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A novel method to calculate SSP-consistent remaining carbon budgets for the building sector: A case study of Canada

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ABSTRACT

Decarbonising the built environment is imperative to reach any net zero global GHG emissions targets. However, there remains uncertainty on how to orchestrate the mitigation efforts. Given a remaining global carbon budget, how should it be assigned both nationally and sectorally? Within this paper, we present a method and Python script to calculate country-specific carbon budgets using open-source datasets, for several scenarios and allocation methods. The script is run for Canada as a case study. Grounded in Canada's calculated carbon budget, tentative budget shares are explored for the Canadian building sector. The feasibility of meeting these budgets is broadly assessed using a streamlined calculation. Even under optimistic assumptions, the Canadian building sector is unlikely to meet its allocated budget share. Key limitations, data requirements and research avenues are highlighted to improve upon the presented approach.

1. Introduction

Under the Paris Agreement, parties to the United Nations Framework Convention on Climate Change (UNFCCC) must commit and periodically strenghten a nationally determined contribution (NDC): a climate action plan to reduce greenhouse gas emissions (GHG) and adapt to climate impacts. Current NDCs are unlikely to result in emissions reductions consistent with limiting global warming to 2 °C [1]. Including the implementation of planned NDCs until 2030, estimates suggest peak temperatures in the range of 2.1 – 2.8 °C in the twenty-first century [2]. Furthermore, NDCs may not represent each nation's fair share of the global mitigation efforts [3–5].

The concept of remaining global carbon budget (RCB) can alleviate these issues and help bridge the gap between climate science and climate policy [6]. The RCB represents the total amount of CO_2 humans can emit without exceeding a given global warming limit (e.g., 2 °C under the Paris Agreement) [7–9]. It is derived from the transient climate response to cumulative CO_2 emissions (TCRE), a quasi-linear relationship between CO_2 emissions and global temperatures [8]. Contrarily to emissions pathways, the RCB only accounts for CO_2; assumptions on the contribution of non-CO_2 emissions are included in the RCB by reducing the remaining allowable warming to respect a given warming level [7,9]. RCB estimates depend on several methodological choices, notably the maximum allowed warming level (e.g., 1.5 – 2.0 °C) and the probability (e.g., 50 – 90%) of conforming to it. They involve geophysical, socio-economic, and methodological uncertainties that arise from the carbon cycle response to GHG emissions, the climate response to radiative forcing, and future emissions of non-CO_2 GHG and aerosol precursors [8,9]. Moreover, Paris-relevant RCB estimates are small relative to their uncertainty, which makes their use challenging [7]. Keeping these limitations in mind, the RCB concept remains useful both as a comparative (to highlight the shortcomings of current mitigation efforts) and as an effective communication device to illustrate the physical understanding of the climate system and its implications for policy-making [6,10]. Among key benefits of the RCB, setting a finite cap on CO_2 emissions clearly establishes that to stabilize global temperatures at a given level, net-zero CO_2 emissions must be achieved and maintained thereafter. It also emphasizes that delaying mitigation will require faster, larger, and likely more expensive emissions reductions in the future [9,10]. Subdividing the RCB for different time periods (e.g.,

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1–5 years) or scales (national, regional, sectoral) can encourage the adoption, reporting, monitoring and continuous improvement of carbon budgets. It can help validate the consistency (and fairness) of NDCs with the Paris Agreement goals, and it can help account for past and current emission inequities [4,10–13].

There are several methods to distribute the RCB among countries, at the cost of additional allocation uncertainties. Each allocation method conveys a given perspective of the equality–responsibility–capacity principles [10]. Grandfathering upholds inertia by granting future emission rights based on past or current emissions [5]. The equality principle reflects the equal human right to development. The responsibility principle acknowledges that countries have understood, contributed to, and benefitted from GHG emissions differently over time. The capability principle recognizes that the different contexts and means (e.g., financial resources, technical expertise) of countries affect their capacity to address climate change mitigation [10]. The cost-effectiveness principle considers the relative costs of decarbonisation options [13]. These basic principles can be combined into several quantitative allocation methods (Table 1), and are also subject to different interpretations. For instance, Williges et al. [14] argue that by itself, distributing carbon budgets based on each country's capacity to afford their cost (ability to pay) or to bear their implementation efforts (ability to contribute) does not guarantees the right of all countries to secure the basic needs of their population. To satisfy fairness concerns, they suggest a four-fold qualifed equal-per-capita approach that gives weight to basic needs, historical emissions (and benefits received through them), and societally-feasible reduction rates [14].

One issue when trying to distribute the RCB to specific countries, regions or economic sectors is that several allocation methods require prospective data on CO_2 emissions, population and GDP. This data is often unavailable or sourced from national scenarios (e.g., in the context of NDCs) that can be difficult to link to coherent global narratives. And though global narratives like the shared socioeconomic pathways (SSP) exist, they have a limited regional resolution, which prevents their use for country-specific anaylsis [19].

The goal of this study is threefold: first, to derive carbon budget estimates for Canada that are consistent with global scenarios; second, to calculate the budget share of Canada's building sector; third, to estimate its feasibility. To do so, Canada's national carbon budget is calculated using harmonized country-level SSPv2 data derived from the Coupled Model Intercomparison Project phase 6 (CMIP6) [19]. We estimate the sectoral budget of Canada's building sector, discuss its feasibility, and highlight key limitations, data requirements and research avenues to improve the presented approach.

2. Methods

Carbon budgets estimations are sensitive to several assumptions, uncertainties, and wider political considerations, and focusing on these limitations could risk delaying mitigation action [20]. Therefore, rather than selecting a single carbon budget scenario, a range of possible values is explored in a programming approach. Based on recommended updates, the remaining carbon budget (RCB) for the Paris Agreement targets were set to: 250 $GtCO_2$ to limit global warming to 1.5 °C with a 50% chance; 940 and 500 $GtCO_2$ to respectively limit warming to 2.0 °C with a 66% and 90% chance [7].

2.1. Identifying a global consistent dataset

Depending on the selected allocation methods, distributing carbon budgets requires assumptions on e.g., future national and global emissions levels, population, and gross domestic product (GDP). Different official sources describe such projections for Canada, for instance Canada's long-term strategy (LTS) [21] and Canada Energy Regulator's (CER) outlook towards net-zero by 2050 [22,23]. However, it is sometimes unclear how such scenarios relate to global narratives. Gütschow et al. [19] provide harmonized country-level datasets derived from the SSPv2 CMIP6 data. The datasets differ by input scenario source, accounting of international shipping and aviation (bunkers), and downscaling technique (Version 1.0, ref: 10.5281/zenodo.3638137). They contain historical (1850–2017) and projected (2017–2100) GHG

Table 1
Effort-sharing principles and related allocation methods (methods implemented in this study are emphasized in bold) – Adapted from [5,14–18].

Category	R	C	E	Description	Examples from the literature
Responsibility (R)	X			Using historical emissions to derive future reduction goals	Historical emissions qualification (Historical)
Capability (C)		X		Relating mitigation goals to the capacity to pay for—or efficiently contribute to—emissions reduction, e.g., based on gross domestic product (GDP) or the human development index (HDI); other basic-needs-fulfilling approaches	Basic-needs qualification (N-qualified) Ability to pay (AP)
Equality (E)			X	Allocating emissions based on immediate or converging per capita emissions, applying current and/or future population projections	Equal per capita (EPC) approach **Immediate per capita convergence (IEPC)**
Responsibility, capability and need	X	X		Placing an emphasis on historical responsibility, balanced with capability and the need for sustainable development	Basic needs, historical emissions and benefits qualifications; EPC with reasonable burden limit qualification (NHBC-qualified) Greenhouse Development Rights (GDR)
Equal cumulative per capita	X		X	Combining the equality and responsibility categories (cumulative accounting for historical emissions)	Historical emissions and benefits qualifications (HB-qualified) **Equal cumulative per capita (ECPC)**
Staged approaches	X	X	X	Compromise over different principles, e.g., differentiated commitments, various stages, sectoral approaches or grandfathering approaches. Also includes studies using equal percentage reduction targets, which maintain current emissions ratios (i.e., grandfathering).	Contraction and convergence approach (CAC simple) **Per capita convergence (PCC)** Triptych approach Sectoral approach **Grandfathering (GF in this study),** also known as Constant emissions ratio (CER)
Cost-effectiveness				Listed as a benchmark in [15]. Using 'equal marginal abatement cost' as a reference case for globally cost-effective mitigation.	Cost-optimal (CO)

emissions, GDP, and population data for 182 countries and eight country groups. We used the recommended default dataset for downscaled SSP IAM scenarios (PMSSBIE), where bunker fuels are removed before downscaling [19]. Out of 180 combinations of socio-economic pathway (SSP), radiative forcing level, and integrated assessment model (IAM), the PMSSBIE dataset describes 127 valid scenarios (Fig. 1).

2.2. Selecting allocation methods

Canada's share of the RCB was estimated by computing several combinations of methods and parameters in a programming approach. The main script takes two inputs: i) a configuration file containing the required parameters for each allocation method (Table 2), and ii) region-specific and global CO_2 emissions, gross domestic product based on purchasing power parity (GDP-PPP), and population (POP) data. The main script first reads the run parameters and paths from a configuration file. To reduce memory consumption and expedite data exploration, it then loads the relevant PMSSBIE data into a SQLite database. Though the PMSSBIE dataset covers 182 countries, there are data coverage differences for different variables (emissions, population, GDP-PPP) and countries [19]. Missing group data was calculated by summing over each group's member countries. For example, global (EARTH) GDP-PPP and POP levels were defined as their sum for all available countries c, and were calculated for each of 127 scenario s (Eqs.1-2). The results were used as proxies for the missing global CO_2 emissions and population.

$$GDPPPP_s = \sum_c GDPPPP_{c,s} \tag{1}$$

$$POP_s = \sum_c POP_{c,s} \tag{2}$$

We implemented four allocation methods, each representing different effort-sharing principles: grandfathering (GF), immediate per capita convergence (IEPC), per capita convergence (PCC) and equal cumulative per capita emissions (ECPC) [18]. The default input parameters are based on Van den Berg et al.'s ESM questionnaire results [18] and on recently updated RCB estimates [7]. Using the prepared dataset and input parameters, the main script computes the carbon budget shares by global RCB estimate (budget), region (country), and scenario (SSP, forcing, IAM), then outputs the results and figures. Running the script for one country (i.e., Canada) takes approximately 90 seconds on a Microsoft Surface Book 2 (Intel® Core™, i7–8650U CPU @ 1.90GHz, 16.0 Go RAM). The source code is freely available on GitHub (https://github.com/CBreton026/carbonpie) under a permissive MIT license. It can replicate the methods and results presented in this section, or apply the presented methodology to any of the 178 countries for which all relevant data is included in the dataset .

Table 2
Main input parameters and default values used for the four allocation methods.

Parameter	Value	GF	IEPC	PCC	ECPC
Remaining carbon budget ($GtCO_2$)	[250, 500, 940]	X	X	X	X
Historic start year	1850				X
Reference year	2010	X	X	X	X
End year	2100		X	X	X
Weighting factor	0.5			X	
Discount factor	0.02				X

2.3. Determining likely ranges for the Canadian building sector's budget share

There are several obstacles when assigning a carbon budget to the building sector. There are inherent scope differences between the building sector emissions (in a life cycle perspective) and those reported in national inventories [16]. Canada's national inventory reports (NIR) use specific sectoral aggregations in which the direct building emissions are limited to the direct operational emissions due to stationary combustion, and the consumptions of halocarbons (SF_6, NF_3) due to air conditioning and refrigeration units. While consistent from an accounting point of view, this underestimates the total GHG emissions of

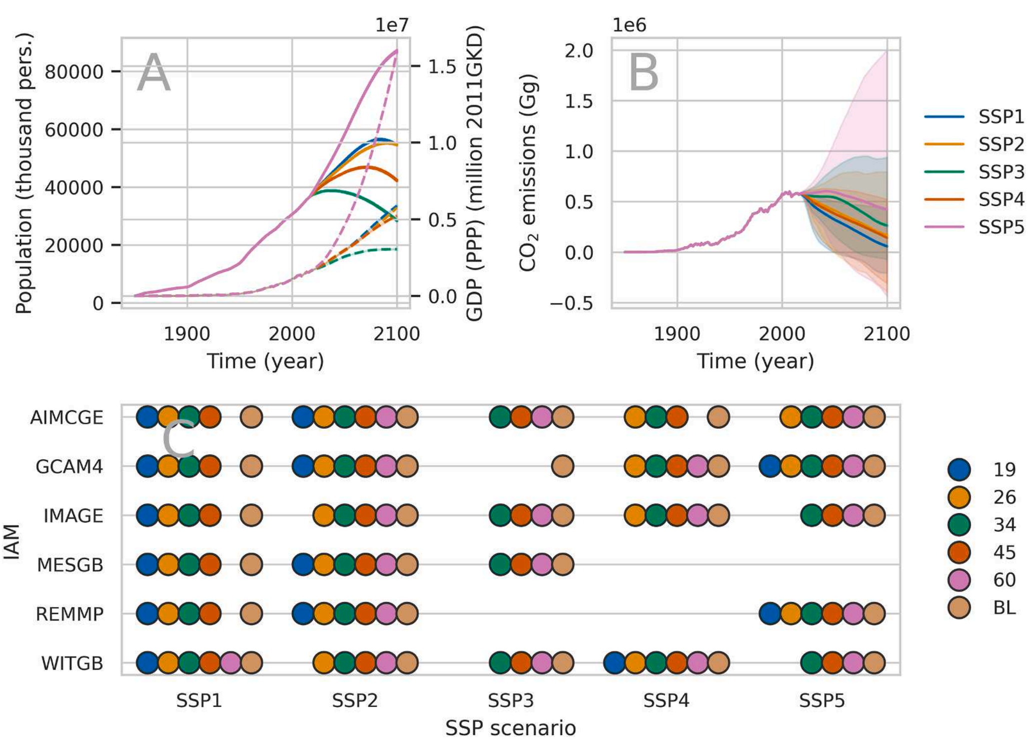

Fig. 1. Downscaled population (solid) and GDP-PPP (dashed) (A), CO_2 emissions projections (B), and scenario coverage (C) for 127 possible combinations of SSP (SSP1–5), forcing level (baseline, 1.9, 2.6, 3.4, 4.5, 6.0 W/m^2) and IAM (AIM/CGE, GCAM4, IMAGE, MESGB, REMMP, WITGB) for Canada – Adapted from [19].

buildings by splitting them across several sectors. The indirect emissions (i.e., emissions from fuel consumed by utility electricity generation and used in buildings due to heating, cooling, lighting, appliances, etc.) are relegated to the electricity economic sector, while embodied emissions (e.g., extraction and production of building materials and systems) are included in the industry and construction sectors [24]. Splitting the building emissions across different sectors breaks the functional unity of buildings [25], and may lessen the perceived contribution of the building sector to GHG emissions. From a policy-making perspective, it could also lead to self-fulfilling prophecies: for example, if the building sector's impacts are limited to operational emissions, then mitigation policies will naturally target electrification and energy efficiency. The NIR also uses a production-based approach: they include the emissions from a given year of national production and exports, but exclude the imported emissions. This is at odds with life cycle assessment results, which aggregate all emissions related to a chosen functional unit, disregarding where and when emissions occur. This key accounting difference is progressively acknowledged in the literature [16,26]. Another difficulty is that carbon budgets are expressed in CO_2, whereas the NIR and projections are usually reported in CO_2e, which include other greenhouse gases. This leads to inconsistencies when trying to determine sectoral shares.

In this study, similarly to previous approaches in the literature [4,27,28], Canada's carbon budget is split by economic sector using two variants of grandfathering. The simple grandfathering approach (GF) is based on the 2021 NIR emissions by economic sector, reported in total GHG (CO_2e) and in CO_2 emissions [24,29,30]. Grandfathering with future capability relies on sector-specific GHG emission projections for Canada (only available in CO_2e) (Fig. 2). Some complete datasets were available [22]; however, most available scenarios in Canada's long-term strategy (LTS) only contain partial data, i.e., sectoral emission targets for 2030 and 2050 [21]. We interpolated the missing values using a linear approximation and then calculated the cumulative sum of the positive emissions for each economic sector; for sectors reaching carbon neutrality before 2050, further negative emissions were set to zero. Including negative emissions would artificially inflate the carbon budgets and may reduce the focus on reducing emissions. There are also indications that positive and negative emissions have asymmetric impacts on warming [31].

To calculate the building sector's budget share, the sector's indirect emissions were estimated using current and projected end-use electricity demand. The calculated 2021 shares for grandfathering are similar to reported electricity consumption by sector [32]. For grandfathering with future capability, the shares were estimated using projected emissions for the electricity sector, as well as the projected end-use demand of electricity (in PJ). Due to data limitations, this could only be calculated for the Canada Energy Regulator (CER) scenarios. The sector's embodied emissions were estimated using the share of national production that goes into building materials and construction, similarly to previous studies [28]. The emissions from cement, steel, aluminium and glass industries were used as a proxy for all embodied emissions, recognizing that this provides an incomplete estimate. These materials were selected because i) they usually represent a large share of embodied emissions and ii) they are listed as distinct categories in the industry economic sector. The share of each material consumed by the building sector (Table 3) was estimated using global material flows as proxies [33–37]. The emissions from relevant NIR subsectors were identified and cross-referenced by economic sector and IPCC category (Annex 10–3 of [24]). These emissions were scaled down based on the contribution of each subsector to the category total, using GDP shares by industry [38] as a proxy for the relative contribution of each subsector to GHG emissions. As the data is only available in CO_2e, the CO_2 emission levels were estimated using sector-specific conversion factors that cross-reference the Canadian emissions by economic sector and IPCC category, and disaggregate the total emissions by GHG and IPCC category. The conversion factors based on IPCC categories were selected as they provided the closest estimates to reported NIR CO_2 emissions. Using this estimate for embodied emissions is an imperfect approximation, and should be interpreted carefully. It only allocates the embodied emissions of a single production year to new buildings. This disregards materials produced before or after (possibly with other technologies), future replacements, and waste. Due to data limitations, the embodied emissions could not be calculated for the grandfathering with future capability method. We used the share calculated by grandfathering for this method, assuming it stays constant over 2022–2050. This is a limiting assumption, as the share of total industrial emissions allocated to buildings will likely change as different industrial sectors evolve and decarbonise, or as new industries appear. Table 3 synthesizes the relevant assumptions for calculating the building sector's budget share based on direct, indirect and embodied emissions.

There are inherent scope issues when defining a carbon budget for buildings [16]. The share of imported emissions – emissions in other countries for materials consumed in Canada – were not considered in the present study. This is consistent with the calculated carbon budget and with the scope of the underlying production-based NIR. However, this approach is hard to reconcile with the concept of whole-life carbon of buildings [16,39]. A consumption-based approach could better represent the total life cycle impacts of buildings and could naturally promote cleaner production [40]; it could also prevent countries from shifting their emissions abroad through imports [41]. However, there would be trade-offs in the form of increased assumptions and uncertainty, and a more complex geo-political decision making environment [40]. For the specific case of Canada, we surmise that the difference between production- and consumption-based approaches could be lower than for other countries. Contrarily to most OECD countries, Canada is a net exporter of CO_2 (53.1 Mt in 2018, ~9%) [42–44]. Canada remains a net CO_2 importer for manufacturing sectors (-3%), and more so for specific industries like basic metals and fabricated metal products (-58%), or other non-metallic minerals (-90%). In a consumption-based approach, about 30% of CO_2 embodied in Canada's final demand is emitted abroad [43,44]. Overall, a consumption-based approach could increase the budget share of Canadian buildings, as it would likely increase the emission shares of building-related sectors (electricity, specific heavy industry subsectors, waste) while generally decreasing Canadian emissions. However, this approach would be incompatible with the production-based carbon budgets. Estimating the precise consumption-based emissions of the Canadian building sector would require further work outside the scope of the current study (see, e.g., [39,45]), for instance using Multi-Regional Environmentally Extended Input-Output (MREEIO) databases like OpenIO-Canada (https://github.com/CIRAIG/OpenIO-Canada) and available Python libraries like Pymrio and pyLCAIO [46,47].

2.4. Analyzing current and projected building sector emissions

A counterfactual scenario was designed to validate if the Canadian building sector could comply with the calculated budgets (Section 2.3). This exercise was meant as a streamlined calculation to broadly assess the feasibility of two distinct budgets: one accounting solely for the sector's direct emissions, and another including the estimated contributions of both indirect and embodied emissions. Firstly, the total indirect emissions were estimated from the projected GHG emissions of the electricity sector and the projected end-use electricity demand for buildings (see Section 2.3 and Table 3).

Secondly, the direct emissions were modelled by applying the Kaya identity, a decomposition of CO_2 emissions into separate drivers [49,50]. As previously adapted for buildings [51,52], the drivers are carbon emissions (*C*), energy consumption (*E*), and floor area (*A*). Consequently, the CO_2 emissions of buildings were disaggregated into the average carbon intensity of the energy supply of buildings (CI), the average energy intensity per unit floor area (EUI), and the total floor area (FA), analyzed for each building type *t* and year *y* (Eq. 3).

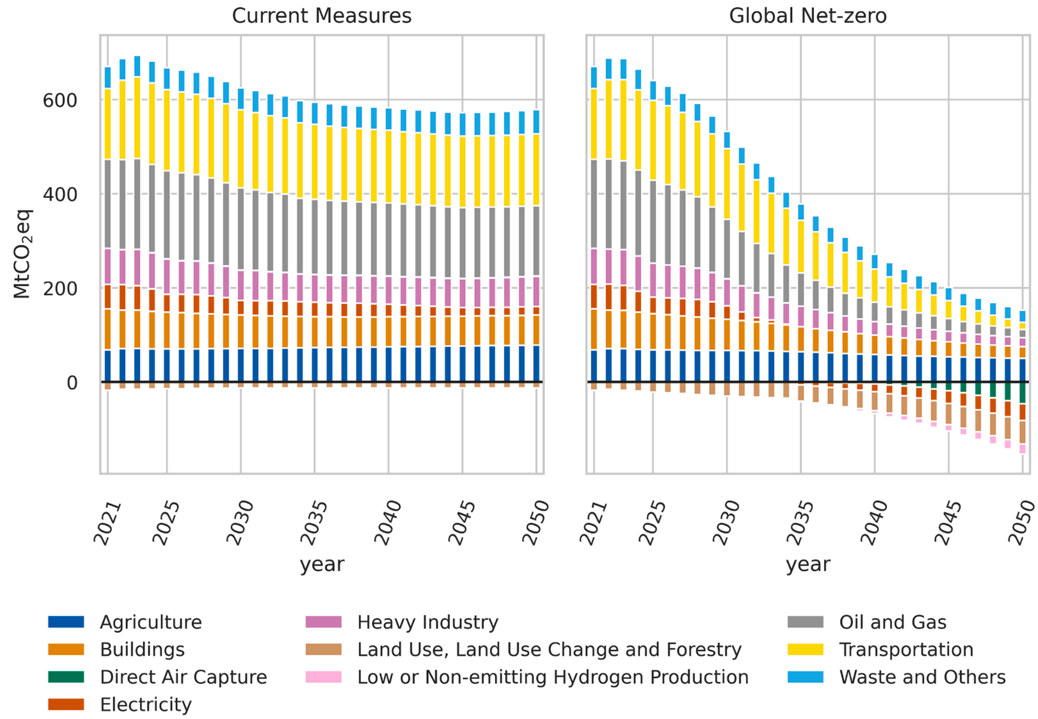

Fig. 2. GHG emissions projections by economic sector for Current Measures and Global Net-zero scenarios – Adapted from Canada Energy Futures [22].

Table 3
Key assumptions for estimating direct, indirect, and embodied emissions in calculating the Canadian building sector's carbon budget allocation.

Emissions	Grandfathering (2021)	Grandfathering with future capability (2021–2050)	Sources
Direct	CO_2 and CO_2e emissions by economic sector.	CO_2e emissions projections by economic sector	[21,22, 29]
Indirect	Building sector GHG emissions, including and excluding electricity, based on end-use demand (in CO_2 and CO_2e). Excludes indirect emissions due to embodied emissions (industry, construction)	Electricity end-use demand projections, based on available CEF future scenarios. Excludes indirect emissions due to the embodied emissions (industry, construction)	[22,48]
Embodied	Estimated embodied emissions from the Canadian Industry sector, using shares of Iron & Steel, Cement, Aluminium, and Lime & Gypsum subsectors. The share of each subsector is based on its global consumption by buildings. GDP is used as a proxy to estimate the impact share of each material in the aggregated NIR report. The relevant NIR categories are multiplied with the calculated shares to estimate the material emissions of the building sector.	Considering there are no detailed industrial emissions projections for the expected evolution of industrial sectors and subsectors, we assume a similar share of industrial emissions over time until 2050 (based on the grandfathering approach).	[33–37]
	Iron & Steel: ~50% of global steel is used by the construction industry, of which ~60% is used in buildings		
	Cement: ~60% of USA cement is used in buildings		
	Lime and gypsum: ~50% of silica, limestone and soda ash extraction goes to global flat glass, of which ~83% is used in buildings		
	Non-ferrous metals: ~24% of global aluminium goes to the construction industry, of which ~92% is used in buildings		

$$C = \frac{C}{E} \times \frac{E}{A} \times A \quad \text{or} \quad GHG_{t,y} = CI_{t,y} * EUI_{t,y} * FA_{t,y} \tag{3}$$

Among the three drivers, the future carbon intensity of the building energy supply (CI) was the least straightforward to estimate. The CER's Canada's Energy Future 2023 data supplement reports indexed Kaya identity drivers, including CI [22]; this economy-level CI can also be estimated from the projected energy-related GHG emissions and the primary energy demand.[1] However, the CI for buildings may differ from the average CI. To confirm this assumption, we attempted to reproduce the CER Global Net-zero (CER GNZ) results from the available data supplement and appendices. The projected GHG emissions of buildings were directly available. The projected floor area (FA) was estimated by applying annual growth rates to 2021 historic stocks [48]. The effective EUI was obtained by dividing the projected residential and commercial end-use energy demand by their respective FA. Knowing the projected floor area (FA), energy intensity (EUI), and building emissions (GHG), the projected CI of buildings was derived from Eq. (3).

Then, the counterfactual scenario was prepared by updating the EUI and FA drivers. The projected building activity (FA) was modelled using a published floor area model (floor area by subsector, 1970–2050), which itself relies on the IMAGE SSP2 baseline scenario [53,54]. In this model, Canada's residential and service building stock sustain continued growth. The main drivers of this growth are the increasing population, urbanization, and affluence (GDP) under SSP2 (see Fig. 1), which lead to larger floor area per capita over time [53–55]. For service buildings, this relationship is expressed through a regression analysis of floor area per capita and service value added per capita [53]. The model's results are lower than reported official Canadian datasets for 2000–2020 [48]. This could be due to the underlying model using lower floor area per capita than other estimates [53,54,56]. To account for this, the results were scaled using 2021 official data as a reference (Fig. 3). Conveniently, the

[1] Personal communication with a CER Market Analyst, 2024-07

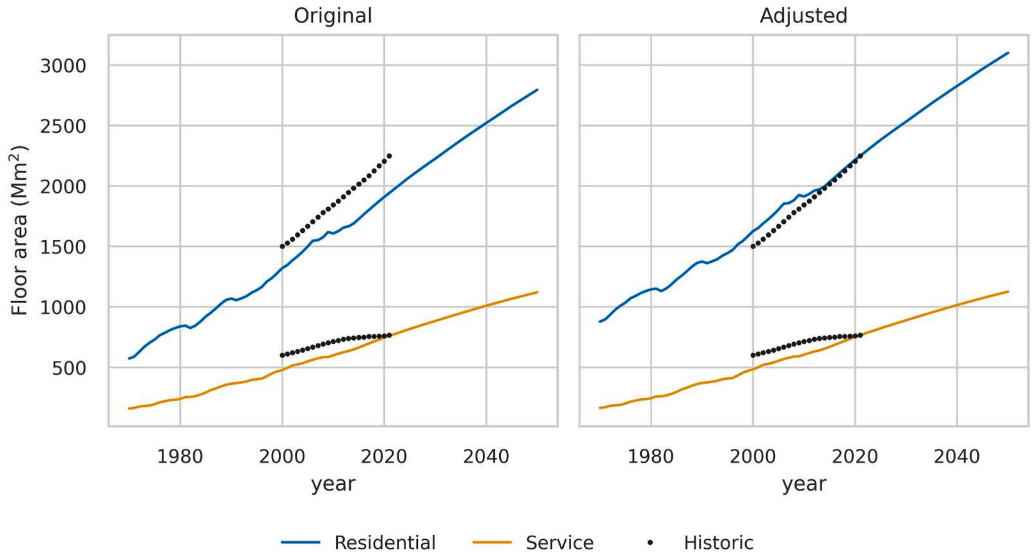

Fig. 3. Original and adjusted floor area for Canadian residential and service buildings compared to historical stocks (2000–2020) - Adapted from Deetman et al. (2020) and the National energy use database (2004).

scaled model agrees with the published CER GNZ growth rates, with yearly differences in the range of 0–3% [22]. However, even when scaled, the total floor area sums to ~2755 Mm^2 for 2016, which is 2.3–4.3 times lower than other estimates for the same year [57]. This might suggest a poor coverage of unconditioned floor space, and thus an underestimation of embodied emissions [57]. The modelled inflows, outflows and stocks were then converted into three stock components: existing buildings (i.e., unrenovated stock), renovations, and new constructions. This process used two main assumptions. Firstly, different perspectives can be adopted regarding renovations: either renovation cycles extend the lifetime of buildings, or they simply maintain it. In the first perspective, the building lifetime is shorter, and extended with each renovation cycle. In the second, the building lifetime is set, and routine renovations and maintenance allow buildings to reach their expected lifetime. Though both perspectives can be defended [58,59], here the second one is adopted for data reasons. Extending the building's lifetime based on the renovation rate would influence the underlying model inflows, outflows and stocks. Adopting the second perspective respects the underlying dataset and implies that projected outflows will inevitably happen; i.e., renovations happen *after* inflows and outflows. In this perspective, since buildings that reach the end of their lifetime are not renovated, there is a finite cap on possible renovations, equivalent to the initial stock minus the cumulative sum of outflows (2022–2050). Moreover, no new constructions are renovated; based on an average lifetime of 51 years (Weibull, shape=1.97, scale=57.53) [53], new and renovated floor areas are assumed to stay in the stock with no major renovations (i.e., no further EUI changes) for at least 30 years, after the chosen time horizon (2050). Secondly, current annual renovation rates are below 1%; different sources argue that 2.5–5% rates would be required to meet Canada's objectives [60,61]. For this case study, an optimistic 5% renovation rate was selected (Fig. 3) to decompose the adapted floor area dataset into existing, new and renovated floor areas. Compared to current practices, this rate is extremely high. This was a deliberate choice to assert the budget feasibility under ideal conditions. In reality, renovation rates of 0–2.5% would be more likely.

For the counterfactual scenario, the energy use intensity (EUI, GJ/m^2) of the stock was based on historic 2021 data (residential: 0.62 GJ/m^2, service: 1.56 GJ/m^2) [48]. These values are lower than the effective EUI values calculated from the CER projected end-use demand, especially for service buildings. This is because CER's commercial sector definition also includes other end-uses, e.g., street lighting and pipelines [22]. One limitation of using the building stock's average EUI is that it represents no buildings in particular [28,62]. Having no information on specific EUI or floor area cohorts, we assumed that as floor area (FA) leaves the stock through outflows and retrofits, the average EUI of the existing stock is reduced by pseudo-randomly cutting from the top 50% of the distribution, to represent the loss of higher-emitting buildings. We also assumed that both new and renovated floor areas perform at 80% lower EUI, relative to 2021 levels (residential: 0.12 GJ/m^2, service: 0.31 GJ/m^2); this corresponds to the higher tiers of performance for Canadian residential buildings [63], and to the absolute top performers recorded by the ENERGY STAR benchmarks for Canadian service buildings [64]. Previous studies demonstrated that EUI improvements of this scale were feasible for large parts of the Canadian housing stock [65]. Overall, this set of assumptions is optimistic, and likely underestimates the total stock EUI. The large share of renovations and new constructions (Fig. 4) lead to halving the residential and service EUI over the next decade, and reaching the designed performance by 2050 (residential: 0.12 GJ/m^2, service: 0.31 GJ/m^2). Compared to the CER GNZ scenario assumptions, this leads to lower EUI and lower operational GHG emissions [22]. Using these EUI estimates, the updated FA, and the derived building CI, the direct emissions of the existing, renovated, and newly constructed buildings were calculated (Eq. 3).

Finally, the embodied emissions were estimated from existing European benchmarks for residential (400–800, μ=600 kg CO_2e/m^2) and service buildings (100–1200, μ=600 kg CO_2e/m^2) [27]. The average embodied emissions were split into upfront (64%), recurring (22%), and end-of-life (14%) emissions [27]. Factoring the 64% share of upfront emissions leads to average upfront embodied carbon emissions of 384 kg CO_2e/m^2. This is higher than recent estimates of 39–121 kg CO_2e/m^2 (A1-A3) for single-family residential buildings in the United States [66], and 148–181 kg CO_2e/m^2 (A1-A3) [63] and 138–357 kg CO_2e/m^2 (A1-A3) [67] for Canadian houses, but within previous ranges and benchmarks from the North American literature [66,68–72]. Based on these comparatives, using an average of 384 kg CO_2e/m^2 for upfront emissions could overestimate the impacts of single-detached houses; this effect could be important considering their prevalence in the Canadian building stock. Better data (e.g., by building type, main materials, period of construction) would help improve this conservative assumption. The scope of the embodied emissions factors differs from that of the calculated production-based budgets. To account for imported emissions, the embodied emissions factors were reduced by 30% [43,44]. This lead to, e.g., upfront embodied emissions of 269 kg CO_2e/m^2 (179–358 kg CO_2e/m^2) for residential buildings and 269 kg CO_2e/m^2 (45–538 kg

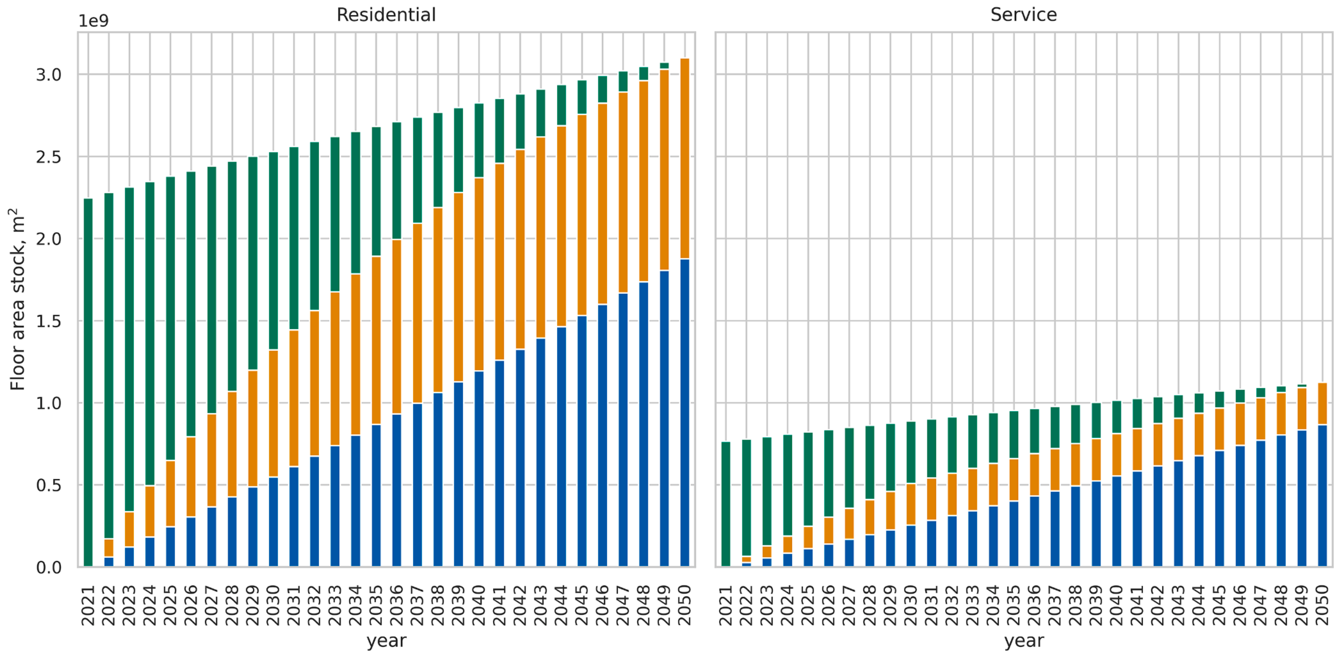

Fig. 4. Projected existing, renovated and new floor area for Canadian residential and service buildings (5% renovation rate).

CO_2e/m^2) for service buildings. This estimated 30% reduction is higher than the 20% recently found for France [39], and comparable with the 30% found for the UK [73]; it is also coherent with the 30–40% range found for Canadian residential buildings in a recent study [45]. Upfront emissions were applied to all floor area inflows to model new constructions, and end-of-life emissions to all floor area outflows to model demolitions. Having no explicit way to account for renovations, the recurring embodied emissions were distributed uniformly over the total floor area stock, based on an average lifetime of 51 years [53]; this assumption is consistent with that of the selected embodied emissions benchmarks, and can represent the annualized emissions due to cleaning, maintenance, and replacement activities [74]. The total recurring emissions of 132 $kgCO_2e/m^2$ for residential (88–176 $kgCO_2e/m^2$) and service (22–264 $kgCO_2e/m^2$) buildings align with typical ranges for renovations (125–200 $kgCO_2e/m^2$) [74,75]. However, the accuracy of this approximation depends on specific assumptions in the selected building LCA benchmarks, specifically regarding maintenance, replacement rates, and material selection [74,75]. These estimates may not fully capture the trade-offs between embodied emissions and EUI improvements for the renovation depth considered in the counterfactual scenario. Tracking specific building archetypes, cohorts, and renovations cycles would provide more detailed insights. Meanwhile, the current annualized approach likely overestimates the recurring emissions for both new and renovated buildings, and neglects the timing of embodied emissions from renovation activities. These temporal dynamics could play a critical role in achieving specific carbon budgets and warrant further exploration.

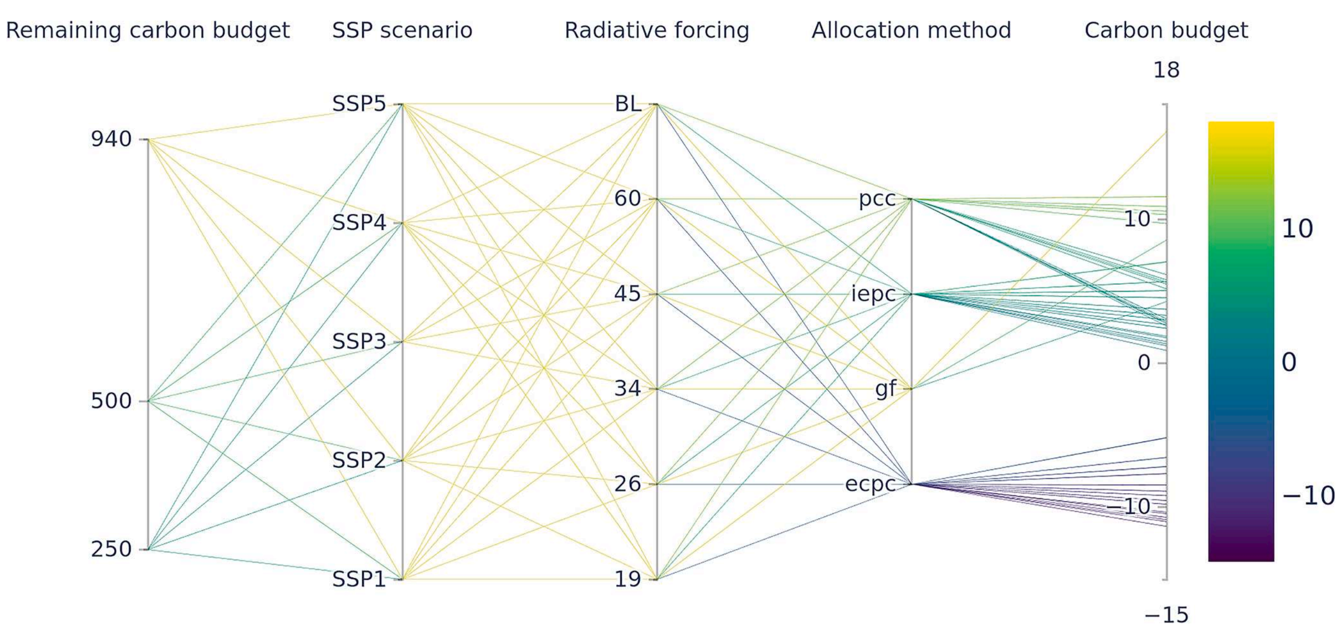

Fig. 5. Carbon budget estimates for Canada (in $GtCO_2$) based on 127 scenarios and four allocation methods.

3. Results and discussion

3.1. Canada's remaining budget

Depending on the chosen remaining carbon budget, scenario, input parameters, and allocation method, Canada's carbon budget varies between -11 and 16 $GtCO_2$ (Fig. 5). At current 2021 emission levels (537 $MtCO_2$), this translates to -21 (i.e., zero) to 30 remaining years [29].

The choice of allocation method highly influences Canada's carbon budget. As expected from the literature [14], grandfathering (GF) provides the largest budgets and prolongs the status quo by allocating future allowances based on current emission shares. Conversely, the equal cumulative per capita (ECPC) approach leads to negative budgets, which is common for developed countries when accounting for historical emissions [11,14,18]. However, by definition, negative carbon budgets are unattainable. The per capita convergence (PCC) approach results represents a middle ground between GF and immediate equal per capita (IEPC) budgets (Table 4).

Henceforth, the PCC approach is used to estimate Canada's fair share of the RCB. The PCC budgets should be seen as an upper estimate: by disregarding emissions before and after 2010, and by giving greater budget shares to higher emitting countries, PCC implies unequal per capita shares of emission rights, which constrains the budgets required to secure basic needs in developing countries [14]. For the five IPCC Tier I scenarios [76] and a 90% chance of meeting the 2.0 °C target, the PCC approach leads to a 5.7 $GtCO_2$ carbon budget for Canada (M: 5.7, SD: 0.3) (Table 5).

3.2. The building sector's remaining budget

Different estimation approaches lead to similar budget shares for Canada's building sector (Table 6). By simple grandfathering, the building sector captures 13.0–13.9% of Canada's budget depending on the GHG emissions considered. The share is higher when considering only CO_2 emissions, as the contribution of other sectors with high non-CO_2 emissions drops (e.g., agriculture, waste). When accounting for future emissions, the CER Current Measures and Global Net-zero scenarios lead to shares of 11.2% and 13.3%, respectively. Both values fall within the range of the other LT scenarios (M: 12.6, SD: 0.6). Due to data limitations, these values are in CO_2e, and likely underestimate the building sector's share. Hence, instead of selecting a single approach, the building sector's budget is approximated using a triangular distribution (low: 12%, mode: 13%, high: 14%) and a normally distributed Canadian budget (Table 6). The Monte Carlo simulation (n=20 000) results in an average budget of 742 $MtCO_2$ (SD: 45).

The shares in Table 6 and the calculated building sector budget only account for direct emissions. When considered, indirect emissions of buildings increase the grandfathering shares to 17.6% (in CO_2e) and 19.6% (in CO_2) (Table 7). These results are similar to previous findings of 18% [77,78]. For grandfathering with future capability, considering indirect emissions increases the building sector's share to 14.0% (Current Measures) and 15.3% (Global Net-zero). In the projected scenarios, electricity production is progressively decarbonised, decreasing the contribution of indirect emissions over time. Though only partially covered (Table 3), embodied emissions also increase the building sector's share. Overall, the embodied emissions contribute ~12% of total building emissions. This may seem small. However, this value represents the embodied emissions from a single year and thus disregards embodied emissions due to, e.g., the use and end of life of materials. When compared to the total heavy industry sector emissions, the calculated embodied emissions represent ~15%, which is close to what previous studies found for the Swiss building stock, where embodied emissions represent ~19% of the national industry [28]. Overall, when both indirect and embodied impacts are included, buildings represent up to 22.3% of total Canadian CO_2 emissions (Table 7), and 20.3% of total CO_2e emissions. Again, instead of directly using a single assumption, a triangular distribution is used to represent a range of possible carbon budgets for direct, indirect and embodied emissions (low: 17%, mode: 20%, high: 23%). The Monte Carlo simulation (n=20 000) results in an average budget of 1141 $MtCO_2$ (SD: 93).

Table 4
Canadian carbon budget ranges ($GtCO_2$) for three RCB targets and the GF, PCC and IEPC allocation methods.

	1.5 °C, 50% (250 $GtCO_2$)	2.0 °C, 90% (500 $GtCO_2$)	2.0 °C, 66% (940 $GtCO_2$)
Grandfathering (GF)	4.3	8.6	16.1
Per capita convergence (PCC)	2.6–3.1	5.2–6.2	9.7–11.6
Immediate equal per capita (IEPC)	0.9–1.9	1.8–3.7	3.3–7.0

Table 5
Carbon budgets (in $GtCO_2e$) for the five IPCC Tier I scenarios and a 500 $GtCO_2$ RCB (90% chance of limiting warming to 2.0 °C).

Scenario		Count	Budget ($GtCO_2e$)	
id	forcing	n	mean	std
SSP1–1.9	1.9	6	5.784	0.002
SSP1–2.6	2.6	6	5.784	0.002
SSP2–4.5	4.5	6	5.615	0.002
SSP3–BL	7.0	5	5.159	0.002
SSP5–BL	8.5	5	6.148	0.003
Average	-	-	**5.7**	**0.3**

Table 6
Carbon budget shares for Canada's building sector, based on NIR economic sectors and direct emissions only.

Economic sector	Grandfathering		Grandfathering with future capability (CO_2e, 2021–2050)			
	CO_2, 2021	CO_2e, 2021	CER Current Measures	CER Global Net-zero	Other LTS	
					mean	std
Oil and Gas	28.1	28.2	27.0	21.8	26.6	1.2
Electricity	9.5	7.7	4.9	3.5	4.1	1.0
Transport	27.0	22.4	26.3	25.8	25.9	4.5
Heavy Industry	13.9	11.5	10.5	11.1	9.2	1.1
Buildings	**13.9**	**13.0**	**11.2**	**13.3**	**12.6**	**0.6**
Agriculture	3.2	10.2	12.1	15.8	16.3	1.4
Waste	0.0	3.1	7.9	8.8	3.8	0.4
Coal Production	0.3	0.4			0.4	0.0
Light Manufacturing, Construction and Forest Resources	4.2	3.5			1.8	0.3

3.3. Can the building sector meet its allocated budget?

Interestingly, even though most available long-term strategy (LTS) and CER scenarios aim towards net-zero or limiting warming to 1.5 °C, they all surpass the calculated carbon budget before 2050. The LTS and CER projected emissions pathways lead to cumulative positive direct emissions of 10.2–17.7 $GtCO_2$, 1.8–3.1 times more than Canada's 5.7 $GtCO_2$ carbon budget (PCC, 2 °C 90%). These scenarios align with a PCC 2 °C 66% carbon budget (Table 4). The CER Current Measures scenario also surpasses the highest calculated carbon budget of 16.1 $GtCO_2$ (grandfathering, 2 °C 66%).

In the proposed counterfactual scenario (Section 2.4), the chosen renovation perspective means that ~54% of current residential floor area and ~34% of current service floor area can be renovated; the remaining floor area is not renovated as it is expected to be demolished before the end of the time horizon. This is a limiting assumption, as more buildings could likely be renovated before their end of life in ~30 years. Using an optimistic 5% renovation rate, the renovation cap would be

Table 7
Estimated direct, indirect and embodied emissions of Canada's building sector using two grandfathering approaches.

	Grandfathering (ref. 2021)						Grandfathering with future capability ($MtCO_2e$, 2021–2050)	
	$MtCO_2$			$MtCO_2e$			Current Measures	Global Net-zero
	Res.	Serv.	Build.	Res.	Serv.	Build.	Buildings	Buildings
Direct (Energy)	35.8	34.7	70.5	38.0	35.6	73.6	1986.6	1506.4
Direct (IPPU)	0.0	4.4	4.4	1.8	11.8	13.6		
Indirect	16.5	13.7	30.1	16.7	13.9	30.9	483.9	229.5
Embodied	-	-	14.9	-	-	17.6	460.2	318.9
Total	-	-	119.8	-	-	135.7	2930.8	2054.8
Share (%)	22.3%					20.3%	16.5%	18.1%

These estimates are based on a production-based approach, and do not include imported emissions
Totals may not add up due to rounding

met by 2043 (residential) and 2031 (service). Rates lower than ~2.5% would not suffice to conduct all possible renovations by 2050. Several studies found that investments in renewable energy, energy efficiency, and electrification could provide large emissions reductions for the built environment [79–81]. Here, the scenario uses high renovation rates, low EUI values for all renovated and new buildings, and the selected CI is constrained within the broader CER Global Net-zero scenario which by definition relies on optimistic assumptions for carbon intensity and electrification. Even under this optimistic scenario, the direct operational emissions surpass the allocated budget by 2038 (Fig. 6B).

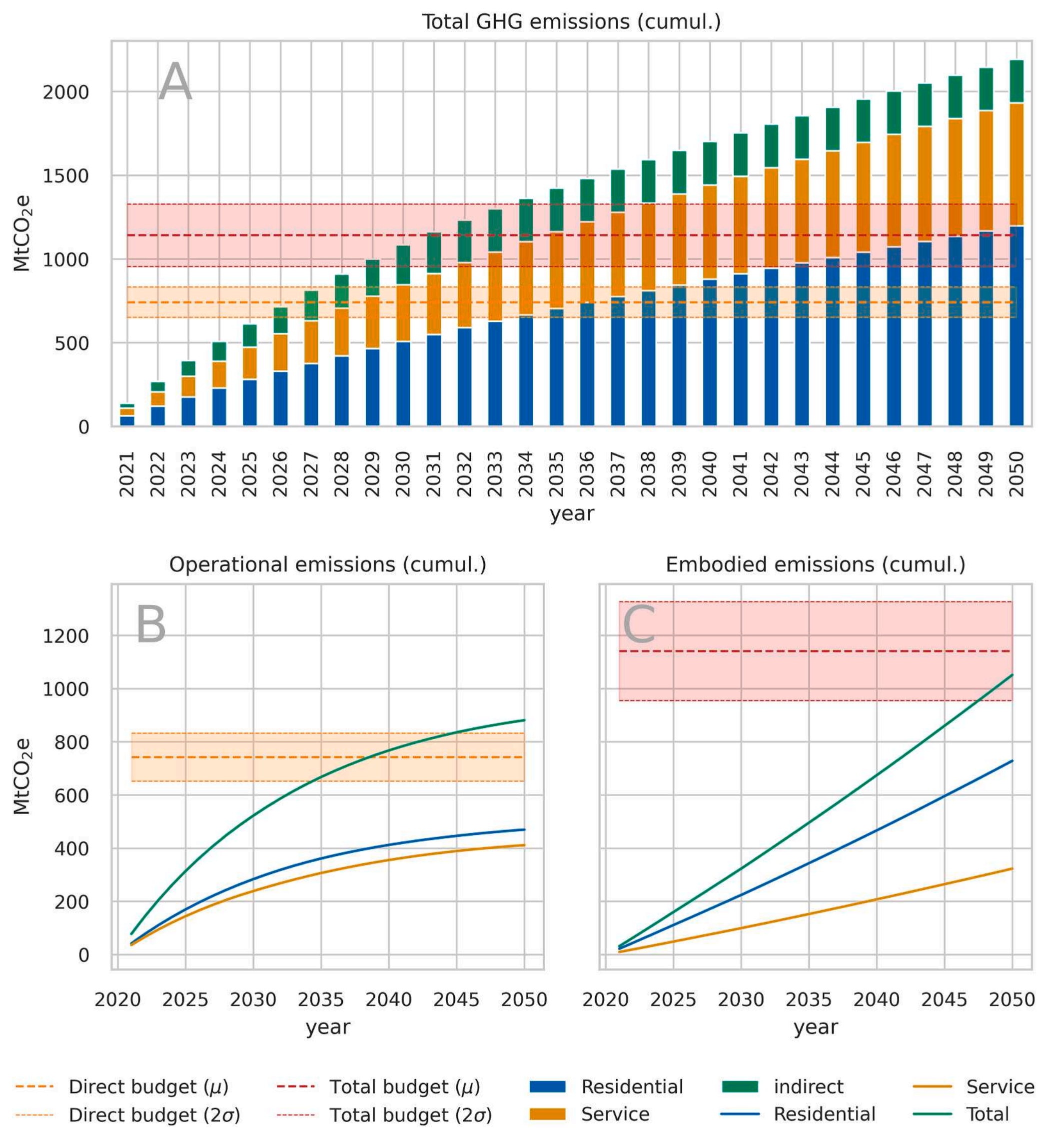

Fig. 6. Cumulative total (A), operational (B), and embodied (C) emissions ($MtCO_2e$) of Canadian residential and service buildings under a counterfactual scenario. The embodied emissions are scaled down to account for 30% imported emissions. The dashed lines and shaded areas represent the allocated mean budget and confidence interval (CI: 95%) based on direct emissions only (in orange) and total emissions (incl. direct, indirect and embodied, in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Reducing the EUI of all new and renovated floor area to zero would result in cumulative emissions of 674 $MtCO_2e$, thus meeting the allocated 2050 budget. This is due to the large expected growth, high renovation rates, and high stock turnover in floor area over 2022–2050. However, this would still spend most of the 742 $MtCO_2e$ budget, and falls within the confidence interval, meaning that there would be little to no direct emissions budget left thereafter. These results are sensitive to several assumptions. For instance, more aggressively targeting the floor area with the highest EUI (i.e., removing the top 10% of the existing EUI distribution rather than the top 50%) would help reduce the contribution of the existing stock. This could help meet the allocated budget or alleviate the immediate pressure to achieve low EUI in new and renovated buildings. In the context of the Kaya identity (Eq. 3), the results are also directly proportional to the CI assumptions: a 10% increase in CI leads to a corresponding 10% increase in GHG emissions. In this study, the CI were approximated from Eq. 3 due to limited data (Section 2.4). The derived CI starts at 30 tCO_2e/TJ and progressively declines to 10 tCO_2e/TJ by 2050; this is consistent with historic CI data for direct emissions, excluding electricity production [48]. However, CI can vary significantly across Canadian provinces and over time (e.g., 0–125 tCO_2e/TJ) [63]. Further research on the projected CI of Canadian buildings would enhance the robustness of these results. Overall, these results agree with previous studies that found a substantial performance gap between current mitigation efforts and climate necessity [27], or that recognized the large contribution of the existing residential stock to emissions [79,82].

The embodied emissions presented in Fig. 6C are not directly comparable to the 1141 $MtCO_2$ carbon budget calculated for direct, indirect, and embodied emissions (Fig. 6). First, while the total emissions (Fig. 6A) include indirect emissions, these were omitted from Fig. 6C to focus on embodied emission levels. Overall, indirect emissions contribute marginally to total emissions due to a relatively low carbon Canadian grid mix, and a weakening contribution of indirect emissions in a context where electricity production is quickly decarbonised and reaches net-zero by 2035 [22]. Second, due to the scope differences between whole-life carbon and national inventories [16,39], a large share of embodied emissions is emitted in other countries and should not be included in a production-based approach. To account for this effect, the embodied emissions benchmarks from the literature were manually reduced by 30% (Section 2.4). However, the temporal scope discrepancy remains, as there are currently no studies on the timing of embodied emissions for buildings in Canada. Recent developments in prospective [83,84] and time-explicit [85] LCA constitute promising pathways to bridge this knowledge gap. In the meantime, from a wider perspective, embodied emissions contribute similarly to the projected Canadian building sector's operational emissions (direct and indirect), with upfront embodied emissions from the construction and renovation activity contributing the most, followed by recurring and end-of-life embodied emissions. By 2050, Canada's total building floor area is expected to grow by 38% (residential) and 47% (service), due to the effect of increasing population and floor area per capita [53].Cumulative inflows represent 83% (residential) and 113% (service), and cumulative outflows 46% (residential) and 66% (service) of current stocks. New constructions could account for 61% (residential) and 77% (service) of the 2050 stock. These results imply a high turnover, which could lead to increased quantities of construction and demolition waste, and a possible opportunity for circular economy for parts of the required new constructions. By definition, this high turnover also results in lower operational emissions (low average EUI), but higher embodied emissions (Fig. 6). These results depend on the average lifetime of buildings, here set as 51 years in the FA model for both residential and service buildings [53]. Obtaining more detailed lifetime data and conducting sensitivity analyses would help make the results more robust. Considering both (i) the projected stock growth and (ii) the scale and timing of embodied emissions underscores the importance of considering sufficiency measures (e.g., lower material intensities, more intensive use, longer lifetimes) in future mitigation scenarios and policies. It also highlights the trade-offs between operational and embodied emissions when high renovation rates are considered.

The large differences in total floor area and energy intensity for residential and service buildings lead to similar contributions to operational emissions, but not to embodied emissions, where the residential sector dominates. These findings highlight the importance of service buildings in future mitigation efforts studies [86]. However, they depart from previous findings by the authors of the selected floor area model [53], who found a greater contribution of service buildings to material flows. One contributing factor is that their global results are based on several countries with varying building lifetimes by building type; however, for Canada, both residential and service buildings share the same lifetime distribution.

There is a growing awareness of the necessary contribution of buildings to global carbon mitigation targets. Overall, the streamlined approach and results presented in this study converge with the emerging, but quickly growing field of prospective national modelling of building whole-life carbon emissions. Indeed, similar studies and approaches have been applied in the context of Australia [81], Austria [87,88], Denmark [89], France [80,90], Ireland [91], New Zealand [92–95], the UK [79,96], the US [97] and Switzerland [28]. To the author's knowledge, this study is the first attempt to establish a carbon budget for Canada's building sector.

Several observations presented here are echoed in the literature, for instance: the scope differences between building sector emissions, national GHG inventories, and IPCC GHG accounting guidelines [27,90,91]; the challenges of reconciling the temporal scope of LCA with yearly carbon budgets [80,89,90]; the large contribution of residential buildings to embodied emissions [80,91]. While this study focused on a production-based approach, many studies argue that a consumption-based approach is more appropriate to assess the emissions of the built environment [27,73,90,93]. The consumption-based approach aligns more closely the scope of building LCA, and offers greater transparency by directly linking emissions to the countries or sectors that consume them. Though it can increase complexity, there are ongoing efforts to improve the robustness of the approach [98,99]. Further research could extend the presented carbon budget approach to recent consumption-based estimates of the Canadian construction sector's embodied emissions [45]. Due to the large embodied impacts of new constructions [82,93,94], some studies also highlight the tension between the demand for new housing and reducing building emissions [89,96]. Many studies highlight the need for sufficiency measures, arguing that reaching net-zero requires preventing or limiting new constructions [27,80,89,96,97]. This paper primarily focused on carbon budget allocation. The streamlined method and results in this section are not intended to accurately predict the future emissions of the Canadian building stock, but rather to illustrate the challenges of meeting its likely carbon budget allocation (PCC, 2.0 °C, 90%). They provide a first step towards more detailed modelling efforts. Exploring mitigation scenarios using other models, e.g., national-scale macroeconomic simulation models [81], MRIO-based approaches [89,90,93] or more detailed dynamic building stock models [100–102] would be a logical improvement on the presented approach.

4. Limitations and further research

The results presented in this study are subject to many limitations. Our estimates for Canada's carbon budget depend on future prospective scenarios (LTS, CER) for which only partial data is publically available. It is often unclear how these projections relate to the international context, which makes it difficult to calculate consistent scenario-specific budgets, especially for allocation methods that depart from simple grandfathering. Other limitations include:

- Using average data (EUI, CI, FA) and a general low-granularity for building stock data, which obscures presumably important effects linked to e.g., building types and functions, cohorts, and stock dynamics, notably vacancies and the specifics of renovations;
- The disconnection between modelling building stock in continuous floor area distributions (Mm^2) instead of actual dwellings or buildings (i.e., discrete groups of floor area with given properties), which could influence the selection, application and results of future mitigation efforts;
- Additional uncertainties from relying on several datasets expressed either in CO_2 or CO_2e, when carbon budgets are measured in CO_2, or reported in categories or classifications with no clear equivalencies;
- The crude approximations for estimating the current contribution of the heavy industry sector to the building sector budget share through embodied emissions;
- The simplified assumptions for the EUI of existing, new, and renovated buildings, which do not account for relevant energy-related parameters such as heating and cooling degree days, the use of specific technologies and carriers, the share of end-use demand by services, etc. (see, e.g., [63,103]);
- Adjusting the floor area model to fit historical data is, by definition, more accurate for 2021 levels; it maintains the original flows, and is consistent with the published CER growth rates. However, this approximation is not a model *per se*; further work would be required to develop a Canadian dynamic building stock model, which would also allow tracking specific cohorts and renovation states;
- Using static, aggregated European benchmarks to model the embodied emissions of Canadian buildings, rather than region-, type- and period- specific values, introduces both temporal and spatial uncertainties. This approximation is likely inaccurate, and disregards the decarbonisation of building materials and technologies over time.

More generally, there remain several difficulties in estimating sectoral carbon budgets:

- Having consistent national and international datasets. In the current study, this effect was limited, as the four allocation methods are based on historical data. However, for several methods concerned with fairness (e.g., ability to pay), inconsistency is introduced between the SSP scenarios and the future emission scenarios. A better integration of national emission projections and global narratives and models is needed;
- Among the many uncertainties in evaluating the RCB, the choice of model and scenario family influences the remaining carbon, notably through non-CO_2 warming. The RCB values used in this study (250, 500, and 940 $GtCO_2$) were applied for all scenarios as a simplification, but these values could be incompatible with certain scenario combinations and their underlying assumptions;
- Choosing a production-based or consumption-based approach, and finding data consistent with the chosen scope;
- Not accounting for how different technologies, materials and industrial sectors will (or could) evolve and decarbonise over the next decades;
- Relying on several different models and projections, for example the RCB which is subject to large uncertainties and is often updated [7,104], or the SSP scenarios which may diverge from real-world trends [105].

There is several ways the Canadian building sector's budget could be further subdivided, for instance to determine allowable operational and embodied emissions targets per m^2 [4,27]. Another likely option for Canada would be to split the carbon budget by Province, and let each manage their own carbon budget. These questions are relevant for policy-making, but exploring them would require higher granularity of data and assumptions than those available in the context of this study.

The identified limitations suggest important research avenues and methodological improvements. Sustained modelling efforts to develop a more granular Canadian building stock model (e.g., building cohorts and types, archetype-specific energy and material consumption) would help improve this study. Further research in reconciling the temporal and spatial scope of LCA with the current limited scope of national emissions inventories also seems promising.

5. Conclusion

The implicit grandfathering approach behind current nationally determined contributions (NDC) is unlikely to lead to emission levels consistent with limiting global warming to 2 °C, and implies an unfair share of global mitigation efforts. Using the remaining carbon budget (RCB) concept and open-source datasets, this study presents a method and Python script to calculate country-specific carbon budgets for a combination of 127 scenarios (SSP, forcing, IAM) and four allocation methods. The data, assumptions and Python scripts are freely available (https://github.com/CBreton026/carbonpie). They can produce similar results for any other of the 178 countries covered in the underlying dataset.

In a case study, likely ranges for the Canadian building sector's budget share are explored, and the feasibility of meeting this budget using is estimated using a back-of-the-envelope calculation. In all its published long-term net-zero scenarios, Canada's projected emissions lead to cumulative emissions 1.8–3.1 times higher than the selected 5.7 $GtCO_2$ budget (2.0 °C, 90%). Based on 2021 emissions levels, this represents roughly 10 years before spending the budget. In the building sector, even under optimistic assumptions, operational emissions are likely to exceed the 742 $MtCO_2$ (13%) sectoral budget by the mid-to-late 2030s. However, the definition of the building sector in national inventory reports is limiting. When accounting for indirect and embodied emissions, buildings could capture closer to 20% of national emissions, for a budget of 1141 $MtCO_2$. Compliance to this budget is much harder to assess due to accounting differences between national inventories, available datasets, and life cycle assessment methods. However, direct and indirect operational emissions are projected to spend most of this budget by 2050, and embodied emissions of a similar scale push the sector's total emissions to 38% of the Canadian budget. This streamlined calculation reiterates the importance of accounting for embodied emissions when selecting mitigation strategies and policies going forward.

Canada has committed to mitigating climate change by achieving net-zero emissions by 2050. This study highlights significant challenges for the building sector to meet its allocated carbon budget. Using the proposed methods, Canada could strengthen its commitment to sufficient and equitable mitigation efforts by adopting, monitoring, and periodically updating sectoral carbon budgets. As more data and refined assumptions become available, the method presented here could be improved to determine more robust budgets for Canada's building sector. Similarly, sustained building stock modelling efforts would enhance the streamlined approach, enhance the robustness of the results, and help identify key mitigation strategies. Nonetheless, with the goal of limiting global warming to 1.5 °C appearing increasingly unattainable, the findings of this paper suggest that Canada must act swiftly to align its actions with its ambitions and avoid the risk of surpassing the 2 °C target.

CRediT authorship contribution statement

Charles Breton: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Pierre Blanchet:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Ben Amor:** Writing – review & editing, Supervision, Conceptualization. **Francesco Pomponi:** Writing – review & editing, Supervision, Conceptualization.

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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Data availability

Data will be made available on request. Research code, notebooks, and public datasets will be hosted on GitHub on manuscript acceptance.

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