	Adhesive 375 ml. Sturdi-Bond	m	2.60	0.06	0.00
SuspendedTimberFloorR3.2Batt	10g x 45mm 304 SS screws	kg	0.05	1.00	0.00
SuspendedTimberFloorR3.2Batt	R3.2 Fibre Glass Batts (10.5 m2)	kg	2.60	0.96	0.00
SuspendedTimberFloorR3.2Batt	100 x 4.0 JH GalvanisedH BS 5 kg	kg	0.02	1.00	0.00
SuspendedTimberFloorR3.2Batt	75 x 3.15 JH BS 5 kg	kg	0.01	1.00	0.00
SuspendedTimberFloorR3.2Batt	30 x 2.5 Clts Galvanised 5 kg	kg	0.02	1.00	0.00
SuspendedTimberFloorR3.2Batt	Misc fixings allowance timber floor constrn	kg	0.20	1.00	0.00
SuspendedTimberFloorR3.2Batt	17.5 MPa Concrete in pile bases 350X350X250	kg	32.91	0.09	0.00
SuspendedTimberFloorR3.2Batt	125x125 Rad Sq. House Piles H5 900	kg	2.67	0.19	-1.63
SuspendedTimberFloorR3.2Batt	Galvanised Wire Dogs	kg	0.02	1.00	0.00
SuspendedTimberFloorR3.2Batt	6 Kn Galv bearer connectors 1/4.5 m bearer	kg	0.01	1.00	0.00
SuspendedTimberFloorR3.2Batt	140 x 45 Rad MSG8 H3.2 MG SL	kg	2.47	0.17	-1.63
SuspendedTimberFloorR3.2Batt	90 x 70 Rad MSG8 H5 MG SL	kg	2.56	0.19	-1.63
SuspendedTimberFloorR3.2Batt	M12 x 220 Galv. Coach bolt, nut, 2 lge washers	kg	0.10	1.00	0.00
SuspendedTimberFloorR3.2Batt	100 x 4.0 JH Galvanised 5 kg	kg	0.13	1.00	0.00
SuspendedTimberFloorR3.2Batt	90 x 45 Rad MSG8 H3.2 MG RL	kg	3.15	0.17	-1.63
SuspendedTimberFloorR3.2Batt	Hardiflex Fibre cement 7.5 mm	m2	0.35	7.40	0.00
SuspendedTimberFloorR3.2Batt	Hardijointer PVC 2400 7.5 mm	kg	0.08	3.52	0.00
SuspendedTimberFloorR3.2Batt	Base Vents 300x150 white powder coated Galv	kg	0.06	1.00	0.00
SuspendedTimberFloorR3.2Batt	8T10 Nailplate connectors	kg	0.01	1.00	0.00
SuspendedTimberFloorR3.2Batt	40 x 2.8 Clts Galvanised 5 kg	kg	0.01	1.00	0.00
SuspendedTimberFloorR3.2Batt	Exterior primer	m2	0.32	0.27	0.00
SuspendedTimberFloorR3.2Batt	250 um polythene (4 x 50 m roll)	kg	0.26	2.57	0.00

Table 22 Concrete slab

Assembly	Material	Reference (unit)	Quantity	A1 - A3 (GWPF per unit)	A1 - A3 (GWPB per unit)
ConcreteRaftSlabAP2.5	Basecourse fill AP20 or similar	kg	316.88	0.01	0.00
ConcreteRaftSlabAP2.5	Sand blinding 25 mm thick	kg	55.25	0.00	0.00
ConcreteRaftSlabAP2.5	20 MPa Raftmix Concrete in slab and ribs	kg	283.80	0.10	0.00
ConcreteRaftSlabAP2.5	Expol Tuff-pod EPS 1100x1100x220 to ribraft floors	kg	2.08	3.14	0.00
ConcreteRaftSlabAP2.5	Firth 100 mm recycled polypropylene spacer	kg	0.26	2.55	0.00
ConcreteRaftSlabAP2.5	Firth 300 mm recycled polypropylene spacer	kg	0.01	2.55	0.00
ConcreteRaftSlabAP2.5	HD12 G550E reinf in ribs 6 m	kg	1.70	4.03	0.00
ConcreteRaftSlabAP2.5	SE62Res 500E mesh (10.1m2-8.64m2 cover)	kg	3.23	4.03	0.00
ConcreteRaftSlabAP2.5	Black annealed steel Tie wire 1.6 x 300 mm 1 kg	kg	0.01	0.99	0.00
ConcreteRaftSlabAP2.5	250 um polythene (4 x 50 m roll)	kg	0.26	2.57	0.00
ConcreteRaftSlabAP2.5	48 mm PVC Adhesive tape (30 m roll)	m2	0.03	3.04	0.00
ConcreteRaftSlabAP2.5	20 MPa Raftmix Concrete in 300x300 perlimeter	kg	88.49	0.10	0.00
ConcreteRaftSlabAP2.5	HD12 G550E reinf in footing 6 m	kg	1.28	4.03	0.00
ConcreteRaftSlabAP2.5	300 x 19 Black faced ply to outside face	kg	0.30	1.02	-1.51
ConcreteRaftSlabAP2.5	45 x 45 Rad MSG6 H1.2 MG double pegs @ 600 cs	kg	0.18	0.28	-1.59
ConcreteRaftSlabAP2.5	Notional 6 X 65 nails/screws/m of oly or framing	kg	0.00	1.00	0.00
ConcreteRaftSlabAP2.5	30mm x 300mm high x 2.4 long XPS edge insulation	kg	0.14	2.91	0.00
ConcreteRaftSlabAP2.5	Hardiflex Fibre cement 7.5 mm protection to last	m2	0.13	7.40	0.00
ConcreteRaftSlabAP2.5	Hardijointer PVC 2400 7.5 mm to last	kg	0.03	3.52	0.00
ConcreteRaftSlabAP2.5	30mm "Z" Flashing Aluminium 3000 to last	kg	0.21	12.43	0.00
ConcreteRaftSlabAP2.5	Exterior perimeter protection	m2	0.13	0.43	0.00
ConcreteRaftSlabAP2.5	Exterior primer	m2	0.13	0.27	0.00

Appendix C Sources of manufacturing GWP(fossil) and GWP(biogenic) data

This Appendix sets out sources of data used for fossil and biogenic global warming potentials for modules A1 – A3. Sources of data in the tables below are assessed for data quality, using the Data Quality Matrix in CO_2NSTRUCT (https://www.branz.co.nz/environment-zero-carbon-research/framework/branz-co2nstruct/). This is reproduced at the end of this Appendix.

C1 Truss roof

Table 23 Truss roof with profiled steel cladding

Material	Data source (modules A1 - A3)	Data quality
Roof Trusses	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Galvanised Nailplates to trusses say 4/1.2 m	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Galvanised Wire Dogs	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
L/L Galv strip brace & tensioner(30m)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Galv Multigrips say	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
70x 35 Rad Mch UT MG RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
70 x 45 Rad MSG8 H1.2 MG KD RL wet	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Purlin screws - box of 250	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
R7.0 Fibre Glass Batts (2.6 m2)	Tasman Insulation New Zealand Ltd (2017), Environmental Product Declaration for Tasman Insulation: Pink® Batts® glass wool insulation: segments, blankets and boards (EPD Registration No. S-P-01169, accessed from www.epd-australasia.com.	A
Thermakraft Watergate plus 295 to roof	Generic data (modelling using EcoInvent 3.1)	G
Galv wire netting 75 (100 m2 roll)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
13 mm Gibraltar Board	Winstone Wallboards Ltd (2018), Environmental Product Declaration for GIB® plasterboard (EPD Registration No. S-P-01000), version 1.1, accessed from www.epd-australasia.com.	A
100 x 4.0 JH BS 25 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
75 x 3.15 JH BS 25 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
40 x 2.8 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
75 x 14 Batten screws (25)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Misc fixings allowance timber roof constrn	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
0.40 STEEL TO CORRUGATED ROOFING	New Zealand Steel Ltd (2018), Environmental Product Declaration – Colorsteel® (EPD Registration No. S-P-01001), accessed from www.epd-australasia.com. Includes estimate of processing following primary manufacture. NZ Steel (2018); Environmental Product Declaration – Addendum – rollforming data, accessed from www.epd-australasia.com.	A
Ceilings	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for ceiling paints (EPD Registration No. S-P-00860), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A

Table 24 Truss roof with concrete tile cladding

Material	Data source (modules A1 - A3)	Data quality
Roof Trusses	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Galvanised Nailplates to trusses say 4/1.2 m	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Galvanised Wire Dogs	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
L/L Galv strip brace & tensioner(30m)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Galv Multigrips say	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
70x 35 Rad Mch UT MG RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
50 x 50 Rad MSG8 H1.2 MG KD RL wet	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
90 x 45 Rad MSG8 H1.2 MG KD RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
70 x 45 Rad MSG8 H1.2 MG KD RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
R7.0 Fibre Glass Batts (2.6 m2)	Tasman Insulation New Zealand Ltd (2017), Environmental Product Declaration for Tasman Insulation: Pink® Batts® glass wool insulation: segments, blankets and boards (EPD Registration No. S-P-01169, accessed from www.epd-australasia.com.	A
Thermakraft Watergate plus 295 to roof	Generic data (modelling using EcoInvent 3.1)	G
Galv wire netting 75 (100 m2 roll)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
13 mm Gibraltar Board	Winstone Wallboards Ltd (2018), Environmental Product Declaration for GIB® plasterboard (EPD Registration No. S-P-01000), version 1.1, accessed from www.epd-australasia.com.	A
100 x 4.0 JH BS 25 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
75 x 3.15 JH BS 25 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
40 x 2.8 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
75 x 14 Batten screws (25)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Misc fixings allowance timber roof constrn	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Concrete tiles, underlay & battens	Based on modelling using generic data from EcoInvent 3.1, AusLCI, Sacayon Madrigal (2016) and primary data for concrete mixes. Madrigal, S. (2016). Assessment of the life cycle-based environmental impacts of New Zealand electricity (master's thesis), Massey University, Palmerston North.	G
Ceilings	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for ceiling paints (EPD Registration No. S-P-00860), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A

B2 External wall

Table 25 Timber frame

Material	Data source (modules A1 - A3)	Data quality
M12 x 100 Galv steel Ankascrews	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
90 Dampcourse (20 m roll)	Generic data (modelling using EcoInvent 3.1)	G
90 x 45 Rad MSG8 H1.2 MG KD RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
45 x 21 Rad Mch H3.1 D2F RL cavity batten	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
L/Lock galv angle brace 3.6 m.	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
R2.2 Fibre Glass Batts (13.9 m2)	Tasman Insulation New Zealand Ltd (2017), Environmental Product Declaration for Tasman Insulation: Pink® Batts® glass wool insulation: segments, blankets and boards (EPD Registration No. S-P-01169, accessed from www.epd-australasia.com.	A
Thermakraft Watergate plus 295 to walls	Generic data (modelling using EcoInvent 3.1)	G
DanBand Blue fixing strap 300mx19mm	Generic data (modelling using EcoInvent 3.1)	G
Rapid Galv staples 140-06 2000s	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Hardies PVC cavity vrnt strip 3.0m	Iplex Pipelines (2017); Environmental Product Declaration – PVC non-pressure pipes for building applications (EPD registration no.: S-P-00713), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
150x 25 bev. back H3 FJ P/P W/Bd	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Flat Soakers 150 mm Galvanised	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
10 mm Gibraltar Board	Winstone Wallboards Ltd (2018), Environmental Product Declaration for GIB® plasterboard (EPD Registration No. S-P-01000), version 1.1, accessed from www.epd-australasia.com.	A
Cornice 40 mm bevelled (No 8)	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Skirt. 60x10 bevel 1 edge(No 20)	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
100 x 4.0 JH BS 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
8T10 Nailplate connectors	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
50 x 2.0 PP BS 500 g	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30 x 1.6 PP BS 500 g	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
60 x 2.8 JH Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30 x 2.5 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Misc fixings allowance stud wall constrn	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Exterior walls	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G
Exterior primer	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G
Interior walls painted	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for wall paints (EPD Registration No. S-P-00859), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Skirting & Cornice ne 150	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for wall paints (EPD Registration No. S-P-00859), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer - Skirting	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A

Table 26 Steel frame

Material	Data source (modules A1 - A3)	Data quality
M12 x 100 Galv steel Ankascrews	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
90 Dampcourse (20 m roll)	Generic data (modelling using EcoInvent 3.1)	G
89 x 41 x 0.75 x 189 girth Z275 steel framing	Updated data supplied by New Zealand Steel for this study (to be published)	A
89 x 41 x 0.75 x 189 girth Z275 steel framing	Updated data supplied by New Zealand Steel for this study (to be published)	A
45 x 21 Rad Mch H3.1 D2F RL cavity batten	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
90 x 70 x 10 Assumed thermal break packer	Dow Deutschland GmbH & Co OHG (2013), Environmental Product Declaration – Xenergy™ extruded polystyrene foam insulation (EPD Registration No. EPD-DOW-2013111-E), accessed from https://ibu-epd.com/en/published-epds/. Based on manufacture in Europe and excludes import to New Zealand.	A
75 x 10 mm XPS	Dow Deutschland GmbH & Co OHG (2013), Environmental Product Declaration – Xenergy™ extruded polystyrene foam insulation (EPD Registration No. EPD-DOW-2013111-E), accessed from https://ibu-epd.com/en/published-epds/. Based on manufacture in Europe and excludes import to New Zealand.	A
Adhesive 375 ml. Sturdi-Bond	3M (2019), Environmental Product Declaration – 3M™ baseboard and multi-use adhesive – 290 ml cartridge (EPD Registration No. S-P-00588), version 1.1, accessed from www.environdec.com. Based on manufacture in Europe and excludes import to New Zealand.	A
R2.8 Fibre Glass Batts (6.4 m2)	Tasman Insulation New Zealand Ltd (2017), Environmental Product Declaration for Tasman Insulation: Pink® Batts® glass wool insulation: segments, blankets and boards (EPD Registration No. S-P-01169, accessed from www.epd-australasia.com.	A
Thermakraft Watergate plus 295 to walls	Generic data (modelling using EcoInvent 3.1)	
DanBand Blue fixing strap 300mx19mm	Generic data (modelling using EcoInvent 3.1)	G
Rapid Galv staples 140-06 2000s	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Hardies PVC cavity vrnt strip 3.0m	Iplex Pipelines (2017); Environmental Product Declaration – PVC non-pressure pipes for building applications (EPD registration no.: S-P-00713), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
150x 25 bev. back H3 FJ P/P W/Bd	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Flat Soakers 150 mm Galvanised	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
10 mm Gibraltar Board	Winstone Wallboards Ltd (2018), Environmental Product Declaration for GIB® plasterboard (EPD Registration No. S-P-01000), version 1.1, accessed from www.epd-australasia.com.	A
Cornice 40 mm bevelled (No 8)	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Skirt. 60x10 bevel 1 edge(No 20)	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
60 x 6 galvanised screws 1000	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
10g - 19 mm Xdrive	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
50 x 2.0 PP BS 500 g	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30 x 1.6 PP BS 500 g	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
60 x 2.8 JH Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30 x 2.5 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Misc fixings allowance (reduced for steel)	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Exterior walls	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G
Exterior primer	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G
Interior walls painted	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for wall paints (EPD Registration No. S-P-00859), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Skirting & Cornice ne 150	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for wall paints (EPD Registration No. S-P-00859), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A
Interior primer - Skirting	DuluxGroup (Australia) Pty Ltd (2017), Environmental Product Declaration for undercoats, sealers and primers (EPD Registration No. S-P-00861), version 1.1 of 25/05/2017, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	A

B3 Ground floor

Table 27 Suspended timber

Material	Data source (modules A1 - A3)	Data quality
140 x 45 NZDF SG8 H1.2 MG SL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Pynefloor 3600 x 1800 x 20 mm	FWPA (2017), Environmental Product Declaration – particleboard (EPD Registration No. S-P-00562), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	B
Adhesive 375 ml. Sturdi-Bond	3M (2019), Environmental Product Declaration – 3M™ baseboard and multi-use adhesive – 290 ml cartridge (EPD Registration No. S-P-00588), version 1.1, accessed from www.environdec.com. Based on manufacture in Europe and excludes import to New Zealand.	A
10g x 45mm 304 SS screws	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
R2.8 Fibre Glass Batts (10.5 m2)	Tasman Insulation New Zealand Ltd (2017), Environmental Product Declaration for Tasman Insulation: Pink® Batts® glass wool insulation: segments, blankets and boards (EPD Registration No. S-P-01169, accessed from www.epd-australasia.com.	A
100 x 4.0 JH GalvanisedH BS 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
75 x 3.15 JH BS 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30 x 2.5 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Misc fixings allowance timber floor constrn	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
17.5 MPa Concrete in pile bases 350X350X250	Firth Industries Ltd (2020); Environmental Product Declaration – for ready-mixed concrete (EPD Registration No. S-P-02050), accessed from www.epd-australasia.com.	A
125x125 Rad Sq. House Piles H5 900	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Galvanised Wire Dogs	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
6 Kn Galv bearer connectors 1/4.5 m bearer	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
140 x 45 Rad MSG8 H3.2 MG SL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
90 x 70 Rad MSG8 H5 MG SL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
M12 x 220 Galv. Coach bolt, nut, 2 lge washers	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
100 x 4.0 JH Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
90 x 45 Rad MSG8 H3.2 MG RL	WPMA (2021), Environmental Product Declaration – solid, finger-jointed and laminated timber products including timber preservation options (EPD Registration No.: S-P-00997), version 1.1, accessed from www.epd-australasia.com.	B
Hardiflex Fibre cement 7.5 mm	Based on James Hardie Australia Pty Ltd (2020), Environmental Product Declaration – fibre cement products from James Hardie Australia Pty Ltd (EPD Registration No. S-P-02052), accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
Hardijointer PVC 2400 7.5 mm	Iplex Pipelines (2017); Environmental Product Declaration – PVC non-pressure pipes for building applications (EPD registration no.: S-P-00713), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
Base Vents 300x150 white powder coated Galv	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
8T10 Nailplate connectors	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
40 x 2.8 Clts Galvanised 5 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
Exterior primer	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G

Table 28 Concrete slab

Material	Data source (modules A1 - A3)	Data quality
Basecourse fill AP20 or similar	Generic data (modelling using EcoInvent 3.1)	G
Sand blinding 25 mm thick	Generic data (modelling using EcoInvent 3.1)	G
20 MPa Raftmix Concrete in slab and ribs	Firth Industries Ltd (2020); Environmental Product Declaration – for ready-mixed concrete (EPD Registration No. S-P-02050), accessed from www.epd-australasia.com.	A
Expol Tuff-pod EPS 1100x1100x220 to ribraft floors	EUMEPS European Manufacturers of Expanded Polystyrene (2017), Environmental Product Declaration – expanded polystyrene (EPS) foam insulation (density 15 kg/m3) (EPD Registration No. EPD-EUM-20160269-IBG1-EN), accessed from https://ibu-epd.com/en/published-epds/. Based on manufacture in Europe and excludes import to New Zealand.	C
Firth 100 mm recycled polypropylene spacer	Generic data (modelling using EcoInvent 3.1)	G
Firth 300 mm recycled polypropylene spacer	Generic data (modelling using EcoInvent 3.1)	G
HD12 G550E reinf in ribs 6 m	Updated data supplied by New Zealand Steel for this study (to be published)	A
SE62Res 500E mesh (10.1m2-8.64m2 cover)	Updated data supplied by New Zealand Steel for this study (to be published)	A
Black annealed steel Tie wire 1.6 x 300 mm 1 kg	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN	E
250 um polythene (4 x 50 m roll)	Generic data (modelling using EcoInvent 3.1)	G
48 mm PVC Adhesive tape (30 m roll)	3M (2020), Environmental Product Declaration – 3M™ flexible air sealing tape FAST-D 8069E (EPD Registration No. S-P-00988), version 2.0, accessed from www.environdec.com. Based on manufacture in Europe and excludes import to New Zealand.	A
20 MPa Raftmix Concrete in 300x300 perlimeter	Firth Industries Ltd (2020); Environmental Product Declaration – for ready-mixed concrete (EPD Registration No. S-P-02050), accessed from www.epd-australasia.com.	A
HD12 G550E reinf in footing 6 m	Updated data supplied by New Zealand Steel for this study (to be published)	A
300 x 19 Black faced ply to outside face	FWPA (2017), Environmental Product Declaration – plywood (EPD Registration No. S-P-00564), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	B
45 x 45 Rad MSG6 H1.2 MG double pegs @ 600 cs	FWPA (Revised 2022); Environmental Product Declaration – Softwood timber (EPD Reg No.: S-P-00560), version 2.0, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	B
Notional 6 X 65 nails/screws/m of oly or framing	ArcelorMittal Brasil, Steel annealed wire and nails, EPD-ARC-20180140-CBD1-EN and galvanising based on Galvanizers Association of Australia (2019), Hot dip galvanizing in Australia, S-P-01166 (accessed www.epd-australasia.com)	E
30mm x 300mm high x 2.4 long XPS edge insulation	Dow Deutschland GmbH & Co OHG (2013), Environmental Product Declaration – Xenergy™ extruded polystyrene foam insulation (EPD Registration No. EPD-DOW-2013111-E), accessed from https://ibu-epd.com/en/published-epds/. Based on manufacture in Europe and excludes import to New Zealand.	
Hardiflex Fibre cement 7.5 mm protection to last	Based on James Hardie Australia Pty Ltd (2020), Environmental Product Declaration – fibre cement products from James Hardie Australia Pty Ltd (EPD Registration No. S-P-02052), accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
Hardijointer PVC 2400 7.5 mm to last	Iplex Pipelines (2017); Environmental Product Declaration – PVC non-pressure pipes for building applications (EPD registration no.: S-P-00713), version 1.2, accessed from www.epd-australasia.com. Based on manufacture in Australia and excludes import to New Zealand.	C
30mm "Z" Flashing Aluminium 3000 to last	Based on BRANZ modelling using generic data from EcoInvent 3.1, World Aluminium (2013) and Sacayon Madrigal (2016). Madrigal, S. (2016). Assessment of the life cycle-based environmental impacts of New Zealand electricity (master's thesis), Massey University, Palmerston North. World Aluminium (2013), Global life cycle inventory data for the primary aluminium industry – 2010 data.	F
Exterior perimeter protection	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G
Exterior primer	AkzoNobel. (2014). Weathershield range. Environmental Product Declaration S-P00551. Now deregistered (expired).	G

B4 Data quality matrix (extract from CO_2NSTRUCT)

Data quality		
Go to summary of material classes		
Good quality/ more reliable	A	EN 15804-compliant EPD, specific product, geographical scope includes manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. **Product - specific**
↑	B	EN 15804-compliant EPD, sector average, manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. **Product - average**
	C	EN 15804-compliant EPD, specific product or sector average, geographical scope excludes New Zealand but data used as a proxy for product used in New Zealand. **Product - proxy**
	D	EPD, compliant with another standard e.g. ISO 21930, specific product or sector average, geographical scope includes manufacture in New Zealand or manufacture of product overseas, which may be imported to New Zealand. Data may be used as a proxy for New Zealand product. **Product - proxy**
	E	Other form of published product or sector average carbon footprint or LCA, e.g. PAS 2050. **Product - proxy**
↓	F	Unpublished or published data based on modelling taking into account local conditions using a mix of primary data and generic data, e.g. from EPDs, AusLCI, EcoInvent. May include data gaps. **Product - generic**
Poorer quality/ less reliable	G	Unpublished or published result based on modelling/assumptions that do not take account of local conditions. May include data gaps. **Product - generic**

Appendix D. Modelling the Fate of Timber In New Zealand Landfills

Estimating the decay of harvested wood products (HWPs) in landfills involves the application of various decay distributions. These distributions include the exponential decay, gamma distribution, and alternative variations of gamma distribution such as chi-squared, standard gamma, and k = 2 distributions (Marland et al., 2010). The exponential decay or first-order decay (FOD) model has been extensively employed in earlier literature including IPCC (Pipatti et al., 2006) and in New Zealand's Greenhouse Gas Inventory 1990–2019 (Ministry for the Environment, 2021) due to its straightforward nature and the absence of a clear alternative (Bates et al., 2017). This decay process is mathematically represented by the FOD model, expressed in equation (5):

$$DDOCm = DDOCm_0 \, . \, e^{-kt} \quad (5)$$

Where "t" denotes a time variable, measured in years. "DDOCm" represents the quantity of degradable organic carbon that undergoes anaerobic decomposition in a landfill over a period of time "t." The initial amount of degradable organic carbon at time 0 is denoted as "DDOCm0." The decay rate constant "k" indicates how quickly the decomposition occurs, measured per year.

$$k = \frac{\ln(2)}{half - life} \quad (6)$$

The decay constant rate (k) for each commodity class I of HWP is expressed in units of ($year^{-1}$) and is calculated based on the half-life of the specific HWP commodity within the HWP pool, given in years, according to equation (6) (Rüter et al., 2019).

We have followed Pipatti et al. (2006) in modelling landfill decay with an exponential function which assumes that losses are greatest immediately after landfilling. In practice there may be a delay due to a degree of decay resistance of the product and the time taken for decay organisms to colonise the material. This has no effect on sLCA but would further delay emissions in dLCA.

Degradable organic carbon decays anaerobically to produce CH_4 and/or aerobically to produce CO_2, depending on landfill management. Landfill gases produced when anaerobic decay occurs can follow two potential paths leading to greenhouse gas emissions. The first path involves capturing CH_4 with flaring and direct release of CO_2. The proportions of these emissions are approximately 99.7% CO_2 and 0.3% CH_4 (ECCC, 2017). On the other hand, the second path entails the direct release of landfill gas into the atmosphere, with emissions consisting of roughly 10% CO_2 and 90% CH_4 (IPCC, 2006).

APPENDIX E. SENSITIVITY ANALYSIS DETAILED TABLES

Tables in this appendix provide results for all the sensitivity analyses in Figure 12, in kg CO_2eq. Biogenic column is the net result for biogenic carbon storage in timber and engineered wood products minus landfill emissions due to biogenic carbon degradation.

Wall (timber)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		12.579	1.939	0.000	0.000	0.000	0.174	-0.116	-32.839	-18.264
SA1	90 year service life	n.c.	n.c.	n.c.	7.142	n.c.	n.c.	-0.214	-55.895	-34.275
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	Corrosion Zone D	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
SA3	Auckland	n.c.	0.951	n.c.	n.c.	n.c.	0.110	-0.117	n.c.	-19.317
	Christchurch	n.c.	1.265	n.c.	n.c.	n.c.	0.238	-0.117	-32.859	-18.895
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-29.935	-15.360
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-47.187	-32.612
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-15.273	-0.698
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-10.086	4.490
	Incineration	n.c.	1.963	n.c.	n.c.	n.c.	0.433	-31.211	0.707	-15.529

Wall (steel)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		23.909	1.931	0.000	0.000	1.249	0.151	-2.913	-24.687	-0.360
SA1	90 year service life	n.c.	n.c.	n.c.	7.142	2.118	n.c.	-3.011	-47.690	-15.450
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	Corrosion Zone D	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
SA3	Auckland	n.c.	0.773	n.c.	n.c.	1.361	0.095	-2.920	-24.681	-1.463
	Christchurch	n.c.	1.386	n.c.	n.c.	1.167	0.207	-2.920	-24.707	-0.959
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-22.525	1.802
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-35.369	-11.042
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-11.610	12.717
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-7.748	16.579
	Incineration	n.c.	1.949	n.c.	n.c.	n.c.	0.344	-26.112	0.596	1.936

Roof (steel)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		25.928	1.204	0.000	16.759	0.000	0.123	-8.213	-12.912	22.889
SA1	90 year service life	n.c.	n.c.	n.c.	33.518	n.c.	n.c.	-12.308	-12.915	35.551
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	0.000	n.c.	n.c.	-4.118	n.c.	10.225
	Corrosion Zone D	n.c.	n.c.	n.c.	33.518	n.c.	n.c.	-12.308	n.c.	35.553
SA3	Auckland	n.c.	0.511	n.c.	16.547	n.c.	0.078	-8.224	n.c.	21.927
	Christchurch	n.c.	1.094	n.c.	16.971	n.c.	0.169	-8.224	-12.920	23.018
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-11.809	23.993
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-18.364	17.438
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-6.238	29.563
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-4.267	31.534
	Incineration	n.c.	1.213	n.c.	n.c.	n.c.	0.222	-19.954	0.267	24.435

Roof (concrete)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		23.721	2.544	-1.665	0.000	0.000	-0.885	-2.852	-17.197	3.666
SA1	90 year service life	n.c.	n.c.	-2.996	14.450	n.c.	-0.425	-5.672	-17.200	14.421
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	Corrosion Zone D	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
SA3	Auckland	n.c.	1.476	n.c.	n.c.	n.c.	-1.013	-2.852	n.c.	2.470
	Christchurch	n.c.	1.881	n.c.	n.c.	n.c.	-0.757	-2.852	-17.207	3.121
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-15.700	5.163
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-24.592	-3.729
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-8.144	12.719
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-5.470	15.393
	Incineration	n.c.	2.556	n.c.	n.c.	n.c.	-0.752	-18.779	0.362	5.444

Floor (timber)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		26.418	4.086	-0.750	0.000	6.986	0.336	-1.398	-39.036	-3.359
SA1	90 year service life	n.c.	n.c.	n.c.	n.c.	11.842	n.c.	n.c.	-38.753	1.781
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	Corrosion Zone D	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
SA3	Auckland	26.464	1.482	n.c.	n.c.	17.740	0.212	-1.408	-38.447	5.293
	Christchurch	26.276	3.103	n.c.	n.c.	-1.492	0.460	-1.369	-39.529	-13.302
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-35.089	0.588
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-58.539	-22.862
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-15.160	20.517
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-8.109	27.568
	Incineration	n.c.	4.391	n.c.	n.c.	n.c.	3.567	-40.771	1.283	1.123

Floor (concrete)

Sensitivity analyses		A1-A3	A4-A5	B1	B4	B6	C1-C4	D	Biogenic	Total
Baseline		74.036	9.855	-1.901	0.000	0.000	3.038	-8.959	-0.491	75.577
SA1	90 year service life	n.c.	n.c.	-2.251	n.c.	n.c.	3.168	n.c.	n.c.	75.357
SA2	Corrosion Zone B	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
	Corrosion Zone D	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.
SA3	Auckland	76.195	6.806	n.c.	n.c.	n.c.	1.791	-9.416	n.c.	72.982
	Christchurch	72.323	9.178	n.c.	n.c.	n.c.	4.286	-8.626	-0.491	74.769
SA4	IPCC	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-0.442	75.627
	EPD	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-0.735	75.334
	Methane direct release	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-0.193	75.876
	Non-municipal landfill	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	n.c.	-0.105	75.964
	Incineration	n.c.	9.916	n.c.	n.c.	n.c.	n.c.	-9.448	0.000	75.640

Appendix F. Energy simulation Sensitivity (ESS) Analysis

Energy simulations were carried out for the external wall and ground floor assemblies due to differences in construction R values and/or thermal mass. The basis for the baseline energy simulations is provided in Appendix A, with results shown in Section 4 as "module B6".

In all energy simulation sensitivities, the source of energy for heating and cooling is assumed to be electricity. The building service life is 50 years.

This section investigates how energy simulation results vary according to the following:

- ESS1 Use of less or more heating/cooling energy
- ESS2 Consideration of linear junction heat losses
- ESS3 Inclusion of a floor covering (ground floor assemblies only).

Full energy simulation results are provided in Appendix G.

To convert energy simulation results (in kWh) into climate change results, a Grid electricity carbon intensity needed to be derived. The method used to obtain this is provided in Section 3.3.2.3.2.

ESS1 Use of less or more heating/cooling energy

Simulation of energy use in houses for heating and cooling relies on many assumptions and defaults that seek to reflect human behaviour, physical characteristics e.g. construction R values, location e.g. climate zone, and source(s) of energy e.g. heat pump, resistive electric heater.

In reality, people occupying houses can exhibit very different behaviours which can result in significantly different demand for heating and cooling. Examples of these behaviours may include tolerance for colder and hotter room temperatures, when people are home and when and where they want heating/cooling, and how often windows are opened (and how many, and how wide).

Energy models can be a useful tool for estimating potential energy use for heating/cooling (respecting the inherent uncertainties with such an exercise) and can be particularly useful when investigating alternative scenarios to ascertain trends through differences in results.

In this sensitivity study, the Baseline energy simulation in Appendix A is replaced with the Low and High energy simulations (also in Appendix A). The Low energy simulation uses defaults and assumptions that lend themselves to use of less energy for heating and cooling, in comparison with the Baseline. Similarly, the High energy simulation sets defaults and assumptions that tend towards higher energy use for heating and cooling, in comparison with the Baseline.

Results are presented in Table 29 and Table 30. These are provided excluding consideration of additional linear heat losses that can occur at junctions between assemblies e.g. ground floor with external wall, roof with external wall (investigated in ESS2 below).

Table 29 ESS1: Summary of additional electricity use for heating/cooling (kWh/m²/year) by climate zone

Climate zone		External wall [1]			Ground floor					
		Steel frame			Timber			Concrete		
		Baseline	Low	High	Baseline	Low	High	Baseline	Low	High
1	Auckland	0.30	0.14	1.20	3.95	1.35				2.50
2	Napier	0.36	0.17	1.48	4.26	1.80				3.81
3	Wellington	0.16	0.10	1.00	1.15	1.11				15.00
4	Turangi	0.29	0.17	1.45	2.50	1.55				14.61
5	Christchurch	0.26	0.18	1.27		1.72		0.33		20.20
6	Queenstown	0.30	0.29	1.54		2.01		2.20		24.75
	Simple average	**0.28**	**0.18**	**1.32**	**1.56**	**1.59**				**13.48**

Table 30 ESS1: Summary of module B6 impact due to additional electricity use for heating/cooling (kg CO_2eq / m²) by climate zone

Climate zone		External wall [1]			Ground floor					
		Steel frame			Timber			Concrete		
		Baseline	Low	High	Baseline	Low	High	Baseline	Low	High
1	Auckland	1.35	0.65	5.34	17.64	6.04				11.17
2	Napier	1.62	0.77	6.62	19.03	8.03				16.99
3	Wellington	0.73	0.44	4.45	5.16	4.95				66.97
4	Turangi	1.27	0.76	6.48	11.15	6.94				65.24
5	Christchurch	1.16	0.82	5.66		7.67		1.48		90.20
6	Queenstown	1.32	1.28	6.89		9.00		9.81		110.50
	Simple average	**1.24**	**0.79**	**5.91**	**6.95**	**7.10**				**60.18**

Results appear to be sensitive in a scenario where demand for heating and cooling is greater. The High scenario in Table 29 and Table 30 assumes heating and cooling 24 hours a day, seven days a week, to maintain indoor temperatures between 22°C and 25°C using resistive heaters with a Coefficient of Performance (COP) of 1. It shows that the concrete floor, in particular, is sensitive to such a scenario, with an average of over 60 kg CO_2eq / m² added to baseline module B6 results over a 50 year service life.

This is likely to be due to the high heating setpoint of 22°C, which allows little room for heat to be stored in thermal mass, before ventilation/cooling strategies are initiated, such as window opening, to remove heat from the house.

The scenario may be considered as extreme. It may be argued that people who prefer a high indoor temperature would also have a higher cooling setpoint and would also be more likely to use more efficient systems such as heat pumps rather than resistive heaters.

ESS2: Consideration of linear junction heat losses

Baseline results consider heat losses through 1 m² of a construction, without including additional losses that occur at their junctions with other assemblies e.g. where a wall construction joins with a ground floor construction. These provide additional linear sources of heat loss, in addition to heat loss through the construction itself.

This sensitivity study includes allowance for additional heat losses through junctions between assemblies. This has been undertaken using the R-value derating method (Morrison Herschfield Limited, 2021). Ψ-(psi) values for the junctions (e.g. external corners, roof/wall junctions, window junctions etc.) were multiplied by their lengths to produce the additional heat loss associated with them. This was then converted into a U-value adjustment for the walls by dividing the heat loss by the external wall area. For simplicity, the ψ-values were taken from existing New Zealand data, taking the closest matches in the PHINZ high performance details construction handbook (Quinn, 2022). The exception to this was the external wall/concrete slab junction as the ISO 10211 method essentially assigns the edge losses to the junction, but EnergyPlus already includes the edge losses in its model of the concrete slab.

To avoid double-counting the edge losses, the wall/slab junction ψ-value was calculated in THERM to align with the way the foundation is modelled in EnergyPlus.

In the absence of specific data being available for linear heat losses at the junction of a steel framed wall with another construction, the initial analysis assumed the same linear heat losses as for timber framed walls to ascertain whether these appear to be significant in absolute terms. They were additionally tested assuming linear heat losses at 50% and 150% of those for timber framed walls.

Results in energy terms are presented in Table 31 and in carbon terms in Table 32.

Table 31 ESS2: Summary of additional electricity use for heating/cooling (kWh/m²/year) due to exclusion/inclusion of additional linear heat losses at junctions

Climate zone		External wall		Ground floor	
		No juction heat losses	With juction heat losses	No juction heat losses	With juction heat losses
1	Auckland	0.30	0.29	-3.95	-4.30
2	Napier	0.36	0.37	-4.26	-4.53
3	Wellington	0.16	0.17	-1.15	-1.20
4	Turangi	0.29	0.31	-2.50	-2.54
5	Christchurch	0.26	0.29	0.33	0.49
6	Queenstown	0.30	0.34	2.20	2.47
Simple average		**0.28**	**0.29**	**-1.56**	**-1.60**

Note 1: For the external wall constructions, a positive number means additional energy demand for the steel framed wall in comparison with the timber framed wall.

Note 2: For the ground floor constructions, a negative number means additional energy demand for the suspended timber floor in comparison with the concrete floor slab. A positive number means additional energy demand for the concrete floor slab in comparison with the suspended timber floor.

Note 3: Ground floor constructions use Kiva for ground modelling.

Table 32 ESS2: Summary of module B6 impact due to exclusion/inclusion of additional linear heat losses at junctions (kg CO_2eq / m²)

Climate zone		External wall		Ground floor	
		No juction heat losses	With juction heat losses	No juction heat losses	With juction heat losses
1	Auckland	1.35	1.29	-17.64	-19.21
2	Napier	1.62	1.64	-19.03	-20.24
3	Wellington	0.73	0.77	-5.16	-5.37
4	Turangi	1.27	1.37	-11.15	-11.34
5	Christchurch	1.16	1.28	1.48	2.17
6	Queenstown	1.32	1.53	9.81	11.01
Simple average		**1.24**	**1.31**	**-6.95**	**-7.16**

Note 1: For the external wall constructions, a positive number means additional energy demand for the steel framed wall in comparison with the timber framed wall.

Note 2: For the ground floor constructions, a negative number means additional energy demand for the suspended timber floor in comparison with the concrete floor slab. A positive number means additional energy demand for the concrete floor slab in comparison with the suspended timber floor.

Note 3: Ground floor constructions use Kiva for ground modelling.

The steel frame wall construction appears to require, on average, a small additional energy demand in comparison to the timber frame wall when additional linear junction heat losses are not included. This is calculated as adding less than 2 kg CO_2 eq / m^2 in any climate zone over a 50 year building service life. When junction heat losses are included (and assuming they are the same as for the timber frame wall), the additional average energy demand (and therefore, climate change impact) changes very little (5%), with greater variation by climate zone (from 1% to 16%) albeit the additional energy demand continues to add less than 2 kg CO_2 eq over a 50 year building service life.

This analysis assumed that linear heat losses at junctions for steel frame walls was the same as for timber frame walls (in the absence of data for steel frame walls). If linear junction losses are greater relative to timber framed walls (in this work, 50% higher values were tested), then they would significantly add to the module B6 results of the steel framed wall. However, since the results of this study show that the steel framed wall results are already higher than the timber framed wall results from a climate change impact perspective, this was not further investigated. Conversely, if the linear junction heat losses at junctions for steel frame walls are significantly less (in this work, of the order of half), then results indicate that the climate change results, unsurprisingly, become closer. We can therefore conclude that results appear sensitive to any significant differences in linear junction heat losses between the two wall types. To progress, it would be useful to better understand the Ψ-value for the steel frame wall linear junctions, and model both timber frame and steel frame walls at higher framing ratios akin to the range and average measured in Ryan et al. (2019).

For the ground floor assemblies without consideration of linear heat losses, there appears to be an additional energy demand (and module B6 impact) for the suspended timber floor option in climate zones 1 – 4, and an additional energy demand (and module B6 impact) for the concrete floor slab option in climate zones 5 and 6. The estimated average module B6 climate change impact of the suspended timber floor is about 13 kg CO_2eq / m^2 over 50 years for climate zones 1 – 4, whereas the average module B6 climate change impact added to the concrete slab floor in climate zones 5 and 6 is about 5.7 kg CO_2eq / m^2 over 50 years.

The estimated additional energy demand for the suspended timber floor in climate zones 1 to 4 appears to be due to the benefit of the concrete's thermal mass in these warmer regions, despite the differences in construction R values. In climate zones 5 and 6, the lower construction R value of the concrete floor slab suggests that it does not perform as well as the suspended timber floor, as heat losses outweigh thermal mass benefits.

With consideration of additional linear heat losses, these findings change little (the average module B6 climate change impact of the suspended timber floor increases to just over 14 kg CO_2eq / m^2 over 50 years for climate zones 1 -4, and the concrete slab floor option increases by an average of 6.6 kg CO_2eq / m^2 over 50 years for climate zones 5 and 6).

By climate zone, all but one region appear to exhibit a variability of 12% or less when junction heat losses are included, except for climate zone 5, which displayed a much higher variability of 46%. However, in absolute terms, this is an increase of 1.5 kg CO_2eq / m^2 over 50 years to less than 2.2 kg CO_2eq / m^2 over 50 years for the concrete slab option.

As with the external walls, these findings do not have implications for the findings and conclusions of this study, and therefore were not explored further.

ESS3: Presence of a floor covering in ground floor assemblies

In the baseline assessment, the ground floors are assumed to be exposed. However, people frequently use some form of floor covering, for example, carpet, tiles, linoleum or laminate.

This sensitivity study seeks to estimate the module B6 implications of using a floor covering. Therefore, it does not include the embodied carbon implication of the floor covering itself (modules A1 – A3), nor the potential for that floor covering to be replaced during a 50 year service life of a residential building (module B4).

Results are presented in Table 33 and Table 34.

Table 33 Summary of heating/cooling energy without/with a floor covering (kWh / m^2 /year)

	Climate zone	No floor covering	Floor covering
1	Auckland	-4.0	-2.3
2	Napier	-4.3	-2.8
3	Wellington	-1.2	-1.5
4	Turangi	-2.5	-2.3
5	Christchurch	0.3	-0.4
6	Queenstown	2.2	0.3
	Simple average	**-1.6**	**-1.5**

Note 1: A negative number means the suspended timber floor requires more heating/cooling energy than the concrete slab floor. A positive number means the concrete slab floor option requires more energy for heating/cooling than the suspended timber floor.

Note 2: Modelled excluding linear junction losses.

Note 3: Uses Kiva for ground modelling.

Table 34 Summary of climate change impact as a result of heating/cooling energy without/with a floor covering (kg CO_2eq / m^2)

Climate zone		No floor covering	Floor covering
1	Auckland	-17.6	-10.5
2	Napier	-19.0	-12.7
3	Wellington	-5.2	-6.8
4	Turangi	-11.2	-10.3
5	Christchurch	1.5	-2.0
6	Queenstown	9.8	1.1
	Simple average	**-6.9**	**-6.8**

Note 1: A negative number means the suspended timber floor requires more heating/cooling energy than the concrete slab floor. A positive number means the concrete slab floor option requires more energy for heating/cooling than the suspended timber floor.

Note 2: Modelled excluding linear junction losses.

Note 3: Uses Kiva for ground modelling.

Table 33 Table 33 Summary of heating/cooling energy without/with a floor covering (kWh / m^2 /year)and Table 34 show that calculated results do not change very much, when expressed as simple averages. However, this hides greater variability when results are considered by climate zone. Using climate zone 1 as an example, the suspended timber floor option is estimated to have an additional module B6 climate change impact of 17.6 kg CO_2eq / m^2 over 50 years relative to the concrete slab option, due to the thermal mass provided by the concrete.

When both floor options include a floor covering, this additional module B6 climate change impact reduces to 10.5 kg CO_2eq / m^2 over 50 years (almost half), presumably due to the decreased influence of the concrete's thermal mass once covered.

In climate zones 5 and 6, baseline results indicate an additional module B6 climate change impact, due to increased energy demand for the concrete floor slab option (primarily due to heat losses arising from a lower construction R value outweighing the thermal mass benefit of the concrete). When a floor covering is added to both assemblies, it reduces the thermal mass benefit of the concrete but also reduces the calculated additional heat loss.

Thus, in climates/scenarios where the mass of the slab is able to be used effectively and it is advantaged, the addition of a floor covering reduces its advantage. In situations where the thermal mass of the concrete slab appears less effective, and heat losses appear to be more significant, the addition of a floor covering reduces those heat losses and the overall heating load and so again reduces the difference between the assemblies.

Separately, the concrete floor slab receives a calculated carbon benefit of 1.9 kg CO_2eq when exposed during the 50 year building service life, due to carbonation (module B1). This small benefit is likely to be reduced when the concrete has a floor covering.

APPENDIX G. DETAILED ENERGY SIMULATION SENSITIVITY (ESS) RESULTS

ESS1: Use of less/more heating/cooling energy (external walls)

Baseline Scenario

Baseline							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	304	1155	1459		
Zone 1 - Auckland	Wall	Steel	324	1173	1497	38	0.3032671
Zone 2 - Napier	Wall	Timber	309	2383	2693		
Zone 2 - Napier	Wall	Steel	328	2409	2738	45	0.3633927
Zone 3 - Wellington	Wall	Timber	49	3447	3496		
Zone 3 - Wellington	Wall	Steel	56	3460	3516	20	0.1626561
Zone 4 - Turangi	Wall	Timber	146	4537	4682		
Zone 4 - Turangi	Wall	Steel	158	4560	4717	35	0.2850404
Zone 5 - Christchurch	Wall	Timber	150	5666	5816		
Zone 5 - Christchurch	Wall	Steel	162	5686	5848	32	0.2599015
Zone 6 - Queenstown	Wall	Timber	88	7446	7534		
Zone 6 - Queenstown	Wall	Steel	98	7473	7571	37	0.29562
							0.2783129

Low Energy Scenario

Low							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	246	175	421		
Zone 1 - Auckland	Wall	Steel	259	181	439	18	0.1448175
Zone 2 - Napier	Wall	Timber	239	413	652		
Zone 2 - Napier	Wall	Steel	251	422	673	21	0.1717882
Zone 3 - Wellington	Wall	Timber	47	568	615		
Zone 3 - Wellington	Wall	Steel	52	575	628	12	0.0985959
Zone 4 - Turangi	Wall	Timber	121	846	967		
Zone 4 - Turangi	Wall	Steel	130	859	988	21	0.1691322
Zone 5 - Christchurch	Wall	Timber	111	1106	1217		
Zone 5 - Christchurch	Wall	Steel	118	1121	1240	23	0.1838303
Zone 6 - Queenstown	Wall	Timber	83	1546	1629		
Zone 6 - Queenstown	Wall	Steel	91	1574	1665	36	0.2873033
							0.1759112

High Energy Scenario

High							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	363	6756	7119		
Zone 1 - Auckland	Wall	Steel	389	6878	7267	148	1.1958114
Zone 2 - Napier	Wall	Timber	410	9185	9594		
Zone 2 - Napier	Wall	Steel	441	9338	9778	184	1.4817849
Zone 3 - Wellington	Wall	Timber	129	11566	11695		
Zone 3 - Wellington	Wall	Steel	144	11674	11818	124	0.9973274
Zone 4 - Turangi	Wall	Timber	225	13264	13489		
Zone 4 - Turangi	Wall	Steel	250	13419	13669	180	1.4524676
Zone 5 - Christchurch	Wall	Timber	225	14634	14858		
Zone 5 - Christchurch	Wall	Steel	246	14769	15015	157	1.2682269
Zone 6 - Queenstown	Wall	Timber	155	17159	17314		
Zone 6 - Queenstown	Wall	Steel	176	17330	17506	192	1.5443249
							1.3233238

ESS1: Use of less/more heating/cooling energy (ground floors)

Baseline Scenario

Kiva							
Climate	**Element**	**Var**	**Total Cooling (kWh)**	**Total Heating (kWh)**	**Total Heating + Cooling (kWh)**	**ΔkWh**	**ΔkWh/m2**
Zone 1 - Auckland	Floor	Suspended Timber	304	1157	1461		
Zone 1 - Auckland	Floor	Ribraft slab	144	700	845	-616	-3.9522618
Zone 2 - Napier	Floor	Suspended Timber	308	2385	2693		
Zone 2 - Napier	Floor	Ribraft slab	131	1898	2029	-665	-4.2633137
Zone 3 - Wellington	Floor	Suspended Timber	49	3451	3500		
Zone 3 - Wellington	Floor	Ribraft slab	4	3317	3320	-180	-1.1548717
Zone 4 - Turangi	Floor	Suspended Timber	145	4543	4688		
Zone 4 - Turangi	Floor	Ribraft slab	40	4258	4298	-390	-2.4978381
Zone 5 - Christchurch	Floor	Suspended Timber	149	5671	5821		
Zone 5 - Christchurch	Floor	Ribraft slab	33	5839	5873	52	0.33247669
Zone 6 - Queenstown	Floor	Suspended Timber	88	7456	7544		
Zone 6 - Queenstown	Floor	Ribraft slab	18	7868	7886	343	2.19794241
							-1.556311

Low Energy Scenario

Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Floor	Suspended Timber	246	175	421		
Zone 1 - Auckland	Floor	Ribraft slab	125	85	210	-211	-1.3526513
Zone 2 - Napier	Floor	Suspended Timber	238	413	651		
Zone 2 - Napier	Floor	Ribraft slab	98	273	371	-280	-1.7983358
Zone 3 - Wellington	Floor	Suspended Timber	47	568	615		
Zone 3 - Wellington	Floor	Ribraft slab	3	438	442	-173	-1.109697
Zone 4 - Turangi	Floor	Suspended Timber	121	847	967		
Zone 4 - Turangi	Floor	Ribraft slab	39	685	725	-242	-1.5540133
Zone 5 - Christchurch	Floor	Suspended Timber	110	1107	1217		
Zone 5 - Christchurch	Floor	Ribraft slab	26	922	949	-268	-1.718721
Zone 6 - Queenstown	Floor	Suspended Timber	83	1546	1629		
Zone 6 - Queenstown	Floor	Ribraft slab	19	1296	1315	-314	-2.0149258
							-1.5913907

High Energy Scenario

Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Floor	Suspended Timber	362	6769	7131		
Zone 1 - Auckland	Floor	Ribraft slab	105	7417	7521	390	2.503051
Zone 2 - Napier	Floor	Suspended Timber	409	9199	9607		
Zone 2 - Napier	Floor	Ribraft slab	92	10109	10201	593	3.805048
Zone 3 - Wellington	Floor	Suspended Timber	129	11585	11714		
Zone 3 - Wellington	Floor	Ribraft slab	4	14049	14053	2339	15.00122
Zone 4 - Turangi	Floor	Suspended Timber	224	13284	13508		
Zone 4 - Turangi	Floor	Ribraft slab	31	15756	15787	2279	14.61394
Zone 5 - Christchurch	Floor	Suspended Timber	224	14656	14880		
Zone 5 - Christchurch	Floor	Ribraft slab	32	17998	18030	3151	20.20344
Zone 6 - Queenstown	Floor	Suspended Timber	155	17186	17341		
Zone 6 - Queenstown	Floor	Ribraft slab	14	21187	21201	3860	24.75024
							13.47949

ESS2: Consideration of linear junction heat losses (external walls)

Baseline							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	304	1155	1459		
Zone 1 - Auckland	Wall	Steel	324	1173	1497	38	0.3032671
Zone 2 - Napier	Wall	Timber	309	2383	2693		
Zone 2 - Napier	Wall	Steel	328	2409	2738	45	0.3633927
Zone 3 - Wellington	Wall	Timber	49	3447	3496		
Zone 3 - Wellington	Wall	Steel	56	3460	3516	20	0.1626561
Zone 4 - Turangi	Wall	Timber	146	4537	4682		
Zone 4 - Turangi	Wall	Steel	158	4560	4717	35	0.2850404
Zone 5 - Christchurch	Wall	Timber	150	5666	5816		
Zone 5 - Christchurch	Wall	Steel	162	5686	5848	32	0.2599015
Zone 6 - Queenstown	Wall	Timber	88	7446	7534		
Zone 6 - Queenstown	Wall	Steel	98	7473	7571	37	0.29562
							0.2783129
With junction heat losses							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	314	1497	1811		
Zone 1 - Auckland	Wall	Steel	333	1514	1847	36	0.2886577
Zone 2 - Napier	Wall	Timber	318	2930	3248		
Zone 2 - Napier	Wall	Steel	337	2957	3293	45	0.3664464
Zone 3 - Wellington	Wall	Timber	50	4179	4228		
Zone 3 - Wellington	Wall	Steel	56	4194	4250	21	0.1718836
Zone 4 - Turangi	Wall	Timber	152	5425	5577		
Zone 4 - Turangi	Wall	Steel	164	5451	5615	38	0.305825
Zone 5 - Christchurch	Wall	Timber	156	6679	6835		
Zone 5 - Christchurch	Wall	Steel	168	6703	6870	35	0.285952
Zone 6 - Queenstown	Wall	Timber	93	8731	8823		
Zone 6 - Queenstown	Wall	Steel	102	8764	8866	42	0.3422567
						mean	0.2935036
Steel junction HL 50% of timber							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	314	1497	1811		
Zone 1 - Auckland	Wall	Steel	328	1342	1670	-141	-1.136357
Zone 2 - Napier	Wall	Timber	318	2930	3248		
Zone 2 - Napier	Wall	Steel	332	2682	3014	-234	-1.8862642
Zone 3 - Wellington	Wall	Timber	50	4179	4228		
Zone 3 - Wellington	Wall	Steel	56	3824	3880	-348	-2.8059614
Zone 4 - Turangi	Wall	Timber	152	5425	5577		
Zone 4 - Turangi	Wall	Steel	161	5005	5166	-411	-3.3140642
Zone 5 - Christchurch	Wall	Timber	156	6679	6835		
Zone 5 - Christchurch	Wall	Steel	165	6194	6358	-477	-3.84199
Zone 6 - Queenstown	Wall	Timber	93	8731	8823		
Zone 6 - Queenstown	Wall	Steel	100	8118	8218	-606	-4.8851674
						mean	-2.9783007
Steel junction HL 150% of timber							
Climate	Element	Var	Total Cooling (kWh)	Total Heating (kWh)	Total Heating + Cooling (kWh)	ΔkWh	ΔkWh/m2
Zone 1 - Auckland	Wall	Timber	314	1497	1811		
Zone 1 - Auckland	Wall	Steel	337	1671	2009	198	1.5942784
Zone 2 - Napier	Wall	Timber	318	2930	3248		
Zone 2 - Napier	Wall	Steel	342	3208	3550	302	2.4348199
Zone 3 - Wellington	Wall	Timber	50	4179	4228		
Zone 3 - Wellington	Wall	Steel	56	4530	4587	359	2.8906455
Zone 4 - Turangi	Wall	Timber	152	5425	5577		
Zone 4 - Turangi	Wall	Steel	167	5855	6022	445	3.5901451
Zone 5 - Christchurch	Wall	Timber	156	6679	6835		
Zone 5 - Christchurch	Wall	Steel	171	7163	7334	499	4.0225112
Zone 6 - Queenstown	Wall	Timber	93	8731	8823		
Zone 6 - Queenstown	Wall	Steel	105	9346	9450	627	5.0545404
						mean	3.2644901

ESS2: Consideration of linear junction heat losses (ground floors)

Kiva							
Climate	**Element**	**Var**	**Total Cooling (kWh)**	**Total Heating (kWh)**	**Total Heating + Cooling (kWh)**	**ΔkWh**	**ΔkWh/m2**
Zone 1 - Auckland	Floor	Suspended Timber	304	1157	1461		
Zone 1 - Auckland	Floor	Ribraft slab	144	700	845	-616	-3.9522618
Zone 2 - Napier	Floor	Suspended Timber	308	2385	2693		
Zone 2 - Napier	Floor	Ribraft slab	131	1898	2029	-665	-4.2633137
Zone 3 - Wellington	Floor	Suspended Timber	49	3451	3500		
Zone 3 - Wellington	Floor	Ribraft slab	4	3317	3320	-180	-1.1548717
Zone 4 - Turangi	Floor	Suspended Timber	145	4543	4688		
Zone 4 - Turangi	Floor	Ribraft slab	40	4258	4298	-390	-2.4978381
Zone 5 - Christchurch	Floor	Suspended Timber	149	5671	5821		
Zone 5 - Christchurch	Floor	Ribraft slab	33	5839	5873	52	0.33247669
Zone 6 - Queenstown	Floor	Suspended Timber	88	7456	7544		
Zone 6 - Queenstown	Floor	Ribraft slab	18	7868	7886	343	2.19794241
							-1.556311
With junction heat losses							
Climate	**Element**	**Var**	**Total Cooling (kWh)**	**Total Heating (kWh)**	**Total Heating + Cooling (kWh)**	**ΔkWh**	**ΔkWh/m2**
Zone 1 - Auckland	Floor	Suspended Timber	313	1500	1813		
Zone 1 - Auckland	Floor	Ribraft slab	150	991	1142	-671	-4.3025832
Zone 2 - Napier	Floor	Suspended Timber	317	2932	3249		
Zone 2 - Napier	Floor	Ribraft slab	135	2407	2542	-707	-4.5328501
Zone 3 - Wellington	Floor	Suspended Timber	50	4184	4234		
Zone 3 - Wellington	Floor	Ribraft slab	4	4043	4046	-188	-1.202544
Zone 4 - Turangi	Floor	Suspended Timber	151	5433	5584		
Zone 4 - Turangi	Floor	Ribraft slab	44	5144	5188	-396	-2.5405532
Zone 5 - Christchurch	Floor	Suspended Timber	155	6687	6842		
Zone 5 - Christchurch	Floor	Ribraft slab	35	6883	6918	76	0.48625916
Zone 6 - Queenstown	Floor	Suspended Timber	92	8743	8835		
Zone 6 - Queenstown	Floor	Ribraft slab	19	9201	9220	385	2.46702748
							-1.6042073

ESS3: Presence of a floor covering in ground floor assemblies

Baseline – ground floor without floor covering

Kiva							
Climate	**Element**	**Var**	**Total Cooling (kWh)**	**Total Heating (kWh)**	**Total Heating + Cooling (kWh)**	**ΔkWh**	**ΔkWh/m2**
Zone 1 - Auckland	Floor	Suspended Timber	304	1157	1461		
Zone 1 - Auckland	Floor	Ribraft slab	144	700	845	-616	-3.9522618
Zone 2 - Napier	Floor	Suspended Timber	308	2385	2693		
Zone 2 - Napier	Floor	Ribraft slab	131	1898	2029	-665	-4.2633137
Zone 3 - Wellington	Floor	Suspended Timber	49	3451	3500		
Zone 3 - Wellington	Floor	Ribraft slab	4	3317	3320	-180	-1.1548717
Zone 4 - Turangi	Floor	Suspended Timber	145	4543	4688		
Zone 4 - Turangi	Floor	Ribraft slab	40	4258	4298	-390	-2.4978381
Zone 5 - Christchurch	Floor	Suspended Timber	149	5671	5821		
Zone 5 - Christchurch	Floor	Ribraft slab	33	5839	5873	52	0.33247669
Zone 6 - Queenstown	Floor	Suspended Timber	88	7456	7544		
Zone 6 - Queenstown	Floor	Ribraft slab	18	7868	7886	343	2.19794241
							-1.556311

Ground floor with floor covering

Kiva							
Climate	**Element**	**Var**	**Total Cooling (kWh)**	**Total Heating (kWh)**	**Total Heating + Cooling (kWh)**	**ΔkWh**	**ΔkWh/m2**
Zone 1 - Auckland	Floor	Suspended Timber	307	1129	1436		
Zone 1 - Auckland	Floor	Ribraft slab	263	809	1071	-365	-2.3408356
Zone 2 - Napier	Floor	Suspended Timber	314	2334	2648		
Zone 2 - Napier	Floor	Ribraft slab	249	1956	2205	-443	-2.8431333
Zone 3 - Wellington	Floor	Suspended Timber	50	3374	3424		
Zone 3 - Wellington	Floor	Ribraft slab	27	3160	3188	-236	-1.5152805
Zone 4 - Turangi	Floor	Suspended Timber	147	4439	4587		
Zone 4 - Turangi	Floor	Ribraft slab	99	4126	4225	-361	-2.3163207
Zone 5 - Christchurch	Floor	Suspended Timber	153	5554	5707		
Zone 5 - Christchurch	Floor	Ribraft slab	92	5546	5638	-69	-0.4399159
Zone 6 - Queenstown	Floor	Suspended Timber	89	7299	7388		
Zone 6 - Queenstown	Floor	Ribraft slab	52	7376	7428	39	0.2522568
							-1.5338715

Appendix H. Contribution of Materials To Climate Change Results for Modules A1-A3

For modules A1-A3, Figure 16 shows the contributions made to the climate change results by different materials.

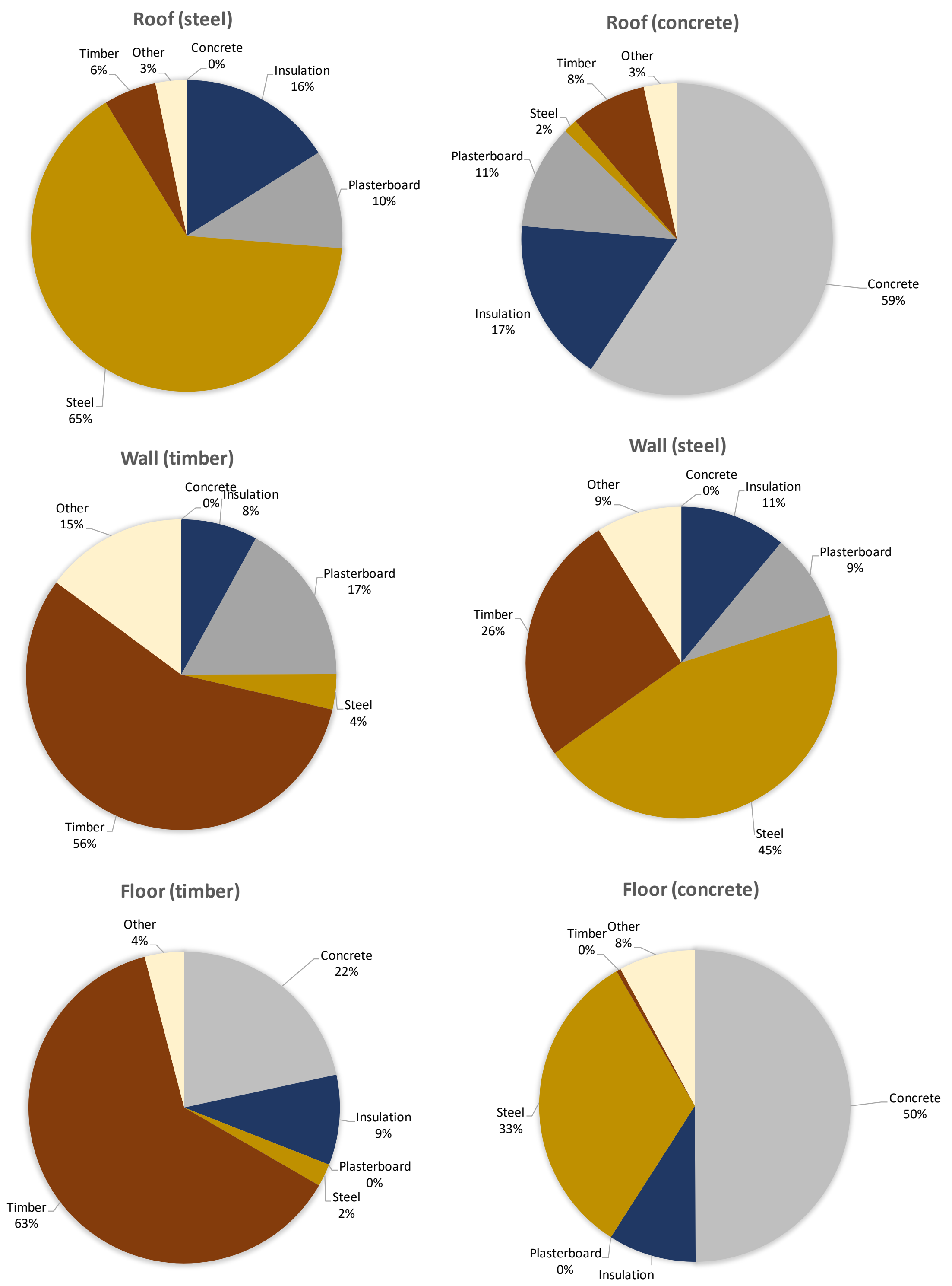

Figure 16 Contribution of different materials to climate change results in modules A1-A3