






Dynamic carbon budgets and carbon debts for Aotearoa New Zealand and its building sector

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ABSTRACT

The remaining carbon budget (RCB) is a crucial parameter when setting climate budgets for nations and economic sectors that want to measure their progress in climate change mitigation. The Paris Agreement is the most widely used and accepted climate change mitigation target, and the global RCB specified by the Intergovernmental Panel for Climate Change (IPCC) provides the carbon budget remaining from the beginning of 2020 that can be emitted as CO₂ before the Paris Agreement's target is exceeded. This research investigates the global RCB allocation to the national and building sector level in Aotearoa New Zealand, including consideration of different sharing approaches and modelling of potential future dynamic parameters for the RCB allocation, that are required to stay below 1.5 °C warming between the years 2024 and 2050. The average national RCB ranges from 159 to 339 MtCO₂ from year 2024; based on an average annual emissions rate of 38 MtCO₂, it will be depleted in 4–8 years. Therefore, this study proposed a dynamic carbon debt framework that provides a more realistic representation of dynamic RCBs and the carbon debt over future years. Key findings include the urgency of timely interventions, the need for additional mitigation strategies beyond the current policy approach which is largely focused on increased plantation forestry, and the usefulness of time-disaggregated carbon budgeting to address exhaustion of the RCB. Overall, this study demonstrates the relevance of dynamic budgeting to guide effective climate policy at both the national and building sector levels.

1. Introduction

The building and construction sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 37 % of emissions when considering both operational and embodied carbon [1]. In Aotearoa New Zealand (ANZ), GHG emissions from building and construction sector is increasing over years, accounting for 11.5 MtCO₂eq in the year 2021, which is an increase of 5.3 % from the year 2020 based on consumption-based accounting approach [2]. Overall,

the built environment accounts for 20 % of GHG emissions in ANZ [3]. The ANZ built environment's consumption-based emissions comprise: 8.7 % for embodied emissions arising from building products, 8.6 % for operational energy use, 2.1 % for imported embodied emissions, and 0.5 % for building and garden waste [3]. There is therefore a need for both global and more local mitigation efforts related to this sector, and an important question concerns how much this sector must reduce its GHG emissions to meet the global climate targets set under the Paris Agreement [4].

Abbreviations: ANZ, Aotearoa New Zealand; AP, Ability to Pay; BECCS, Bioenergy with Carbon Capture and Storage; CB, Consumption-based; CBDR, Common But Differentiated Responsibilities; CDR, Carbon Dioxide Removal; CH₄, Methane; CO₂, Carbon dioxide; DACS, Direct Air Capture and Storage; EPC, Equal Per Capita; EVA, Economic Value Added; GDP, Gross Domestic Product; GF, Grandfathering; GHG, Greenhouse Gas; IPCC, Intergovernmental Panel for Climate Change; LULUCF, Land Use, Land Use Change and Forestry; N₂O, Nitrous oxide; NDC, Nationally Determined Contribution; NZ ETS, New Zealand Emission Trading Scheme; RCB, Remaining Carbon Budget; TCRE, Transient Climate Response to cumulative CO₂ Emissions.

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Science-based carbon budgets are widely accepted as a way of measuring progress to stay within climate targets. These budgets are quantified at the global scale and then allocated to national and/or sectoral scales, supporting policymakers to set emission reduction pathways [5]. Recent literature has explored carbon budgets for ANZ [6] and for specific building typologies such as residential buildings [7,8] and non-residential buildings [9–11]. These studies used a static accounting approach to set budgets without considering temporal dynamics over the years. In this paper, we include temporal dynamics by considering global and national population growth, economic growth in the building sector, and policy changes with associated emission reduction pathways in ANZ over the next few decades.

This dynamic LCA approach provides more informative modelling of future emissions by integrating consideration of temporal dynamics over time. Additionally, it enables calculation of dynamic carbon debts arising from ongoing GHG emissions and budgets, thereby enabling timely interventions to inform policies and strategies for the decarbonisation of the building sector. Unlike conventional approaches that represent GHG emissions and carbon budgets over extended periods as a single aggregate value, this dynamic approach identifies critical moments for intervention. Alongside the dynamic carbon debts, the main additional carbon removal strategy that is practically available at a national scale - carbon removal through planting exotic forests - is quantified in this study, showing that additional decarbonisation pathways are required for the building sector to align with the 1.5 °C climate goal.

2. Background

2.1. Global carbon budgets concepts and definitions

Aotearoa New Zealand's GHG emission profile in 2022 comprised 40.3 % carbon dioxide (CO₂), 48.9 % methane (CH₄), 8.8 % nitrous oxide (N₂O) and 2 % fluorinated gases (F-gases), and was dominated by the agriculture and energy sectors' emissions [12]. The climate target for 2050 is to achieve net zero GHG emissions except for biogenic CH₄ where the target is to achieve a reduction of 24 % to 47 % in CH₄ emissions [13]. Measuring progress towards achieving climate targets require the development of specific methodologies, among which the concept of the carbon budget has gained significant prominence [5]. The IPCC define the carbon budget as "the maximum amount of cumulative net global anthropogenic CO₂ emissions that would result in limiting global warming to a specified level with a specified likelihood" [14]. Therefore as CO₂ accounts for more than 90 % of GHG emissions contributed by both the global building sector [15] and the ANZ building sector [16], this study focuses on CO₂ rather than including all GHGs; this also aligns with the carbon budget accounting of the IPCC [14].

The carbon budget concept has led to several budgetary calculations that use specific parameters. These parameters include limiting temperature rise to a certain degree, limiting temperature rise to align with a certain historical period or base year, limiting radiative force to a certain level, incorporating confidence levels, inclusion/exclusion of non-CO₂ warming, and with reference to a target year in the future [17]. The proposed budgets include: the total carbon budget, total GHG budget, remaining carbon budget (RCB), and remaining GHG budget. These budgets are intended to guide mitigation strategies at global, local, and sectoral levels, assisting in understanding of the appropriate scale of required responses to align with global climate targets. The total carbon budget is defined as the maximum amount of cumulative net global anthropogenic CO₂ emissions from pre-industrial times up to the present (or to some future year) that can be emitted whilst limiting global warming to a given temperature level with given probability. When these emissions are accounted from a more recent specified date, then the carbon budget is defined as the RCB [14].

Researchers have derived carbon budgets using different methods in the scientific literature. Matthews and colleagues [18] calculated the

RCB based on the Transient Climate Response to Cumulative CO₂ Emissions (TCRE) metric for 1.5 °C warming with 33 %, 50 % and 67 % likelihood from year 2020 as 670 GtCO₂, 440 GtCO₂ and 230 GtCO₂ respectively. Rogelj and colleagues [19] estimated annual CO₂ budgets to limit global warming to 1.5 °C using different scenarios based on five Shared Socio-economic Pathways (SSPs) and six different integrated assessment models that will limit radiative forcing to 1.9 Wm⁻². From 13 different scenarios, the average CO₂ emissions were estimated as 725 GtCO₂ from year 2016 to 2050. Rogelj and colleagues [20] then developed a further approach to determine the RCB for specific temperature change limit considering five variables: historical human-induced warming up to date, non-CO₂ warming (net additional contribution of aerosols and non-CO₂ GHGs) to future temperature rise, net-zero commitments, TCRE, and Earth system feedback. The RCBs using this framework were estimated to limit global warming to 1.5 °C with 33 %, 50 % and 66 % likelihood as 740 GtCO₂, 480 GtCO₂ and 320 GtCO₂ respectively, and to limit global warming to 2 °C with 33 %, 50 % and 66 % likelihood as 1930 GtCO₂, 1400 GtCO₂ and 1070 GtCO₂ respectively [20].

However, the IPCC established the global RCB from the beginning of 2020 as 500 GtCO₂ for a 50 % chance of limiting global warming to 1.5 °C, and 1150 GtCO₂ for a 67 % chance of limiting it to 2 °C [14]. These RCB estimates are derived with the assumption that future non-CO₂ warming aligns with stringent mitigation scenarios, meaning that non-CO₂ GHG and aerosols make a net additional contribution of around 0.1 °C above the 2010–2019 level [21]. However, Rogelj and Lamboll [22] note that if actual non-CO₂ emissions differ from this assumption, the RCB estimation will need to be adjusted accordingly i.e. if non-CO₂ emissions are higher than expected, the RCB will need to be reduced (and vice versa). According to the IPCC [14], if this occurs, the RCB for a 50 % chance of limiting warming to 1.5 °C could decrease to around 300 GtCO₂. Conversely, if the global warming associated with non-CO₂ warming is reduced to 0.05 °C, the RCB for limiting warming to 1.5 °C with 50 % chance could increase to around 600 GtCO₂ [14].

The 1.5 °C target has been endorsed by most of the world leaders, in view of the IPCC's warning that exceeding this threshold could lead to significantly more severe climate change impacts, including more frequent and intense droughts, heatwaves, and heavy rainfall [4,14]. Therefore, we use the IPCC's calculated RCB for limiting global warming to 1.5 °C with a 50 % chance (500 GtCO₂) for this research. We also investigate the significant influence of non-CO₂ emissions on the RCB, again using the IPCC's estimated range between 300 GtCO₂ (scenarios with higher non-CO₂ global warming) and 600 GtCO₂ (scenarios with lower non-CO₂ warming).

2.2. Allocating shares

Numerous sharing approaches have been used in the literature to downscale global carbon budgets to national and then sectoral levels, each informed by a distinct distributive justice theory and unique assumptions [23]. Existing studies have used a variety of methodologies for budget allocation that are informed by these theories [23–25]. However, there is no consensus to date on a preferred downscaling approach, and the choice of sharing approach can significantly influence the magnitude of the downscaled budgets [23,24,26,27].

Three main distributive justice theories are mostly employed in the literature to allocate global budgets: egalitarian, libertarianism, and utilitarian [23]. The egalitarian distributive justice theory is commonly used in downscaling global budgets to national level; it emphasises that everyone should be treated equally and have equal opportunities (equity-based). The equal per capita (EPC) sharing principle, based on egalitarian distributive justice theory, is the most frequently used sharing principle [23] to downscale from the global budget to national budgets [7,10,28–30]. Following libertarianism distributive justice theory, grandfathering (GF) is a common sharing principle which is based on historical emissions in a reference year [25,29]. This sharing

principle can be applied to downscaling efforts not only at national level but also at other levels, including sectoral and product levels, based on respective historical emissions [7,8,28]. A problem with this approach is that it provides an advantage to historically high GHG emitters. The utilitarian distributive justice theory emphasises that products and services can be prioritised based on their value in an economy. The utilitarian approach is commonly applied to downscale the budget from national to sector level [23], after downscaling from global to the national level using the egalitarian approach.

In addition to these three distributive justice theories and their derived sharing principles, two other sharing principles, ability to pay (AP) and economic value added (EVA), are commonly used in the literature to allocate shares to sectoral levels. The AP sharing principle is classified under prioritarianism distributive justice theory, which prioritises emission allocation based on nations' wealth rather than other parameters such as historical emissions and population. AP is applied based on a country's capability to reduce emissions represented through its Gross Domestic Product (GDP) [29]. For AP, less RCB is allocated to countries with high GDP because they have a greater capability to reduce their climate change impacts [25]. The EVA sharing principle also falls under prioritarianism distributive justice theory, where the fair share is determined based on the economic gross value added by an industry sector to the national economy. Algunaibet, Pozo [31] applied this principle to allocate the planetary boundaries to stay within the safe operating space when downscaling from national scale to the energy sector in the United States. Similarly, Horup, Birgisdóttir and Ryberg [29] used this principle to allocate the carbon budget for the building sector to new buildings based on the contribution of economic activities associated with new buildings to overall economic activity in the construction sector.

As there is currently no universally agreed sharing principle, individual nations and/or sectors can choose their most favourable approaches and this risks compromising the credibility of downscaled budgets [32]. This has led to researchers using a number of different approaches in their studies. For example, combination of AP, EPC and GF sharing principles were used for a framework to allocate budgets (and associated reduction targets) to different countries in the EU to derive national budgets [33]. When downscaling global GHG budgets to Denmark, Tilsted and Bjørn [34] used five different sharing principles to add more perspective to their study. In our study, we have also used multiple approaches to allocate carbon budgets from the global to national and building sector levels. This allows for direct comparison of outcomes under different principles, thereby highlighting the sensitivity of budget allocations to the choice of sharing principle.

2.3. Temporal dynamics

Current approaches for allocating the global carbon budget largely neglect the time-dependency within any time horizons defined for these budgets. For instance, GF generally allocates global share based on historical emissions. However, when setting emission targets over a long time period, reliance on historical emissions may not accurately reflect the carbon budget for future years, as it fails to account for anticipated changes in emissions trajectories that are likely to be affected by dynamic economic, technological, and policy conditions. Additionally, when budgets are set as cumulative values applicable over extended time periods, the policies and strategies required to manage these budgets become complicated. Dividing the total budget equally between number of years is inaccurate as it assumes that emissions and budgets will remain consistent year-on-year, which is not realistic. Similarly, the building sector's contribution to the country's economy over time or a country's capacity to pay based on GDP may fluctuate due to economic growth or contraction, and demographic dynamics such as population growth or decline over years. These dynamics may affect the carbon budgets over a long period. Therefore, the allocation methods should be integrated with dynamic factors that reflect a range of evolving socio-

economic and demographic conditions. Also, cumulative budgets need to be distributed over future years to align with modelled future dynamics; provision of just cumulative values do not provide information on the timing and scale of interventions needed, and thus hinders development of phased and manageable mitigation measures. By distributing the budget over time, decision-makers gain transparent understanding into when mitigation measures must be intensified, and thereby are supported to design time-differentiated, responsive strategies.

2.4. Carbon budget exhaustion and the concept of negative budgets

Recent literature on national carbon budgets in different countries show that their fair share is already exhausted or soon to be exhausted. For example, Li, Pelz [35] found that around 84 to 90 countries in the world, including all major developed nations, had already exhausted their national GHG budgets by 2021 to limit warming to 1.5 °C with 50 % chance. Gueret, Malliet [36] showed that the carbon budgets of major European Union (EU) member states are nearly exhausted, with several countries on the boundary of exceeding their shares in the coming years under the 2 °C climate target. Particularly for Denmark, Horup, Birgisdóttir and Ryberg [29] showed that Danish legislation allows emissions up to 220 % higher than the average of their downscaled national budgets and they would need to reduce their climate impacts of new building activity by 20–70 % compared to recent performance to align with 1.5 °C target. Similarly, Chandrakumar et al. (2020a) found that ANZ and most of its economic sectors had exceeded their GHG budgets regardless of the sharing approach used, based on 2011 consumption- and production-based emissions. The ANZ office building sector for 2018–2050 exceeded their GHG budget by a factor of 4.0 and newly built offices exceeded their budget by a factor of 5.3 based on 2012 consumption-based emissions [10]. New-built residential dwellings also exceeded their GHG budget by a factor of 6.7, 6.8 and 10.9 for detached, medium density housing and apartments, respectively [8]. Therefore, additional strategies for achieving climate targets for the ANZ building sector must be investigated.

As carbon budgets are now either exhausted or rapidly approaching depletion, the concept of net-negative emissions has emerged as a focus area for both academia and policy making. By removing more emissions than are emitted, net negative emissions can help mitigate the cumulative effects of past emissions [37,38]. In response, studies have emphasised the need for robust economic and political instruments to support the transition toward net-negative emissions. Among the proposed mechanisms, Carbon Removal Obligations (CROs) have emerged as a novel approach that holds emitters accountable for the removal of their historical emissions [39,40]. In parallel, there is a growing interest in political reforms that embed the concept of negative carbon budgets in policy agendas. Peters and Geden [41] argued that there needs to be a political shift from low carbon to net negative carbon in climate policies. This negative emission approach has been adopted in practice in several economically advanced nations - mainly through implementation of carbon dioxide removal (CDR) technologies [42]. Current CDR practices are mostly concerned with afforestation and reforestation (particularly in China and Brazil), direct air capture and storage (DACs) (in the United States (US), EU state members, the UK and Canada), and bio-energy with carbon capture and storage (BECCS) in Denmark and the US [43–45].

ANZ mostly relies on forestry for CDR, and accounts for only the carbon removal from exotic forests in their international climate commitment reporting for the Paris Agreement [46]. This reliance on exotic forests (e.g. *Pinus radiata*) in current carbon removal calculations is primarily driven by the fast growth rates and rapid carbon sequestration capacity of exotic compared to native species [47]. However, the ANZ government intends to include other CDR strategies into the emission reduction plan including activities such as biological processes storing carbon in vegetation, wood products, marine sediments and

organic oils including rewetting of drained peatlands, restoring wetlands, and engineered chemical and geochemical processes for DACS in minerals [46,48]. Although CDR from exotic forestry is more widely implemented and aligns with nature-based approaches, it is constrained by limitations such as land availability, risks like fire and disease, adverse impacts on biodiversity, and relatively slower rates of carbon sequestration compared to technological alternatives [49,50].

Given the near exhaustion of RCBs, along with existing gaps in incorporating temporal dynamics into budget allocation methodologies, and recent attention to potential CDR strategies in ANZ, this study examines the use of RCBs in ANZ using two dynamic lenses: (i) use of CDR strategies to stay within carbon budgets at the national level, and (ii) decarbonisation pathways for the building sector to stay within its carbon budget(s). The first approach primarily focuses on how implementation of CDR strategies in ANZ affects the exhaustion of carbon budgets over time. The second approach focuses on how the carbon budgets and carbon debts of ANZ building sector change over time and their implication for a building sector decarbonisation pathway.

3. Methodology

3.1. Downscale global remaining carbon budgets for New Zealand

This study adopts the IPCC's global RCB to allocate ANZ's fair share for a 50 % chance of limiting warming to 1.5 °C from 2020, using an average value of 500 GtCO₂, and considering a lower and an upper bound of 300 and 600 GtCO₂ to reflect scenarios with higher and lower non-CO₂ warming, respectively (see Section 2). Since ANZ has committed to achieving net zero status by 2050 for long-lived gases, we allocate the RCB across 2020 to 2050 in this study i.e. assuming net zero emissions by 2050.

For downscaling the RCB from global to national level, we used both the EPC and GF sharing principles. The EPC sharing principle was chosen as it gives a low value for the RCB due to the relatively small population of ANZ: in 2020, ANZ's population was approximately 5.03 million, which represents only about 0.064 % of the global population of 7.85 billion [51]. The GF sharing principle was chosen as it gives a high value for the RCB primarily based on ANZ's emissions relative to the global scale: in 2020, ANZ's CO₂ emissions were 0.11 % of the global production-based CO₂ emissions [52]. In addition to EPC and GF, AP is generally used to allocate national shares. However, a smaller share of global RCBs can be expected for ANZ with its higher GDP ranking in the world (52nd globally) [53]. Therefore, AP yields a relatively low carbon budget allocation, although not as low as that derived from the EPC method [29] due to NZ's small share of the global population (ranked 119th by population size [51]).

Firstly, the EPC was used to allocate the RCB to ANZ (see Eq. (1)), reflecting equity in that carbon budgets should be distributed among individuals regardless of geographical scope, a country's wealth or its historical emissions [23]. Conventionally, this is calculated using the existing global and national populations in a selected year [23]. To introduce dynamic accounting into this sharing principle, the forecasted global and national populations from 2020 to 2050 were calculated [51].

$$RCB_{(EPC)National,2020-2050} = \frac{Pop_{National,2020-2050}}{Pop_{Global,2020-2050}} \times RCB_{Global,2020-2050} \quad (1)$$

Where, $Pop_{National,2020-2050}$ is the cumulative annual population of ANZ during 2020–2050, $Pop_{Global,2020-2050}$ is the cumulative annual population of the world during 2020–2050, $RCB_{Global,2020-2050}$ is the global RCB for 2020–2050, and $RCB_{(EPC)National,2020-2050}$ is the national RCB for 2020–2050 based on the EPC principle.

Similarly, the GF sharing principle was used to allocate the RCB to ANZ (see Eq. (2)). The year 2023 was chosen as the GF year to allocate a national share for 2020–2050 as the COVID-19 pandemic would have

affected the usual emissions pattern during the 2020–2021 period [54].

$$RCB_{(GF)National,2020-2050} = \frac{Emissions_{National,2023}}{Emissions_{Global,2023}} \times RCB_{Global,2020-2050} \quad (2)$$

Where, $Emissions_{National,2023}$ is NZ's consumption-based CO₂ emissions in 2023 extracted from Ministry for the Environment [55], $Emissions_{Global,2023}$ is the global consumption-based CO₂ emissions in 2023 extracted from Crippa, Guizzardi D [52] and $RCB_{(GF)National,2020-2050}$ is the national RCB for 2020–2050 based on GF principle. The consumption-based CO₂ emissions include CO₂ emissions generated domestically and those embodied in imports and excludes CO₂ emissions from goods and services produced domestically but exported for consumption elsewhere.

To obtain the national annual RCB from 2024 onwards, the national CO₂ emissions in 2020, 2021, 2022 and 2023 (from 2020–2023) were subtracted from the calculated RCB (see Eq. (3)) [56] for both the EPC and GF sharing principles.

$$RCB_{National,2024-2050} = RCB_{National,2020-2050} - Emissions_{National,2020-2023} \quad (3)$$

Where, $Emissions_{National,2020-2023}$ is the cumulative national annual consumption-based CO₂ emissions from 2020–2023.

Then, for the EPC sharing principle, the RCB from the beginning of 2024 was distributed over the years 2024 to 2050 (including 2050) to obtain national annual RCBs (Eq. (4)):

$$RCB_{(EPC)National,t} = \frac{Pop_{National,t}}{Pop_{National,2024-2050}} \times RCB_{National,2024-2050} \quad (4)$$

Where, $RCB_{(EPC)National,t}$ is the national annual RCB of year t based on the EPC sharing principle.

For the GF sharing principle, a dynamic approach was adopted based on the annual emissions forecasted by the Ministry for the Environment [55] up to the end of 2050. Then, the national annual RCB was calculated considering the forecasted consumption-based emissions in each year (Eq. (5)):

$$RCB_{(GF)National,t} = \frac{Emissions_{National,t}}{Emissions_{National,2024-2050}} \times RCB_{National,2024-2050} \quad (5)$$

Where, $RCB_{(GF)National,t}$ is the national annual RCB of year t based on the GF sharing principle.

Allocation of RCB from the national level to the building sector was performed using the GF and EVA principles for both the downscaled national annual RCBs (using EPC and GF), resulting in four different combinations of RCB allocations for the building sector: EPC+GF, EPC+EVA, GF+GF, and GF+EVA). In this study, the building sector refers to both residential and non-residential buildings, and the building sectoral emissions and carbon budgets in the analysis covers the entire life cycle of buildings. For the GF sharing principle, the sectoral RCB from 2024–2050 is allocated based on the share of the emissions by the building sector relative to national consumption-based emissions in 2023 (Eq. (6)):

$$RCB_{(GF)Sector,2024-2050} = \frac{Emissions_{Sector,2023}}{Emissions_{National,2023}} \times RCB_{National,2024-2050} \quad (6)$$

Where $RCB_{(GF)Sector,2024-2050}$ is the sectoral RCB for 2024–2050 based on the GF sharing principle, and $Emissions_{Sector,2023}$ is the sectoral consumption-based emissions for the reference year (2023).

For the EVA sharing principle, it was assumed that the building sector's carbon budget for 2024–2050 reflects the sectoral economic value added to the national GDP in 2023 (Eq. (7)):

$$RCB_{(EVA)Sector,2024-2050} = EVA_{Sector} \times RCB_{National,2024-2050} \quad (7)$$

Where $RCB_{(EVA)Sector,2024-2050}$ is the sectoral RCB from 2024–2050 based on the EVA sharing principle, and EVA_{Sector} is the average building

sector's economic value added to the national GDP in 2023 [57].

Finally, using the GF sharing principle, annual sectoral RCBs were calculated (Eq. (8)):

$$RCB_{Sector,t} = \frac{Emissions_{Sector,t}}{Emissions_{Sector,2024-2050}} \times RCB_{National,t} \quad (8)$$

Where, $RCB_{Sector,t}$ is sectoral RCB at year t, $RCB_{National,t}$ is national RCB at year based on either EPC or GF, $Emissions_{Sector,t}$ is forecasted consumption-based sectoral emissions at year t, and $Emissions_{Sector,2024-2050}$ is forecasted consumption-based sectoral emissions from 2024–2050.

And using the EVA sharing principle, sectoral annual RCBs were calculated assuming the EVA from the building sector to the national GDP continues for 2024–2050 the same as the EVA in 2023 (Eq. (9)):

$$RCB_{Sector,t} = EVA_{Sector} \times RCB_{National,t} \quad (9)$$

3.2. National carbon debts and building sector decarbonisation

In this section, we calculate the carbon debt for ANZ when emissions exceed the fair share of the RCB based on the carbon debt concept [58]. Dynamic carbon debts for ANZ are derived using annually assessed RCBs. For the first time in ANZ, we propose this dynamic carbon debt framework to assess the feasibility of carbon removal strategies available within the country, mainly focusing on forestry. We evaluate the extent to which land use, land use and change and forestry (LULUCF) can contribute to pay off the national carbon debt and realign national RCB with forecasted emissions. For that, ANZ government projections on LULUCF removals data were used in this study. These projections are based on the central estimate from the Ministry for the Environment [55]'s official projections under its first Nationally Determined Contribution (NDC). These projections assume afforestation on Crown-owned land in ANZ of up to 320,000 hectares from year 2027–2050 [59] which is guided by existing environmental regulations, including the National Environmental Standards for Commercial Forestry (NES-CF), which manage potential negative impacts such as biodiversity loss, water quality degradation, wildfire risk, and downstream hazards, thereby incorporating land-use constraints and ecological considerations into the afforestation scenarios [60]. Furthermore, this analysis is extended to the building sector, examining its potential role in avoiding the overshoot of RCB through sector-specific timely interventions.

First, we calculated the national annual carbon debt during 2024–2050 taking the difference between the forecasted annual CO₂ emissions and the annual RCB (for both EPC and GF methods) (Eq. (10)). We then calculated the requirement of additional CDR to stay within the allocated RCB after accounting for the forecasted LULUCF removals by Ministry for the Environment [55] in each year (Eq. (11)).

$$Carbon\ debt_t = RCB_t - Emissions_t \quad (10)$$

$$Additional\ CDR_t = Carbon\ debt_t - LULUCF\ Removal_t \quad (11)$$

Where, $Carbon\ debt_t$ is national carbon debt at year t, RCB_t is RCB at year t, $Emissions_t$ is consumption-based emissions at year t, $Additional\ CDR_t$ is CDR that is needed in addition to the forecasted LULUCF removals at year t, and $LULUCF\ Removal_t$ is forecasted LULUCF removal at year t.

For the building sector's annual carbon debt, we used the same approach as in Eq. (10), i.e. taking the difference between sector's annual RCB and sector's forecasted annual consumption-based emissions. We present this sectoral annual carbon debt as the sectoral decarbonisation pathway up to 2050 to stay below 1.5 °C.

3.3. Sensitivity analysis

Sensitivity analysis was undertaken to quantify the influence of key dynamic parameters on the estimated RCBs and associated carbon debts

at both national and building sectoral levels. The selection of parameters was informed by their relevance to carbon budget allocation principles and the uncertainties linked with their future trajectories (see Table 1).

For population, sensitivity bounds were defined by applying a 25 % increase (approximately another 11 % increase with current predictions) and a 10 % decrease to the baseline population growth. For EVA from the building sector to the national GDP, sensitivity bounds were selected by applying $a \pm 10\%$ from the baseline projections. For the GHG emissions forecast, high- and low- estimation scenarios were applied based on projections by the Ministry for the Environment [55]. High- and low-projections of future carbon budgets and debts were calculated based on these changes, assuming climate change policies and other measures remained the same as modelled for the base case [55]. For each sensitivity analysis, the RCB and carbon debt were recalculated using the allocation procedures described in Sections 2.1. and 2.2.

4. Results

Section 4.1 presents the RCBs for ANZ and its building sector from the year 2020 to 2050, and from the year 2024 to 2050 after the consumption of the RCB during 2020–2023, based on the chosen different sharing principles. The time available to exhaust these RCBs for each approach is presented, based on the forecasted emissions [55] with existing measures to mitigate these emissions, which reflects the economic conditions and policies in late 2024.

Section 4.2 examines the carbon debts at national and building sectoral levels, and shows the additional CDR needed at national scale to stay within the allocated RCBs.

Section 4.3 examines the influence of dynamic parameters on the RCBs and carbon debts at national and building sectoral levels and how selection of sharing principles to downscaled budgets influence the development of policies and strategies in countries and sectors.

4.1. National and sectoral RCBs

National RCBs based on EPC and GF from year 2020 and from year 2024 are presented in Fig. 1. The results show that EPC allocates national RCB that are lower than those allocated based on GF, primarily due to the lower ANZ population, and the higher consumption-based CO₂ emissions associated with ANZ's economy, relative to other

Table 1
Summary of the parameters used in sensitivity analysis.

Parameter	Sensitivity analysis	Description
Population	Base Case	ANZ population growth rate will increase by 14 % from 2020 to 2050 based on UNPD [51]
	Sensitivity Analysis 1.1 (SA 1.1)	ANZ population growth rate will increase by 25 % from 2020 to 2050
	Sensitivity Analysis 1.2 (SA 1.2)	ANZ population growth rate will decrease by 10 % from 2020 to 2050
EVA	Base Case	Building construction EVA to national GDP remains on average rate of 1.96 %
	Sensitivity Analysis 2.1 (SA 2.1)	Building construction EVA to national GDP and forecast increases by 10 %
	Sensitivity Analysis 2.2 (SA 2.2)	Building construction EVA to national GDP and forecast decreases by 10 %
CO ₂ emission projection	Base case	Central estimation
	Sensitivity Analysis 3.1 (SA 3.1)	High estimation
	Sensitivity Analysis 3.2 (SA 3.2)	Low estimation

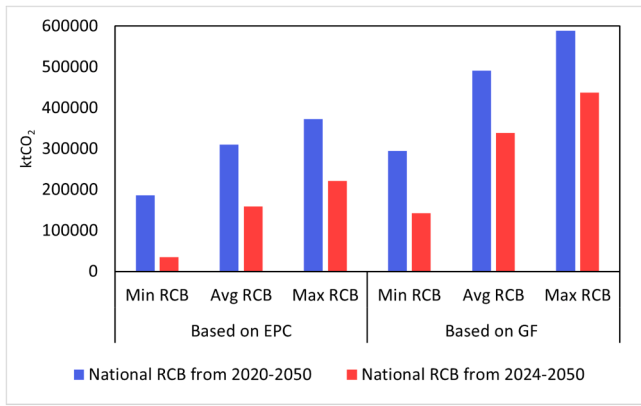


Fig. 1. Remaining carbon budgets of Aotearoa New Zealand from 2020–2050 and from 2024–2050 using equal per capita and grandfathering sharing approaches.

countries in the world. Furthermore, using EPC, the RCBs from 2024 show a 41–81 % reduction range compared to RCBs from 2020, highlighting the significant impact of consumption-based emissions in ANZ from 2020–2023 on RCB. Similarly, for GF, RCBs from 2024 are 26–51 % lower than RCBs from 2020. These results highlight how fast current emission trajectories are exhausting the RCBs. Based on these RCBs up to 2050, it is important to understand the decarbonisation pathway that ANZ needs to follow over these future years to stay within the RCBs.

The RCB exhaustion timelines based on the forecasted consumption-based emissions are presented in Fig. 2 for both EPC and GF sharing principles, showing the variations between the exhaustion years based on RCBs from 2020 and from 2024. Fig. 2 highlights the extent to which the actual consumption-based emissions from 2020–2023 affect the exhaustion timeline. Following the consumption of the allocated RCB from 2020–2023, the exhaustion years occur significantly earlier. This contraction suggests that current rate of emissions in ANZ may continue to contract the timeline even more after 2023. The RCB for the lower bound derived using EPC has already been exceeded in 2024. Across all the RCBs analysed, the budget exhaustion has now drawn significantly closer, with current emission trends indicating exhaustion of the lower bound RCB within the next 10 years.

The national dynamic RCB allocations are presented in Fig. 3, illustrating how the previously calculated RCBs for 2024–2050 have been distributed over the years. The results show the EPC and GF principles yield distinctly different budgets at year 2024 but converge towards year

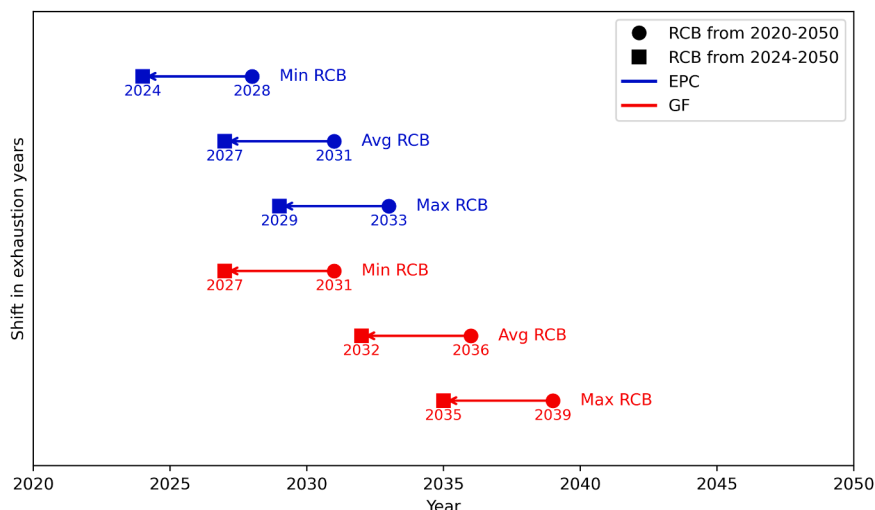


Fig. 2. National dynamic remaining carbon budgets from 2024–2050 using equal per capita and grandfathering sharing principles.

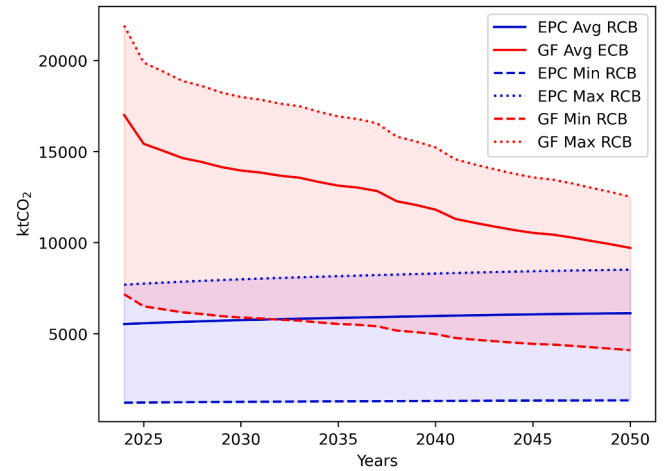


Fig. 3. Possible exhaustion years of remaining carbon budgets and their shifts due to the emissions from 2020–2023 in Aotearoa New Zealand.

2050 with overlapping ranges. For the EPC, the dynamic RCB gradually increases due to the population growth forecast [51]. For the GF, the dynamic RCB decreases reflecting ANZ forecasted emission pathway towards net-zero emissions [55].

Dynamic RCBs allocated to ANZ building sector throughout 2024–2050 and the actual sectoral emissions in year 2022 are illustrated in Fig. 4. The RCBs are shown using the four principles described in Section 3.1. The results show that the sectoral dynamic RCBs are significantly lower compared to the actual sectoral consumption-based emissions in year 2022. For all the RCBs derived from the four approaches, none are achievable in the near term if sectoral emissions continue to be same as in 2022. To achieve at least the maximum RCB using GF+GF approach, a 41 % reduction from the year 2022 emissions is required. Similarly, for the minimum RCB using EPC+EVA approach, a 99 % reduction is necessary. These findings suggest that the current sectoral emission levels are significantly above target, making it exceptionally challenging for ANZ building sector to operate within 1.5 °C.

4.2. National and sectoral carbon debts

National dynamic RCBs, carbon debts and the forecasted emission pathways are shown in Fig. 5(a). Our analysis suggests that ANZ needs to remove a total of 283.2–685.8 MtCO₂ during 2024–2050 to align with

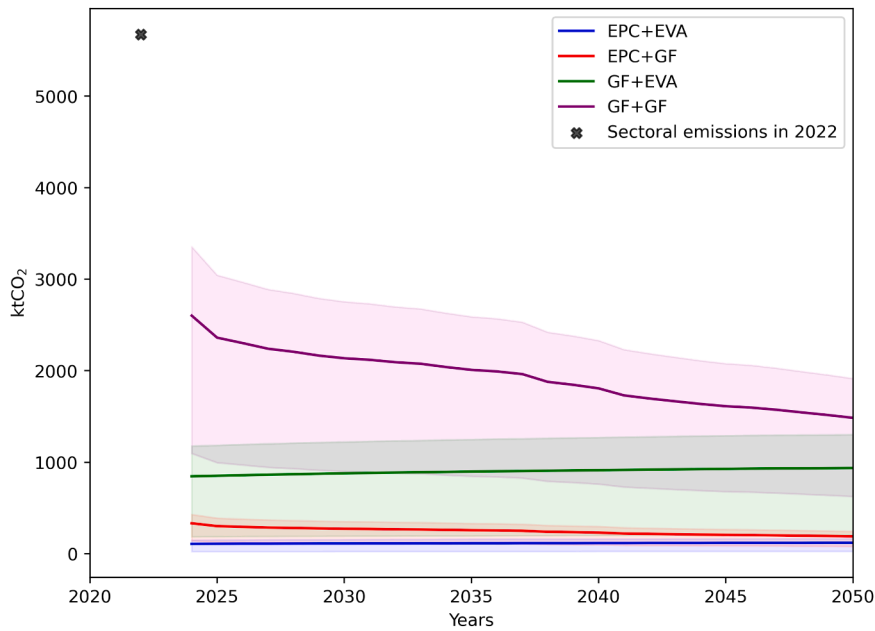


Fig. 4. Sectoral annual remaining carbon budgets from 2024–2050 using different approaches and actual emissions in year 2022.

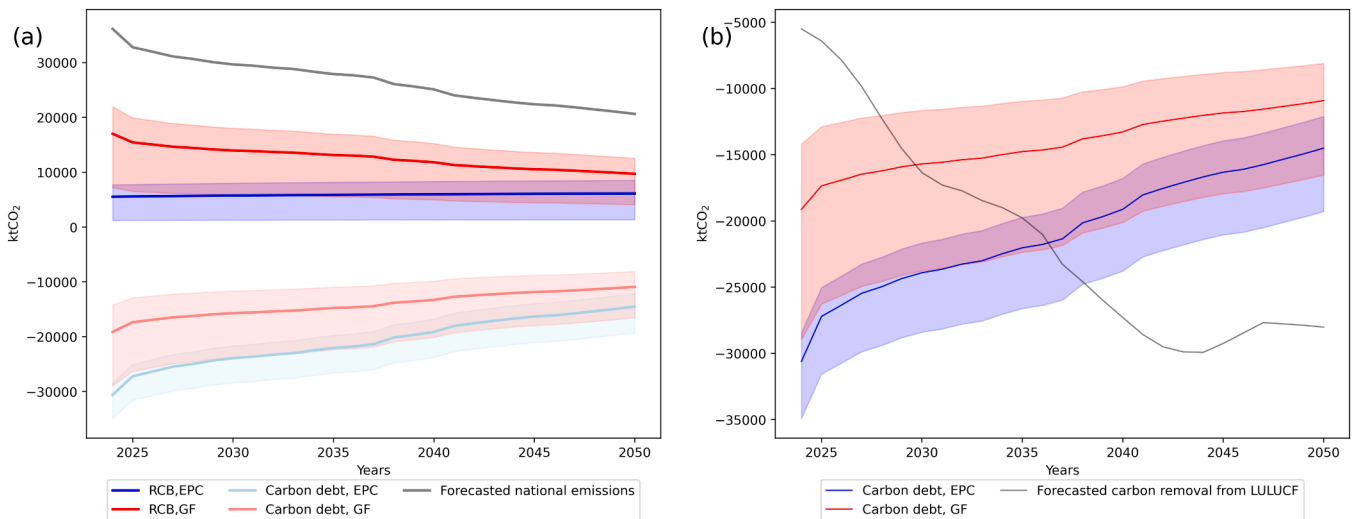


Fig. 5. (a) National dynamic remaining carbon budgets and dynamic carbon debts from 2024–2050 to stay below 1.5 °C warming and forecasted national emissions (b) National dynamic carbon debts and forecasted carbon removal from land use, land use change and forest.

the 1.5 °C target. The results were derived based on EPC and GF principles, with a minimum and maximum range over years 2024–2050. For EPC, the higher carbon debts are due to lower allocated RCBs, and for GF the lower carbon debts are due to higher allocated RCBs. For all the results, Fig. 5(a) shows that, initially, the carbon debts are relatively high due to current emissions. However, carbon debts reduce over time as the forecasted emissions gradually reduce, requiring fewer offset efforts to stay within the budgetary limits.

Fig. 5(b) presents the calculated national dynamic carbon debts alongside the forecasted carbon removal from LULUCF as projected by the Ministry for the Environment [55] for NDC calculations. During 2024–2050, the total carbon removal forecasted by the ANZ Ministry for the Environment is 574.2 MtCO₂. Based on the allocated national RCBs and forecasted national CO₂ emissions, there needs to be a total carbon removal of 283.2 MtCO₂ based on upper bound and 685.8 MtCO₂ based on lower bound estimations during the same period; this amount can be interpreted as the additional mitigation requirement. However, use of

the dynamic approach has allowed for a more precise identification of the required timing and magnitude of these mitigation activities. For example, Fig. 5(b) shows the annual credit from forecasted removals due to afforestation (grey line) goes below the annual carbon debt after 2028 (lower bound based on GF) and after 2038 (higher bound based on EPC); in other words, this is the year when the national carbon removal via afforestation starts to offset the lower bound of the carbon debt to align with the 1.5 °C target. This highlights that national carbon removal via afforestation is not sufficient until 2028 even for the lower bound carbon debt. It highlights the urgent need for near-term mitigation actions, as delays will mean that ANZ is not aligned with the 1.5 °C target.

Due to the substantial gap between forecasted building sectoral emission levels and RCBs, our analysis shows that the building sector needs to remove a total of 43.3–109.6 MtCO₂ (lower and upper bounds) during 2024–2050 to align with the 1.5 °C target. The timing and annual carbon debts that need to be addressed during 2024–2050 are presented in Fig. 6 for each approach. The four approaches result in different

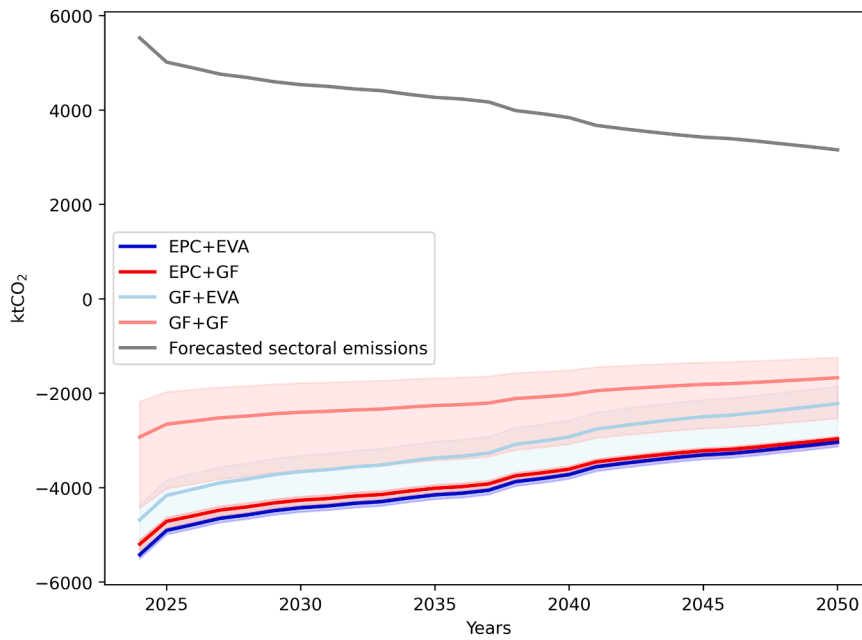


Fig. 6. Building sector annual carbon debts during 2024–2050 and forecasted sectoral emission pathway with existing measures.

carbon debts; the lower bound is associated with the GF+GF approach and the upper bound is associated with the EPC+EVA approach. Moreover, Fig. 6 shows that, although annual emissions in the building sector are forecasted to decline over time, the corresponding carbon debts continue up to 2050. This indicates that the importance of defining additional and continuing mitigation strategies in the building sector over future years.

4.3. Sensitivity analysis results

The sensitivity analysis examined the influence of future changes in three dynamic parameters (population growth rate, EVA for the building sector as a proportion of the national GDP, and CO₂ emission projection) (see Section 3.3.) on the estimated RCBs for 2024–2050 and on cumulative carbon debts until 2050. The scenarios were developed assuming that other policies and measures remain the same as those in the baseline

Table 2
Impact of parameter variation on the national remaining carbon budgets for 2024–2050 under the EPC and GF sharing principles.

Sensitivity Analysis	EPC			GF		
	Min	Avg	Max	Min	Avg	Max
SA 1.1 (+25 % population growth)	17.06 %	6.22 %	5.36 %	-	-	-
SA 1.2 (-10 % population growth)	-67.75 %	-24.68 %	-21.30 %	-	-	-
SA 2.1 (+10 % EVA to GDP)	-	-	-	-	-	-
SA 2.2 (-10 % EVA to GDP)	-	-	-	-	-	-
SA 3.1 (High emission forecast)	-0.08 %	-0.02 %	-0.01 %	-0.02 %	-0.01 %	-0.01 %
SA 3.2 (Low emission forecast)	2.40 %	0.52 %	0.38 %	0.58 %	0.25 %	0.19 %

calculations. Table 2 presents the percentage change in the national RCB from 2024–2050 relative to the baseline for each sensitivity analysis for both EPC and GF sharing principles.

The results indicate that population forecast exert the biggest influence on the RCB when calculated using the EPC sharing principle. In particular, a + 25 % increase in the population growth rate results in a RCB increase ranging from 5 % to 17 % while a -10 % decrease in the population growth results in a RCB decline ranging from 21–67 % compared to the baseline results. Conversely, variations in population growth rate have no effect on the RCB when derived using GF sharing principle. National CO₂ emissions forecasts have a relatively small influence on national RCBs under both sharing principles. Lower CO₂ emissions estimates lead to an increase in RCB, whereas higher emissions estimates reduce the available budget. As expected, changes in the relative contribution of the building sector’s EVA to national GDP demonstrates no measurable effect on RCB outcomes for either sharing principle, as the relevant national parameters are not changed.

The influence of these parameters on the cumulative carbon debts is shown in Table 3. It shows the percentage change in the carbon debt until 2050 relative to the baseline carbon debt for each sensitivity case for both the EPC and GF sharing principles.

The sensitivity analysis for carbon debts gives results that inversely mirror the patterns observed for the sensitivity analysis of the RCBs, although the magnitude of change does not correspond exactly to the percentage variations in the RCB. The inverse mirroring effect arises because an increased RCB reduces the carbon debt that must be

Table 3
Impact of parameter variation on national cumulative carbon debts until 2050 under EPC and GF sharing principles.

Sensitivity Analysis	EPC			GF		
	Min	Avg	Max	Min	Avg	Max
SA 1.1	-0.86 %	-1.76 %	-2.37 %	-	-	-
SA 1.2	3.43 %	6.98 %	9.42 %	-	-	-
SA 2.1	-	-	-	-	-	-
SA 2.2	-	-	-	-	-	-
SA 3.1	4.81 %	5.87 %	6.60 %	5.71 %	8.64 %	11.64 %
SA 3.2	-6.96 %	-8.50 %	-9.56 %	-8.27 %	-12.52 %	-16.86 %

addressed to meet 1.5 °C warming. Conversely, a reduction in RCB results in a higher carbon debt for the given forecasted emissions, thereby requiring greater mitigation efforts to achieve the required targets. However, the magnitude of the changes varies because carbon debts depend on both RCBs and the removals from LULUCF.

For the building sector RCB sensitivity analysis, the results were evaluated using the same four sharing approaches as used for the national analysis (EPC+EVA, EPC+GF, GF+EVA and GF+GF). The sectoral RCBs for the EPC+GF and GF+GF sharing approaches exhibit change patterns similar to the corresponding national change patterns. However, where EVA formed part of the sharing approach (SA2.1 and SA2.2), it resulted in $\pm 10\%$ change in RCBs (i.e. for the EPC+EVA and GF+EVA sharing approaches). Similarly, the influence of emissions projections on sectoral RCBs (SA 3.1 and SA 3.2) revealed the same proportional changes in national RCBs. For instance, sectoral RCBs derived from EPC+EVA and GF+EVA responded in a manner comparable to the national RCBs from the EPC sharing principle, while sectoral RCBs from EPC+GF and GF+GF reflected change patterns similar to those of the national RCBs derived from the GF sharing principle. The supplementary materials provide detailed results of these sensitivity analyses for both sectoral carbon budgets and the corresponding carbon debts.

5. Discussion

5.1. Communication of the urgency to undertake near-term mitigation actions

The importance of near-term rapid emissions reduction at both national and sectoral levels is highlighted using the dynamic approach described in this research. Regardless of the sharing principles employed, the projected possible exhaustion years shift closer to the present as each year passes, indicating a more rapid depletion of the available RCB. This is primarily driven by the current emission trajectories, which accelerate the RCB reduction rate. Also, the results suggest a high probability that the average RCB derived using EPC and minimum RCB derived using GF may have already been exhausted or is at imminent risk of being exhausted based on current emissions. Although the maximum RCB is also declining rapidly, similar to the minimum and average budget scenarios, its projected exhaustion under current emission trends is expected around the year 2029 and 2035 based on the EPC and GF sharing principles respectively (Fig. 2). This shows a comparatively extended timeline for mitigation under the maximum RCB which is based on scenarios where climate change due to non-CO₂ GHG emissions are limited to approximately 0.05 °C [14,22]. Conversely, failure to achieve significant reductions in non-CO₂ GHG emissions will lead to a substantially smaller RCB, thereby necessitating the near-term implementation of additional mitigation measures to remain within the 1.5 °C target. However, government emission projections such as those calculated for emission reduction plans, the national GHG inventory, and LULUCF are subject to change, potentially altering carbon budgets, exhaustion timelines and carbon debts. Therefore, the most recent emissions projections need to be accounted when communicating the degree of urgency for mitigation measures in the medium to long term.

The results highlight the necessity of timely mitigation strategies instead of relying on long-term recovery to avoid the overshoot [61]. The dynamic carbon debt framework based on forecasted emissions pathways and dynamic RCBs described in this research can inform development of quantitative and time-sensitive strategies to mitigate climate change. Particularly at the building sector level, the dynamic carbon debts suggest the sector's urgent requirement for additional mitigation measures to address climate change to stay within the 1.5 °C target. A time-phased decarbonisation strategy for the ANZ's building sector can align with national legislated climate targets under the Climate Change Response Act [13]. For short-term strategies

(2025–2030), government procurement rules and Green Building Star rating frameworks could require low carbon construction materials for designing new buildings and refurbishing existing buildings [62]. As ANZ plans to achieve 100 % renewable electricity generation by 2030 [63], Building Code updates could mandate net-zero operational emissions for all new buildings. Other short-term additional measures include the promotion of circular economy principles through programme to support the reuse and recycling of building components, refurbishment of existing buildings rather than constructing new buildings, design for disassembly and reuse, and more efficient use of existing buildings [64]. In the medium-term (2030–2040), as ANZ plans to develop a road map for the ANZ Building Code, it could include mandatory requirements to achieve net-zero for whole life embodied carbon for building materials, processes and disposal of materials [62]. In addition to that, the ANZ Building Code could introduce legally binding whole-life carbon limit values for new buildings [65] and introduce roadmaps for limit values of new buildings and refurbishments of existing buildings aligning with international best practices (e.g. OECD [66]). In the long-term (2040–2050), policies could be strategically aligned across relevant industries (e.g. aluminium and steel), the energy sector, and the building sector to achieve net-zero by 2050 [59]. This could also extend to address the role of the New Zealand Emission Trading Scheme (NZ ETS) in supporting cross-sectoral emission strategies [59].

Furthermore, this research suggests that a critical reassessment of national mitigation pathways needs to be conducted in order to show alignment – or not - with dynamic RCBs. It should include, where appropriate, integration of dynamic parameters into the investigated mitigation pathways [61,67]. Delays in implementing low-carbon measures will accelerate carbon budget depletion (as observed under high-emission projections in the sensitivity analysis, Section 3.3). Therefore, future research on alternative policy interventions should include sensitivity analysis of the timing of policy interventions as a dynamic parameter. This could also include how the NZ ETS can be used to support sectoral decarbonisation aligned with advanced policies like carbon taxes [66,68,69].

5.2. Use of a dynamic approach for setting budgets

A key contribution of this study is the use of a dynamic modelling approach, in which the main parameters used to downscale budgets are modelled as time-dependent in order to calculate national and sectoral RCBs and debts. At the national level, population growth projections up to 2050 were integrated into the population calculations for the EPC principle, and forecasted CO₂ emissions up to 2050 were used for the GF principle, to reflect their influence on the share of future national budgets. However, it should be noted that these forecasts are inherently uncertain due to the influence of parameters such as future socio-economic conditions, weather patterns, pandemics, technology advancements, and national and international politics. For example, the Ministry for the Environment [55] emphasises that forecasting of future electricity GHG emissions is particularly uncertain due to the changing weather conditions affecting hydroelectricity generation in ANZ. Moreover, in ANZ, there is significant potential for emission reductions driven by technological advancements in wind and solar energy systems, which could alter future energy scenarios if there is accelerated renewable energy deployment [70].

In addition to the use of dynamic parameters for calculating future population and CO₂ emissions, this study allocates annual budgets across future years up to 2050. The results emphasise the need for additional mitigation efforts beyond those projected in ANZ government forecasts [55]. The annual national RCBs enable a time-differentiated comparison with forecasted removals, and identify the timing and magnitude of any shortfalls that require additional interventions. At the building sectoral level, this approach exposes unrealistic budget allocations, thereby emphasising the urgent need to implement realistic

mitigation measures to address near-term annual carbon debts. From a policy perspective, this dynamic approach enables policymakers to identify critical time-differentiated intervention points so that they can prioritise time-differentiated mitigation strategies.

This study focused on a limited number of dynamic parameters in setting RCBs and carbon debts. However, future research could address additional dynamic parameters affecting the RCB such as atmospheric CO₂ concentrations [71], the influence of land and ocean CO₂ uptake [71,72], the influence of non-CO₂ radiative agents [72], the country's GDP forecasts, and sectoral economic contribution forecasts. For carbon debt calculations, it was assumed that removals due to exotic forest expansion could proceed without any external constraints over future years - but future studies could account for how dynamics in agricultural, urban and conservation practices might influence this intervention. Additionally, for carbon debts, future research could explore how the rate of technology diffusion for alternative CDR technologies might influence the timing of carbon removals in the ANZ context. Finally, future research could assess the intersectoral dynamics - in particular, activities in the energy, transport, and material extraction and processing sectors - may contribute to mitigating the building sector's carbon debt. For example, climate change mitigation strategies in ANZ concrete industry [73] and steel industry [74], and low-carbon innovations in the building sector [75,76] will influence the embodied GHG emissions of future construction materials.

5.3. Provision of a range of RCBs

The choice of sharing principle directly influences the magnitude of RCBs, which in turn affects decision-making processes and the formulation of long-term strategies. Consequently, relying solely on one single sharing principle to determine RCBs and carbon budgets could lead to overly or insufficiently restricted climate change mitigation policy [77]. The use of two sharing principles, chosen to provide upper and lower bounds for allocating global RCBs among nations, reflects an appropriate level of accuracy for informing policymaking given the uncertainties in forecasting population sizes, GHG emissions, technology development, economic trajectories, etc. up to 2050.

The sharing approaches are based on different sharing principles. As such, choice of a sharing approach is associated with an implicit value judgment that may advantage certain countries by aligning with their specific socio-economic or demographic characteristics [30]. For example, the EPC principle inherently prioritises distributive equality, whereas the GF principle advantages countries with relatively higher historic GHG emissions, providing a relative carbon accounting advantage to countries with higher populations and higher GHG emissions respectively. This fairness concern is relevant not only for national level policies but also for political acceptability and legitimacy at a global scale. Therefore, future research could investigate the setting of dynamic RCBs and carbon debts by incorporating a responsibility-capability-based allocation guiding principle (e.g. common but differentiated responsibilities (CBDR) which is recognised by the UNFCCC [78]).

In addition, this study is also limited by the assumptions used in setting the global RCB [14]. This has been addressed to a certain extent by incorporating RCBs with maximum and minimum values to account for uncertainties related to the assumption that future non-CO₂ warming aligns with stringent mitigation pathways (where non-CO₂ GHG and aerosols contribute approximately 0.1 °C of additional warming above the 2010–2019 baseline). Minimum and maximum global RCB values were used as calculated by the IPCC [14], i.e. accounting for the situation where actual non-CO₂ emissions are either higher or lower than the projected contribution of non-CO₂ GHG emissions.

6. Conclusion

This study addresses the limitations of conventional static carbon

budget allocation methods by explicitly integrating dynamic parameters into calculation of national and sectoral dynamic RCBs over time. A dynamic carbon debt framework is proposed that can inform the development of additional strategies needed to achieve climate targets. The dynamic carbon budget framework described in this study facilitates a greater appreciation of the urgency of implementing rapid mitigation strategies at national and economic sector levels. This is achieved by: (i) integrating temporal dynamics into parameters that affect forecasted GHG emissions and RCBs, (ii) calculating dynamic carbon debt results that show the shortfall between forecasted mitigation measures and GHG emissions, (iii) presenting time-differentiated results, and (iv) representing modelling uncertainties through use of ranges based on two sharing approaches as upper and lower bounds for the assessment, and use of minimum and maximum values for the RCB to account for the uncertainties in non-CO₂ GHG emissions.

For Aotearoa New Zealand, the dynamic carbon debt framework facilitates understanding of the magnitude and need for timely interventions for CDR. At the building sectoral level, the study results using this framework highlight that the downscaled RCBs are unrealistic and currently unachievable for this sector. There is therefore an urgent need for development of an immediate building sector time-differentiated decarbonisation pathway in order to stay below the 1.5 °C target. Furthermore, as the dynamic carbon debt framework shows the range of downscaled RCBs and carbon debts depend upon future non-CO₂ GHG emissions, it highlights the importance of additionally limiting non-CO₂ GHG emissions in the wider ANZ economy.

In summary, use of the dynamic carbon debt framework can inform translation of ambitious carbon targets (such as alignment with the 1.5 °C target by 2050) into time-differentiated milestones with associated mitigation strategies to support climate policymaking at national and sectoral levels.

CRedit authorship contribution statement

Sachini Nidusha Weerasinghe: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Sarah J McLaren:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Mikael Boulic:** Writing – review & editing, Supervision. **David Dowdell:** Writing – review & editing, Supervision. **Chanjief Chandrakumar:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2025.113805](https://doi.org/10.1016/j.buildenv.2025.113805).

Data availability

Data will be made available on request.

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