Study Report

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Housing stock strategies responding to New Zealand's 2050 carbon target

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Preface

This stand-alone report identifies decarbonisation strategies and specific initiatives for new and existing dwellings in New Zealand to estimate potential savings over the period 2020–50.

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Authors

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Abstract

This study investigates three possible future scenarios to better understand the potential to reduce New Zealand's carbon contributions from dwellings. The scenarios represent an increasingly proactive response to the climate change challenge. It builds on previous BRANZ and Massey University research to identify and quantify potential areas for significant dwelling-related carbon reduction at a stock level between the years 2020–50. Both operational and embodied carbon emissions for new and existing dwellings are accounted for. Three dwelling typologies are examined: detached, townhouses (medium density) and apartments. The objective is to prioritise areas for policy development so that New Zealand is better able to meet our 2050 climate goals. Ideally, this report should be a 'living' document to be updated every 5 years or so to reflect changing conditions and new technologies and building practices.

Keywords

Housing stock, residential, carbon footprint modelling, stock modelling, scenario modelling, climate change mitigation, decarbonisation strategies.

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Executive summary

This study demonstrates that it seems highly unlikely that, even with the most drastic carbon-reduction initiatives, our nation's 2050 zero-carbon dwelling-related goal will be met. This holds true even with a near-zero carbon grid and accounting for biogenic carbon storage. Nevertheless, the residential construction industry has a crucial role to play in contributing to the 2050 goal, with the following issues seen as critical.

To be carried out immediately:

- Encourage/incentivise switch to heat pumps for both space and water heating with very low or zero GWP refrigerants.
- Implement requirements for limits on embodied carbon and design for low operational energy use in new builds as soon as possible.
- Restrict use of gas in new builds.
- Encourage/incentivise the construction of smaller, high-performance houses.
- Implement measures to minimise waste during construction.
- Encourage/incentivise replacement of household appliances at end of life with the most-efficient options.

To be carried out in the medium term:

- Identify and implement the most cost-effective measures to reduce operational energy use within existing dwellings.
- Decarbonisation of electricity generation.
- Decarbonisation of the production/supply of building materials.
- Identification and testing of alternative low-carbon building materials.

1. Introduction

1.1 Background

The IPCC 6th Assessment Report states that global greenhouse gas (GHG) emissions from buildings in 2019 were 12 $GtCO_2eq$, equivalent to 21% of global GHG emissions that year (IPCC, 2022, Chapter 9). Of this, 57% were indirect emissions from off-site generation of electricity and heat, 24% were direct emissions produced on site and 18% were embodied emissions from the use of cement and steel.

Globally, residential buildings are a key contributor to carbon emissions and have a significant potential to reduce this contribution (Zhong et al., 2021; WGBC, 2019). Aligned with this, the IPCC 6th Assessment Report states the following:

> **Well-designed and effectively implemented mitigation actions in the buildings sector have significant potential for achieving the United Nations Sustainable Development Goals**. The impacts of mitigation actions in the building sector go far beyond the goal of climate action and include…health gains through improved indoor air quality and thermal comfort as well as reduced financial stresses in all world regions. Overall decarbonised building stock contribute to wellbeing and has significant macro- and micro-economic effects, such as increased productivity of labour, job creation … reduced energy poverty, and improved energy security that ultimately reduces … costs. (IPCC, 2022, p. 9-6)

The construction and use of residential buildings accounts for approximately 10% of New Zealand's total carbon footprint[1] (Bullen et al., 2021). Improving the carbon performance of New Zealand housing provides a significant opportunity to contribute to the goal of net-zero carbon emissions by 2050 (MBIE, 2020).

Previous research has shown that, based on current projections, the carbon footprint of the New Zealand residential building stock between 2018–2050 could be over six times greater than a carbon target consistent with a 1.5°C increase in global temperatures. Approximately two-thirds of the predicted carbon footprint is due to use of existing dwellings and one-third due to the construction and use of new-builds (McLaren et al., 2020). A recent unpublished update of these calculations by BRANZ has indicated that the carbon footprint of the residential sector between 2020 and 2050 could be over eight times greater than the available carbon budget.

This project builds on previous research (Chandrakumar et al., 2019; Jaques et al., 2020) to identify and quantify potential areas for significant reduction in the carbon footprint of New Zealand housing at a stock level. The objective is to prioritise areas for further research and policy development so that New Zealand is better able to meet our 2050 climate goals.

[1] Estimated GHG emissions associated with residential housing as a proportion of New Zealand's total consumption-based GHG emissions in 2012.

1.2 Purpose

The purpose of this project is to:

- identify potential decarbonisation strategies for existing and new dwellings and estimate the potential GHG savings associated with these strategies relative to 'business as usual' emissions during the period 2020–50
- identify the combination of strategies that provide the greatest potential for net carbon savings in the context of New Zealand's commitment to net-zero carbon by 2050
- evaluate the potential savings from both embodied and operational carbon emissions.

This report presents the findings of the project and describes the methodology and underlying assumptions used to develop the 2020–50 Business as Usual (BAU), Climate Emergency (Emergency) and Climate Emergency Plus (Emergency Plus) scenarios and the associated housing stock models. These three models comprise the primary assessment upon which the conclusions of the study are based.

> "There's never been a better opportunity to move to a thriving, low-emissions Aotearoa than right now. When there's so much uncertainty and pressure to make rapid changes, there can be a temptation to try to slow the pace of change. Living with uncertainty is our reality. Delaying action in the expectation uncertainty will be reduced or resolved comes at a cost." (Dr Rod Carr, Climate Change Commission Chair, Stakeholder Letter, May 2022)

2. Methodology

2.1 Introduction

The carbon footprint of New Zealand residential buildings is calculated using a bottom-up approach based on several residential reference buildings for which carbon footprint and modelled energy use data is available. This building-level information is combined with BRANZ projected residential building activity between 2020 and 2050 to estimate the overall carbon footprint of the residential sector for three contrasting but feasible scenarios.

The carbon footprint is expressed as annual and cumulative GHG emissions 2020–50 for the New Zealand housing stock, consisting of detached houses (DH), townhouses (TH) and apartment buildings (AP). Retirement villages, boarding houses, hostels, prisons and other non-private dwellings are excluded from the assessment - but similar modelling principles could be used in these cases.

Three models representing alternative future scenarios for the New Zealand housing stock are provided based on the following general approaches:

- **Business as Usual (BAU)** reflects current projections incorporating broadly accepted market trends, current legislation and anticipated regulatory changes as expressed in government policy.
- **Climate Emergency (Emergency)** explores the possibility of government, industry and individuals responding to the climate change threat in a proactive, ambitious and urgent manner. The basis is what is technically feasible with a practical overlay (for example, replacement of existing technology at end of life).
- **Climate Emergency Plus (Emergency Plus)** expands on changes and efficiency improvements identified in the Climate Emergency scenario by incorporating accelerated decarbonisation of the electricity sector, additional reductions in household energy use and adoption of smaller, high-performing new-build houses.

Detailed assumptions in relation to embodied carbon and energy use of the different housing typologies have been adopted to represent these three scenarios. These are set out in sections 3, 4 and 5.

The above scenarios are not intended as predictions of future performance or recommendations of specific policy direction. They are presented as a tool to explore areas of potential carbon reduction and the extent of change to existing practice and performance that is required to achieve these reductions.

In terms of operational emissions included within scope, only key energy end uses (and therefore likely carbon contributors) are included. Thus, space conditioning, water heating, lighting, plug loads and water delivery were included. The carbon impact of refrigerants used in heat pump technology and micro-renewables – now accounted for in whole-building environmental profiling tools such as Homestar (NZGBC, 2021) – was also assessed but not included in the main assessment. The reasons for their exclusion are detailed within Appendices A and B.

Dwelling embodied carbon emissions resulting from construction and maintenance are based on the BRANZ reference buildings of each typology for which material quantities are available. The reference dwellings comprise three detached homes, one townhouse and one apartment. The life cycle stages considered differ between the new and existing dwellings and are outlined in detail in section 2.3.

2.2 Consumption versus production carbon accounting

There are several different approaches that can be used to measure the carbon footprint of an activity, sector or country. Consumption and production-based carbon accounting are two different approaches that can be adopted. Consumption-based carbon accounting estimates the carbon emissions associated with all goods and services consumed within a country, including those emissions that arise outside of the country's borders such as the embodied emissions associated with the production and transport of imported goods. Production-based accounting estimates the carbon emissions that arise from activities within the country regardless of whether the products of those activities are consumed within or outside the country.

The focus of this project is on consumption-based carbon accounting because:

- it is more meaningful for residential housing, which is essentially a consumption activity – residential housing involves the consumption of building materials, building services and operational energy from producing sectors such as the manufacturing and construction sectors and energy suppliers
- the approach is consistent with previous research on the carbon footprint of New Zealand residential housing that this project builds upon (Bullen et al., 2021; Chandrakumar et al., 2019, 2020; McLaren et al., 2020)
- relying on a production-based approach risks encouraging carbon leakage – the use of imported building materials as these emissions are allocated to the producing country rather than to New Zealand residential housing
- information on the proportion of different building materials used in residential housing that are produced in New Zealand versus those produced overseas is not readily available, which makes it challenging to accurately estimate production-based emissions for construction materials used in residential housing.

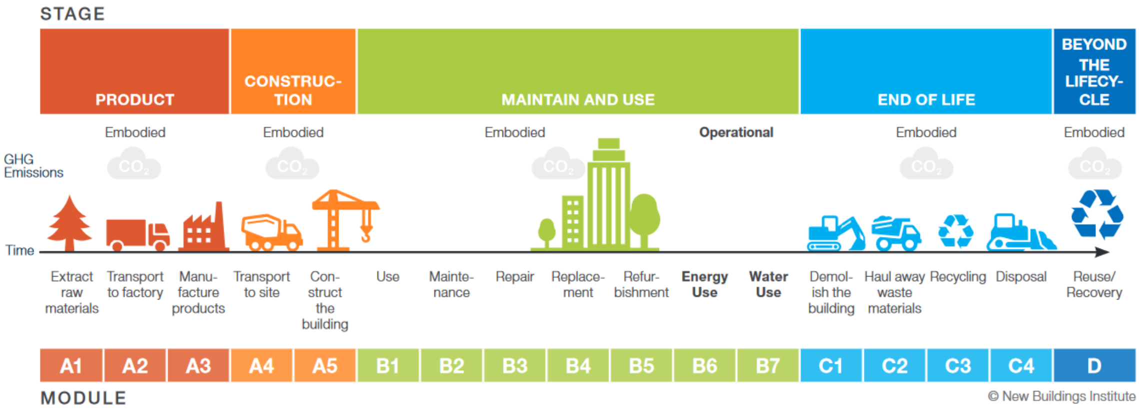
2.3 Calculating a future carbon footprint

The carbon footprint for the New Zealand residential sector for each year from 2020 to 2050 was calculated using the methodology developed by Chandrakumar et al. (2019, 2020).

The following building life cycle stages, as defined in standard BS EN 15978 *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*, are included in the calculation of the carbon footprint (see Figure 1 for coding convention).

- **Product stage:** Modules A1–A3 –- raw material supply, transport and manufacturing.
- **Construction process stage:** Modules A4–A5 – transport and construction installation.
- **Use stage:** Module B2 (maintenance), Module B4 (replacement), Module B6 (operational energy use) and Module B7 (operational water use).
- **End of service life:** Modules C1–C4 – deconstruction/demolition, transport, waste processing and disposal.

The carbon footprint results in this study are calculated excluding the potential benefits of biogenic carbon storage in timber products and excluding the potential benefits and loads beyond the building life cycle (i.e. excluding Module D). The potential role of biogenic carbon (the carbon dioxide sequestered by trees that go on to be made into timber and engineered woods) is explored in section 6.4.



Source: New Buildings Institute, 2022.

Figure 1. BS EN 15978:2011 complete life cycle modules detailed.

GHG emissions associated with the New Zealand building stock are calculated based on the modelled emissions of BRANZ reference buildings for which detailed material quantities and energy use modelling is available (see section 2.4.1). This baseline information is modified where appropriate to reflect the three scenarios (BAU, Emergency and Emergency Plus) based on the assumptions outlined in sections 3–5.

The energy use impact associated with each reference dwelling was estimated for each of the proposed six climate zones outlined in the MBIE *Building Code Update 2021* discussion document (MBIE, 2021a). The GHG emissions of each reference dwelling vary depending on climate zone due to differences in space and water heating demand and transport distances for delivery of materials.

Average GHG emissions by life cycle stage are calculated for each housing typology (DH, TH and AP) for an average-sized new and existing house[2] in each of the six climate zones.

The total carbon footprint of the residential sector for each year between 2020 and 2050 is calculated as follows:

- Multiplying the product stage and construction process stage GHG emissions by the projected number of new-builds of each typology and climate zone per year based on BRANZ residential building stock projections.
- Multiplying annualised use stage impacts by the projected number of houses of each typology and climate zone in operation each year (i.e. existing houses less demolitions plus new-builds). It is assumed that the newly built houses are operational for 6 months in the year of construction and demolished houses are operational for the full year in which they are demolished. Maintenance and replacement GHG emissions are averaged over the lifetime of the house.

[2] Average gross floor area of new-builds: DH = 198 m², TH = 114 m², AP = 94 m² (Stats NZ, 2020). Assumed average gross floor area of existing dwellings: DH = 166 m², TH = 115 m², AP = 99 m².

- Multiplying the end-of-life GHG emissions by the number of demolitions each year. Demolitions per year are estimated based on Page and Fung (2009).

A total annual carbon footprint for the residential sector is calculated by summing the impacts for all typologies and climate zones for each year from 2020 to 2050.

2.4 Thermal modelling approach

2.4.1 General modelling assumptions

Representative housing models for a particular era were sourced from the following house performance options (or combinations of these options) outlined below:

- **Performance option 1 (historical):** lower than current (circa 2020) New Zealand Building Code (NZBC) R-values sourced using the default schedule, infiltration rate of 0.5 air changes per hour (ACH) (traditional) with the living room(s) heated in the morning (7–10am) and evening (5–11pm) and the bedrooms heated from 7–11pm, set point of 18°C, no cooling.
- **Performance option 2 (medium):** using the MBIE 'comparable to international standards' medium R-values (MBIE, 2021a), infiltration rates of 0.35 ACH (minimum allowed by NZS 4303:1990 *Ventilation for acceptable indoor air quality* for fresh air) with all spaces conditioned in the morning (7–10am) and evening (5–11pm), heating set point of 20°C, cooling set point of 25°C.
- **Performance option 3 (high):** as above, but instead using the MBIE 'going further than international standards' R-values (MBIE, 2021a).

A summarised breakdown of the proportions of dwelling types projected out to 2050 for each of the six climate zones is shown in Appendix C. This forecast was compiled by BRANZ economists in August 2021 and reflects the understanding at that time.

Specific R-values utilised for each of the building elements (roof, walls, windows and floor) are shown in Tables 1–3.

Table 1. Option 1 (historical) R-values (m^2°C/W).

Climate zone	Roof	Walls	Floor	Windows
All	2	1	1	0.15

Table 2. Option 2 (medium) R-values (m^2°C/W).

Climate zone	Roof	Walls	Floor	Windows
1	5	2.4	1.9	0.39
2	5.4	2.6	2.2	0.42
3	6	2.8	2.5	0.45
4	6.6	3.2	2.8	0.49
5	7.0	3.5	3.2	0.55
6	7.4	3.8	3.6	0.62

Table 3. Option 3 (high) R-values (m²°C/W).

Climate zone	Roof	Walls	Floor	Windows
1	6.6	2.9	2.5	0.48
2	7.0	3.2	2.8	0.52
3	7.4	3.5	3.2	0.55
4	7.8	3.8	3.6	0.62
5	8.4	4.4	4.2	0.68
6	9.0	5.0	4.8	0.76

Neither the medium and high thermal performance characteristics in Table 2 and Table 3 equate to the recently released H1 Acceptable Solution H1/AS1 (Table 4), which applies to all new housing up to 300 m² and came into effect in November 2022. The assumptions in this study were made prior to the public release by MBIE of NZBC H1/AS1. For example, MBIE has chosen to keep the wall and roof insulation constant throughout the diverse climate zones and only alter the floor insulation slightly. It should be noted that, even though this BRANZ report's assumptions for new housing differ from MBIE's, they are still appropriate as they show the wider implications of an equally significant improvement in thermal performance but dynamically over an extended time period and are more inclusive of a wider set of end-use variables.

Table 4. NZBC H1/AS1 construction R-values effective November 2022.

Building element	Construction R-values (m²·K/W)[1]					
	Climate zone 1	Climate zone 2	Climate zone 3	Climate zone 4	Climate zone 5	Climate zone 6
Roof[2]	R6.6	R6.6	R6.6	R6.6	R6.6	R6.6
Wall	R2.0	R2.0	R2.0	R2.0	R2.0	R2.0
Floor						
Slab-on-ground floors	R1.5	R1.5	R1.5	R1.5	R1.6	R1.7
Floors other than *slab-on-ground*	R2.5	R2.5	R2.5	R2.8	R3.0	R3.0
Windows and doors[3]	R0.46[3]	R0.46[3]	R0.46	R0.46	R0.50	R0.50

The three housing typologies – stand-alone (detached), townhouses and apartments – were examined in this study. Unfortunately, no formal thermally representative model dwelling exists for the New Zealand situation. Thus, the models developed were based on examples previously used by BRANZ for similar studies (such as Jaques et al., 2020). In all, five residential building models were utilised: three detached houses (166 m², 194 m² and 194 m²), one townhouse complex (887 m²) and 1 apartment building (3,721 m²). Their wireframe outlines are provided in Figure 2. All have been modelled in the six climate zones defined in the recent MBIE H1 update (MBIE, 2021a). Thus, zone 1 = Auckland, zone 2 = Napier, zone 3 = Wellington, zone 4 = Taupō, zone 5 = Christchurch, zone 6 = Queenstown. EnergyPlus 9.4, a well-respected program, was utilised for the thermal and energy simulation. Hourly weather files for New Zealand produced by NIWA[3] were applied.

[3] https://energyplus.net/weather-region/southwest_pacific_wmo_region_5/NZL

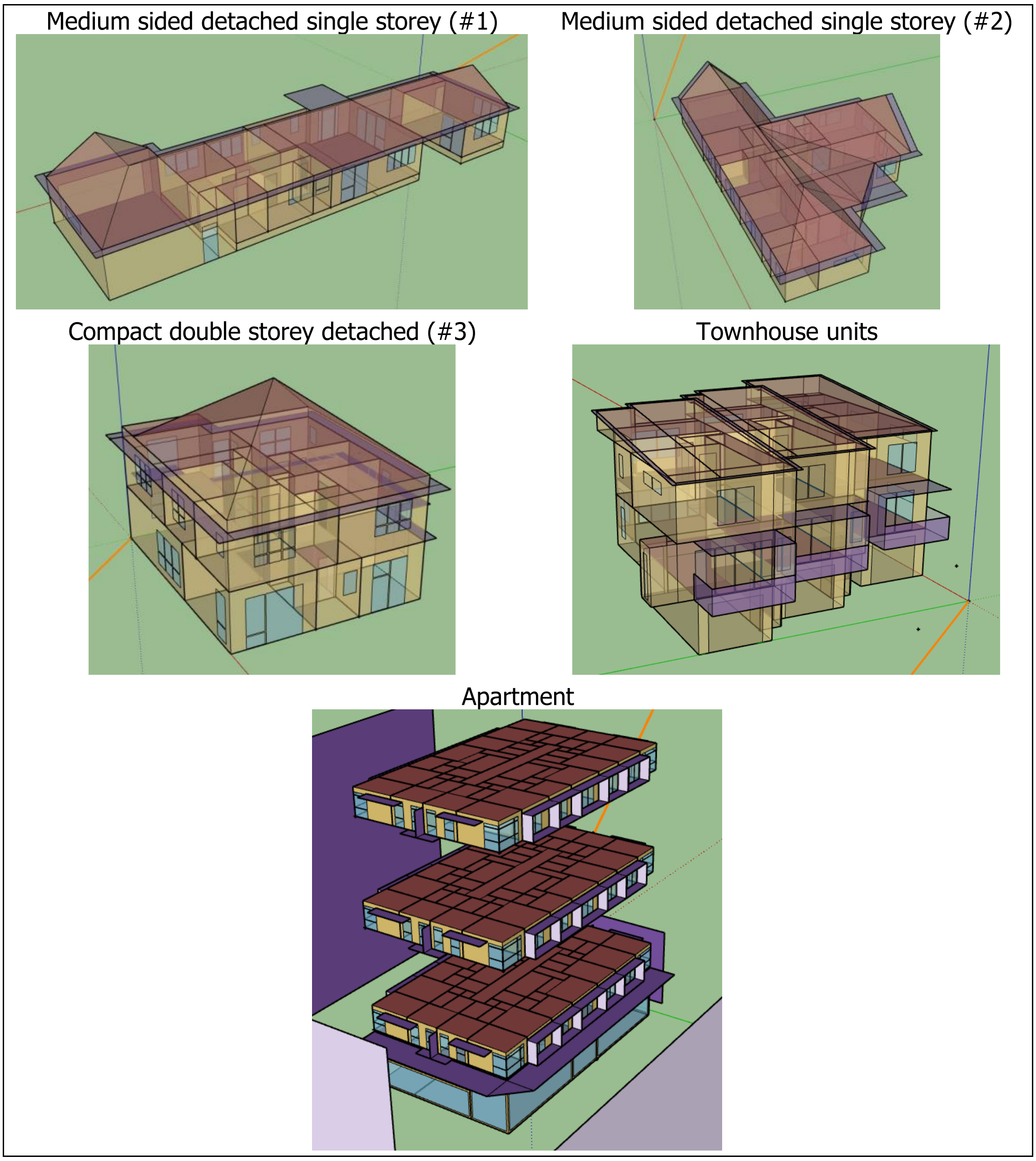


Figure 2. Wireframe models of the five dwellings used for thermal modelling.

Some adjustments were made to previous BRANZ thermal simulation work (Jaques et al., 2020; Jaques, 2019), reflecting an ongoing refinement in thinking:

- Adjusting the internal gains away from the very high values used in NZS 4218:2009 *Thermal insulation – Housing and small buildings* and accounting for modern appliance efficiencies (see Appendix D for detailed discussion on both issues).
- Using the complex glazing constructions rather than the simple constructions typically applied in simulation work (see section 2.4.5).

No adjustments were made from the existing publicly available NIWA-derived hourly climate files to account for climate change.

Other key modelling assumptions were applied to this study:

- Site shading was not modelled, as this can be highly variable and many houses do not suffer significant shading from their surroundings.
- Curtains were not modelled due to uncertainty regarding assumptions around usage and installation quality.
- In the case of the apartment, the model was simplified by only modelling the top, bottom and middle floors. The total energy use was estimated by multiplying the results of the middle floor to cover the others. This simplification approach has previously been verified for accuracy (Ellis & Torcellini, 2005). Similarly, in the medium-density development, the middle and end dwellings were modelled, with the middle one being multiplied to cover the others.

For the option 1 (historical) houses, it is recognised that the existing housing stock has a wide variation in insulation levels and infiltration rates. This diverse range of thermal performances was simplified in the BRANZ modelling by defaulting to the 166 m² floor area detached reference house (#1) with Table 1 R-values to better reflect an average existing house. This simplification represents a limitation of the modelling but is considered a pragmatic solution to reflect a diverse portfolio of existing houses. For example, a recently constructed existing house is likely to have lower emissions per m² but a larger floor area than the default existing house.

2.4.2 Infiltration and ventilation

As per NZS 4218:2009 and standard practice, infiltration was assumed to be 0.5 ACH in most zones. The exception was the roof space, which was assumed to have a constant infiltration/ventilation rate of 5 ACH, and the subfloor in detached house #1, which was assumed to have 11 ACH based on consultation with BRANZ ventilation experts. Note that these assumptions are highly uncertain, and measurements of identical houses on the same site have found significant variation in the recorded roof infiltration.

Ventilation was set to activate at 23°C. Maximum ventilation rates were assumed to be 30 ACH in the main living spaces where they had good cross-ventilation potential and openable outside doors and 10 ACH in other rooms. In the apartment building, due to its design, there is much less capacity for cross-ventilation between different rooms, and ventilation rates may be lower. A maximum of 15 ACH was assumed in the living spaces with openable balcony doors and 5 ACH in the rooms with only small openable windows. These assumptions were based on estimates of the high-end ventilation rates that were readily reached in more-complicated airflow network models when the windows were opened.

2.4.3 Heating and cooling

Space conditioning was provided using an ideal loads approach (a simplified 'perfect' system), which effectively has a coefficient of performance (COP) of 1. A multiplication factor was used to reflect the efficiencies applied (see Table 6 to Table 8 for exact COP factors used). Note that the set points were set using operative temperature, which is an average of air and radiant temperature. This is considered to better align with human perceptions of temperature.[4]

Results were all provided as a combined heating and cooling figure in units of kWh/m².

[4] https://designbuilder.co.uk/helpv2/Content/Calculation_Options.htm

2.4.4 Ground modelling of concrete slabs

Thermal modelling ground-coupled concrete slabs is complex and is often greatly simplified in thermal studies as a result. The concrete slabs and ground in this study were modelled using the GroundDomain model in EnergyPlus.

Soil properties were assumed as shown in Table 5.

Table 5. Soil properties used in thermal simulation.

Conductivity	1.2 W/m-K	BRANZ recommended value for New Zealand (Trethowen, 2000)
Density	1500 kg/m^3	ANSI/ASHRAE Standard 140-2007 Standard method of test for the evaluation of building energy analysis computer programs, Addendum B Table B18-1 NZS 4214:2006 *Methods of determining the total thermal resistance of parts of buildings* (clay soil)
Specific heat	800 J/kg-K	ANSI/ASHRAE Standard 140-2007 Addendum B Table B18-1

To model the under-slab insulation and account for the fact that the insulation does not go all the way to the edge of the slab (due to the slab thickenings at the foundations), an approximation was used. The R-value of the slab insulation was taken as the difference between the R-value of an uninsulated slab and a slab with under-slab insulation in the BRANZ *House insulation guide* (5th edition). Thus, it was modelled as providing an additional R-value of ~R0.5 rather than R1.2.

2.4.5 Glazing

The windows were modelled using the detailed window modelling methods in EnergyPlus rather than the simple glazing modelling method that is commonly used. Previous BRANZ studies (MBIE, 2021a) have found that the simple modelling method appears to have problems with aluminium frame conductivity as well as underestimating the benefits of low-E coatings. Consequently, LBNL WINDOW8.0 was used to put together combinations of glass, air gap, spacer and frame to meet the target R-values as described in the constructions. These were then exported into the EnergyPlus IDF format and modelled.

2.5 Building stock projections

The projected growth in housing stock for all three scenarios is based on BRANZ stock projections of new-build activity differentiated into detached houses, townhouses and apartments in each of the six climate zones. These projections are based on the figures produced in the *National Construction Pipeline Report 2021* (MBIE, 2021c). For the outer-years, we assume that the general level of new-build activity returns to the long-run average in 10 years' time before growing steadily by the long-term average growth rate. We note that it is likely that activity will return to the boom-bust cycle that is prevalent in the industry. However, these figures aim to illustrate the longer-term trend rather than short-term peaks and troughs (Matthew Curtis, BRANZ Building Economist, personal communication, 2021).

3. Business as Usual scenario assumptions

3.1 Introduction

The Business as Usual (BAU) scenario is intended to reflect current projections incorporating broadly accepted market trends, current legislation and anticipated regulatory changes as expressed in government policy (early 2022). A summary of the key assumptions adopted in this scenario is provided in Table 6 and further elaborated on in sections 3.2–3.7.

At the time this study was carried out, MBIE had begun developing its Building for Climate Change (BfCC) programme. Given the consultative nature of this early development, any suggested BfCC thresholds were not specifically used to guide the modelling in this scenario.

3.2 Electricity emissions factors

In the BAU scenario, life cycle-based GHG emissions factors for future electricity use are taken from previous BRANZ research (BRANZ, 2021), based on the generation mix and new-build generation infrastructure associated with the Environment scenario in the MBIE electricity demand and generation scenarios (MBIE, 2019).

The GHG emissions factors per kWh of electricity consumed incorporate emissions associated with extraction and transportation of fossil fuels for thermal generation, operation and maintenance activities of electricity generation (including renewable generation), geothermal fugitive emissions, transmission and distribution losses and the embodied impacts of new electricity generation infrastructure.

3.3 Embodied carbon

Dwelling embodied carbon emissions are based on the BRANZ reference buildings of each typology for which material quantities are available. The reference houses include three detached houses, one townhouse and one apartment building. The embodied GHG emissions associated with Modules A1–A5, B2, B4 and C1–C4 have been calculated for each reference building[5] using BRANZ LCAQuickV3.5.[6] The average impacts per m² are then calculated for each typology and applied to the current average-sized new-build (Modules A1–A5, B2, B4) or existing house (Modules B2, B4, C1–C4) of each typology.

3.4 Space heating/cooling

In New Zealand, heat pumps are subject to Minimum Energy Performance Standards (MEPS) and Mandatory Energy Performance Labelling (MEPL) requirements.[7] There is a new Zoned Energy Rating Label introduced in 2021. It provides a more accurate performance indication of the appliance. The new label will be mandatory for all new heat pumps and provide heating capacity (in kW) at outdoor temperatures of 2°C and

[5] A limitation of these calculations is that manufacturing emissions are based on current data and remain static over the study period (2020–50). The future emissions associated with Modules A1–A3 and B4 are therefore likely to be overstated in the BAU scenario.
[6] www.branz.co.nz/environment-zero-carbon-research/framework/lcaquick/
[7] www.eeca.govt.nz/assets/EECA-Resources/Product-regulations/The-new-Zoned-Energy-Rating-Label-for-heat-pumps-air-conditioners.pdf

7°C, thereby providing indicative seasonal efficiencies. In most New Zealand climates, outdoor temperatures will not fall below 7°C for extended periods over winter. The exceptions to those are the new zone 5 and zone 6 climates (which incorporate Southland, Canterbury and Queenstown Lakes Districts). This study reflects the lower COPs due to falling outdoor temperatures.

The residential heat pump current and future performance approach was largely leveraged off the New Zealand Energy Scenarios TIMES-NZ 2.0 model.[8] This analysis is, in turn, based on AS/NZS 3823.4.2:2014 *Performance of electrical appliances – Air conditioners and heat pumps* modelling. Utilising the EECA study was necessary to ensure some consistency between the two residential housing models but also to provide better guidance on cold weather performance and consequent seasonal efficiency. In short, AS/NZS 3823.4.2:2014 provides a model for the decline in heat pump output and efficiency with temperature. In calculating the COP, top-up-resistance heating is assumed when the heat pump output is lower than the heating load (which has the effect of lowering the COP when this is needed).

Keeping in line with this approach, the starting point for heat pump heating efficiency (COP) in this BRANZ study was as follows:

- COP for climate zones 1–4 – 3.75
- COP for climate zones 5–6 – 2.5.

These COPs were then increased periodically (in the years 2030 and 2040) to represent improvements in technology and installation. The increases were based on discussion with experts and historical performance gains.

The types of heating appliances and their associated fuel types and efficiencies in new and existing buildings were informed by two BRANZ study reports. For new dwellings, the BRANZ longitudinal benchmarking study was utilised (Jaques, 2019). As the benchmarking study only focuses on detached dwellings, estimations for the two other building types were based on pragmatism and BRANZ expertise. For the existing dwellings, findings from the BRANZ House Condition Survey completed in 2015/16 and capturing a total of 560 houses throughout the country were utilised (White & Jones, 2017; White et al., 2017).

3.4.1 New dwellings

Dwellings built in 2020–22 are assumed to have a thermal performance equivalent to the (weighted by dwelling floor area) average of the option 1 (historical) and option 2 (medium), named 'current'. Dwellings built between 2023 and 2034 reflect option 2 (medium) thermal modelling results. From 2035, it is assumed that further changes to the H1 clause result in new dwellings having a heating/cooling demand that is an average of current and option 3 (high).

Apartments are the exception to this rule. In the BAU scenario, it is assumed that new apartments have a thermal envelope consistent with the current thermal envelope. Due to the challenges of achieving significant improvements in the thermal envelope of apartments compared to the current thermal modelling assumption, post 2030, more-modest improvements are assumed. Thus, from 2030, it is assumed a 10% reduction in heating/cooling demand results, with a further 10% reduction from 2040 onwards.

[8] www.eeca.govt.nz/insights/data-tools/new-zealand-energy-scenarios-times-nz/

All stand-alone houses and townhouses use either electricity, gas or wood burners for space heating. In climate zones 1–4, in 2020, it is assumed that 66% of new detached houses and townhouses use electricity for space heating and 27% use gas. These baseline proportions are based on projections in the residential energy baseline study for New Zealand 2000–30 (Energy Consult, 2015) for the year 2020. It is also assumed that use of gas for heating decreases gradually over 10 years to reach 0% in 2030 with an equivalent increase in the use of electricity. Use of wood for space heating is assumed to remain constant at 7% throughout the modelling period (Energy Consult, 2015). It is assumed that there is no use of gas for space heating in climate zones 5 and 6 and therefore the proportion of fuel use remains constant throughout the modelling period at 93% electricity and 7% wood.

Apartments in climate zones 1–4 use either gas or electricity for space heating, with 90% using electricity and 10% using gas in 2020. The use of gas for heating decreases gradually over 10 years to reach 0% in 2030 substituted for electricity use. In climate zones 5 and 6, it is assumed there is 100% use of electricity for space heating throughout the modelling period. It is assumed there is no use of wood for space heating in apartments.

3.4.2 Existing dwellings

In the BAU scenario, it is assumed that the thermal envelope and energy demand for heating/cooling of existing dwellings reflects the modelling assumptions and results of option 1 (historical). It is also assumed that there is no change to the space heating/cooling demand of existing houses over the modelling period.

The fuel mix for existing detached houses and townhouses in climate zones 1–4 in 2020 is 52% electricity, 17% gas and 31% wood. In climate zones 5 and 6, it is 69% electricity and 31% wood. The fuel mix for existing apartments in 2020 is the same as noted above for new apartments. Unlike new houses, this mix remains constant until 2039, being considerably more difficult to change en masse. Between 2040 and 2050, there is a gradual phase-out of gas used for heating/cooling, reaching 0% in 2050 for all typologies. Energy demand previously met by gas is assumed to transfer to electricity.

3.5 Water heating

3.5.1 General assumptions

The following general assumptions regarding water heating apply to both new and existing houses of all typologies and in all scenarios:

- Household water heating energy use has no relation to the building's age or typology (Isaacs et al., 2010).
- Due to the lack of any detailed information, natural gas and LPG have been combined into one generic gas figure, reflecting reticulated and bottled gas.
- A weighted average approach has been taken in the calculation of carbon emissions associated with natural gas and LPG, recognising that the bulk of the fuel is likely to be reticulated (natural) gas, and the global warming potential (GWP) emissions factor has been adjusted accordingly.

- All homes in the North Island have a 68/24/8%[9] split for electricity/gas/wood energy end use for water heating in 2020, respectively.
- An insignificant amount of South Island homes have gas water heating (Williamson & Clarke, 2004).
- No fuel wood is used for water heating in apartments.
- In 2020, all housing typologies have the same amount of annual water heating demand at 3,900 kWh/household/year (Energy Consult, 2015).
- Dwellings with gas water heaters consume approximately 1.7 times the energy of resistive element style water heaters (Isaacs et al., 2010).

3.5.2 New dwelling fuel mix

In the BAU scenario, the fuel mix used for water heating in new houses between 2020 and 2029 is assumed to be as follows:

- Detached house and townhouses, climate zones 1–4:
    - Electricity – 68%
    - Gas – 24%
    - Wood – 8%
- Detached houses and townhouses, climate zones 5 and 6:
    - Electricity – 80%
    - Wood – 20%
- Apartments, climate zones 1–4:
    - Electricity – 76%
    - Gas – 24%
- Apartments, climate zones 5 and 6:
    - Electricity – 100%

In the BAU scenario, the fuel mix used for water heating in new homes is static until 2030. In 2030, there is a 10% migration from electric resistive heating to more-efficient heat pumps (with an assumed COP of 3). In 2040, there is an additional efficiency improvement of 20% in heat pumps used for water heating. It is also assumed that a mandate from central government will result in no gas water heating in new homes from 2030 and a corresponding increase in electricity used for water heating.

There is no change in the quantity or efficiency of wood used for water heating over the modelling period.

3.5.3 Existing dwelling fuel mix

In the BAU scenario, the water heating fuel mix noted above for new homes from 2020 to 2029 applies to existing homes from 2020 to 2040.

In 2040, there is a 10% migration from electric resistive heating to the more-efficient heat pumps and a 20% efficiency improvement in heat pumps used for water heating. It is also assumed that a mandate from central government will result in a 10-year phase-out of gas water heating in existing homes from 2040 resulting in no gas water heating by 2050 and a corresponding increase in electricity used for water heating over the 10 years.

[9] This 8% figure is an overestimate based on now outdated BRANZ Household Energy End-use Project (HEEP1) figures and will be updated when the new HEEP2 update is complete.

There is no change in the quantity or efficiency of wood used for water heating over the modelling period.

3.6 Lighting

In the BAU scenario, it is assumed that energy demand due to lighting remains steady at 550 kWh/year/house from 2020 to 2024 based on Energy Consult (2015) in both new and existing houses of all typologies. In new houses, it is assumed that this reduces to 470 kWh/year from 2025 due to adoption of a greater proportion of LED lighting in new houses. From 2036 onwards, energy demand in new houses reduces by a further 1% per year due to anticipated improvements in efficiency. In existing houses, it is assumed that energy demand due to lighting reduces by 1% per year from 2025 due to anticipated improvements in efficiency and switching existing lighting to LED technology.

3.7 Plug loads

In the BAU scenario, the energy demand due to plug loads (plug-in appliances such as refrigerators, ovens and cooktops, electronic equipment, stand-alone heaters) is based on the predicted plug loads for the reference buildings of each typology (see Appendix D). The average impacts per m^2 due to plug loads are calculated for each typology and applied to the current average-sized new-build or existing house of each typology.

Table 6. BAU scenario cases for dwellings 2020–50.

<table>
<tr><th></th><th colspan="4">Space heating related</th><th colspan="3">Water heating related</th><th></th><th></th><th></th></tr>
<tr><th></th><th>Thermal envelope</th><th>Gas</th><th>Electricity</th><th>Fuel wood</th><th>Gas</th><th>Heat pumps</th><th>Fuel wood</th><th>Lighting</th><th>Plug loads</th><th>Water use</th></tr>
<tr><td>NEW stand-alone and townhouses</td><td>2020: Current

2023: Medium

2035: Average of current and high</td><td rowspan="2">2020–29: Phase out gas to zero from 2030</td><td rowspan="2">2020–30: 50% space heating met by heat pumps (HPs)

2031–50: 80% met by HPs

HP COP = 3.75 zones 1–4 and COP = 2.5 zones 5 and 6

20% HP efficiency improvement from 2040</td><td>No change in percentage of wood heating or efficiency</td><td rowspan="2">No gas water heaters from 2030</td><td rowspan="2">From 2030: 10% of new water heaters are HPs

20% efficiency improvement in 2040</td><td>No change in quantity or efficiency</td><td rowspan="2">2020–24: 550 kWh/yr

2025–35: 470 kWh/yr

2036–50: Energy demand reduces by 1%/yr</td><td rowspan="2">Average kWh per m² of typology reference house(s)</td><td rowspan="2">2020–50:
20% reduction in water use</td></tr>
<tr><td>NEW apartments</td><td>10% reduction in 2030 and 2040</td><td>NA</td><td>NA</td></tr>
<tr><td>EXISTING stand-alone and townhouses</td><td rowspan="2">2020–50: Historical</td><td rowspan="2">2040–50: Phase out of gas to zero in 2050</td><td rowspan="2">2020–30: 50% by HPs

2031–50: 60% met by HPs

HP COP = 2.5 zones 1–4 and COP = 2.0 zones 5 and 6

20% HP efficiency improvement from 2040</td><td>No change in percentage of wood heating or efficiency</td><td rowspan="2">2040–49: Phase out gas water heaters to zero in 2049</td><td rowspan="2">2040–50: 10% of electricity convert to heat pump

20% efficiency improvement in 2040</td><td>No change in quantity or efficiency</td><td rowspan="2">2020–24: 550 kWh/yr

2025–50: Energy demand reduces by 1%/yr</td><td rowspan="2">Average kWh per m² of typology reference house(s)</td><td rowspan="2">2020–50:
20% reduction in water use</td></tr>
<tr><td>EXISTING apartments</td><td>NA</td><td>NA</td></tr>
</table>

4. Climate Emergency scenario assumptions

4.1 Introduction

The Climate Emergency (Emergency) scenario explores the possibility of government, industry and individuals responding to the climate change threat in a proactive, sustained, ambitious and urgent manner. The basis is what is technically and practically feasible (for example, replacement of existing technology at end of life).

A summary of the key assumptions adopted in this scenario is provided in Table 7. The Emergency scenario is based on altering some of the assumptions within the BAU scenario to reflect a more proactive response to the climate emergency. A description of the key assumptions that vary from the BAU assumptions is provided in sections 4.2–4.7. The issues that have a more ambitious climate change response compared to the BAU response (outlined in Table 6) are shown in red in Table 7.

4.2 Electricity emissions factors

Electricity emissions factors used in the Emergency scenario are based on a transition to a higher level of renewable electricity generation than assumed within the BAU scenario. In the Emergency scenario, assumptions regarding the proportion of renewable generation are in line with the Climate Change Commission (2021) recommendations of 95–98% renewable generation by 2030. In the MBIE Environmental Electricity scenario, renewable generation comprises 96% of total generation in 2050, and an emissions factor for electricity consistent with this generation mix is used to represent electricity generation in 2030 in the Emergency scenario. The emissions factor in 2020 is based on the average generation mix reported by MBIE (2022a) for the 2020 year, and a gradual transition between these two values is used to estimate emissions factors for the period 2021–29.

It is also assumed that the proportion of renewable electricity generation continues to increase post-2030 and reaches 100% renewable generation in 2050. An electricity emissions factor consistent with a 100% renewable electricity scenario (ICCC, 2019) is used to represent electricity generation in 2050 (BRANZ, 2021), and a gradual transition between the 2030 and 2050 emissions factors is estimated for the intervening years.

Note that renewable generation includes a proportion of geothermal generation and associated GHG fugitive emissions. These emissions together with the embodied emissions associated with new electricity generation infrastructure and other minor operational emissions results in a low, but not insignificant, level of GHG emissions even with 100% renewable electricity generation.

4.3 Embodied carbon

In the Emergency scenario, it is assumed that New Zealand adopts and achieves increasingly more challenging embodied carbon emissions thresholds. These thresholds are reflective of the NZGBC Homestar v5 (NZGBC, 2021) [10] targets for embodied

[10] At the time of undertaking this study, MBIE BfCC targets were not based on specific modelling. Therefore, building targets were based on NZGBC Homestar targets, developed using BRANZ modelling compatible with a maximum 1.5°C temperature increase in 2050.

carbon (EN-2). Modules A1–A5 for new buildings become progressively more ambitious compared to the BAU scenario embodied carbon values (>190 $kgCO_2eq/m^2$), as follows:

- 2025–30: 84 $kgCO_2eq/m^2$
- 2031–35: 60 $kgCO_2eq/m^2$
- 2036–50: 40 $kgCO_2eq/m^2$

For modelling purposes, these combined Module A1–A5 thresholds were allocated to Modules A1–A3 and Modules A4–A5 on an 82:18 basis. It was assumed that all new dwellings were built to the relevant threshold values irrespective of the typology or location of the house. This simplification is needed for practical reasons.

Lower embodied carbon of construction materials would also result in lower GHG emissions associated with Modules B2 and B4. In the absence of specific targets for these life cycle modules, it was assumed that the GHG emissions associated with these modules decreased on an approximately proportional basis compared to the Modules A1–A5 reductions for detached houses. The resulting Modules B2 and B4 values used in the Emergency scenario were as follows:

- 2025–30: 1.08 $kgCO_2eq/m^2$
- 2031–35: 0.81 $kgCO_2eq/m^2$
- 2036–50: 0.54 $kgCO_2eq/m^2$

The above thresholds were assumed irrespective of the typology or location of the house.

4.4 Space heating/cooling

4.4.1 New dwellings

Dwellings built from 2023 onward are assumed to have a thermal envelope equivalent to option 3 (high). This is true for all dwelling typologies.

All typologies use either electricity, gas or wood burners for space heating. With a more climate-responsive scenario, although the gas phase-out remains unchanged from the BAU case, space heating heat pumps get a 20% efficiency improvement both in 2030 and in 2040. In terms of fuel wood heating for new detached and townhouses, a 2% efficiency improvement in 2030 and 2040 now occurs in the Emergency scenario.

4.4.2 Existing dwellings

The thermal envelope for existing stand-alone and townhouses will upgrade to current thermal requirements at a constant rate between 2026 and 2040. However, existing apartments will achieve a 5% thermal upgrade in both 2030 and 2040, reflecting minor changes. The embodied carbon associated with retrofitting existing houses to achieve this improved thermal performance is not accounted for in the modelling.

In terms of space heating appliances, gas is now phased out by 2035 for stand-alone and townhouses, with a 2% increase in wood burner efficiency in both 2030 and 2040. The thermal performance upgrades for apartments are more modest, reflecting practical limitations. A 5% reduction in demand for 2030 and then again in 2040 is modelled. In terms of electrical-based heating, a 20% efficiency improvement now occurs in both 2030 and 2040. No other space heating-related changes are modelled for this scenario in apartment buildings.

4.5 Water heating

4.5.1 New dwellings

In the Emergency scenario, there are several differences for new dwellings. Gas water heating is now phased out earlier (2025), and from 2025, all new dwellings (all typologies) are required to use very energy-efficient heat pumps. These heating appliances are expected to increase in efficiency by 20% both in 2030 as well as 2040. Wood burner contributions are expected to achieve modest efficiency improvement with a 2% improvement in 2030 and 2040.

4.5.2 Existing dwellings

In the Emergency scenario, there are many changes from the BAU assumptions, reflecting a concerted response to the threat of climate change. Gas water heating is now phased out for all dwelling types by 2040. Heat pump technologies are utilised for 50% of all dwellings by 2040, and these improve in efficiency by 20% in both 2030 and 2040. Finally, as for new houses, there is a 2% efficiency improvement in fuel wood technologies in 2030 and 2040.

4.6 Lighting

For new dwellings, where the opportunities for change are greater, by the year 2025, lighting is expected to reduce to 390 kWh/yr per dwelling then decrease in energy demand by 1% a year through to 2050. This is true for all dwelling types.

For existing dwellings, there are no differences in the Emergency scenario compared to the BAU scenario. Thus, until 2024, lighting energy usage is expected to be at around 550 kWh/yr, dropping 1% per year right through to the year 2050. This is true for all dwelling types.

4.7 Plug loads

For all new and existing dwellings, plug loads are assumed to be the same as the BAU scenario until 2030, when they reduce by 20%, and then again by the same amount in 2040. This is the same for all typologies.

Table 7. Emergency scenario cases for dwellings 2020–50 (upgrades from BAU scenario in red).

	Space heating related				Water heating related					
	Thermal envelope	**Gas**	**Electricity**	**Fuel wood**	**Gas**	**Heat pumps**	**Fuel wood**	**Lighting**	**Plug loads**	**Water use**
NEW stand-alone and townhouses	2020: Current 2023: High	2020–29: Phase out gas to zero from 2030	2020–30: 50% space heating met by heat pumps (HPs) 2031–50: 95% met by HPs HP COP = 3.75 zones 1–4 and COP = 2.5 zones 5 and 6 30% HP efficiency improvement in 2030 and 2040	No change in percentage of wood heating 2% efficiency improvement in 2030 and 2040	No gas water heaters from 2025	From 2025: All new water heating is from HPs 20% efficiency improvement in 2030 and 2040	No change in quantity 2% efficiency improvement in 2030 and 2040	2020–24: 550 kWh/yr 2025: 390 kWh/yr 2026–50: Energy demand reduces by 1%/yr	2020–29: Same as BAU 2030: 20% reduction 2040: 20% reduction	2020–50: 32% reduction in water use
NEW apartments				NA			NA			
EXISTING stand-alone and townhouses	2020: Historical 2026–40: Thermal upgrades to current	2020–34: Phase out gas to zero from 2035	2020–30: 50% met by HPs 2031–50: 70% met by HPs HP COP = 2.5 zones 1–4 and COP = 2.0 zones 5 and 6 30% HP efficiency improvement in 2030 and 2040	No change in percentage of wood heating 2% efficiency improvement in 2030 and 2040	2025–40: Phase out gas water heaters to zero in 2040	2025–40: 50% of existing water heating converts to HPs over 15 years 20% efficiency improvement in 2030 and 2040	No change in quantity 2% efficiency improvement in 2030 and 2040	2020–24: 550 kWh/yr 2025–50: Energy demand reduces by 1%/yr.	2020–29: Same as BAU 2030: 20% reduction 2040: 20% reduction	2020–50: 32% reduction in water use
EXISTING apartments	2030 and 2040: 5% reduction in demand due to thermal upgrades	2020–30: 10% gas (zones 1–4) 2031: Zero gas		NA			NA			

5. Climate Emergency Plus scenario assumptions

5.1 Introduction

A summary of the key assumptions adopted in this scenario is provided in Table 8. The Emergency Plus scenario is based on a more ambitious stock-wide effort to reduce the carbon emissions from dwellings. The changes assumed and consequential response are more proactive than that of the Emergency scenario. A description of the key assumptions which vary from the Climate Emergency assumptions is provided in Sections 5.2 to 5.7. The issues which have had a more ambitious climate change response compared to the previous Emergency scenario response (outlined in Table 7) are shown in red in Table 8.

5.2 Electricity emissions factors

Electricity emissions factors used in the Emergency Plus scenario are based on a transition to 100% renewable generation by 2050 as assumed within the Emergency scenario. In addition, the Emergency Plus scenario assumes that, in 2030 and 2050, there will be a 67% reduction in geothermal emissions and a 20% reduction in embodied infrastructure emissions compared to the Emergency scenario emissions. A linear change in electricity emissions is assumed between 2020 and 2030 and between 2030 and 2050.

5.3 Embodied carbon

In the Emergency Plus scenario, it is assumed that New Zealand adopts and achieves embodied carbon emissions thresholds based on the NZGBC Homestar v5 EN-2 embodied carbon in Modules A1–A5 for new buildings on a progressively more ambitious basis. Thus, the response remains unchanged from the Emergency scenario (see section 4.3 for more details).

5.4 Space heating

5.4.1 New dwellings

There is a fundamental change to the way new dwellings are designed – a very high level of year-round thermal performance is now required. Beacon Pathway's Waitākere NOW Home is used as a reference building, having been thermally very well designed for the climate and also reflecting a shift to a more compact form. The thermal envelope area – and therefore conditioned volume – reduces to 114 m^2. All new dwellings must meet the high-performance option requirements from 2023.

Space heating appliance types and proportions remain the same as for the Emergency scenario.

5.4.2 Existing dwellings

Space heating appliance types and proportions remain the same as for the Emergency Plus scenario.

5.5 Water heating

5.5.1 New dwellings

Water heating appliances and proportions for new dwellings remain the same as for the Emergency scenario.

5.5.2 Existing dwellings

Water heating appliances and proportions for existing dwellings remain the same as for the Emergency scenario.

5.6 Lighting

Lighting energy use reduces by 2% over the 2026–50 period for all new dwellings.

For existing dwellings, lighting energy use reduces progressively, reaching 390 kWh/year during 2025–35 for all existing dwellings. Energy use further reduces by 2% per year for 2036–50 period.

5.7 Plug loads

Plug loads energy use for all new dwellings reduces by 30% in 2030 and another 30% in 2040, reflecting technical advancements. The same is true for existing dwellings.

Table 8. Emergency Plus scenario cases for dwellings 2020–50 (upgrades from Emergency scenario in red).

	Space heating related				Water heating related					
	Thermal envelope	**Gas**	**Electricity**	**Fuel wood**	**Gas**	**Heat pumps**	**Fuel wood**	**Lighting**	**Plug loads**	**Water use**
NEW stand-alone and townhouses	2020: Current 2023: High 2028: NOW Home, high	2020–29: Phase out gas to zero from 2030	2020–30: 50% space heating met by heat pumps (HPs) 2031–50: 95% met by HPs HP COP = 3.75 zones 1–4 and COP =2.5 zones 5 and 6 30% HP efficiency improvement in 2030 and 2040	No change in percentage of wood heating 2% efficiency improvement in 2030 and 2040	No gas water heaters from 2025	From 2025: All new water heating is from HPs 20% efficiency improvement in 2030 and 2040	No change in quantity 2% efficiency improvement in 2030 and 2040	2020–24: 550 kWh/yr 2025: 390 kWh/yr 2026–50: Energy demand reduces by 2%/yr	2020–29: same as BAU 2030: 30% reduction 2040: 30% reduction	2020–50: 40% reduction in water use
NEW apartments	2020: Current 2023: High			NA			NA			
EXISTING stand-alone and townhouses	2020: Historical 2026–40: Thermal upgrades to current	2020–34: Phase out gas to zero completed 2035	2020–30: 50% met by HPs 2031–50: 70% met by HPs HP COP = 2.5 zones 1–4 and COP =2.0 zones 5 and 6 30% HP efficiency improvement in 2030 and 2040	No change in percentage of wood heating 2% efficiency improvement in 2030 and 2040	2025–40: Phase out gas water heaters to zero in 2040	2025–40: 50% of existing water heating converts to heat pumps HPs over 15 years 20% efficiency improvement in 2030 and 2040	No change in quantity 2% efficiency improvement in 2030 and 2040	2020–24: 550 kWh/yr 2025–35: Energy demand reduces progressively reaching 390 kWh/yr 2036–50: Energy demand reduces by 2%/yr	2020–29: Same as BAU 2030: 30% reduction 2040: 30% reduction	2020–50: 40% reduction in water use
EXISTING apartments	2030 and 2040: 5% reduction in demand due to thermal upgrades	2020–30: 10% gas (zones 1–4) 2031: Zero gas		NA			NA			

6. Results

This section provides summaries of the carbon footprint results for the three scenarios.

The summaries examine different aspects of the carbon impacts by:

- life cycle module (section 6.1)
- typology (section 6.2)
- individual new-build detached house (section 6.2.1)
- cumulative contributions over the 2020–50 modelling period (section 6.3).

In addition, section 6.4 examines the potential benefits of considering the role of biogenic carbon when calculating the carbon footprint of residential housing.

6.1 Examination by life cycle module

Figure 3 through Figure 5 present the annual carbon footprint for each scenario by life cycle module and age of dwelling (new or existing).

Table 9 provides a summary of the carbon footprint of the housing stock in 2020 and 2050 and the percentage reduction between these dates for each scenario.

Some key features and trends that can be observed include the following.

BAU scenario

- The annual carbon footprint of residential dwellings at a residential stock level decreases by 28% between 2020 and 2050 in the BAU scenario.
- The biggest reduction occurs in operational energy use. This reduction is largely due to anticipated reductions in carbon emissions associated with electricity generation, which are modelled to reduce by 58% per kWh between 2020 and 2050.
- Other contributors to operational energy use reductions include improvements in the thermal envelope of new houses, the phase-out of gas for space and water heating, a transition to heat pump technology and improvements in efficiency of heat pumps.
- It is noted that the growth and then decrease in emissions associated with the product and construction stages between 2020 and 2029 are due to changes in the number of anticipated new-builds during this period.

Emergency scenario

- The annual carbon footprint for all residential dwellings decreases by 71% between 2020 and 2050.
- Overall, compared to the BAU scenario, the total annual carbon footprint in 2050 is 60% lower and there is a 40% reduction in operational emissions.
- Operational energy use of existing dwellings dominates the remaining carbon footprint, making up 41% of the total carbon footprint in 2050. This reflects the challenges of reducing operational energy use within existing homes.
- There is a significant reduction in the carbon footprint in 2025 due to an approximately 60% reduction per dwelling in embodied emissions. Smaller reductions in embodied emissions also occur in 2031 and 2036.
- A steady reduction in operational emissions compared to the BAU scenario occur from 2023 onwards due to a combination of more-ambitious emissions reduction

measures and an accelerated reduction in the GHG emissions associated with electricity generation.

- Accelerated decarbonisation of electricity generation results in a 68% reduction in GHG emissions per kWh of electricity in 2050 compared to 2020.
- Other contributors to a reduction in operational emissions include improvements in the thermal envelope of both new and existing dwellings, a quicker phase-out of gas used for space and water heating, heat pump efficiency improvements, an accelerated transition to heat pump technology and reductions in electricity demand due to plug loads and lighting.

Emergency Plus scenario

- The annual carbon footprint for all residential dwellings decreases by 82% between 2020 and 2050.
- The annual carbon footprint in 2050 is 37% lower than the carbon footprint in the Emergency scenario and 75% lower than the carbon footprint in the BAU scenario.
- Operational energy use of existing dwellings remains significant, but the contribution is reduced to 36% of the total carbon footprint in 2050.
- The Emergency Plus scenario incorporates a move to significantly smaller and more thermally efficient homes from 2028, which is reflected both in reduced embodied emissions and reduced energy demand in new dwellings.
- The carbon footprint in this scenario also reflects an even more accelerated reduction in the carbon emissions associated with electricity generation with an 83% reduction in emissions per kWh of electricity in 2050 compared to 2020.
- In addition, the Emergency Plus scenario incorporates further reductions in water use and electricity demand due to lighting and plug loads in both new and existing dwellings.

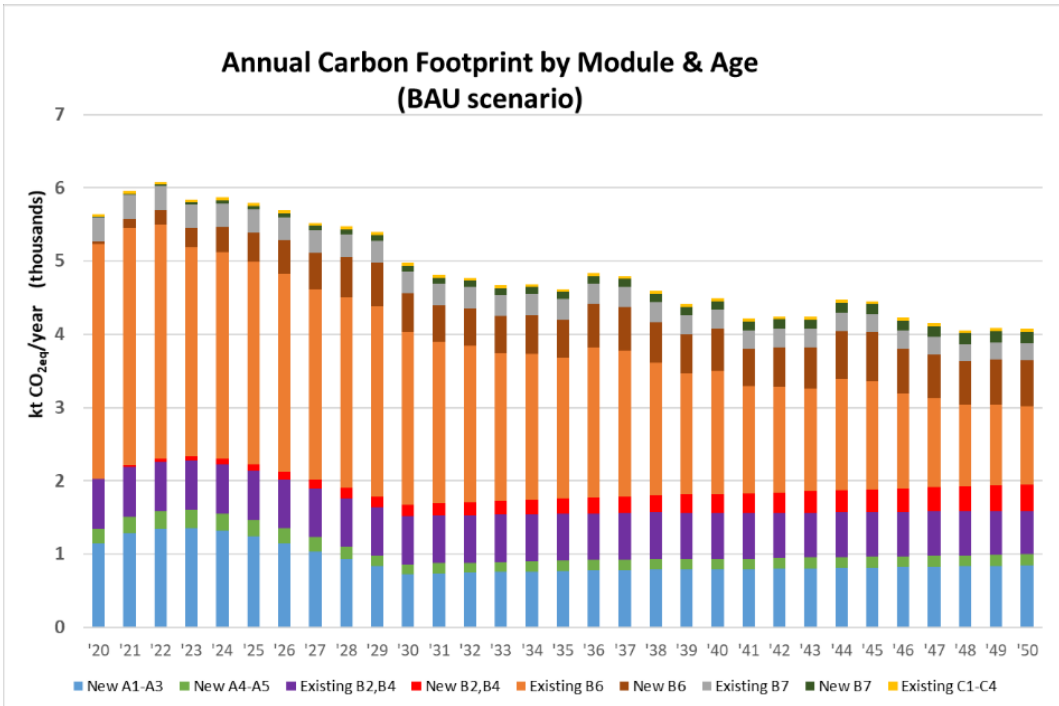


Figure 3. 2020–50 carbon footprint by module – BAU scenario.

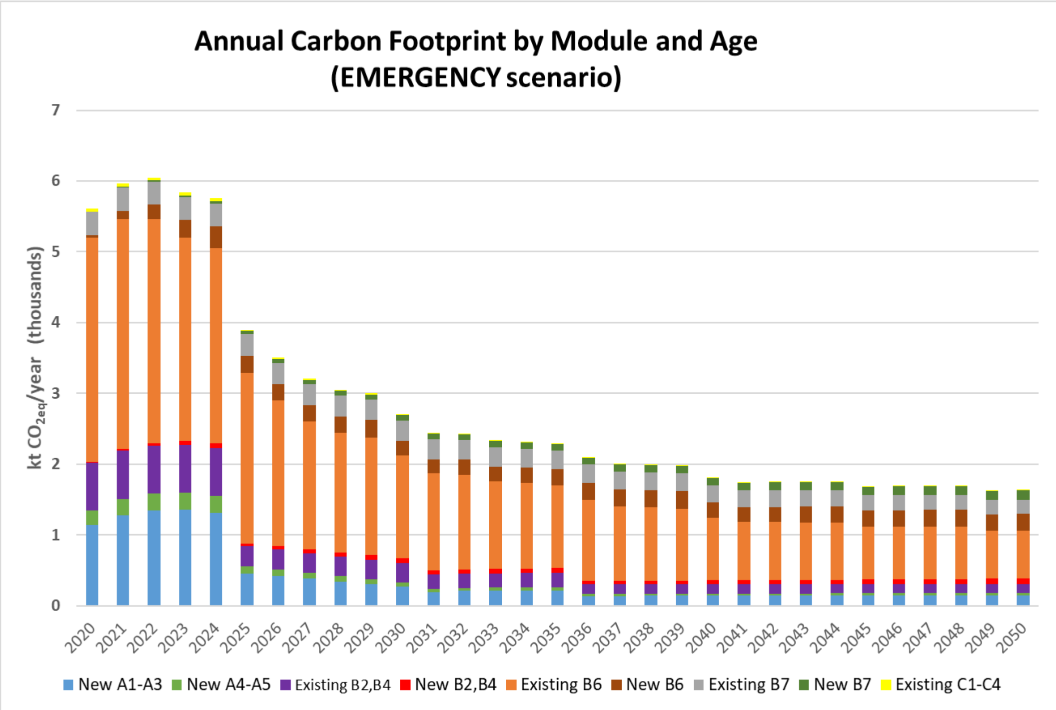


Figure 4. 2020–50 carbon footprint by module – Emergency scenario.

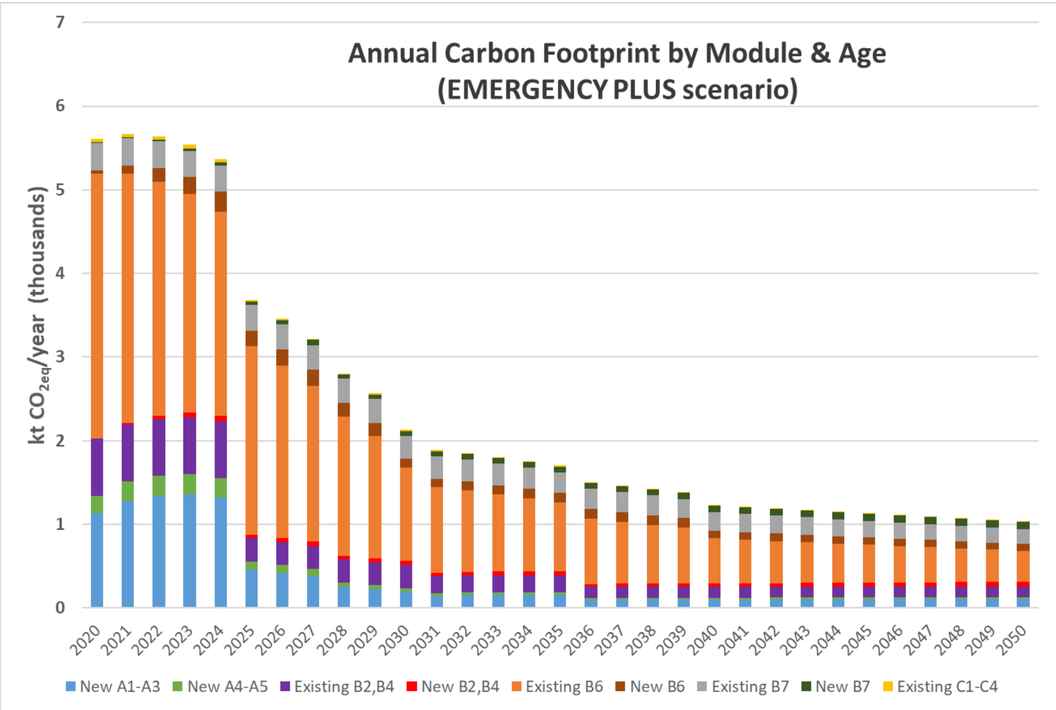


Figure 5. 2020–50 carbon footprint by module – Emergency Plus scenario.

Table 9. Carbon footprint of New Zealand housing stock summary (2020 and 2050).

Scenario	Typology	Carbon footprint in 2020 ($ktCO_2eq$)[11]	Carbon footprint in 2050 ($ktCO_2eq$)	Reduction achieved between 2020 and 2050 ($ktCO_2eq$)
Business as Usual	Detached	4,616	3,199	31%
	Townhouses	688	565	18%
	Apartments	339	308	9%
	Total	**5,643**	**4,072**	**28%**
Emergency	Detached	4,587	1,327	71%
	Townhouses	685	217	68%
	Apartments	338	91	73%
	Total	**5,610**	**1,635**	**71%**
Emergency Plus	Detached	4,583	816	82%
	Townhouses	685	152	79%
	Apartments	338	66	80%
	Total	**5,606**	**1,033**	**82%**

Figure 6 provides a breakdown of the contribution to the Module B6 carbon footprint for an average existing detached dwelling in the BAU scenario to provide an example of relative contribution to operational energy use emissions from different energy uses.

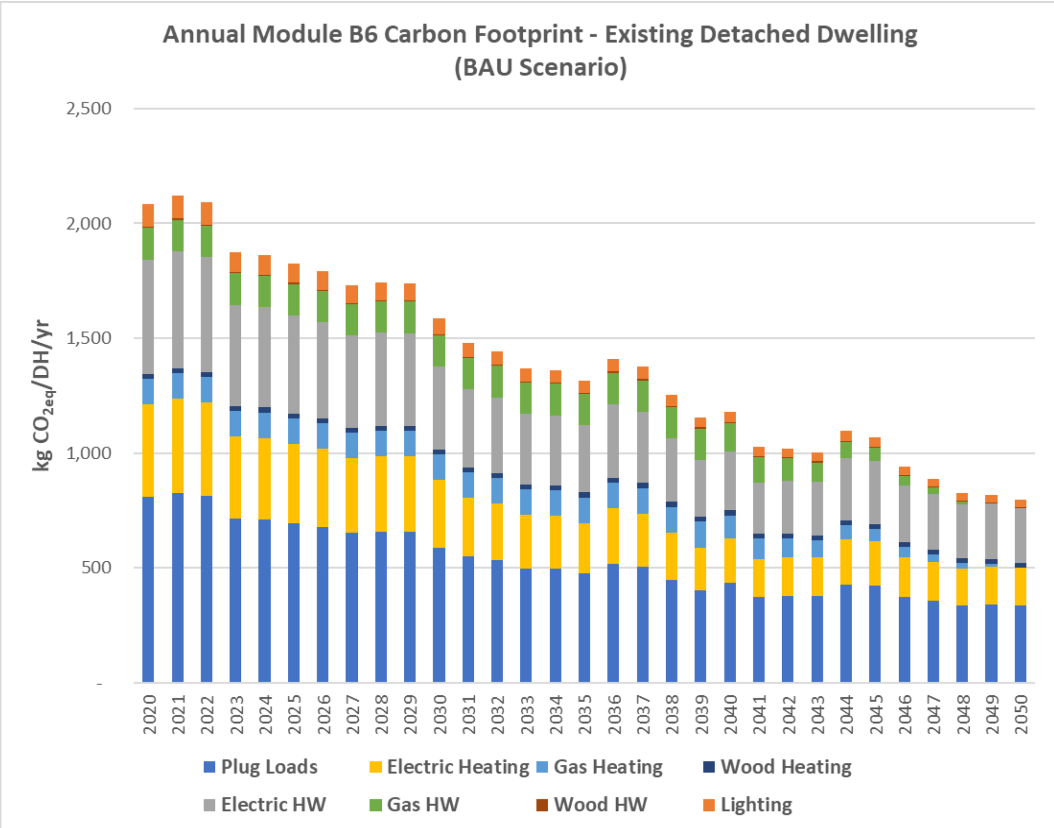


Figure 6. 2020–50 Module B6 carbon footprint, average existing detached dwelling – BAU scenario.

[11] 2020 values vary slightly between scenarios due to differences in rounding and application of assumptions.

The exact breakdown and level of emissions differ between new and existing houses and the different scenarios but follow a similar pattern. Plug loads, space heating and water heating contribute significantly to operational energy use emissions. It is noted that values used for plug loads in this study are an estimate and should be considered indicative. The ongoing BRANZ HEEP2 study is expected to provide more-accurate information on the role of plug loads for New Zealand households. The contribution from lighting and wood used for space and water heating is relatively minor.

6.2 Examination by dwelling typology

Figure 7 through Figure 9 present the annual carbon footprint for each scenario by the dwelling typology (detached, townhouse or apartment) and age (new or existing). The key observation is the dominance of detached houses, both new and existing, compared to the other two typologies. This dominance is seen in all three scenarios and throughout the study period despite small variations over time and between the strategies. In 2020, detached dwellings account for 82% of the carbon footprint in all strategies. In 2050, the proportion of impacts due to detached dwellings varies between 78% (BAU) and 81% (Emergency).

New dwellings are defined in this study as those built in or after 2020. Thus, the cumulative number of new dwellings and associated operational carbon footprint, increases over time. Conversely, the number of existing dwellings reduces by 13% between 2020 and 2050 as a proportion of the existing stock reaches its end of life each year and is removed from the existing dwelling stock. This change in the proportion of new versus existing dwellings is reflected in the carbon footprint results. New dwellings account for 25% of the annual carbon footprint in 2020 but increase to 48% in 2050 in the BAU scenario.[12] In 2050, the carbon footprint due to new dwellings accounts for 39% of the total carbon footprint in the Emergency scenario and 35% in the Emergency Plus scenario.

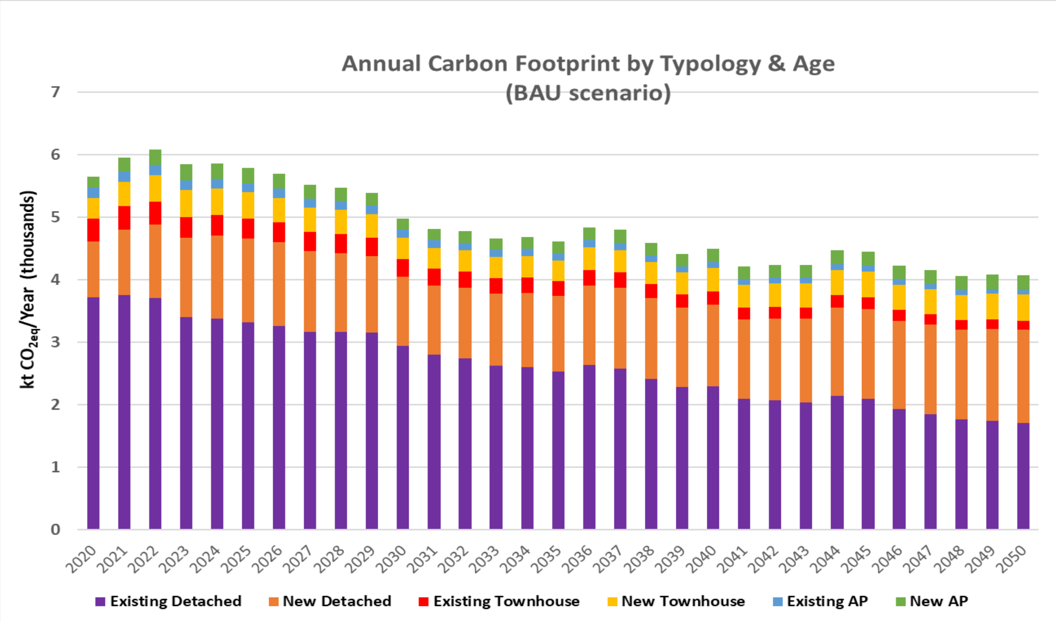


Figure 7. 2020–50 carbon footprint by typology – BAU scenario.

[12] The large upfront carbon cost with new-builds means they contribute sizeably to the carbon footprint in the year of build.

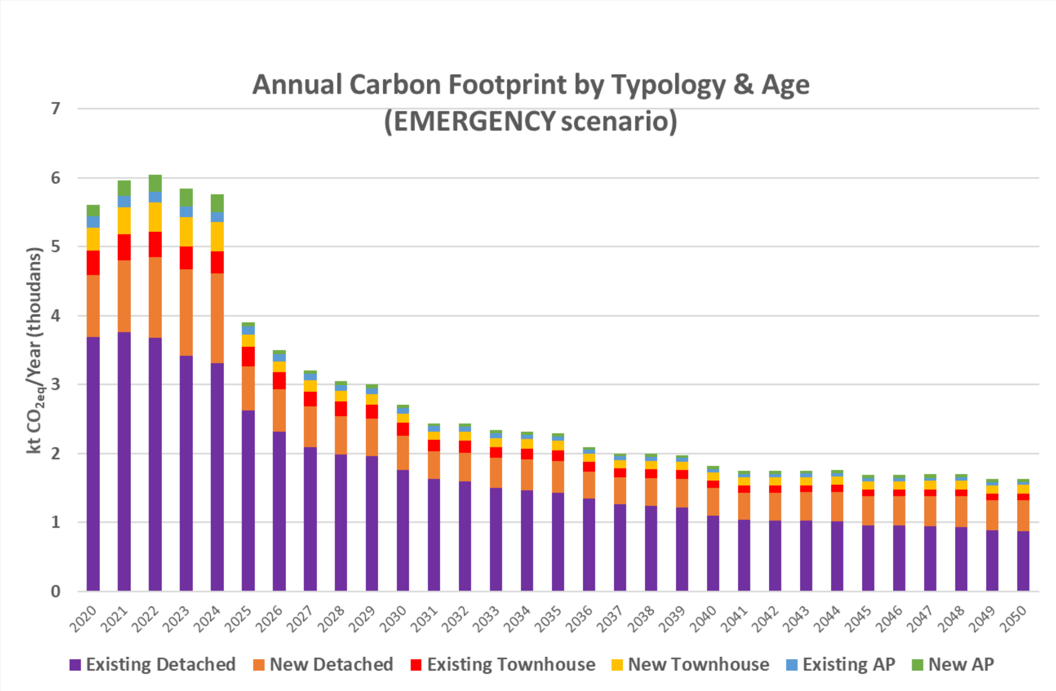


Figure 8. 2020–50 carbon footprint by typology – Emergency scenario.

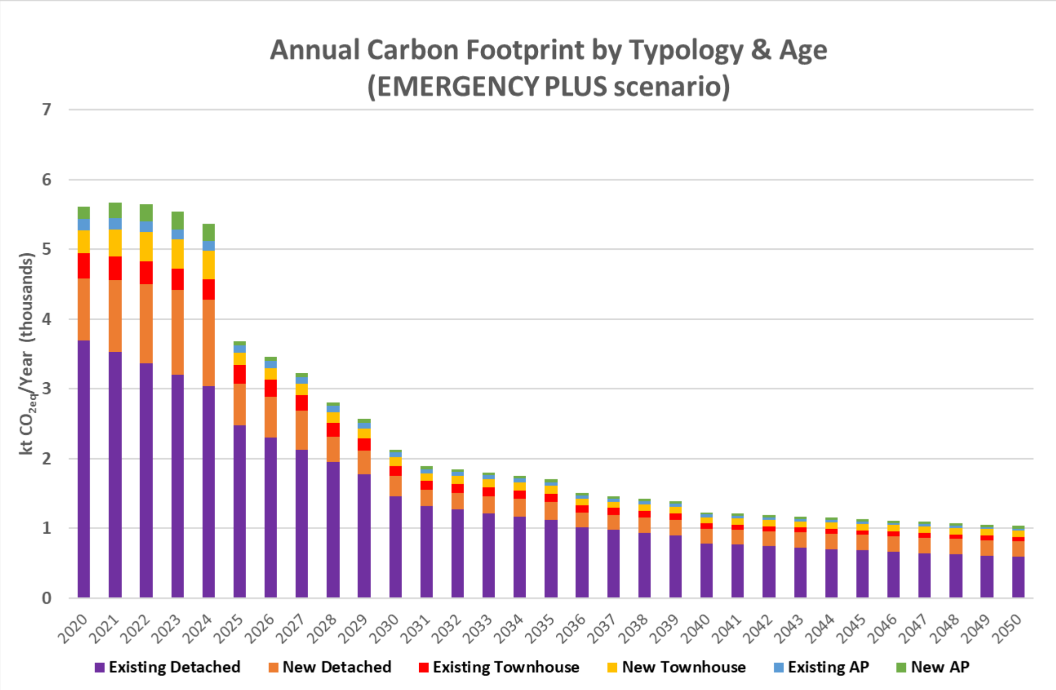


Figure 9. 2020–50 carbon footprint by typology – Emergency Plus scenario.

The differences between the three scenarios in 2050 reflect the different focus of improvement measures. For example, a focus on reducing the size of new houses in the Emergency Plus scenario results in a lower contribution from new dwellings compared to the Emergency scenario. Similarly, more proactive improvements for new dwellings compared to existing houses in both the Emergency and Emergency Plus scenarios results in a lower contribution to the carbon footprint from new dwellings compared to the BAU scenario.

6.2.1 Examination by individual new-build detached house

Figure 10 through Figure 12 present the annual carbon footprint of an individual new-build detached dwelling for each scenario.

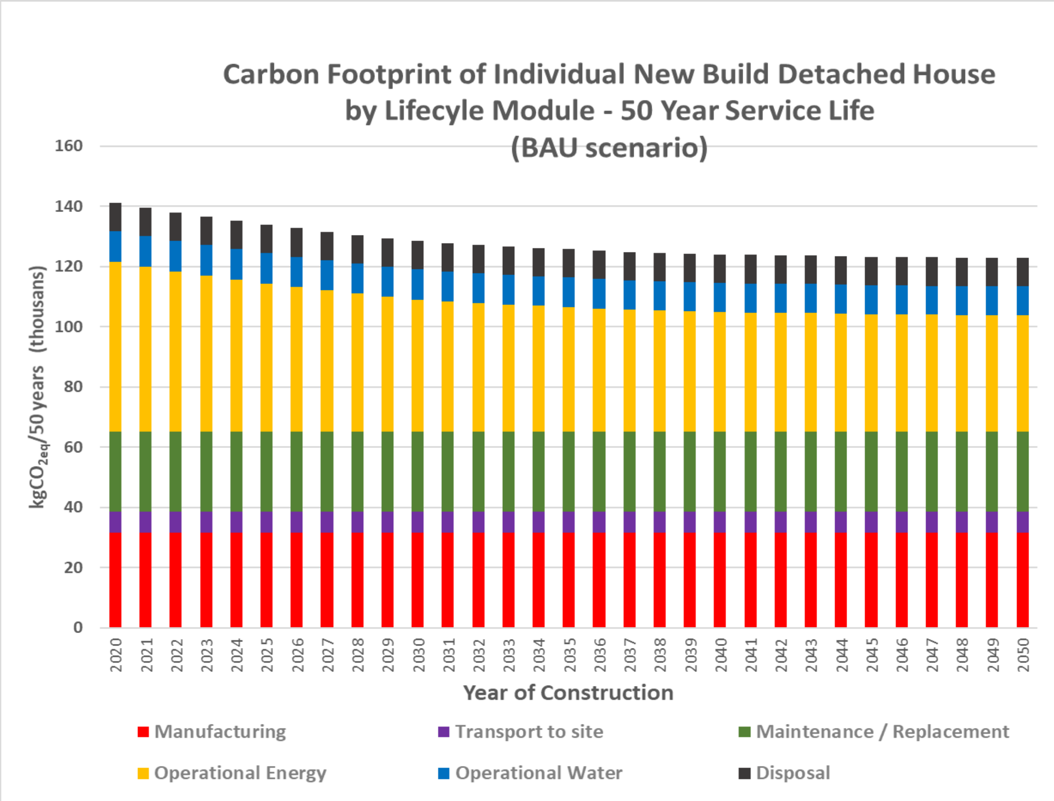


Figure 10. Carbon footprint, individual new detached house – BAU scenario.

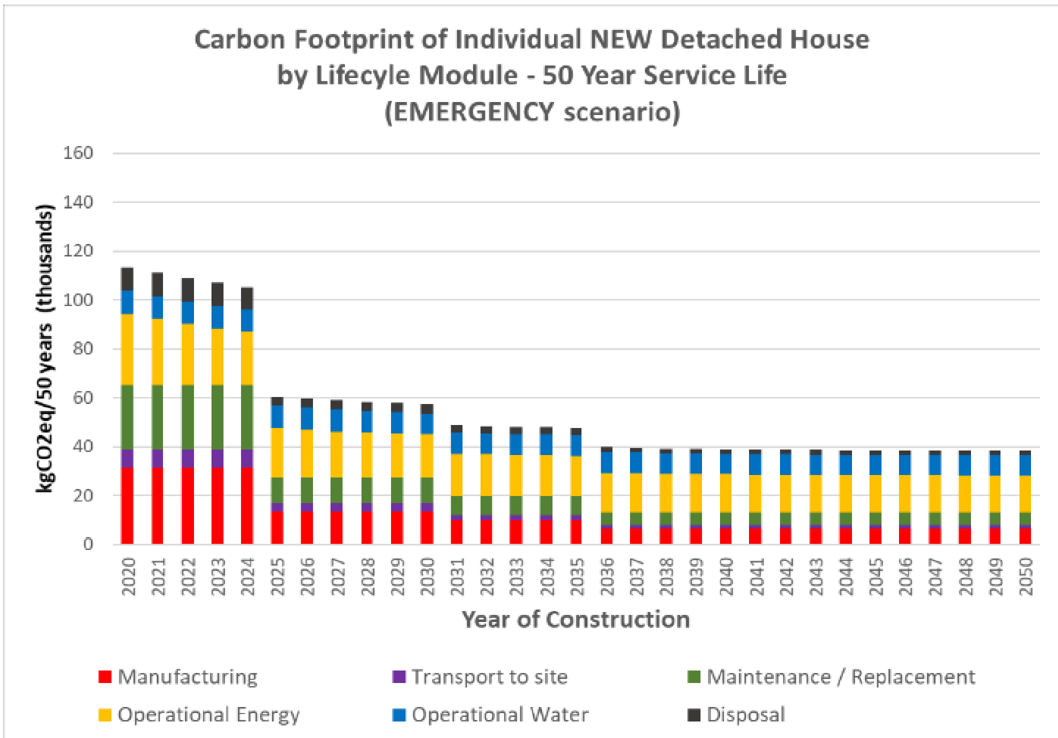


Figure 11. Carbon footprint, individual new detached house – Emergency scenario.

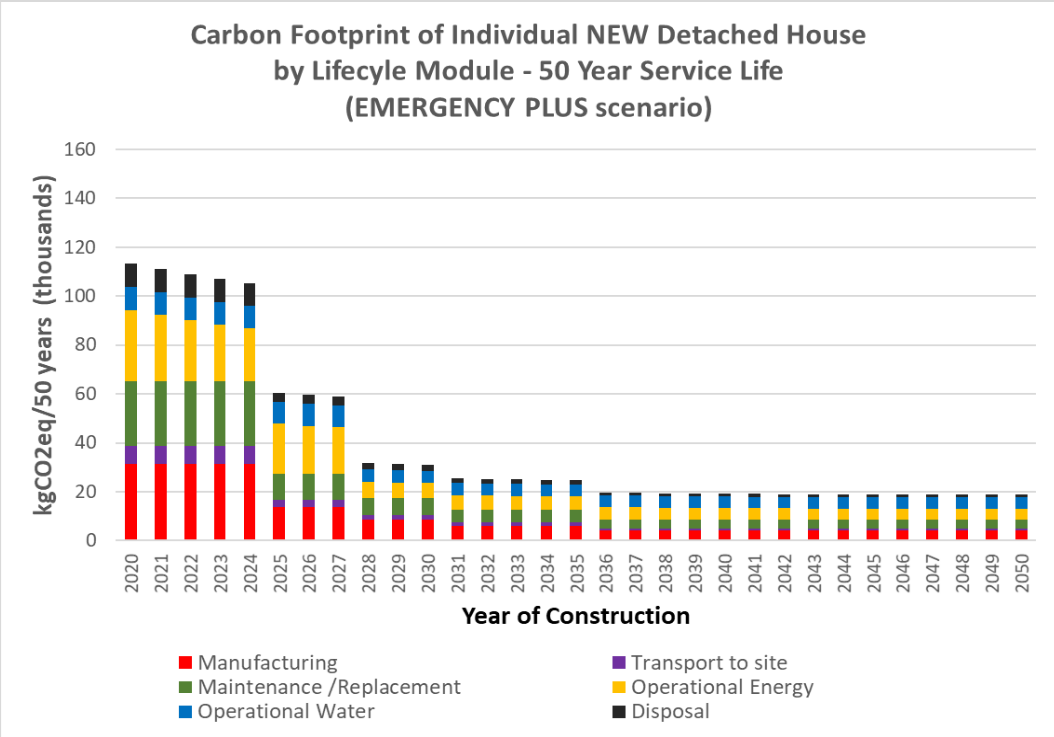


Figure 12. Carbon footprint, individual new detached house – Emergency Plus scenario.

Each bar in these graphs represents the lifetime carbon footprint of a new-build detached dwelling built in that year. A 50-year service life is assumed consistent with the assumed service life in the MBIE embodied carbon technical methodology document (MBIE, 2022b). A detached dwelling is used for this examination due to it being the dominant residential typology in New Zealand.

In the BAU scenario, there is a relatively small 13% reduction in the lifetime carbon footprint of a dwelling constructed in 2050 compared to a dwelling constructed in 2020. In the Emergency scenario, this lifetime carbon footprint reduces by 66%, while in the Emergency Plus scenario, it reduces by 83%.

In the BAU scenario, the gradual reduction in the carbon footprint over the study period reflects a range of improvements related to the operational carbon footprint. These include reductions in the carbon footprint of electricity generation, phasing out the use of gas and a transition to more efficient air conditioner technology and lighting as well as reduced water usage. In the BAU scenario, there is no change in the embodied carbon footprint of dwellings over the study period.

We would expect that initiatives to decarbonise heat generation and grid electricity as well as initiatives to reduce manufacturing waste and reuse, recycle or recover much of the waste that is generated will result in lower manufacturing emissions. The extent and pace of manufacturing GHG emissions reductions is likely to vary significantly for different products and manufacturers, based on technology advances, adoption of new practices and levels of investment. Emissions arising due to replacement of materials during the building service life would be expected to decrease for the same reasons. Additionally, supply chains should become less reliant on fossil fuels, further providing opportunities to reduce embodied carbon. Due to the range of variables, these are not specifically considered in this study.

In the Emergency scenario, the same kinds of carbon-reduction measures are implemented but in a more proactive way than the BAU scenario, resulting in a more pronounced reduction in the carbon footprint over time. In addition, a reduction in the calculated embodied carbon footprint of new-build dwellings results in a significant drop in the overall carbon footprint in 2025 and smaller reductions in 2031 and 2036. These reductions reflect the large upfront carbon impacts of new-build dwellings in the year of construction (see section 4.3).

In the Emergency Plus scenario, the additional measure of a reduction in house size can particularly be seen in the reduced carbon footprint of dwellings built from 2028 onwards. Reduced house size has an immediate and substantiative impact of reducing the embodied carbon footprint associated with construction of a dwelling as well as an ongoing benefit due to the reduced heating and maintenance requirements.

Operational emissions improvements such as a gradual reduction in the carbon emissions associated with electricity generation are less obvious for dwellings built in different years due the influence of these reductions over the whole lifetime of a building. For example, two dwellings built 5 years apart will be subject to identical electricity generation emissions for 45 years of their 50-year service life. Therefore, improvements in the upfront embodied carbon footprint associated with construction are more obvious when examining an individual new-build dwelling, and improvements in operational emissions will tend to be more obvious from changes in the annual carbon footprint of the entire building stock over time. This study assumed that no further carbon reduction measures are implemented after 2050 so the operational carbon footprint remains constant for all years after 2050 that are within the service life of the dwelling.

6.3 Total cumulative carbon contribution by stage

Table 10 through Table 12 show the cumulative carbon impact of the progressively more intensive reduction strategies employed in the three scenarios over 2020–50.

Table 10. 2020–50 carbon impact – BAU scenario by typology and stage.

BAU Scenario		LIFECYCLE STAGE A1-A3: Manufacturing (ktCO2eq)	A4-A5: Transport to site (ktCO2eq)	B2+ B4: Maintenance & Replacement (ktCO2eq)	B6: Operational Energy Use (ktCO2eq)	B7: Operational Water Use (ktCO2eq)	C1-C4: Disposal (ktCO2eq)	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)
NEW	Detached	18,040	4,040	5,032	10,377	1,994	0	39,482
	MDH	5,998	739	691	3,762	555	0	11,745
	Apartments	4,191	370	471	1,190	336	0	6,557
EXIST'G	Detached	0	0	18,228	55,079	7,498	1,162	81,967
	MDH	0	0	835	6,119	695	66	7,715
	Apartments	0	0	747	2,341	552	36	3,676
	TOTAL	28,228	5,148	26,003	78,868	11,631	1,264	151,143

Table 11. 2020–50 carbon impact – Emergency scenario by typology and stage.

Emergency Scenario		LIFECYCLE STAGE A1-A3: Manufacturing (ktCO2eq)	A4-A5: Transport to site (ktCO2eq)	B2+ B4: Maintenance & Replacement (ktCO2eq)	B6: Operational Energy Use (ktCO2eq)	B7: Operational Water Use (ktCO2eq)	C1-C4: Disposal (ktCO2eq)	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)
NEW	Detached	7,959	1,753	1,344	4,715	1,815	0	17,585
	MDH	2,539	398	336	1,601	506	0	5,380
	Apartments	1,296	157	116	506	306	0	2,380
EXIST'G	Detached	0	0	7,210	39,357	7,012	448	54,027
	MDH	0	0	500	4,324	650	33	5,506
	Apartments	0	0	279	1,666	517	15	2,476
	TOTAL	11,794	2,307	9,783	52,169	10,805	496	87,354

Table 12. 2020–50 carbon impact – Emergency Plus scenario by typology and stage.

Emergency Plus Scenario		LIFECYCLE STAGE						
		A1-A3: Manufacturing (ktCO2eq)	A4-A5: Transport to site (ktCO2eq)	B2+ B4: Maintenance & Replacement (ktCO2eq)	B6: Operational Energy Use (ktCO2eq)	B7: Operational Water Use (ktCO2eq)	C1-C4: Disposal (ktCO2eq)	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)
NEW	Detached	6,849	1,513	951	2,275	1,143	0	**12,731**
	MDH	2,539	398	336	1,072	473	0	**4,819**
	Apartments	1,296	157	116	345	286	0	**2,199**
EXIST'G	Detached	0	0	7,210	32,036	6,688	448	**46,381**
	MDH	0	0	500	3,490	620	33	**4,642**
	Apartments	0	0	279	1,360	493	15	**2,146**
	TOTAL	**10,685**	**2,067**	**9,390**	**40,578**	**9,702**	**497**	**72,919**

These are the main takeaways:

- **Timely implementation of policies and strategies are needed in several areas** that contribute to the carbon footprint of the residential sector, including:
    - operational energy demand in both new and existing houses[13]
    - carbon emissions associated with electricity generation
    - embodied emissions associated with new-build houses
    - emissions associated with maintenance, replacement and operational water use particularly in existing detached houses.
- There are **considerable opportunities to reduce New Zealand's housing stock carbon footprint** even with a shift from the projected BAU scenario to the 'urgent but technically feasible' Emergency scenario. The total carbon reduction from BAU to the Emergency scenario is 42% and from BAU to the more ambitious Emergency Plus scenario is 52%, new and existing dwellings inclusive.
- To **provide some comparative context**, the carbon reduction in shifting from BAU to the Emergency scenario is approximately 36 $MtCO_2eq$ over a 30-year period. This is based on the BAU scenario reducing from 5.6 Mt in 2020 to 4 Mt in 2050, giving an average ~4.8 Mt * 30 years = 144 Mt, while the Emergency scenario reduces from 5.6 to 1.6 Mt, giving an average ~3.6 * 30 years = 108 Mt. Compare this to New Zealand's national CO_2 emissions of 78.8 $MtCO_2eq$ for the 2020 year[14] alone, with the energy sector contributing 31.5 $MtCO_2eq$. As an alternative comparison, the carbon emissions associated with household transport in 2017 (direct) were 8.9 $MtCO_2eq$ in 2017[15] alone.
- **Whatever future scenario develops, the same strategies (policies) apply** if the goal is to target the most significant carbon contributors whether examining new or existing houses. For new dwellings, manufacturing should be the target, as it is approximately twice the next most important contributor – operational energy use. This is true no matter the typology. This divide between manufacturing and operational energy use is further extended for the Emergency Plus scenario. For existing dwellings, this changes to the operational stage first with maintenance a distant second (at about one-fifth as important for both the Emergency and Emergency Plus scenarios), regardless of scenario.

[13] Whilst not specifically modelled in this study, it will be important that any incentives aimed at reducing operational energy use in existing houses consider potential embodied carbon implications to achieve this. Failure to do this could result in increasing near-term embodied carbon emissions to obtain future operational carbon savings (that may well not be realised in all cases).

[14] https://environment.govt.nz/assets/publications/GhG-Inventory/New-Zealand-Greenhouse-Gas-Inventory-1990-2020-Chapters-1-15.pdf [Table ES 4.1].

[15] www.stats.govt.nz/news/transport-drives-households-carbon-footprint-up

- The **importance of addressing detached houses** (whether new or existing) first – even if their overall proportion of all dwelling typologies is diminishing – is clearly seen.
- The area of greatest potential for improvement should be on targeting the operational energy use aspects of **existing detached homes**. This issue has 4.9 times the carbon impact of the next highest contributor for the Emergency scenario and 4.7 times that in the Emergency Plus scenario, being manufacturing of new detached homes for both cases. This single-issue needs to incorporate a suite of changes, and measures to improve the thermal envelope of houses may not necessarily result in significant reductions in energy use due to people using a similar amount of energy but enjoying a more comfortable and healthier indoor environment. Therefore, a focus on other potential areas of energy use such as water heating and plug loads is required in addition to improvements in space heating demand.
- **The carbon intensity of the electricity grid** has a major impact on housing stock carbon emissions for both operational and embodied contributions. The findings of this study suggest that decarbonising the electricity supply is more important than reducing operational energy demand. However, the ability to decarbonise the electricity grid is, in turn, significantly impacted by the level of peak electricity demand from housing. For example, Jack et al. (2021) calculated that rapid uptake of currently achievable best-practice standards for energy-efficient buildings could reduce the winter-summer electricity demand variation by three-quarters from business as usual by 2050 and help facilitate a low-carbon energy transition.

6.4 The role of biogenic carbon

6.4.1 Background

Carbon that originates from biological sources is referred to as biogenic carbon. Timber and engineered woods used in residential buildings have the potential to temporarily store biogenic carbon within their biomass over the lifetime of the building and potentially longer depending on the end-of-life treatment of the material.

Previous sections within this study report do not account for the benefits of this temporary storage of biogenic carbon within wood products and consequently reports the carbon footprint of the different scenarios on an 'excluding biogenic carbon' basis. This section examines the impact on the carbon footprint of New Zealand dwellings of accounting for the benefits of biogenic carbon.

Data on the carbon footprint of the reference buildings used to calculate the embodied impacts of New Zealand dwellings in the BAU scenario are available on both an 'excluding biogenic carbon' and 'including biogenic carbon' basis. In the Emergency and Emergency Plus scenarios, the embodied impacts of dwellings beyond 2025 are based on theoretical improvements in the embodied carbon of dwellings and therefore comparative data on including and excluding biogenic carbon values based on actual reference dwellings are not available for these scenarios. The BAU scenario is therefore used to explore the potential benefits of biogenic carbon storage.

An assessment of the carbon footprint of New Zealand dwellings including the benefits of carbon sequestered within timber products was undertaken by repeating the BAU scenario assessment using 'including biogenic carbon' values for Modules A1–A3, A4–A5, B2 and B4. The results of this assessment are then compared with the base case

BAU scenario assessment, which utilises 'excluding biogenic carbon' values for these modules. All other assumptions within the BAU scenario remain unchanged.

6.4.2 Results

Table 13 shows the carbon footprint when biogenic carbon has been included, using the BAU scenario, by life cycle module and dwelling typology. Accounting for the benefits of the biogenic carbon stored in timber products results in a 9% reduction in the total carbon footprint due to residential dwellings (all typologies) over the 2020–50 period. The largest contributor to this reduction is manufacturing (Modules A1–A3), which reduces by 42%. Smaller reductions occur in relation to transport to site/construction installation (Modules A4–A5)[16] and maintenance and replacement (Modules B2 and B4). The dwelling typology that contributes the most to the reduction is new detached houses for which the carbon footprint reduces by 30% when including biogenic carbon.

Table 13. Impact of biogenic carbon introduction – BAU scenario (2020–50).

BAU Scenario including biogenic carbon		% Change by LIFECYCLE STAGE: A1-A3: Manufacturing	A4-A5: Transport to site	B2+ B4: Maintenance & Replacement	B6: Operational Energy Use	B7: Operational Water Use	C1-C4: Disposal	Total % Change by Typology	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)
NEW	Detached	-59%	-25%	-1%	0%	0%	-	-30%	27,745
	MDH	-17%	-12%	-3%	0%	0%	-	-10%	10,603
	Apartments	-5%	-5%	-2%	0%	0%	-	-4%	6,326
EXIST'G	Detached	-	-	-1%	0%	0%	0%	0%	81,869
	MDH	-	-	-3%	0%	0%	0%	0%	7,689
	Apartments	-	-	-2%	0%	0%	0%	0%	3,659
Total % Change		-42%	-21%	-1%	0%	0%	0%	-9%	
TOTAL (ktCO2eq)		16,285	4,042	25,801	78,868	11,631	1,264		137,890

[16] Due to the stored biogenic carbon associated within timber-based products within Module A5 (construction installation).

7. Conclusions and discussion

7.1 Introduction

The latest IPCC report on the mitigation of climate change in relation to buildings identifies the potential co-benefits of decarbonising the building stock:

> Mitigation actions in buildings generate multiple co-benefits (e.g., health benefits due to the improved indoor and outdoor conditions, productivity gains in non-residential buildings, creation of new jobs particularly at local level, improvements in social wellbeing etc.) beyond their direct impact on reducing energy consumption and GHG emissions. (IPCC, 2022)

However, it is also noted that there are several barriers to decarbonisation and that a range of solutions is required to overcome those barriers:

> Several barriers (information, financing, markets, behavioural, etc.) still prevents the decarbonisation of buildings stock, despite the several co-benefits, including large energy savings. Solutions include investments in technological solutions (e.g., insulation, efficient equipment, and low-carbon energies and renewable energies) and lifestyle changes. In addition, the concept of sufficiency is suggested to be promoted and implemented through policies and information, as technological solutions will be not enough to decarbonise the building sector. Due to the different types of buildings, occupants, and development stage there is not a single policy, which alone will reach the building decarbonisation target. (IPCC, 2022)

In this study, potential decarbonisation strategies for existing and new residential housing in New Zealand have been explored using scenarios representing three possible (carbon) futures.

- **Business as Usual (BAU)** reflects current projections incorporating broadly accepted market trends, current legislation and anticipated regulatory changes as expressed in government policy.
- **Climate Emergency (Emergency)** explores the possibility of government, industry and individuals responding to the climate change threat in a proactive, ambitious and urgent manner. The basis is what is technically feasible with a practical overlay (for example, replacement of existing technology at end of life).
- **Climate Emergency Plus (Emergency Plus)** expands on changes and efficiency improvements identified in the Climate Emergency scenario by incorporating accelerated decarbonisation of the electricity sector, additional reductions in household energy use and adoption of smaller, high-performing new-build houses.
- These scenarios do not represent predictions of future outcomes but are used as a tool to explore the combination of strategies that provide the greatest potential for net carbon savings in the context of New Zealand's commitment to net-zero carbon by 2050.

7.2 Discussion

This section summarises the main findings of the study (section 7.2.1) followed by a discussion on the potential strategies that could be utilised to decarbonise residential building in New Zealand (sections 7.2.1–7.2.5).

Every effort has been made to provide three robust pathways NZ Inc[17] could take to effectively contribute to the nation's Zero Carbon Act to reach net zero by 2050. Like any forecasting study, especially one with so many critical variables, it relies on a series of assumptions, based on historical data, related studies (both national and international), pragmatism and occasionally even informed guesses. However, given all these qualifiers, this study report should still provide valuable information for policy makers, regulators and others involved in low-carbon residential planning, design and specification.

It is not expected that a future update of this report will have fewer variables to model. The only advantage will be that the forecast period will be shorter.

7.2.1 Main findings

The following is a summary of the main findings of this study, aside from the need to go well beyond a BAU scenario:

- **Importance of operational energy use.** Operational energy use is the largest contributor to the total cumulative 2020–50 carbon footprint in all scenarios accounting for 52% of the total residential carbon footprint in the BAU scenario, 60% in the Emergency scenario and 56% in the Emergency Plus scenario. The relative importance of different energy uses varies between the three scenarios and depends on the estimations made. However, space heating, water heating and plug loads are all significant contributors to this life cycle stage. Most of this stage's carbon footprint is due to existing dwellings – accounting for 81% (BAU) to 91% (Emergency Plus) of the total cumulative Module B6 impacts and reflecting the proportional abundance of existing dwellings in operation.
- **Importance of detached dwelling typology.** In 2020, detached dwellings account for 82% of the carbon footprint in all strategies. In 2050, the proportion of impacts due to detached dwellings varies between 78% (BAU) and 81% (Emergency). Regardless of the scenario, detached houses dominate the results as they account for 84% of all dwellings over the 2020–50 study period. Although detached houses make up a lower proportion of new-builds (62%), the large number of existing detached houses results in this typology dominating the results throughout the study period.[18]
- **Impact of decarbonising electricity generation.** The contribution from operational energy use decreases over the study period in all scenarios. Assumptions regarding the decarbonisation of electricity generation are an important contributor to this reduction. In the Emergency Plus scenario, the assumed reduction in the emissions from electricity generation account for 42% of the reduction in the carbon footprint of the housing stock between 2020 and 2050. In the Emergency scenario the projected reduction in emissions from electricity generation account for 37% of the reduction in the carbon footprint of the housing stock. Under the BAU scenario, the carbon footprint of the housing stock would increase rather than decrease between 2020 and 2050 if there was no reduction in the carbon emissions associated with electricity generation.
- **Phase-out of gas.** In this study, a phase-out of gas was assumed in all scenarios, with a more ambitious phase-out in the Emergency and Emergency Plus scenarios with no gas in new homes from 2030 and the elimination of gas in existing homes by 2035. An assessment of the impact of this phase-out of gas was undertaken,

[17] In this case, meaning New Zealand as a whole – government, business and society.
[18] The same building stock numbers and typology mix are assumed for all three scenarios.

which showed that, in the BAU scenario, the 2020–50 carbon footprint of the housing stock would increase 3% if gas use remained unchanged. In the Emergency scenario, there would be an 11% increase in the carbon footprint, and in the Emergency Plus scenario, there would be a 13.5% increase if gas use remained unchanged at 2020 levels.

- **Importance of new-build embodied impacts.** The embodied carbon footprint is an important contributor to the overall carbon footprint of the New Zealand housing stock. Embodied carbon emissions arise during all stages of the life cycle of a house, but the embodied emissions associated with the product stage (Modules A1–A3) and construction stage (Modules A4–A5) of building new houses is particularly significant. In the BAU scenario, the emissions associated with the product and construction stage account for 22% of the total cumulative carbon footprint of the housing stock between 2020 and 2050. In the Emergency and Emergency Plus scenarios, this reduces to 16% and 17% respectively. As the impact of operational energy use is expected to decrease over time, the role of embodied impacts will become increasingly important if there are not also significant reductions in the role of embodied emissions. For example, if it is assumed there are no reductions in the embodied emissions associated with new-build houses, product and construction stage emissions would account for 31% of the total cumulative carbon footprint of the housing stock in the Emergency scenario. Compared to the BAU scenario, the assumed reduction in embodied emissions of new-builds in the Emergency scenario results in a reduction in product and construction stage emissions of 58%. The assumed reduction in the average size of detached houses in the Emergency Plus scenario results in another 10% reduction compared to the Emergency scenario.
- **Water use, maintenance and replacement and end-of-life impacts.** The carbon footprint associated with Modules B2 and B4 (maintenance and replacement), operational water use (Module B7) and end of life (Modules C1–C4) are smaller contributors to the overall carbon footprint of New Zealand housing compared to operational energy use and the embodied impacts of new-builds. However, the combined contribution from these modules is significant. In the BAU scenario, the combined contribution from these modules accounts for 26% of the total cumulative carbon footprint between 2020 and 2050. In the Emergency and Emergency Plus scenarios, these modules account for 24% and 27% respectively. It is noted, however, that the assumptions within the Emergency and Emergency Plus scenarios include reductions in these modules broadly in line with the reductions achieved in the other modules. Without these assumed reductions across all life cycle stages, Modules B2, B4, B7 and C1–C4 would become much more significant in terms of their contribution. For example, if it is assumed there are no reductions in the carbon emissions associated with these modules compared to the BAU scenario, they would then account for 37% of the total cumulative carbon footprint of the housing stock in the Emergency scenario.

The analysis in this study was built on previous investigations of the carbon footprint of New Zealand dwellings (Bullen et al., 2021 Chandrakumar et al., 2019, 2020; McLaren et al., 2020; Jaques et al., 2020). It further extends this work through the differentiation of impacts based on six climate zones and the predicted number of dwellings in each climate zone. In addition, the exploration of three possible future scenarios has enabled potential strategies to reduce the carbon footprint of New Zealand's housing stock to be explored. Although the detailed results of this study vary from the previous work due to alternative assumptions and further development of the method, the findings of this study confirm and reinforce the broad conclusions of previous studies. This includes the identification of both operational and embodied emissions as important contributors to the carbon footprint of New Zealand's housing stock, the need for significant and wide-ranging reductions across all life cycle stages, the importance of the detached house typology and the importance of addressing the emissions associated with existing stock as well as new-builds.

There are considerable opportunities to reduce the carbon footprint of New Zealand's housing stock, and the results of this study show that action on multiple fronts is required to make significant reductions in carbon emissions. Strategies and approaches to best address this for the New Zealand situation are discussed below.

This study has made certain assumptions about possible future scenarios for the housing stock both in terms of numbers and typology of dwellings and carbon emissions reduction measures. These assumptions are highly unlikely to exactly reflect future reality. However, regardless of the future scenario, the results highlight the most significant carbon contributors that need to be targeted with strategies and policies. For new dwellings, manufacturing and operational stages associated with detached housing need targeting first. For existing dwellings, this changes to the operational stage first with maintenance and replacement a distant (but still important) second.

Potential strategies for targeting these different areas are further discussed in the following sections.

7.2.2 Strategies to reduce embodied impacts of new dwellings

This study has highlighted the urgent need for action to significantly reduce the embodied carbon of new-build houses, particularly detached houses. The significant upfront embodied carbon emissions associated with today's new-build houses occur from the sketch design stage onwards and will continue to affect the global climate for hundreds of years.

Smaller houses

The Emergency Plus scenario investigated a specific method to reduce the embodied carbon of new-build dwellings – namely to reduce the average size of new detached houses. This is a strategy that can result in an immediate reduction in the carbon footprint as a smaller house requires less materials and less operational energy.

The construction of smaller houses is a strategy that can be adopted immediately with no need for technological advances or decarbonisation of related industries. The biggest barrier to this strategy is the behavioural change required for consumers to value and aspire to a smaller house. The reduced construction costs associated with a smaller house is an added co-benefit, especially in the current market of unprecedented material costs/supply issues hampering home ownership. Targeted education and incentives would be a very effective means to assist a shift in consumer behaviour.

Careful consideration of the new-build embodied carbon limits proposed under the MBIE BfCC programme is required to encourage more modestly sized houses. Choosing carbon thresholds that consider both absolute ($kgCO_2$/dwelling) and relative ($kgCO_2/m^2$) limits will avert the inherent advantage of larger houses.

Reducing the embodied carbon of building materials

Constructing smaller houses alone will not be sufficient to markedly reduce new-build emissions. Significant and ongoing reductions in building material emissions will be required for the Emergency and Emergency Plus scenarios. This could be through the more considered selection and replacement of building materials with lower-carbon alternatives. This may require some degree of technological transformation in the manufacture and supply industries. The careful application of life cycle assessment to ensure such materials have demonstrably lower emissions than the materials they are replacing will be critical. It is the authors' opinion that targeted assistance or regulation of New Zealand material suppliers is likely required to accelerate this process.

Use of sustainably sourced timber

Accounting for the benefits of biogenic carbon stored in timber products was shown to reduce the BAU scenario carbon footprint about 9%. Thus, increased use of timber and modified wood products from sustainably managed forests is a potential strategy to reduce the embodied carbon in dwellings.

Note that MBIE's whole-of-life embodied carbon emissions reduction framework (2022b) includes materials' end-of-life contributions as part of 'Future' emissions (Modules C1–C4), recognising that the further down the life cycle the assessment is, the more complex it is and the more unknowns, while noting that the potential for reducing carbon by including end-of-life impacts is high.

7.2.3 Strategies to reduce operational energy use

Strategies that reduce operational energy use in both new and existing homes are essential to achieving a low-carbon housing stock.

Reducing operational energy use in existing homes

The potential benefits to reducing operational energy use in existing homes is significant due to the greater number of existing homes operating in New Zealand compared to new-builds. However, there are also significant barriers to reducing operational energy use in existing homes. The addition of roof and floor insulation[19] to existing homes is generally a cost-effective measure to improve the thermal envelope with the aim of reducing energy demand for space heating. In addition, or possibly as an alternative, this has the benefit of creating warmer and healthier homes. However, to achieve the current level assumed in the Emergency and Emergency Plus scenarios, additional measures will be required in a significant proportion of the existing housing stock (such as installation of double glazing and wall insulation). Due to the costs involved, it is likely that financial incentives or subsidies would be required to action this.

In any assessment of the potential operational carbon savings of retrofitting existing houses to be more energy efficient, it is important to understand the likely embodied carbon cost and ensure this cost is not so high as to outweigh any potential benefit.

The shift to heat pump technology for both space and water heating should have lower barriers to implementation as they are cost-effective over the lifetime of the appliance due to reduced operating costs. However, heat pump technology has financial barriers

[19] Where the floor is suspended and there is sufficient clearance to add insulation underneath.

to overcome due to their relatively high upfront costs compared to less-efficient alternatives.

Global warming contribution from space conditioner refrigerants is dependent on several factors – for example, refrigerant charge, type of refrigerant and extent of fugitive emissions. In this study, which assumes that existing heat pumps have a 1.5 kg R32 refrigerant charge and are replaced with heat pumps with a 0.6 kg R32 refrigerant charge, the contribution appears to be small relative to total operational and embodied contributions. Based on these assumptions, estimations are that refrigerants provide less than a 3.5% contribution to the lifetime carbon footprint of the housing stock depending on the scenario. Such a conclusion requires that the impact from refrigerants is considered (and not just ignored) despite increased take-up of heat pumps. This may be through several means, for example, development of systems requiring a lower refrigerant charge (modelled in this study), use of refrigerants with low or zero global warming potentials and/or use of systems with less risk of fugitive emissions.

Reducing operational energy use in new homes

Compared to existing homes, there is greater scope to achieve minimal operational energy use in new homes due to the lack of limitations of existing design and appliances. Having regard to aspects such as house size, insulation, orientation, energy sources, water heating and lighting during the design and build of new houses will all contribute to minimising operational energy use. EECA's ongoing hot water review[20] to provide consumers with appropriate information to make informed choices about the energy use of hot water systems and their impact on GHG emissions will assist this. Houses built now will be operational for 50+ years, and many of the operational impacts of a new-build house are locked in once the house is constructed. This emphasises the need for the urgent setting of appropriately ambitious performance standards for new-build homes through the proposed BfCC programme.

Plug loads

Another potential area where significant reductions in operational energy use could be made is plug loads. Data on the contribution from plug loads in New Zealand houses is limited at present. The values used in this study are considered indicative only but suggest that the use of more energy-efficient appliances is a potential area for significant savings. As with more-efficient space and water heating appliances, it seems that upfront purchase costs and lack of awareness are the main barriers to implementation. Recent changes requiring increased use and detail on energy rating labels[21] is an encouraging development. In addition, the ongoing BRANZ HEEP2 study should provide valuable data on plug load contribution to household energy use.

Transition from gas to electricity

One potential strategy to reduce the carbon footprint of operational energy use from the housing stock is to ban the use of gas for space and water heating and to encourage a transition to electricity by existing gas users. The Climate Change Commission (2021) recommended that decarbonising the New Zealand energy system should include a process to eliminate natural gas use in residential, commercial and public buildings. Without a transition away from gas use, it is estimated the carbon

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[20] www.eeca.govt.nz/regulations/regulatory-requirements-under-review/hot-water-systems/
[21] www.eeca.govt.nz/regulations/equipment-energy-efficiency/about-energy-rating-labels/zoned-energy-rating-label/

footprint of the housing stock would be 3–13% higher than indicated in the three scenarios used in this study. This shows that a transition away from gas use in the housing stock will not significantly reduce the carbon footprint of the New Zealand housing stock by itself but is an important contributor to the range of strategies required to reduce the carbon footprint to as low as practicable.

Electricity generation emissions

Electricity is the main energy source in New Zealand houses (MBIE, 2021b). Carbon emissions associated with electricity generation are therefore an important contributor to the carbon footprint of the New Zealand housing stock.

The three scenarios in this study assume increasingly ambitious reductions in the carbon emissions associated with electricity. In the Emergency and Emergency Plus scenarios, it is assumed that electricity generation is 100% renewable by 2050 with additional reductions in both the embodied impacts of electricity generation infrastructure and geothermal fugitive emissions assumed in the Emergency Plus scenario. These additional assumptions are important, as even with 100% renewable electricity generation, there are still carbon emissions associated with electricity generation due to the embodied emissions from infrastructure and geothermal fugitive emissions (Bullen et al., 2021).

Anticipated benefits of decreasing electricity emissions will occur gradually over time as new renewable generation infrastructure is constructed and existing fossil fuel-based generation reaches its end of life. A slowing or acceleration of this transition will have a significant impact for climate change. The decarbonisation of electricity generation cannot be relied on as the sole strategy to reduce operational energy use. It is noted that the renewable component of New Zealand electricity generation has varied between 80% and 85% since 2014 (MBIE, 2022a). A significant investment in new infrastructure is required for the levels of renewable generation assumed within this study.

7.2.4 Other life cycle modules

The embodied carbon of new-builds and operational energy use in new and existing houses are the areas with the greatest potential to reduce the carbon footprint of the housing stock. However, to achieve the lowest practicable level of carbon emissions from New Zealand houses, reductions also need to be made in the areas of maintenance and replacement, operational water use and end of life. These life cycle modules all contribute to the overall carbon footprint and will become more significant if reductions are made in upfront embodied carbon and operational energy but not in these modules.

Any measures that decarbonise the upfront embodied carbon of Modules A1–A5 in new-build houses should also be reflected through reduced carbon emissions associated with maintenance and replacement (Modules B2 and B4). Reductions in average house size would mean less materials requiring maintenance and replacement and also a reduction in end-of-life emissions. Reductions in the embodied carbon of building materials or use of alternative low-carbon materials may also have benefits when those materials require replacement. However, a life cycle approach is required to assess the benefits of alternative materials, which considers the replacement frequency and end-of-life aspects in addition to the upfront carbon cost.

Reduced emissions associated with electricity generation would be reflected in a reduced carbon footprint associated with water and wastewater reticulation and treatment. A more direct approach to reduce the operational-related water use carbon footprint is to adopt better water management strategies within New Zealand houses.

Where waste is generated, there is a need to shift to a more circular economy in which reused materials or materials with a high recycled content are more readily demanded and specified.

7.2.5 Identifying priority actions

This study has identified that a range of strategies are required to reduce the carbon footprint of the New Zealand housing stock to as close as practicable to zero. However, it has not assessed the cost of these strategies relative to their carbon-reduction benefit.

A cost-benefit assessment of the relative benefit of different measures and the optimal level for different strategies is an important next step. This is particularly important for existing houses where implementing physical changes is often financially high and physically challenging, with the remaining operational lifetime of many existing houses relatively short. There are typically a range of variables and co-variables to be considered and done on a case-by-case basis. A current BRANZ project developing marginal abatement cost curves (MACC) for a range of different carbon abatement strategies will provide an important contribution to identifying the highest priority ('best bang for your buck') carbon reduction actions. This project is due to finish in 2023.

7.2.6 Other strategies

There are some other strategies that have not specifically been addressed in this study yet are important if a concerted approach to reducing carbon is developed.

Construction waste reduction

The role of reducing construction waste as a potential strategy to reduce the embodied carbon of new-builds was not specifically explored in this study. However, previous related research has shown that construction and demolition waste sent to landfill in New Zealand is considerable. For example, in Porirua, over 50% of waste disposed to landfill comes from construction and demolition (approximately 32,000 tonnes a year).[22] Construction and demolition activity in Auckland produces nearly 570,000 tonnes of waste a year.[23] In terms of residential construction-specific waste, figures are hard to come by, but the defaulted value is 10%.

There is significant opportunity to greatly reduce residential construction waste, as has been documented in many New Zealand-specific case studies.[24] Importantly, this can be done in a cost-neutral manner, as demonstrated in a recent Auckland City Council commissioned report (Rohani et al., 2019). The specific embodied carbon savings through addressing construction waste for dwellings can be estimated assuming a 10% average waste generation per build.[25] Using the BAU scenario, Modules A1–A3 for

[22] www.beehive.govt.nz/release/funding-projects-reduce-waste-construction-and-demolition
[23] www.rnz.co.nz/programmes/the-detail/story/2018802285/the-booming-problem-of-construction-waste
[24] https://ccc.govt.nz/environment/sustainability/target-sustainability/case-studies/
[25] This is a gross simplification as wastage is material-specific.

detached houses emit a total of 704 $kTCO_2$[26] for the building of 22,212 dwellings using 2019 as the base year. Assuming that 50% of the waste stream generated during the build can be viably diverted away from landfills and clean fills, this would save an estimated 1.6 TCO_2 per house.

As stated in a previous BRANZ report (MacGregor et al., 2018), "While the design of residential buildings in New Zealand is characterised by great variety, the market shares of materials used in their construction portray homogeneity in construction methodology and material specification. While these shares do vary from year to year, they are relatively steady in the long run, reflecting a preference across owners, designers and builders for traditional, familiar products and methods."

7.3 Conclusions

"And so here we are … at the last possible moment before the window of opportunity closes forever." (James Shaw, Climate Change Minister, on the eve of the release of the Climate Change Commission's final report to the New Zealand nation, 6 June 2021)

Dwellings are unique in terms of lifetime purchases due to their fundamental societal need, longevity and ability to transform – both the dwelling and its occupants – during their lifetimes. From the scenario work carried out in this study, it seems that it is highly unlikely that, even with the most drastic of initiatives modelled (addressing both operational and embodied emissions), our nation's 2050 zero-carbon dwelling-related goal will be met. This is true even with a near-zero carbon grid and accounting for biogenic carbon storage within timber and timber-based products. Nevertheless, the residential construction industry has a crucial role to play in reducing New Zealand's carbon impact. Given the pace and scope needed for significant change, government commitment and action now is critical. The necessary changes are only likely to occur with continuous, bipartisan government support and mandates.

The following residential-related operational and embodied issues are seen as critical to reducing carbon emissions. As always, it is important to provide a strategy to prioritise issues based on their marginal abatement cost (yet to be calculated) combined with practicalities. The following lists the more-impactful opportunities that need intensive financial cost-carbon benefit calculated.

Most important carbon reduction measures that can be carried out immediately

- Encourage/incentivise switch to heat pumps for both space and water heating (with very low or zero GWP refrigerants).
- Implement requirements for limits on embodied carbon and design for low operational energy use in new-builds as soon as possible – as per BfCC.
- Restrict use of gas in new-builds.
- Encourage/incentivise the construction of smaller, high-performance houses.
- Implement measures to minimise waste during construction.
- Encourage/incentivise replacement of household appliances at end of life with the most-efficient options.

[26] This figure does not account for other dwelling typologies, construction waste, wall and ceiling linings, paint, plumbing and electrical, and fixtures and fittings. Thus it is a gross underestimation.

Most important medium-term carbon reduction measures

- Identify and implement the most cost-effective measures to reduce operational energy use within existing dwellings.
- Decarbonisation of electricity generation and production/supply of building materials – not directly influenced by building design or use but important contributors to carbon footprint of dwellings.
- Identification and testing of alternative low-carbon building materials.

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Appendix A: Residential photovoltaics

The benefits (or not) of residential micro-renewables as a carbon emissions reduction strategy for application in either new or existing dwellings was considered. The most likely micro-renewable resource that is associated with dwellings, due to cost, applicability and availability, is solar photovoltaic (PV). Certainly, grid-tied residential PV is often cited as being a key foil to fuel-related carbon emissions (Fahy, 2022) and its popularity for residential micro-generation has increased over the last 20 years nationally, reflecting its massive fall in price (Feldman et al., 2020).

Carbon emissions associated with the manufacture of PVs is known to be significant (Schwartfeger & Miller, 2015) and needs to be accounted for. Recent independent comprehensive LCA studies on the carbon aspect of PVs are few and far between, even internationally. To further complicate assessing their projected lifetime carbon emissions are the many impacting variables. These include country of manufacture, type of PV panel, projected in-use lifetime, the local electricity grid carbon intensity where the panels are deployed and effectiveness of installation. Together, these issues make micro-PV challenging to include in predictive studies without making many assumptions.

One of the few comprehensive New Zealand-based studies to examine residential PV is from Wellington-based Concept Consulting Group conducted in 2016 and 2017. It explored the likely environmental, economic and social implications associated with widespread uptake of three notable technologies – grid connected PV, batteries and electric cars for New Zealand (Concept Consulting Group, 2016a, 2016b, 2017). Using various sensitivity studies and future scenarios, the reports concluded that, for New Zealand, residential PVs (whether battery-assisted or not) are not particularly beneficial at reducing carbon in the medium and long term. This is because of New Zealand's typical electricity generation mix that is powered mainly via highly efficient, low-carbon renewables – chiefly hydro-electric. In addition, the reports predict that the mass-uptake of residential-installed, grid-tied, battery-less solar PV panels in New Zealand will likely result in fewer considerably lower-emissions hydro-power stations being developed (Concept Consulting Group, 2016a). This contrasts with considerable opportunities residential-based renewable technologies have in countries with coal-dominated electrical grids. The report states: "These conclusions appear robust against a range of different scenarios relating to fuel prices, CO_2 prices and electricity demand growth." (Concept Consulting Group, 2016a, p. iii)

As a result of the many inherent variables and the studies by Concept Consulting Group and others (such as Young, 2020), it has been decided that residential-based micro-renewables will not be included in this BRANZ housing stock strategy study. This exclusion does not reflect, and is separate to, whether PVs are commercially beneficial for some types of households as has been shown in various New Zealand-based research (for example, Miller et al., 2014).

Appendix B: Carbon implications of refrigerants

This study reports on the carbon implications of refrigerants from fixed appliances (non-chattels) such as residential space conditioners (heat pumps) that can provide both heating and cooling. Reporting was deemed necessary for two main reasons: heat pumps are becoming increasing popular in both new and existing houses (Pollard, 2019) and their contributions to global warming stemming from their lifetime refrigerant losses in New Zealand are suspected to be significant.[27] Refrigerant loss/leakage falls under a combination of LCA Modules B1, B4, C3 and C4 depending on where in the life cycle gas losses occur.[28]

Water heating heat pump refrigerant impacts were not considered due to this technology being very scarce in New Zealand dwellings currently. In addition, there is an expectation that low GWP refrigerants – specifically CO_2 – will likely become the default refrigerant technology having minimal environmental consequences.

Currently, up-to-date specifics about space conditioning heat pump refrigerants typically used in New Zealand dwellings is sparse. A quick online poll of the six main space conditioner manufacturers found that R32 is by far the dominant refrigerant gas used in new heat pumps. The Ministry for the Environment (MfE) has produced a series of high-level related documents examining refrigerant stocks, stewardship and forecasting, but little of this information is applicable to this BRANZ study (Brodribb et al., 2017; Ministry for the Environment, 2021; Hennessy & Cleland, 2020).

MfE has a refrigerant working group (Asti Laloli, Ministry for the Environment, personal communication, 2022) and have related initiatives such as the regulated product stewardship scheme,[29] which BRANZ leveraged for this study. Specifically, MfE's hydrofluorocarbon (HFC) projections model was used as a basis to ground various BRANZ refrigerant variables so there would be a degree of consensus on both organisations' future projections.

BRANZ adopted the following variables in line with the MfE HFC projections model:

- Typical heat pump lifetime 12 years.
- Expected proportions, mix and climate warming capabilities of existing, new and future refrigerants typically used in heat pumps.
- Amount of refrigerant gas typically leaked while operational.
- Likely effectiveness of its retrieval at end of life as government-mandated product stewardship efforts ramp up.
- Typical refrigerant gas charge amounts in heat pumps used in New Zealand by type. In this study, existing heat pumps were assumed to have an R32 refrigerant charge of 1.5 kg compared to new heat pumps with an R32 refrigerant charge of 0.6 kg.
- No distinction between various heat pump types (wall mount, floor mount, split, ducted etc.) or their sizes for this study.

[27] https://refrigerantstewardship.co.nz/taking-on-one-of-the-biggest-invisible-causes-of-climate-change/
[28] The BRANZ study doesn't include Module B1 for other impacts.
[29] https://environment.govt.nz/what-government-is-doing/areas-of-work/waste/product-stewardship/regulated-product-stewardship/

Total lifetime GHG equivalent from heat pump refrigerants is the sum of production, in-use leakage and end-of-life emissions to environment minus that retrieved at end of life. The screengrab in Figure 13 provides a breakdown of the life cycle calculation of refrigerant contributions in the case of BAU for the relatively low refrigerant R32. Also known as difluoromethane, R32 is almost used exclusively in new heat pumps in New Zealand (in 2022). It belongs to the HFC family of refrigerants and has a GWP of 675.

New Homes, per heat pump unit				
	NOW - 2022			
BAU	*R32 refrig.*	*675*	*kg CO2e*	
		0.6	*kg refrigerant*	
		6	*% operational leakage rate/yr*	
	Years	**100.0%**		
	1	94.0%	Operational leakage	
	2	88.4%		
	3	83.1%		
	4	78.1%		
	5	73.4%		
	6	69.0%		
	7	64.8%		
	8	61.0%		
	9	57.3%		
	10	53.9%		
	11	50.6%		
End of Life	**12**	47.6%		
retrieval at EoL		11%		
resulting EoL emisisons		89%		
EoL emissions		**171.5**	**kg CO2-e**	
plus Operational Leakage		**212.3**	**kg CO2-e**	
TOTAL lifetime emissions per HP		**383.8**	**kg CO2-e**	
TOTAL lifetime emissions avg. / yr		32.0	(kg CO2/yr)	

Figure 13. Air conditioner refrigerant (R32) life cycle carbon contributions.

The results for the three scenarios – BAU, Emergency and Emergency Plus – are shown in Table 14 through Table 19. Notably, the tables show the following:

- Whatever the scenario or residence type/status, refrigerants from space conditioner contributions in terms of **overall GWP are small**, providing less than a 4% contribution. This finding is dependent on the impact per heat pump significantly decreasing through reduced refrigerant charge, use of lower or zero GWP refrigerants and/or use of systems with less potential for fugitive emissions.
- Heat pump-related **GWP contributions from existing residences are more than double those from new residences**, no matter what the scenario. This is due to the higher 1.5 kg refrigerant charge in existing heat pumps.
- GWP associated with **detached housing is by far the leading carbon contributor** of the three building typologies, with townhouses and apartments trailing far behind.
- The lifetime GWP of heat pump refrigerants between the best-case scenario and the worst-case scenario for new detached homes is 47 $kTCO_2eq$. This is because, for space conditioners, **there is no refrigerant replacement for R32 on the horizon that can easily be deployed** or used as a substitute that also has a much lower GWP. This does assume that the amount of refrigerant charge in new heat pumps is significantly reduced to 0.6 kg/heat pump instead of 1.5 kg.
- **If heat pump policy/mandates were to be introduced in New Zealand, it would be best to target existing detached homes first**, given their impact, then new detached homes.

Table 14. Air conditioner refrigerant impacts (BAU), new homes.

BAU: NEW Residential Typologies -			
Residential Type	TOTAL Carbon footprint (excl refrigerant) ($ktCO_2eq$)	*Lifetime Refrigerant C Impact ($ktCO_2 eq$)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	39,482	341	0.9%
MDH	11,745	155	1.3%
Apartments	6,557	61	0.9%
TOTAL	57,784	557	1.0%

Table 15. Air conditioner refrigerant impacts (BAU), existing homes.

BAU: EXISTING Residential Typologies -			
Residential Type	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)	*Lifetime Refrigerant C Impact (ktCO2eq)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	81,967	1,852	2.2%
MDH	7,715	233	2.9%
Apartments	3,676	115	3.0%
TOTAL	93,359	2,199	2.3%

Table 16. Air conditioner refrigerant impacts (Emergency), new homes.

EMERGENCY: NEW Residential Typologies -			
Residential Type	TOTAL Carbon footprint (excl refrigerant) ($ktCO_2eq$)	*Lifetime Refrigerant C Impact ($ktCO_2 eq$)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	17,585	318	1.8%
MDH	5,380	144	2.6%
Apartments	2,380	56	2.3%
TOTAL	25,345	519	2.0%

Table 17. Air conditioner refrigerant impacts (Emergency), existing homes.

EMERGENCY: EXISTING Residential Typologies -			
Residential Type	TOTAL Carbon footprint (excl refrigerant) ($ktCO_2eq$)	*Lifetime Refrigerant C Impact ($ktCO_2 eq$)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	54,027	1,760	3.2%
MDH	5,506	221	3.9%
Apartments	2,476	109	4.2%
TOTAL	62,009	2,091	3.3%

Table 18. Air conditionaer refrigerant impacts (Emergency Plus), new homes.

EMERGENCY PLUS: NEW Residential Typologies			
Residential Type	TOTAL Carbon footprint (excl refrigerant) ($ktCO_2eq$)	*Lifetime Refrigerant C Impact ($ktCO_2 eq$)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	12,731	294	2.3%
MDH	4,819	134	2.7%
Apartments	2,199	52	2.3%
TOTAL	19,749	480	2.4%

Table 19. Air conditioner refrigerant impacts (Emergency Plus), existing homes.

EMERGENCY PLUS: EXISTING Residential			
Residential Type	TOTAL Carbon footprint (excl refrigerant) (ktCO2eq)	*Lifetime Refrigerant C Impact (ktCO2eq)*	*Lifetime Refrigerant C Impact as % of TOTAL C Impact*
Detached	46,381	1,669	3.5%
MDH	4,642	210	4.3%
Apartments	2,146	103	4.6%
TOTAL	53,170	1,982	3.6%

Appendix C: Projected dwelling type proportions

Table 20. Projected number of new consented dwellings to 2050, by climate zone.

YEAR	2020	2025	2030	2035	2040	2045	2050
Detached	**22,212**	**25,120**	**14,700**	**15,950**	**16,240**	**16,510**	**17,050**
Zone 1	9,141	10,296	6,021	6,542	6,661	6,772	6,993
Zone 2	3,684	4,000	2,333	2,526	2,572	2,615	2,701
Zone 3	2,564	2,851	1,673	1,813	1,846	1,876	1,938
Zone 4	1,186	1,221	715	775	789	802	829
Zone 5	4,408	5,153	3,018	3,272	3,332	3,387	3,498
Zone 6	1,229	1,599	940	1,022	1,041	1,058	1,093
Attached	**17,208**	**17,120**	**9,800**	**9,770**	**10,380**	**11,010**	**11,370**
Zone 1	10,793	10,723	6210	6246	6601	6967	7195
Zone 2	1,784	1,733	965	934	1009	1087	1122
Zone 3	1,929	2,069	1166	1159	1236	1315	1358
Zone 4	162	270	150	146	157	169	174
Zone 5	1,827	1,580	888	869	932	998	1031
Zone 6	713	745	422	416	445	475	490
Townhouses	**11,603**	**11,128**	**6,370**	**6,351**	**6,747**	**7,157**	**7,391**
Zone 1	7,560	6,863	4,036	4,021	4,272	4,531	4,679
Zone 2	1,062	1,144	672	670	712	755	780
Zone 3	911	1,035	607	607	645	684	707
Zone 4	135	216	125	124	132	140	145
Zone 5	1,372	1,106	646	644	684	726	749
Zone 6	563	484	285	284	302	320	330
Apartments	**3,739**	**4,435**	**2,573**	**2,701**	**2,795**	**2,890**	**2,984**
Zone 1	2,619	3,326	1,929	2,025	2,096	2,167	2,238
Zone 2	109	133	77	81	84	87	90
Zone 3	740	665	386	405	419	433	448
Zone 4	3	0	0	0	0	0	0
Zone 5	183	177	103	108	112	116	119
Zone 6	85	133	77	81	84	87	90

Note that a yearly consented number of dwellings was projected to the year 2050 but isn't shown here due to the considerable number of figures (i.e. x 30) required.

Appendix D: Internal gains

As mentioned in the body text, internal gains assumptions can be problematic. For this project, attempts were made to adjust the internal gains schedules derived from HEEP to better reflect the possible energy use of appliances in new houses. In brief, this involved reducing the lighting load by 80% by assuming houses are using LEDs, reducing the range loads by ~10% based on potential improvements to oven efficiency (with stoves having not changed much) and ~24% reductions to equipment loads (based largely on improvements to fridges and standby loads). These were then applied to these houses using the distribution rules presented there.

The total house loads were divided over the different zone types as shown in Table 21.

Table 21. Household energy end use loads proportioned.

Equipment loads Bedrooms 17% Kitchen 36% Living 27% Other 20%	**Lighting loads** Bedrooms 10% Kitchen 25% Living 55% Other 10%
Range loads Assigned to the kitchen	**Hot water cylinder** Assigned to whatever zone it is in (assumed 100 W)
Occupancy Daytime: 60% living, 10% bedrooms, 15% kitchen, 5% other Night-time: 100% bedrooms	**Heated towel rails** Assumed 1 per bathroom (assumed 70 W for 4 hours in the morning and 4 hours in the evening)

Within each zone type, the loads were then divided based on area. It was assumed that there were two people in the master bedroom and one in each of the others. Overall loads for the different houses were scaled by floor area and number of occupants according to the relationships identified by the Household Energy Efficiency Resource Assessment (HEERA) model for HEEP (Isaacs et al., 2010). However, this ran into problems for the apartments, which were far smaller than the houses HEEP had looked at. Here, we estimated the lighting load for a 100 m², two-person house and then halved it. The load in the apartment bedroom and bathroom was then estimated as 10% of this. To deal with the lack of rooms in the apartments, it was assumed that the load in the bathroom was roughly the same as that estimated for the similarly sized bathrooms in the other house models. The same logic was applied to the bedroom.

However, even following this protocol, apartment loads end up being very substantial on a per m² basis. Examining the trends in the HEERA model, it can be seen that, while the lighting load is significantly affected by both area and occupancy, the other equipment loads are largely unaffected by area. The result of this is that the apartment loads – especially the studios – are significantly higher on a per m² basis. This is true even though parts of the total load are reduced by taking the load fraction for the kitchen/living zone and not applying the entire 'other' zone load to the bathroom. This is because the living and kitchen zones are where most of the loads in a house are concentrated.

Note that, for ***Error! Not a valid bookmark self-reference.***, hot water loads are not included. This is because only sensible gains from cylinder losses were modelled, and they do not reflect actual energy consumption.

Table 22. Modelled electricity use for lighting/appliances/cooking.

Dwelling Type	Modelled equipment (kWh/yr/dwelling)
Detached #1	3370
Detached #2	3362
Detached #3	3704
Detached #4	3973
Townhouse (8 dwellings)	2822
Apartments (108 half studios)	1740

In **Error! Not a valid bookmark self-reference.**, garages are not counted, which is why detached dwellings #1 and #2 have much higher internal gains than the other two detached dwellings. Dwellings #3 and #4 have their hot water cylinder in the garage, while the others have them inside the house. It should be noted that these loads do vary slightly over the year, as the lighting load changes depending on the month.

Table 23. Average internal gains across conditioned zones.

Dwelling Type	Average internal gains (W/m^2)
Detached #1	5.2
Detached #2	5.5
Detached #3	4.1
Detached #4	4.4
Townhouse (8 dwellings)	5.2
Apartments (108 half studios)	10.6 (studio), 7.5 (apartment)