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Carbon Budget of New Zealand Buildings: A Sensitivity Assessment

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Carbon Budget of New Zealand Buildings
Sensitivity Assessment

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1 Introduction

Buildings are reported to account for 36% of global final energy use and 39% of energy-and process-related CO_2 emissions (IEA and UN Environment Programme, 2019). Consequently, the building sector has an important role in reducing global greenhouse (GHG) emissions to a level compatible with global climate goals.

An absolute sustainability approach combined with life cycle assessment (LCA) provides a means to determine the required improvement in GHG emissions associated with the New Zealand building sector to achieve identified climate goals. An absolute sustainability approach is based on assessing a product, activity, or system in the context of an identified safe or acceptable operating limit or capacity.

An absolute sustainability approach has previously been used to assess the impacts of the New Zealand detached housing sector in the context of 1.5°C and 2°C climate change targets and concluded that the climate impacts of new-built detached houses exceeded a 2°C climate target by a factor of five (Chandrakumar et al., 2020c). This assessment was subsequently updated and extended to include an assessment of all residential building types against a 1.5°C climate target. It was concluded that new-built dwellings exceed their 1.5 °C climate targets by a factor of 6.7, 6.8 and 10.9 for detached, medium-density housing, and apartments respectively. It was also noted that about two-thirds of the climate impact of residential dwellings for the period 2018-2050 is associated with pre-existing dwellings rather than new-builds (McLaren et al., 2020).

The current study extends these previous absolute sustainability assessments of New Zealand residential houses in the context of climate targets to examine the sensitivity of the outputs to various input parameters. This sensitivity assessment is undertaken to identify priorities for further study or data improvements to support the transformation of the New Zealand built environment to one that is sustainable in the context of global climate change. The current study also extends the previous work to include an assessment of office buildings in addition to residential buildings.

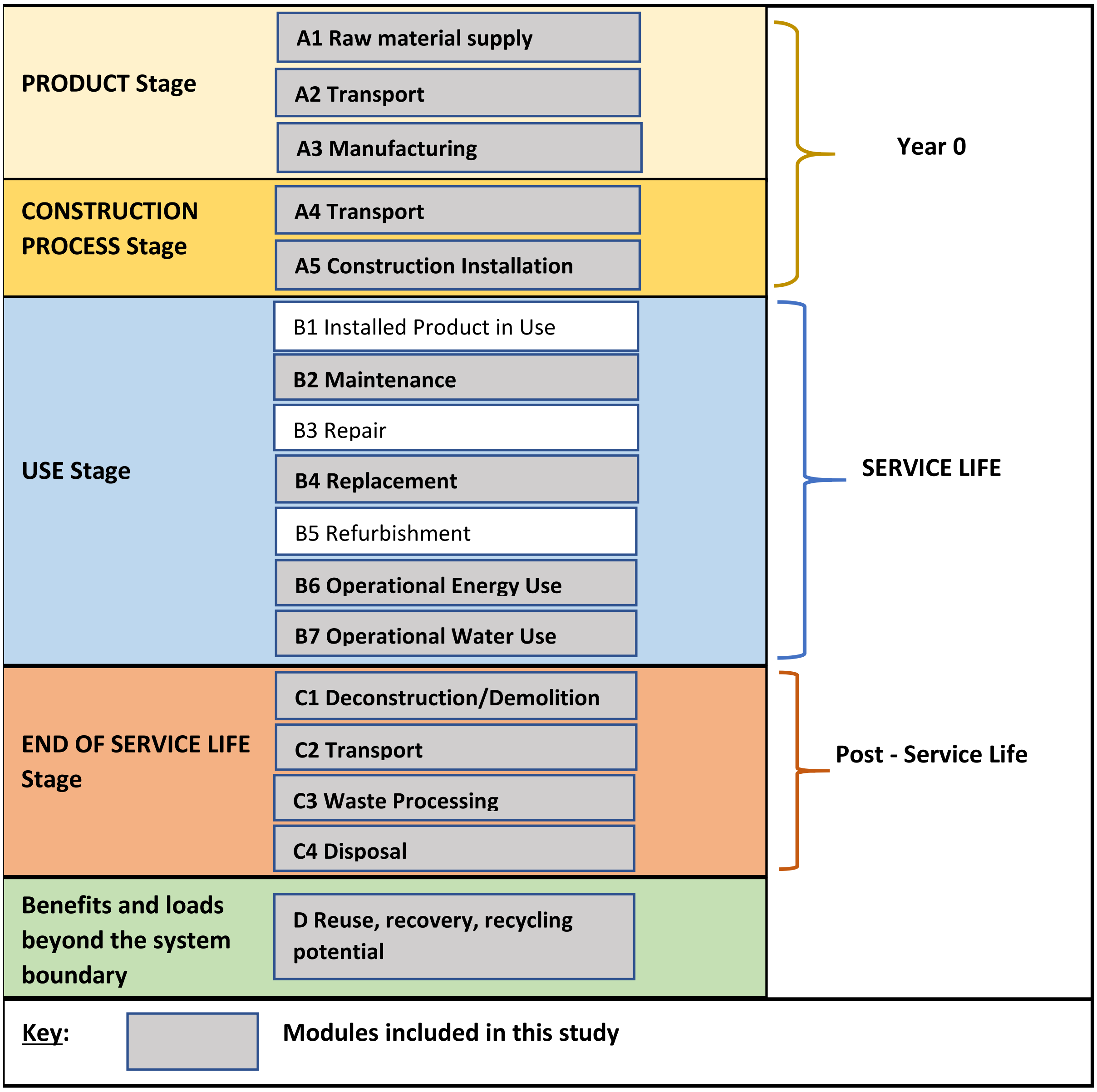
Bjørn et al. (2020) undertook a review of LCA methods used in absolute sustainability assessments and identified a number of recommendations on the selection and implementation of LCA-based absolute environmental sustainability methods as well as communication of the results. These recommendations have been considered in undertaking this study.

2 Methods

2.1 Overview

The life cycle of a building can be divided into a number of stages and modules as defined in standard EN15978 (BSI, 2011) and summarised in Figure 1.

Figure 1: Building Life Cycle Stages as Adapted from Standard EN15978



The scope of the building life cycle considered in this study was limited to the following modules which study are shaded grey in Figure 1:

- Modules A1-A3 - Raw material supply, construction & manufacture
- Modules A4 – A5 – Transport and installation of construction materials

- Modules B2 & B4 - Maintenance and replacement of materials during the building service life
- Module B6 - Operational energy use
- Module B7 - Operational water use
- Modules C1-4 – End of life stage
- Module D – Potential benefits and loads beyond the system boundary

For the purposes of this study, the impacts associated with the Product stage (Modules A1-A3), Construction Process stage (Modules A4 & A5), and the End of Life stage (Modules C1-C4) are collectively referred to as 'embodied' impacts. Use stage impacts are limited to Modules B2,B4, B6 and B7.

Previously calculated carbon budgets (CBs) and carbon footprints (CFs) for residential and office buildings at a sector and individual building level were updated to provide base cases, and then sensitivity analysis was undertaken of various parameters. Section 2.2 describes the methodology used to determine the 'base case' CB and CF for residential and office buildings and Section 2.3 describes the scenarios which were compared with the base case to determine the sensitivity of the base case results to various alternative inputs.

2.2 Development of Base Case

2.2.1 Base Case Residential and Office Building Sector Carbon Budgets 2018-2050

The 'base case' residential housing and office building sector CBs for the period 2018-2050 were calculated according to the following method:

- A global 2018-2050 CB of 786 $GtCO_{2eq}$, representing a 1.5°C low-OS[1] climate target, was adopted based on studies by Rogelj et al. (2015) and Chandrakumar et al. (2020a).
- The New Zealand share of the global CB was determined on an 'equal per capita' sharing basis by multiplying the global CB by the estimated 2018-2050 cumulative New Zealand population as a proportion of the estimated 2018-2050 cumulative global population (Chandrakumar et al., 2019; Yu et al., 2011).
- A proportion of the New Zealand CB was allocated to the residential and office building sectors on a grandfathering basis. A proportion of the 2018-2050 CB was allocated to each sector based on their estimated GHG emissions in 2012 as a proportion of the total New Zealand consumption based GHG emissions in 2012 (Chandrakumar et al., 2020b). This results in 10.0% of the total New Zealand CB being allocated to the residential building sector and 0.46% to the office building sector.
- The residential sector CB was then allocated to each type of residential building (detached house (DH), medium density housing (MDH) and apartment (AP)) on an 'equal per capita' basis. That is, the budget was allocated to each house type in the same proportion as the estimated number of people living in each house type during the 2018-2050 period, calculated using a BRANZ projected residential stock model. This resulted in 78.8% of the residential CB being allocated to DHs, 14.9% to MDHs and 6.3% to APs.
- The office building sector was analysed as a single sector and no further differentiation of the CB was undertaken.

[1] Pathways limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways (Rogelj et al., 2018)

2.2.2 Base Case Carbon Budget for Individual New Buildings

The total residential sector CB for 2018-2050 was allocated to embodied impacts (20%) and use stage impacts (80%) based on the predicted 2018-2050 split between embodied and use stage impacts. The split for office buildings was 35% embodied and 65% use stage. Embodied impacts were defined as Modules A1-3, A4-5 and C1-4 and use stage as Modules B2, B4, B6 and B7. Modules B2 and B4 can be considered as part of whole-of-life embodied emissions rather than use stage emissions; however, for the purposes of this study, they are treated as use stage because they occur during the use stage of the building's life cycle. The 2018-2050 residential sector CB was converted to CBs for individual new build residential houses using both area-based and occupancy-based sharing. The 2018-2050 office building sector CB was converted to a CB for an individual new build office building using area-based sharing only.

Area-based Sharing Carbon Budgets for New Built Residential Dwellings and Office Buildings

The embodied share of the residential and office building sector CBs were converted to a 'per m^2' value by dividing the total embodied CB by the predicted gross floor area in m^2 of all new build residential or office buildings during the 2018-2050 period based on the BRANZ projected stock model. The use stage share of the residential and office building sector CBs were converted to a 'per m^2.yr' value by dividing the use stage CB by the predicted m^2.yr for all existing and new build residential or office buildings during the 2018-2050 period.

The average size of new build residential buildings was based on data from Stats NZ (2020b) (DH=198 m^2, MDH=114 m^2, AP=94 m^2). The average size of new build office buildings (1,136 m^2) was based on the BRANZ projected stock model.

The per m^2 embodied CB was applied to the 'average' size of a new build residential house or office building in each category. The per m^2.yr use stage CB was applied for the 33 years from 2018-2050 assuming the building starts its use stage on 1 January 2018 (i.e. building constructed in 2017). New Zealand has set a domestic target of net zero emissions of all GHGs other than biogenic methane by 2050 through the Climate Change Response (Zero Carbon) Amendment Act 2019, therefore a zero CB for use stage emissions beyond 2050 was adopted in the base case.

Occupancy-based Carbon Budgets for New Built Residential Dwellings

To determine the CB for a single new build residential house in each category on an occupancy basis, the embodied and use stage CBs were converted to 'per occupant' and 'per occupant.yr' values. Average occupancy per house type was determined to be 2.62 occupants for a DH and 1.89 occupants for MDH and APs. These values are based on average occupancy values from 2013 census data (Stats NZ, 2020b) which were then scaled to reflect the anticipated 2018-2050 New Zealand population and projected housing stock.

The embodied and use stage CBs were divided by the total number of occupants in new build houses to determine a 'per occupant' embodied CB and by the total number of occupant.yrs to determine a 'per occupant.yr' use stage CB respectively. These occupancy-based CBs were then applied to new build residential houses in each category based on the same occupancy levels with the use stage CB applied for 33 years assuming the house was constructed in 2017. A zero use stage CB post-2050 was adopted on the basis that measures to avoid or mitigate carbon emissions will need to have been developed by 2050 to meet the commitments within the Paris Agreement and the Climate Change Response (Zero Carbon) Amendment Act 2019.

An occupancy-based CB was not determined for office buildings.

2.2.3 Carbon Footprint of Residential Houses and Office Buildings

Carbon Footprint of Existing and New Build Residential Houses and Office Buildings

The 'base case' CFs of residential houses and office buildings were based on the modelled life cycle impacts of a number of example New Zealand Building Code compliant buildings for which life cycle impact data was available: three DHs, an MDH building, an AP building, and office buildings of different sizes. Data on the life cycle CFs of each building type were provided by BRANZ using LCAQuick v3.4.3 (BRANZ, 2019). The CF of new houses was calculated to be the same as existing houses on a per m^2 basis.

In the base case, Module D (potential benefits and loads beyond system boundary) was excluded and the CF for all life cycle stages was defined as GWP_{100} excluding biogenic carbon.

Modelled life cycle CFs were provided for each building at locations in each of New Zealand's three climate zones according to NZ Building Code Acceptable Solution H1/AS1 Energy Efficiency, these being Auckland (Zone 1), Wellington (Zone 2) and Christchurch (Zone 3). The CFs of each building in the three climate zones were averaged (by a simple average) to determine the 'average' New Zealand CF for each building type. DHs were represented by three different case study houses. An 'average' CF over the three houses and three climate zones was calculated on a per m^2 basis and applied to the average size of an 'existing' and 'new build' DH. Similarly, the CFs provided for an MDH and an AP were 'averaged' over the three climate zones and applied on a per m^2 basis to the average size of an 'existing' and 'new build' MDH and AP.

Office buildings were grouped according to floor area size ranges as defined by Amitrano et al. (2014) and noted in

Table 1. CF of size 1 and 2 office buildings were based on the 'average per m^2' impacts of a residential DH applied to an average size office building in size ranges 1 and 2 as calculated by McLaren et al. (2020). The CF of size range 3-5 office buildings were based on the modelled life cycle CF of actual buildings in each size range averaged over the three climate zones. The CFs were then averaged on a per m^2 basis over all sizes of buildings and applied to the average size of existing (pre-2018) and new built (2018-2050) office buildings based on the BRANZ stock projection model.

The key details of the residential and office properties forming the basis of the assessment are provided in

Table 1.

The original impact assessment data from LCAQuick v3.4.3 incorporates electricity CFs calculated using the 2016 ‘Mixed Renewable’ future electricity scenario produced by MBIE (2016). In this study, the base case electricity component of Modules B6 (operational energy use) and B7 (operational water use) was recalculated using the updated MBIE (2019) ‘Reference’ electricity scenario based on an LCA study of future New Zealand electricity supply (Bullen, 2020). Operational energy use (Module B6) in the residential buildings is entirely from electricity and, for office buildings, is predominately from electricity but also includes some gas used for heating.

Table 1: Details of Residential and Office Reference Buildings Used in Study

Building Type	House ID	Gross Floor Area of Original Study Buildings (m^2)	Average Gross Floor Area of 'Pre-Existing' Building (m^2)	Average Gross Floor Area of 'New Built' Building (m^2)
Residential Buildings				
Detached Houses	DH1	166	166	198
	DH2	194		
	DH3	194		
Medium Density Housing	MDH	887	115	114
Apartment	AP	3,721	99	94
Office Buildings				
Size Range 1: 5 to <650m^2	S1	326[2]	1,152	1,136
Size Range 2: 650 - <1,500 m^2	S2	962[3]		
Size Range 3: 1,500 - <3,500 m^2	S3a	2,021		
	S3b	1,814		
Size Range 4: 3,500 - <9,000 m^2	S4a	7,789		
	S4b	5,911		
Size Range 5: 9,000 m^2 +	S5a	10,864		
	S5b	13,247		

Calculation of 2018-2050 Residential and Office Building Sector Carbon Footprints

The 'average' impacts for existing and new residential and office buildings were combined with data on the number of existing buildings, predicted number of properties to be built and number of demolitions per year from the BRANZ projected stock model to determine the CF from 2018-2050 for each building sector.

The BRANZ stock model was used to determine the number of existing buildings, new builds and demolitions in each year from 2018-2050 in each of the building categories (i.e. DHs, MDH, APs and office buildings). The CF of Modules A1-3 and A4-5 for a single building was multiplied by the number of new buildings predicted to be built in each year. The CF of Module C1-4 for a single building was multiplied by the number of demolitions each year. The use stage CF (Modules B2, B4, B6 & B7) for a single building per year was multiplied by the floor area of new and existing buildings each year. It was assumed that each new build was operational for half of the year in which it was built and that demolished buildings remained operational for the year in which they were demolished.

2.3 Scenarios

A range of sensitivity analyses were undertaken to determine the impact of alternative assumptions on the CB and CF of residential and office buildings. In each analysis, one or more of the base case assumptions were altered while the remaining inputs remained unchanged. A total of 31 scenarios for residential buildings and 26 scenarios for office buildings were undertaken.

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[2] Based on the average 'per m^2' impacts of detached houses applied to a 326m^2 building
[3] Based on the average 'per m^2' impacts of detached houses applied to a 962m^2 building

Table 2 provides a summary of the sensitivity scenarios undertaken.

Residential scenarios 1-13 and office building scenarios 1-12 relate to calculation of the global, New Zealand and building sector CBs. Sensitivity scenarios in relation to the calculation of CBs included scenarios relating to the climate target and global CB, the methods used to share the global CB, methods used to share the New Zealand CB to the residential and office building sectors, assumptions regarding the CB available to a new building post-2050, and the proportion of the residential and office building sector CB allocated to embodied emissions when calculating the CB for individual new buildings.

Residential scenarios 14-31 and office building scenarios 13-26 primarily relate to calculation of CFs although these scenarios can also result in changes to CBs due to the grandfathering of the CB based on historical CFs. Sensitivity scenarios in relation to calculation of CFs included scenarios incorporating different assumptions regarding the energy demand (energy efficiency) of existing and new buildings, the source of energy in office buildings, the location of buildings, inclusion of the carbon sequestration benefits within modules A1-A3 and Modules B2 and B4 (due to use of timber and engineered wood building materials assumed to have been derived from sustainable forestry), the design of new residential buildings, inclusion of the CF of mechanical, electrical and plumbing (MEP) and tenant improvement (TI) elements in new office buildings based on estimates in Rodriguez et al. (2020), the inclusion of Module D benefits for demolished buildings, weighting of impacts based on the number of houses located in different climate zones, an alternative assumption regarding the average size of existing residential buildings (i.e. 121m^2 GFA) based on (Isaacs et al., 2010), and revised BRANZ residential stock projections due to the impacts of Covid-19.

Table 2: Summary of Residential and Office Building Scenarios

Residential Scenario	Office Building Scenario	Scenario Description – Change to Base Case
1	1	Below 1.5^{o}C IPCC climate target
2	2	1.5^{o}C high overshoot IPCC climate target
3	3	Equal per capita sharing of global CB based on 2019 population
4	-	Residential share of the NZ CB based on final consumption expenditure in 2015
5	4	Building sector share of NZ CB based on 2011[4] grandfathering
6	5	Building sector share of NZ CB based on 2015 grandfathering
7	6	Building sector share of NZ CB based on 2017[5] grandfathering
8	7	Post-2050 CBs based on 100% of the 2018-2050 use stage CB
9	8	Post-2050 CBs based on 50% of the 2018-2050 use stage CB
10	9	Post-2050 CBs based on 25% of the 2018-2050 use stage CB
11	-	30% of total residential sector CB allocated to embodied carbon
12	-	40% of total residential sector CB allocated to embodied carbon
13	-	50% of total residential sector CB allocated to embodied carbon
-	10	25% of total office building sector CB allocated to embodied carbon
-	11	45% of total office building sector CB allocated to embodied carbon
-	12	55% of total office building sector CB allocated to embodied carbon
14	13	100% Renewable electricity scenario (ICCC, 2019) (Modules B6 & B7)[6]

[4] Using consumption based GHG emission data from Chandrakumar et al. (2020a)

[5] Using consumption based GHG emission data from Stats NZ (2020a)

[6] 25% of residential sector CB to embodied carbon; 34% of office building sector CB to embodied carbon

Residential Scenario	Office Building Scenario	Scenario Description – Change to Base Case
-	14	Office buildings heated by electricity only; 70% efficiency of gas heating systems when converting gas heating demand to electricity.
-	15	Office buildings heated by electricity only; 90% efficiency of gas heating systems when converting gas heating to electricity
15	-	20% increase in heating demand in existing residential buildings
16	-	50% increase in heating demand in existing residential buildings
17	-	100% increase in heating demand in existing residential buildings
-	16	20% reduction in office building energy demand due to heating, cooling, fans and pumps
-	17	40% reduction in office building energy demand due to heating, cooling, fans and pumps
-	18	1. All office buildings heated by electricity only. 90% efficiency of gas heating systems when converting gas heating to electricity 2. 40% reduction in office building energy demand due to heating, cooling, fans and pumps
18	-	239% increase in 'heating, cooling & fans' energy demand of existing DHs based on modelling of DH compliant with 1978 Building Code
19	-	20% reduction in heating demand of new residential buildings
20	-	50% reduction in heating demand of new residential buildings
21	-	95% reduction in heating demand of new residential buildings
22	19	Assumes all buildings are located in climate zone 1
23	20	Assumes all buildings are located in climate zone 2
24	21	Assumes all buildings are located in climate zone 3
25	-	Weighting of impacts based on estimated number of houses in each climate zones
26	22	Inclusion of biogenic carbon sequestration benefits in Modules A1-3;
27	23	Inclusion of Module D benefits for demolished buildings;
28	-	New build DHs represented by a high timber/high performance house (excluding benefits of carbon sequestration - Modules A1-3, B2 & B4)
29	-	New build DHs represented by a high timber/high performance house (including benefits of biogenic carbon sequestration - Modules A1-3, B2 & B4)
-	24	Inclusion of mechanical, electrical and plumbing (MEP) & tenant improvements (TI) based on low values; replacement every 15 years
-	25	Inclusion of MEP & TI based on medium values; replacement every 15 years
-	26	Inclusion of MEP & TI based on high values; replacement every 15 years
30	-	Impacts of existing DHs based on an average GFA of 121m^2
31	-	Sector impacts based on revised stock projection model reflecting anticipated changes in building patterns due to the impact of Covid-19

3 Results

3.1 Residential Base Case and Scenarios

A summary of the residential base case and sensitivity scenario carbon budget (CB), carbon footprint (CF) and factor of exceedance (FoE) results are provided in Table 3. The base case CB is provided on a global, New Zealand, residential sector and residential sub-sector (i.e. detached house (DH), medium density housing (MDH), apartments (AP)) level as well as for individual new build houses on both an area and occupancy basis. The base case CF is provided for the combined residential sector and for individual sub-sectors as well as for individual new build houses. Scenario results are expressed as percentage difference from the base case results. The CF exceeds the relevant CB for all sectors and new build house types in the base case and for all scenarios. The FoE provides a measure of the size of exceedance (e.g. a 4.5 FoE represents a CF that exceeds the relevant CB by 450%). The numerical results for each residential scenario are contained in Appendix A.

Residential Base Case

The base case CB for the residential sector from 2018 to 2050 is 47,090 ktCO_{2eq} compared to a residential sector CF over this period of 169,651 ktCO_{2eq} resulting in a FoE of 3.6. The FoEs for the different house types ranges from 3.4 for the MDH sector to 5.3 for the AP sector.

For an individual new build house, over a 90 year estimated service life, the CB on an area basis is 34.6 tCO_{2eq} for a DH (GFA=198m^2), 19.9 tCO_{2eq} for MDH (GFA=114m^2) and 16.4 tCO_{2eq} for an AP (GFA=94m^2). On an occupancy basis the CB is 30.1 tCO_{2eq} for a DH (2.6 occupants) and 21.7 tCO_{2eq} for both MDH and an AP (1.9 occupants). The FoEs for individual new build houses vary between 6.2 (MDH, occupancy basis) and 10.9 (AP, area basis).

Residential Sensitivity Scenarios

The residential scenarios which result in a greater than 25% change in the CB compared to the base case are as follows:

- *Scenario 2 – IPCC 1.5°C high overshoot climate target*[7]: The CB increases by 35% on both a sector and individual new build house basis for all house types and results in a 26% reduction in the FoE on a sector and individual new build house basis for all house types.

- *Scenarios 5 & 6 – 2011 & 2015 grandfathering:* The CB reduces by 35% on a sector and individual new build basis when using 2011 as the grandfathering year to apportion a share of the New Zealand CB to the residential sector. The CB reduced by 38% when using 2015 as the grandfathering year. The FoE for all house types consequently increases by 55% when using 2011 as the grandfathering year and by 61% when using 2015 as the grandfathering year compared to a 2012 grandfathering year. These results are due to differences between the grandfathering years in both the total New Zealand consumption based GHG emissions and the GHG emissions due to residential buildings. This results in different proportions of the total New Zealand 2018-2050 CB being allocated to residential buildings when different grandfathering years are used.

[7] Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways (Rogelj et al., 2018).

- *Scenarios 8, 9 & 10 – post-2050 CB for individual new build house*: The base case CB for an individual new build house was based on a zero CB after 2050 on the basis that New Zealand has committed to be net carbon zero by this date. Scenarios 8-10 considered an alternative approach that provides use stage CB during the post-2050 years based on different proportions of the annual 2018-2050 use stage CB. Providing an annual post-2050 CB equal to the annual 2018-2050 use stage CB (Scenario 8) results in an increase in the lifetime CB of a new build house of 99-104%. A post-2050 CB at 50% of the 2018-2050 use stage CB (Scenario 9) increases the lifetime CB of a new build house by 50-52% and a post-2050 CB at 25% of the 2018-2050 use stage CB (Scenario 10) increases the lifetime CB of a new build house by 25-26%. Consequently, FoEs for a new build house reduce by 50-51% for Scenario 8, 33-34% for Scenario 9, and 20-21% for Scenario 10.

- *Scenarios 12 & 13 – increased allocation of residential sector CB to embodied carbon when calculating the CB for individual new build houses:* Increasing the proportion of the total sector CB allocated to embodied carbon to 40% (Scenario 12) results in a 25-28% increase in the CB for a new build house and increasing the proportion allocated to embodied carbon to 50% (Scenario 13) results in a 38-42% increase in the CB for a new build house. FoEs for a new build house reduce by 20-22% for Scenario 12 and 27-30% for Scenario 13.

No scenarios resulted in a greater than 25% change in the CF results compared to the base case.

Scenario 14 represents 100% renewable electricity generation by 2035 and results in a decrease in the CF at both a sector level and for an individual new build of 17-22%. The proportion of the residential sector CB allocated to embodied carbon is also increased to 25% in this scenario to reflect the reduced proportion of use stage emissions and therefore there are also small increases in the CB of a new build house (<10%). The combined effect is that FoEs for an individual new build house reduce by 24-27%, with smaller reductions in FoE at a sector level of 17-22%.

Table 3: Summary of Residential Base Case and Scenario Results

		Parameter	Base Case	Carbon Budget Scenarios													Carbon Footprint Scenarios																	
				Climate Target		Global CB to NZ	FCE Sharing	Grandfathering Year			Post 2050 Use Stage CB (new build)			% Embodied Emissions			Electricity Scenario	Increased Heating (existing)			1978 BC	Reduced heating (new)			Location of Buildings				Incl Biogenic	Module D incl	House Features			COVID 19
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Sector Based (2018-50)	Carbon Budget	World CB	786 $GtCO_{2eq}$	-18%	35%																													
		New Zealand	470.1 $MtCO_{2eq}$	-18%	35%																													
		Residential Sector	47,090 $ktCO_{2eq}$	-18%	35%			-35%	-38%	-15%										14%	18%												-20%	
		DH Sector	37,111 $ktCO_{2eq}$	-18%	35%			-35%	-38%	-15%										14%	18%												-20%	
		MDH Sector	7,033 $ktCO_{2eq}$	-18%	35%			-35%	-38%	-15%										14%	18%												-20%	10%
		AP Sector CB	2946 $ktCO_{2eq}$	-18%	35%			-35%	-38%	-15%										14%	18%												-20%	
	Carbon Footprint	Residential Sector	169,651 $ktCO_{2eq}$														-21%										12%					-17%	-14%	
		DH Sector	130,407 $ktCO_{2eq}$														-21%			10%	15%				-11%		13%					-22%	-18%	
		MDH Sector	23,743 $ktCO_{2eq}$														-22%										10%							16%
		AP Sector	15,501 $ktCO_{2eq}$														-17%																	
	Factor of Exceedance	Residential Sector	3.6	22%	-26%			55%	61%	18%							-21%				-15%						12%					-14%		
		DH Sector	3.5	22%	-26%			55%	61%	18%							-21%				-3%				-11%		13%					-19%		
		MDH Sector	3.4	22%	-26%			55%	61%	18%							-22%				-15%												26%	
		AP Sector	5.3	22%	-26%			55%	61%	18%							-17%			-11%	-15%												26%	
Individual New Build Lifetime Based (2018-2107)	Carbon Budget	DH-area	34.6 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	104%	52%	26%	13%	25%	38%				14%	18%												-11%	
		MDH-area	19.9 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	104%	52%	26%	13%	25%	38%				14%	18%												-11%	
		AP-area	16.4 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	104%	52%	26%	13%	25%	38%				14%	18%												-11%	
		DH-occupancy	30.1 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	99%	50%	25%	14%	28%	42%				14%	18%												-12%	
		MDH-occupancy	21.7 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	99%	50%	25%	14%	28%	42%				14%	18%												-12%	
		AP-occupancy	21.7 tCO_{2eq}	-18%	35%			-35%	-38%	-15%	99%	50%	25%	14%	28%	42%				14%	18%												-12%	
	Carbon Footprint	DH	233.1 tCO_{2eq}														-21%							-11%			11%				13%	-14%		
		MDH	135.4 tCO_{2eq}														-22%																	
		AP	179.0 tCO_{2eq}														-19%																	
	Factor of Exceedance	DH-area	6.7	22%	-26%			55%	61%	18%	-51%	-34%	-21%	-11%	-20%	-27%	-25%			-12%	-15%			-11%			11%				13%	-11%	13%	
		MDH-area	6.8	22%	-26%			55%	61%	18%	-51%	-34%	-21%	-11%	-20%	-27%	-27%			-12%	-15%												13%	
		AP-area	10.9	22%	-26%			55%	61%	18%	-51%	-34%	-21%	-11%	-20%	-27%	-24%			-12%	-15%												13%	
		DH-occupancy	7.7	22%	-26%			55%	61%	18%	-50%	-33%	-20%	-12%	-22%	-30%	-26%			-12%	-15%			-11%			11%				13%	-11%	13%	
		MDH-occupancy	6.2	22%	-26%			55%	61%	18%	-50%	-33%	-20%	-12%	-22%	-30%	-27%			-12%	-15%												13%	
		AP-occupancy	8.2	22%	-26%			55%	61%	18%	-50%	-33%	-20%	-12%	-22%	-30%	-25%			-12%	-15%												13%	

Key:

	no change from base case
	<10% decrease in carbon budget or increase in carbon footprint
	10-25% decrease in carbon budget or increase in carbon footprint
	>25% decrease in carbon budget or increase in carbon footprint
	<10% increase in carbon budget or decrease in carbon footprint
	10-25% increase in carbon budget or decrease in carbon footprint
	>30% increase in carbon budget or decrease in carbon footprint

3.2 Office Building Base Case and Scenarios

A summary of the office building base case and sensitivity scenario CB, CF and FoE results are provided in Table 4. The base case CB is provided on a global, New Zealand and office building sector basis as well as for an averaged sized (GFA=1,136 m^2) new office building. The base case CF is provided for the office building sector and for an individual new office building over a 60 year estimated service life. Scenario results are expressed as percentage difference from the base case results. The CF exceeds the relevant CB at a sector and individual new building level for the base case and all scenarios. The numerical results for each office building scenario are contained in Appendix B.

Office Building Base Case

The base case CB for the office building sector from 2018 to 2050 is 2,140 $ktCO_{2eq}$. The base case office building sector CF over the same period is 8,566 $ktCO_{2eq}$. representing a FoE of 4.0.

For an individual new build office over a 60-year service life the CB is 236 $tCO_{2eq.}$ and the base case CF is 1,259 $tCO_{2eq.}$, representing a FoE of 5.3.

Office Building Sensitivity Scenarios

The office building scenarios which result in a greater than 25% change in the CB compared to the base case are as follows:

- *Scenario 2 – IPCC 1.5°C high overshoot climate target*: The CB increases by 35% for both the office building sector and an individual new office building. This results in a 26% reduction in the FoE for both the office building sector and individual new office building.

- *Scenarios 4 & 5 – 2011 & 2015 grandfathering:* The CB reduces by 31-32% on a sector and individual new build basis when using 2011 or 2015 as the grandfathering years to apportion a share of the New Zealand CB to the office building sector. The FoEs consequently increases by 44-47%.

- *Scenarios 7 – post-2050 CB for individual new office building*: Providing an annual post-2050 CB equal to the annual 2018-2050 use stage CB (Scenario 7) results in an increase in the total CB for a new office building of 45% and a 31% reduction in the FoE.

- *Scenarios 25 & 26 - inclusion of mechanical, electrical, plumbing (MEP) and tenant improvements (TI) (medium & high levels):* The inclusion of MEP and TI at a medium level (Scenario 25) results in an increase in the office building CB of 35% at a sector level and 33% for an individual new building. The inclusion of MEP and TI at a high level results in an increase in the office building CB of 49% at a sector level and 46% for an individual new building. The impacts of including MEP and TI on the CF and FoE are described below.

The office building scenarios which result in a greater than 25% change in the CF compared to the base case are as follows:

- *Scenarios 24, 25 & 26 – inclusion of mechanical, electrical, plumbing (MEP) and tenant improvements (TI) (low, medium & high levels):* The inclusion of MEP and TI at low, medium and high levels results in an increase in the CF of the office building sector of 29-71%. The FoEs for the office building sector increase by 7-14%. The CFs of an individual office building increase by 31-76%. The FoEs for an individual office building increase by 10-20%.

Table 4: Summary of Office Building Base Case and Scenario Results

Parameter			Base Case	Carbon Budget Scenarios												Carbon Footprint Scenarios													
				Climate Target		Global CB to NZ	Grandfathering Year			Post 2050 Use Stage CB (new build)			% Embodied Emissions			Electricity Scenario	Gas heating to electricity		Comfort Efficiency		Scenarios 15 + 17	Location of Buildings			Incl Biogenic	Module D incl	MEP & TI included		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Sector Based (2018-50)	Carbon Budget	World	786 $GtCO_{2eq}$	-18%	35%																								
		NZ	470 $MtCO_{2eq}$	-18%	35%	4%																							
		Sector	2,140 $ktCO_{2eq}$	-18%	35%	4%	-32%	-31%	-4%								-1%	-0.01%	-4%	-9%	-9%	-7%	-2%	9%	-4%	-1%	20%	35%	49%
	Carbon Footprint	Sector	8,566 $ktCO_{2eq}$													-18%	-4%	-4%	-5%	-9%	-11%	-10%	-2%	11%	-3%	-1%	29%	51%	71%
	Factor of Exceedance	Sector	4.0	22%	-26%	-4%	47%	44%	4%							-18%	-3%	-4%	-0.2%	-0.4%	-3%	-2%	0%	2%	1%	-0.1%	7%	11%	14%
New Build Lifetime Based (2018-2077)	Carbon Budget	Building	236 tCO_{2eq}	-18%	35%	4%	-32%	-31%	-4%	45%	23%	11%	-7%	2%	6%	4%	-0.2%	1%	-4%	-7%	-7%	-6%	-2%	8%	-5%	-6%	19%	33%	46%
	Carbon Footprint	Building	1,259 tCO_{2eq}													-20%	-5%	-5%	-5%	-9%	-12%	-10%	-1%	12%	-3%	-5%	31%	54%	76%
	Factor of Exceedance	Building	5.3	22%	-26%	-4%	47%	44%	4%	-31%	-19%	-10%	8%	-2%	-5%	-23%	-5%	-5%	-1%	-2%	-6%	-5%	0.3%	4%	2%	2%	10%	16%	20%

Key:

	no change from base case
	<10% decrease in carbon budget <u>or</u> increase in carbon footprint
	10-25% decrease in carbon budget <u>or</u> increase in carbon footprint
	>25% decrease in carbon budget <u>or</u> increase in carbon footprint
	<10% increase in carbon budget <u>or</u> decrease in carbon footprint
	10-25% increase in carbon budget <u>or</u> decrease in carbon footprint
	>30% increase in carbon budget <u>or</u> decrease in carbon footprint

4 Discussion

4.1 Exceedance of Carbon Budget

The carbon footprint (CF) at both a sector level and for an individual new building exceeds the carbon budget (CB) in the base case and all scenarios for all residential buildings types and office buildings. The lowest residential factors of exceedance (FoE) occur when the IPCC 1.5°C high overshoot climate target is adopted (Scenario 2) resulting in a 2.6 FoE for the DH sector and a 2.5 FoE for the MDH sector. The lowest office building FoE occurs when the IPCC 1.5°C high overshoot climate target is used for the global climate target (Scenario 2) resulting in a 3.0 FoE.

The highest FoE for residential buildings occurs when 2015 is used as the grandfathering year for sharing the New Zealand CB to the residential sectors (residential Scenario 6) resulting in FoEs of up to 17.5 (individual new build AP, area based sharing). The highest FoE for office buildings occurs when 2011 is used as the grandfathering year for sharing the New Zealand CB to the office building sector (office building Scenario 4) resulting in a 5.9 FoE at the sector level and a 7.8 FoE for a new build office).

4.2 Factors Affecting Carbon Budget

Considering both residential and office buildings, the most important factors influencing the carbon budget are:

- CB post-2050 for an individual new building
- Inclusion of MEP (mechanical, electrical, and plumbing) and TI (tenant improvements) elements in office buildings
- Grandfathering year
- Global climate target
- Proportion of sector wide CB allocated to embodied impacts as this influences the CB available to individual new buildings

Carbon Budget Post-2050

The base case CB for individual new build houses and office buildings incorporates a zero CB after 2050 on the basis that all buildings will be net zero carbon by 2050 in line with the target set in the Climate Change Response (Zero Carbon) Amendment Act 2019 that New Zealand will reduce net emissions of all greenhouse gases (except biogenic methane) to zero by 2050.

Achieving a net zero CF in buildings post-2050 will require significant reductions in the CF of materials used for construction, renovation, repair, and maintenance as well as reductions in the CF of supplied energy. The CF of New Zealand electricity is relatively low compared to many countries due to a high proportion of renewable generation. The CF of electricity is expected to continue to decline due to the economic competitiveness of renewable generation technology and the New Zealand government's commitment to achieving 100% renewable generation by 2030 (Ardern, 2020). However, even with 100% renewable generation, there will continue to be some GHG emissions associated with electricity generation due primarily to fugitive emissions associated with geothermal generation and the embodied emissions associated with generation infrastructure (Bullen, 2020). However, embodied emissions associated with generation infrastructure would also be expected to trend toward zero as the manufacturing and logistics industries also decarbonise.

The target of net zero carbon by 2050 will be achieved by both reducing emissions and increasing carbon sequestration, and not all sectors will necessarily need to achieve zero carbon emissions to achieve net zero carbon over the whole economy. The implications of alternative post-2050 CBs for a new building were explored through scenarios which provided a post-2050 CB for both residential and office buildings based on 100%, 50% and 25% of the pre-2050 use stage CB. This results in a 25-104% increase in the CB available for residential buildings and an 11-45% increase for office buildings. Despite the provision of this additional post-2050 CB, the CF of new buildings continues to exceed the available CB by a factor of 3.1-8.7 for residential buildings and by a factor of 3.7-4.8 for office buildings.

Inclusion of Mechanical, Electrical, Plumbing and Tenant Improvements – Office Buildings

The implications of including mechanical, electrical and plumbing (MEP) and tenant improvement (TI) elements on both the office building CB and CF were explored by allocating low, medium and high estimates for the GHG emissions of these elements based on the findings of Rodriguez et al. (2020). The inclusion of MEP and TI in the CF of the office building sector in the base case grandfathering year of 2012 results in a 19-49% increase in the CB available to the office building sector and individual new buildings. The impact of including MEP and TI elements on the CF is discussed in Section 4.3.

Grandfathering Base Year

The use of grandfathering to allocate the New Zealand CB to the residential and office building sectors provides a CB in the same proportion as these sectors contributed to total New Zealand consumption based GHG emissions in the grandfathering year. Consumption based GHG emissions, as opposed to production based GHG emissions, are considered the appropriate basis for grandfathering of emissions in this study as the CF is calculated using a consumption-based approach i.e. based on the service of providing warmth, security, shelter and convenience for people (either at home or work). However, the availability of consumption-based GHG emission data for New Zealand is limited. The base case utilises 2012 consumption based emission data sourced from the EORA full version multi-region input-output (MRIO) database (Chandrakumar et al., 2020b). Scenarios which use 2011 as the base year for grandfathering (residential Scenario 5, office building Scenario 4) utilise the Eora-26 sector database (Chandrakumar et al., 2020a) which is considered to be less accurate than the full EORA database. Scenarios using 2015 as the base year (Residential Scenario 6 and office building Scenario 5) utilise the EORA full version[8] (Lenzen et al., 2012; Lenzen et al., 2013). In contrast, residential Scenario 7 and office building Scenario 6 utilise recently released provisional consumption based emissions for 2017 (Stats NZ, 2020a) which are based on a national input-output approach. The use of a national input-output approach has advantages as it is less data intensive and can be more easily linked to data used for other national accounting purposes. However, it also involves a number of assumptions including estimating the CF of imports based on the CF of equivalent goods produced in New Zealand (Stats NZ, 2020a). This introduces a potentially significant source of inaccuracy compared to a MRIO approach.

The scenario results show that the choice of grandfathering year and the data source can have a significant impact on the available CB. The use of MRIO based 2011 and 2015 emissions result in CBs 31-38% lower than the base case for all building types and the use of 2017 emissions using a national input-output approach results in CBs 15% lower than the base case for residential buildings and 4% lower for office buildings.

The time period between the grandfathering year using the earlier MRIO databases (2011/2012) and the start of the assessment period (2018) will also potentially change the results compared to a 2015

[8] 2015 value was derived from a recent data update for year 2015.

or 2017 grandfathering year due to changes in the CF of buildings over this time (e.g. due to increased renewable electricity generation). An improvement in the CF of buildings during the intervening years will result in a higher CB compared to a grandfathering year immediately prior to the assessment period.

The development of a regularly updated, reliable and consistent methodology for measuring consumption based GHG emissions in New Zealand would provide greater accuracy to future assessments of building sector CBs.

Global Climate Target

Adopting a 1.5°C-high-OS climate target results in a global carbon budget 35% greater than the 1.5°C-low-OS climate target used in the base case. This increase in the global carbon budget results in equivalent increases in the New Zealand CB and consequently the CBs for the residential and office building sectors. Conversely, adopting a below 1.5°C climate target[9] reduces the available CB by 18%.

Clearly, the choice of global climate target and the resulting global CB has a significant influence on the CB available to the building sector and the resulting climate change performance of buildings in an absolute sustainability context.

Proportion of Sector Carbon Budget Allocated to Embodied Impacts when Calculating Carbon Budget for Individual New Building

The use stage CF of buildings is expected to decrease in the future as buildings become more energy efficient and the proportion of renewable energy increases. Consequently, the proportion of the CF due to use stage emissions is expected to decrease and the proportion due to embodied impacts will increase at both a sector level and for an individual building. The implications of this transition were explored through scenarios which allocated increased proportions of the residential and office building sector CBs to embodied emissions which consequently increased the relatively proportion of the total sector budget allocated to an individual new building due to embodied emissions being primarily allocated to new stock. In the residential base case, 20% of the total sector CB was allocated to embodied carbon emissions. Increasing this proportion to 50% increases the CB available to an individual house by 38-42%. Smaller increases of 13-28% occur when the proportion of the CB allocated to embodied emissions is increased to 30% or 40%. These results indicate that the split between the allocation of embodied and use stage emissions at a sector level is an important consideration that should reflect the actual split in emissions as closely as possible. Changes in the CB available to new office buildings were smaller (-7-6%) when the proportion of the sector CB allocated to embodied impacts was changed from the base case of 35% to 25%, 45% or 55%.

2019 Base Year for Equal per Capita Sharing

Equal per capita sharing of the global carbon budget is considered the most appropriate sharing approach in relation to buildings, particularly housing, as all people have an equal need for a safe, warm and secure place to live. The base case allocates a share of the global CB to New Zealand based on the predicted cumulative 2018-2050 New Zealand population as a proportion of the cumulative 2018-2050 global population. This approach could potentially favour countries with high rates of growth compared to those countries with low or declining growth rates. An alternative

[9] Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50–66% likelihood (Rogelj et al., 2018).

approach was explored by basing the equal per capita sharing on the New Zealand population in 2019 as a proportion of the 2019 global population. The resulting New Zealand and building CBs are only 4% higher than the base case reflecting an expected growth in the New Zealand population at a similar rate to the global average over the 2018-2050 time period and therefore this alternative approach results in only a small increase to the CB.

Box 1: Comparison with Alternative Methodology to Calculate Operational Energy Use (Module B6)

The estimation of sector emissions associated with operational energy use (Module B6) are based on modelling the energy use of example houses multiplied by the past (for grandfathering purposes) or estimated future stock levels. An alternative approach to estimating sector-wide historical operational energy emissions using Ministry of Business Innovation and Employment (MBIE) data on residential energy use was explored in relation to the grandfathering years of 2012 (base case) and 2015 (residential Scenario 6). The residential use of electricity, gas, coal, LPG, diesel and solid biofuels (MBIE, 2020a) was multiplied by relevant emission factors for electricity (Bullen, 2020), energy sector greenhouse gas emission factors for fossil fuels (MBIE, 2020c) and Ecoinvent 3.5 emissions for a wood pellet furnace. The electricity and wood pellet furnace emission factors represent life-cycle emissions whereas the fossil fuel emission factors only represent the emissions from combustion and therefore are likely to underestimate the life-cycle emissions. The resulting carbon footprint for operational energy use in 2012 using this alternative residential energy use methodology was 4,174 $ktCO_{2eq}$ compared to 4,517 $ktCO_{2eq}$ using the main methodology used in this study. In 2015, the carbon footprint for residential energy using the alternative methodology was 3,343 $ktCO_{2eq}$ compared to 3,385 $ktCO_{2eq}$ using the study methodology. The values using these two different methods only varied by only 1-8% which provides a high level of confidence in the results using the main methodology adopted in this study.

4.3 Factors Affecting Carbon Footprint

The two most important factors affecting the CF of buildings are the inclusion of GHG emissions associated with MEP and TI elements in office buildings and the CF of supplied electricity. These two aspects are discussed below followed by a discussion of factors associated with buildings design, efficiency, and use.

Inclusion of MEP and TI in Office Buildings

Rodriguez et al. (2020) identified that, with recurring installations, the CF of MEP and TI elements can be equal to the CF of core and shell systems in a commercial building. In this study, the inclusion of the CF associated with MEP and TI elements leads to increases in the CF of an individual office buildings of 31% at a low level and 76% at a high level using CF estimates for MEP and TI from Rodriguez et al. (2020). The low, medium, and high levels represent the range of embodied carbon estimates from a study of five commercial office buildings in the Pacific North-West region of the USA. MEP and TI elements tend to have a relatively short service-life compared to the structural elements of a commercial buildings and therefore it was assumed that these elements are replaced every 15 years (i.e. initial installation plus three replacements over the total service life of the building). This additive effect of repeated replacements results in significant increases in the lifetime CF of an office building when MEP and TI are included, particularly at the high level. At the sector level, the inclusion of MEP and TI also led to large increases in the CF of 29-71%.

For the purposes of this study, it was assumed that the emissions due to MEP & TI elements identified by Rodriguez et al. (2020) for office buildings in the USA are also applicable to New Zealand office buildings. It is noted that BRANZ is currently undertaking a project to calculate the carbon footprint of building services of four New Zealand office buildings which will provide some New Zealand specific data for comparison with these values.

Carbon Footprint of Supplied Electricity

A scenario based on 100% renewable electricity by 2035 (residential Scenario 14) results in the greatest change in the CF of residential buildings with a 17-22% reduction in the CF at both a sector level and for individual new buildings for all residential building types. The proportion of the total sector CB allocated to embodied impacts is also increased to 25% in this scenario (c.f. base case 20%) reflecting the reduced use stage impacts associated with a lower electricity CF which increased the CB for new residential buildings by 6-7%. The combined effect of these two changes is a reduction in the FoE of 24-27% for new buildings. A similar pattern occurred with office buildings with a 18% reduction in the CF and FoE at the sector level and an 20-23% reduction in the CF and FoE for an individual new office building.

It was assumed in this study that all operational energy for residential buildings was sourced from grid electricity. Electricity is estimated to supply 69% of energy needs to New Zealand households (Isaacs et al., 2010) but a number of other energy sources are used in both residential and office buildings including direct use of natural gas, coal and wood, solar water heating and distributed renewable energy sources such as solar PV, wind and micro-hydro. The future mix of energy sources will affect the use stage CF of buildings in addition to the CF of grid electricity. For example, solar PV technology accounted for only 0.3% of electricity generation in 2019 (MBIE, 2020b), but is experiencing significant growth and this is expected to grow further as the cost effectiveness of solar PV improves (Transpower, 2019). The impact of changes in the energy mix supplying buildings and increased use of distributed renewable generation has not been explored in this study but, depending on the extent of uptake, could also be a factor in reducing the use stage CF of New Zealand buildings.

Impact on Carbon Footprint of Other Scenarios

A number of scenarios explore alternative assumptions relating to the design and use of buildings including energy efficiency and alternative house designs and sizes. The differences between climate zones and weighting of impacts based on number of buildings in different climate zones, scenarios including the benefits of sequestration of biogenic carbon, and alternative building stock models are also examined. None of these scenarios result in a greater than 25% change in the CF of residential or office buildings at either a sector or individual building level. The greatest change in CF associated with these scenarios occurs when the GFA of existing DHs is based on an average of 121m^2 (Isaacs et al., 2010) as opposed to the base case of 166m^2. This scenario results in a decrease in the CF of the DH sector of 18% and of the total residential sector of 14%. However, as this change also applied to DHs existing in 2012, the CB also reduces due to the grandfathering of the CB to the 2012 CF. Therefore, the FoEs for DHs in this scenario increase by 3% at a sector level and increase by 13% for individual new DHs, despite a decrease in the CF.

Although heating and cooling is an important source of energy demand in a building, scenarios involving changes in energy demand due to heating have relatively small impacts on the overall CF. Although energy demand can be influenced by building design (e.g. additional insulation, high performance house design), other energy demands such as water heating and plug loads are less affected by design and more affected by occupant behaviour.

5 Conclusions

Box 2: Top Priorities for Further Research Identified by this Study

The main purpose of this study was to identify priorities for further study or data improvements to support the transformation of the New Zealand built environment to one that is sustainable in the context of global climate change. The identified top priorities for further research are:

- Consistent and accurate set of consumption-based emission accounts for New Zealand.
- The contribution of the embodied carbon of building materials to the overall carbon footprint of buildings. In particular, the contribution of mechanical, electrical, plumbing (MEP) and tenant improvements(TI) elements to the carbon footprint of office buildings in the New Zealand context.
- Refinement and update of estimates related to the existing and future building stock, including building size, design, energy supply and consumption, and occupancy.
- The impact of energy efficiency measures on the carbon footprint of buildings.

The choice of grandfathering year, combined with differences in the method used to calculate New Zealand consumption-based emissions, has a significant influence on the CB available for the different building sectors. This highlights the potential value of a consistent and accurate set of consumption-based emission accounts for New Zealand. It is recommended that future studies utilise the most recent year for which New Zealand's consumption-based GHG emissions are available utilising a MRIO-based approach. It is noted that this is expected to significantly reduce the CB available to New Zealand and to buildings compared with the results in this study.

The post-2050 CB provided to New Zealand buildings is also a key determinant of the lifetime CB available for new buildings currently being designed and constructed. The base case assumption of a zero use stage CB for buildings post-2050 is considered appropriate given the New Zealand target of net-zero GHG emissions by 2050. However, even with 100% renewable electricity generation, further reduction in the CF of electricity would be required to achieve a CF consistent with this target – largely due to currently anticipated geothermal fugitive emissions and the embodied carbon of generation infrastructure.

Scenarios involving alternative designs, smaller house size, and energy efficiency of new buildings resulted in relatively modest improvements in the overall CF of buildings. To be compatible with a 1.5^{o}C climate target, improvements will be required in multiple areas within the building sector including building design, energy efficiency and the embodied impacts of materials and construction methods. Behavioural and demand aspects also have an important role in areas such as non-heating energy demand (e.g. hot water, plug loads), the occupancy of buildings, and expectations regarding the size of buildings. The CF of the energy sector, particularly the electricity sector, is also an important factor impacting the CF of buildings. The embodied CF of buildings is expected to become increasingly important as the CF of supplied energy decreases.

The findings of this study have highlighted a number of areas where further study would provide additional clarity on the factors affecting both CBs and CFs of buildings. The importance of accurate consumption-based GHG emission data for New Zealand is noted above. At a sector level, continued refinement and updates of estimates related to the existing and future housing and office building stock, including building size, design, energy supply and consumption, and occupancy are important factors in accurately estimating building sector impacts. At an individual building level, the impact of energy efficiency measures, the impact of alternative building materials, and improvements in the embodied carbon of building materials (e.g. MEP and TI elements in office buildings) are important areas for further study to identify where the most significant and cost effective improvements in the CF of buildings can be achieved.

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References

Amitrano, L., Isaacs, N., Saville-Smith, K., Donn, M., Camilleri, M., Pollard, A., . . . Cory, S. (2014). *BEES Part 1: Final report Building energy end-use study* (No. SR 297/1). Judgeford, New Zealand: BRANZ Ltd.

Ardern, J. (2020). 100% renewable electricity generation by 2030 [Press release]. Retrieved from https://www.labour.org.nz/release-renewable-electricity-generation-2030

Bjørn, A., Chandrakumar, C., Boulay, A.-M., Doka, G., Fang, K., Gondran, N., . . . Ryberg, M. (2020). Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. *Environ. Res. Lett., in press*

BRANZ. (2019). LCAQuick Tool. Retrieved from https://www.branz.co.nz/cms_display.php?st=1&pg=23287&sn=415&forced_id=yes

BSI. (2011). *BS EN 15978:2011: Sustainability of construction works-Assessment of environmental performance of buildings-Calculation method*: BSI Standards Publication.

Bullen, L. (2020). *Life cycle based environmental impacts of future New Zealand electricity supply.* (Master of Environmental Management), Massey University, Palmerston North.

Chandrakumar, C., Malik, A., McLaren, S. J., Owsianiak, M., Ramilan, T., Jayamaha, N. P., & Lenzen, M. (2020a). Setting Better-Informed Climate Targets for New Zealand: The Influence of Value and Modeling Choices. *Environmental Science & Technology, 54*(7), 4515-4527. https://dx.doi.org/10.1021/acs.est.9b06991

Chandrakumar, C., McLaren, S., Malik, A., Ramilan, T., & Lenzen, M. (2020b). Understanding New Zealand's consumption-based greenhouse gas emissions: an application of multi-regional input-output analysis. *The International Journal of Life Cycle Assessment, 25*(7), 1323–1332. https://doi.org/10.1007/s11367-019-01673-z

Chandrakumar, C., McLaren, S. J., Dowdell, D., & Jaques, R. (2019). A top-down approach for setting climate targets for buildings: the case of a New Zealand detached house. Paper presented at Sustainable Built Environment (SBE) Conference, Graz University of Technology, 11-14 September 2019. *IOP Conference Series: Earth and Environmental Science, 323*(1), 012183. https://doi.org/10.1088/1755-1315/323/1/012183

Chandrakumar, C., McLaren, S. J., Dowdell, D., & Jaques, R. (2020c). A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house. *Building and Environment, 169*, 106560. https://doi.org/10.1016/j.buildenv.2019.106560

ICCC. (2019). *Accelerated electrification: evidence, analysis and recommendations*. Retrieved from https://www.iccc.mfe.govt.nz/what-we-do/energy/electricity-inquiry-final-report/

IEA and UN Environment Programme. (2019). *2019 Global Status Report for Buildings and Construction: towards a zero-emission, efficient and resilient buildings and construction sector*. Retrieved from https://webstore.iea.org/download/direct/2930?fileName=2019_Global_Status_Report_for_Buildings_and_Construction.pdf

Isaacs, N., Camilleri, M., Burrough, L., Pollard, A., Saville-Smith, K., Fraser, R., . . . Jowett, J. (2010). *Energy Use in New Zealand Households Final Report on the Household Energy End-use Project (HEEP) BRANZ Study Report 221*. Judgeford, New Zealand: BRANZ Ltd.

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science & Technology, 46*(15), 8374-8381. https://doi.org/10.1021/es300171x

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input-output database at high country and sector resolution. *Economic Systems Research, 25*, 20-49. https://doi.org/10.1080/09535314.2013.769938

MBIE. (2016). 2016 electricity demand and generation scenarios. Mixed renewables data file.

MBIE. (2019). *Electricity demand and generation scenarios: Scenario and results summary* (MBIE 4872). Wellington, New Zealand. Retrieved from https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-modelling/electricity-demand-and-generation-scenarios/

MBIE. (2020a). Energy balance tables. Retrieved from https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-balances/

MBIE. (2020b). *Energy in New Zealand 20*. Wellington: MBIE. Retrieved from https://www.mbie.govt.nz/dmsdocument/11679-energy-in-new-zealand-2020

MBIE. (2020c). New Zealand energy sector greenhouse gas emissions. Retrieved from https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/new-zealand-energy-sector-greenhouse-gas-emissions/

McLaren, S. J., Chandrakumar, C., Dowdell, D., Bullen, L., & Jaques, R. (2020). Application of Absolute Sustainability Assessment to New Zealand Residential Dwellings. *IOP Conference Series: Earth and Environmental Science, 588*, 022064. https://doi.org/10.1088/1755-1315/588/2/022064

Rodriguez, B. X., Huang, M., Lee, H. W., Simonen, K., & Ditto, J. (2020). Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation. *Energy and Buildings, 226*, 110324. https://doi.org/10.1016/j.enbuild.2020.110324

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change, 5*(6), 519-527.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., . . . Vilariño, M. (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global* *response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

Stats NZ. (2020a). Greenhouse gas emissions (consumption-based): Year ended 2017. Retrieved from https://www.stats.govt.nz/information-releases/greenhouse-gas-emissions-consumption-based-year-ended-2017#:~:text=Household%20consumption%20emissions%20were%2042%2C819,energy%20for%20heating%2Fcooling).

Stats NZ. (2020b). NZ Stat table viewer. Retrieved from http://nzdotstat.stats.govt.nz/wbos/

Transpower. (2019). *Te Mauri Hiko-the sun rises on a solar energy future*. Retrieved from https://www.transpower.co.nz/sites/default/files/plain-page/attachments/Te%20Mauri%20Hiko%20%E2%80%93%20the%20sun%20rises%20-%20published.pdf

Yu, S., Gao, X., Ma, C., & Zhai, L. (2011). Study on the concept of per capita cumulative emissions and allocation options. *Advances in Climate Change Research, 2*(2), 79-85. https://doi.org/10.3724/SP.J.1248.2011.00079

Appendix A: Residential Scenarios – Numerical Results

	Parameter		Unit	Scenarios 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Sector Based (2018-50)	Carbon Budget (CB)	World CB	Gt CO_{2eq}	643	1065	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786
		New Zealand	Mt CO_{2eq}	385	637	487	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470
		Residential Sector	kt CO_{2eq}	38,522	63,804	48,821	48,322	30,430	29,316	40,024	47,090	47,090	47,090	47,090	47,090	47,090	47,090	48,369	50,288	53,487	55,716	47,090	47,090	47,090	47,090	47,090	47,090	46,395	45,448	46,956	47,090	45,448	37,498	47,317
		DH Sector	kt CO_{2eq}	30,359	50,284	38,476	38,083	23,982	23,104	31,543	37,111	37,111	37,111	37,111	37,111	37,111	37,111	38,120	39,632	42,153	43,909	37,111	37,111	37,111	37,111	37,111	37,111	36,940	35,817	37,006	37,111	35,817	29,552	36,775
		MDH Sector	kt CO_{2eq}	5,753	9,529	7,291	7,217	4,544	4,378	5,977	7,033	7,033	7,033	7,033	7,033	7,033	7,033	7,224	7,510	7,988	8,321	7,033	7,033	7,033	7,033	7,033	7,033	6,749	6,787	7,013	7,033	6,787	5,600	7,770
		AP Sector CB	kt CO_{2eq}	2,410	3,991	3,054	3,023	1,904	1,834	2,504	2,946	2,946	2,946	2,946	2,946	2,946	2,946	3,026	3,146	3,346	3,485	2,946	2,946	2,946	2,946	2,946	2,946	2,706	2,843	2,937	2,946	2,843	2,346	2,772
	Carbon Footprint (CF)	Residential Sector	kt CO_{2eq}	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	169,651	134,003	172,575	176,962	184,273	169,651	168,853	167,656	165,862	153,397	166,226	189,329	167,101	159,735	169,049	172,341	140,399	146,619	168,525
		DH Sector	kt CO_{2eq}	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	130,407	102,626	133,031	136,967	143,528	150,174	129,695	128,628	127,026	116,460	127,565	147,195	128,877	121,298	130,017	133,097	101,962	107,375	126,843
		MDH Sector	kt CO_{2eq}	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	23,743	18,483	24,007	24,403	25,062	23,743	23,675	23,573	23,419	21,852	23,364	26,013	23,021	23,122	23,684	23,743	23,122	23,743	27,458
		AP Sector	kt CO_{2eq}	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	15,501	12,894	15,537	15,592	15,683	15,501	15,483	15,456	15,416	15,085	15,297	16,120	15,203	15,315	15,349	15,501	15,315	15,501	14,224
	Factor of Exceedance (FoE)	Residential Sector	-	4.4	2.7	3.5	3.5	5.6	5.8	4.2	3.6	3.6	3.6	3.6	3.6	3.6	2.8	3.6	3.5	3.4	3.0	3.6	3.6	3.5	3.3	3.5	4.0	3.6	3.5	3.6	3.7	3.1	3.9	3.6
		DH Sector	-	4.3	2.6	3.4	3.4	5.4	5.6	4.1	3.5	3.5	3.5	3.5	3.5	3.5	2.8	3.5	3.5	3.4	3.4	3.5	3.5	3.4	3.1	3.4	4.0	3.5	3.4	3.5	3.6	2.8	3.6	3.4
		MDH Sector	-	4.1	2.5	3.3	3.3	5.2	5.4	4.0	3.4	3.4	3.4	3.4	3.4	3.4	2.6	3.3	3.2	3.1	2.9	3.4	3.4	3.3	3.1	3.3	3.7	3.4	3.4	3.4	3.4	3.4	4.2	3.5
		AP Sector	-	6.4	3.9	5.1	5.1	8.1	8.5	6.2	5.3	5.3	5.3	5.3	5.3	5.3	4.4	5.1	5.0	4.7	4.4	5.3	5.2	5.2	5.1	5.2	5.5	5.6	5.4	5.2	5.3	5.4	6.6	5.1
Individual New Build Lifetime Based (2018-2107)	Carbon Budget (CB)	DH-m² basis	t CO_{2eq}	28.3	46.8	35.8	35.5	22.3	21.5	29.4	70.3	52.4	43.5	38.9	43.2	47.5	36.7	35.5	36.9	39.2	40.9	34.6	34.6	34.6	34.6	34.6	34.6	34.0	33.3	34.5	34.6	33.3	30.7	35.0
		MDH-m² basis	t CO_{2eq}	16.3	27.0	20.6	20.4	12.9	12.4	16.9	40.5	30.2	25.0	22.4	24.9	27.4	21.1	20.4	21.2	22.6	23.5	19.9	19.9	19.9	19.9	19.9	19.9	19.6	19.2	19.8	19.9	19.2	17.6	20.2
		AP-m² basis	t CO_{2eq}	13.5	22.3	17.0	16.9	10.6	10.2	14.0	33.5	25.0	20.7	18.5	20.6	22.6	17.5	16.9	17.6	18.7	19.5	16.4	16.4	16.4	16.4	16.4	16.4	16.2	15.9	16.4	16.4	15.9	14.6	16.7
		DH-occupancy	t CO_{2eq}	24.6	40.8	31.2	30.9	19.4	18.7	25.6	59.9	45.0	37.5	34.3	38.6	42.9	32.2	30.9	32.1	34.2	35.6	30.1	30.1	30.1	30.1	30.1	30.1	29.6	29.0	30.0	30.1	29.0	26.6	30.2
		MDH-occupancy	t CO_{2eq}	17.8	29.4	22.5	22.3	14.0	13.5	18.5	43.3	32.5	27.1	24.8	27.9	31.0	23.3	22.3	23.2	24.7	25.7	21.7	21.7	21.7	21.7	21.7	21.7	21.4	21.0	21.7	21.7	21.0	19.2	21.8
		AP-occupancy	t CO_{2eq}	17.8	29.4	22.5	22.3	14.0	13.5	18.5	43.3	32.5	27.1	24.8	27.9	31.0	23.3	22.3	23.2	24.7	25.7	21.7	21.7	21.7	21.7	21.7	21.7	21.4	21.0	21.7	21.7	21.0	19.2	21.8
	Carbon Footprint (CF)	DH	t CO_{2eq}	233	233	233	233	233	233	233	233	233	233	233	233	233	185	233	233	233	233	228	220	208	211	229	260	228	216	224	263	199	233	233
		MDH	t CO_{2eq}	135	135	135	135	135	135	135	135	135	135	135	135	135	105	135	135	135	135	134	131	127	126	133	147	131	131	132	135	131	135	135
		AP	t CO_{2eq}	179	179	179	179	179	179	179	179	179	179	179	179	179	144	179	179	179	179	178	177	176	174	177	186	175	178	171	179	178	179	179
	Factor of Exceedance (FoE)	DH-m² basis	-	8.2	5.0	6.5	6.6	10.4	10.8	7.9	3.3	4.4	5.4	6.0	5.4	4.9	5.0	6.6	6.3	5.9	5.7	6.6	6.4	6.0	6.1	6.6	7.5	6.7	6.5	6.5	7.6	6.0	7.6	6.7
		MDH-m² basis	-	8.3	5.0	6.6	6.6	10.5	10.9	8.0	3.3	4.5	5.4	6.1	5.4	4.9	5.0	6.6	6.4	6.0	5.8	6.7	6.6	6.4	6.3	6.7	7.4	6.7	6.8	6.7	6.8	6.8	7.7	6.7
		AP-m² basis	-	13.3	8.0	10.5	10.6	16.9	17.5	12.8	5.4	7.2	8.7	9.7	8.7	7.9	8.3	10.6	10.2	9.6	9.2	10.8	10.8	10.7	10.6	10.7	11.3	10.8	11.2	10.4	10.9	11.2	12.3	10.7
		DH-occupancy	-	9.5	5.7	7.5	7.6	12.0	12.4	9.1	3.9	5.2	6.2	6.8	6.0	5.4	5.7	7.5	7.3	6.8	6.5	7.6	7.3	6.9	7.0	7.6	8.6	7.7	7.4	7.5	8.8	6.9	8.8	7.7
		MDH-occupancy	-	7.6	4.6	6.0	6.1	9.6	10.0	7.3	3.1	4.2	5.0	5.5	4.9	4.4	4.5	6.1	5.8	5.5	5.3	6.2	6.0	5.9	5.8	6.1	6.8	6.1	6.3	6.1	6.2	6.3	7.1	6.2
		AP-occupancy	-	10.1	6.1	7.9	8.0	12.7	13.2	9.7	4.1	5.5	6.6	7.2	6.4	5.8	6.2	8.0	7.7	7.3	7.0	8.2	8.2	8.1	8.0	8.1	8.6	8.2	8.5	7.9	8.2	8.5	9.3	8.2

Key:

	no change from base case
	<10% decrease in carbon budget <u>or</u> increase in carbon footprint
	10-25% decrease in carbon budget <u>or</u> increase in carbon footprint
	>25% decrease in carbon budget <u>or</u> increase in carbon footprint
	<10% increase in carbon budget <u>or</u> decrease in carbon footprint
	10-25% increase in carbon budget <u>or</u> decrease in carbon footprint
	>30% increase in carbon budget <u>or</u> decrease in carbon footprint

Appendix B: Office Building Scenarios – Numerical Results

Parameter			Unit	Carbon Budget Scenarios												Carbon Footprint Scenarios													
				Climate Target		Global CB to NZ	Grandfathering Year			Post 2050 Use Stage CB (new build)			% Embodied Emissions			Electricity Scenario	Gas heating to electricity		Comfort Efficiency		Scenarios 15 + 17	Location of Buildings			Incl Biogenic	Module D incl	MEP & TI included		
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Sector Based (2018-50)	Carbon Budget (CB)	World	Gt CO_{2eq}	643	1,065	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786	786
		NZ	Mt CO_{2eq}	385	637	487	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470	470
		Sector	kt CO_{2eq}	1,751	2,899	2,219	1,456	1,484	2,064	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,120	2,140	2,044	1,948	1,948	1,981	2,097	2,342	2,054	2,125	2,567	2,893	3,194
	Carbon Footprint (CF)	Sector	kt CO_{2eq}	8,566	8,566	8,566	8,566	8,566	8,566	8,566	8,566	8,566	8,566	8,566	8,566	6,997	8,191	8,261	8,167	7,769	7,586	7,740	8,429	9,528	8,276	8,501	11,021	12,899	14,632
	Factor of Exceedance	Sector	-	4.9	3.0	3.9	5.9	5.8	4.1	4.0	4.0	4.0	4.0	4.0	4.0	3.3	3.9	3.9	4.0	4.0	3.9	3.9	4.0	4.1	4.0	4.0	4.3	4.5	4.6
New Build Lifetime Based (2018-2077)	Carbon Budget (CB)	Building	t CO_{2eq}	193	320	245	161	164	228	344	290	263	219	240	250	246	236	238	228	219	220	223	232	254	224	222	280	314	345
	Carbon Footprint (CF)	Building	t CO_{2eq}	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,259	1,013	1,191	1,201	1,200	1,141	1,106	1,130	1,241	1,406	1,219	1,201	1,645	1,941	2,213
	Factor of Exceedance	Building	-	6.5	3.9	5.1	7.8	7.7	5.5	3.7	4.3	4.8	5.7	5.2	5.0	4.1	5.0	5.0	5.3	5.2	5.0	5.1	5.3	5.5	5.5	5.4	5.9	6.2	6.4

Key:

	no change from base case
	<10% decrease in carbon budget <u>or</u> increase in carbon footprint
	10-25% decrease in carbon budget <u>or</u> increase in carbon footprint
	>25% decrease in carbon budget <u>or</u> increase in carbon footprint
	<10% increase in carbon budget <u>or</u> decrease in carbon footprint
	10-25% increase in carbon budget <u>or</u> decrease in carbon footprint
	>30% increase in carbon budget <u>or</u> decrease in carbon footprint