A future infrastructure growth model for building more housing with less embodied greenhouse gas
(Pre-Print)

Keagan Hudson Rankin[1*], Shoshanna Saxe[1]
[1]Department of Civil and Mineral Engineering, Centre for the Sustainable Built Environment, University of Toronto
keagan.rankin@mail.utoronto.ca; s.saxe@utoronto.ca
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Abstract
Rising social and economic pressures to build more housing and infrastructure are in tension with the need to rapidly reduce GHG emissions from resource extraction and use. This paper presents the Future Infrastructure Growth (FIG) model: an open data, bottom-up, generalizable statistical tool for forecasting future embodied GHG emissions associated with the construction of housing and supportive infrastructure. FIG is demonstrated by examining Canada's emissions through 2030 and 2050. Canada needs to build 5.8 million homes by 2030 to restore affordability. If built using current construction practices, embodied emission will be more than 376% of the 2030 national reduction target. FIG is used to analyse the impact of alternative strategies for reducing embodied GHG, including changes in urban form, building design, reductions in material GHG intensity, infill and circularity. FIG is able to find a narrow pathway where all five strategies are combined to meet both housing and climate goals.

1. Introduction

This paper introduces a bottom-up model for forecasting and comparing embodied greenhouse gas (GHG) emissions from future construction of housing and supporting road, water and wastewater infrastructure. Embodied emissions – the upstream GHG emissions from material production and construction processes – are accounting for a large and growing share of global emissions, increasing from 15% in 1995 to ~25% in 2015 [1]. Construction materials (e.g., concrete, steel, wood, asphalt, plastic) account for 40% of all these material emissions. Reductions in embodied emissions, particularly in the built environment, will be critical for achieving global sustainability targets [2], such as net-zero emissions by 2050 [3–10].

Reductions in embodied emissions in the built environment are essential, but they are in tension with global demand for infrastructure and housing growth in both low- and high-income countries. In low-income countries, economic development is expected to spur ~100 billion m^2 of additional building stock construction and related infrastructure construction through 2050 [11–14]. In high-income countries, like Canada, the United States and England, rapid increases in housing costs and a deficit in housing supply compared to demand over the last decades are now driving legislation to encourage rapid increases in construction of housing and supporting infrastructure [15–17]. Given that construction growth is linked with accumulation and lock-in of material stocks and associated embodied emissions [18], strategies are needed to help society achieve its simultaneous commitments of 1) providing adequate housing and infrastructure and 2) curbing resource use and GHG emissions.

While research has established the importance of material use and associated embodied emissions reductions, most existing work on material flow in the built environment has focused on historical flows and stock accumulation rather than lowering embodied emissions of future construction [12,19,20]. Additionally, despite increasing availability of bottom-up data, top-down methods remain the most common approach for studying country-level stocks. Top-down methods lack the spatial detail required to investigate important drivers of embodied emissions (e.g. urban form) which previous research has identified as a critical gap in knowledge [19]. Conversely, studies that use a bottom-up approach to quantify embodied emissions tend to employ data archetypes/typologies (extrapolating a single or few observation(s) to an entire type of infrastructure) that skew results and ignores variability in building and infrastructure design[21]. These studies also tend to look at housing and horizontal infrastructure (e.g. roads, water distribution systems) in isolation rather than as related systems. Finally, existing bottom-up studies tend to not consider mitigation strategies and are generally limited to quantifying city-scale stocks and flows [8,22,23]. To our knowledge, there are no existing studies that project future emissions of multiple infrastructure types using detailed, bottom-up modelling.

In response to these gaps, we present the Future Infrastructure Growth model (FIG). FIG forecasts neighbourhood-scale embodied emission from future construction and analyzes the effectiveness of different strategies (Table 1) for reducing these emissions. FIG takes a bottom-up approach to quantifying embodied emissions, leveraging detailed, open datasets on infrastructure properties and future construction growth scenarios. Furthermore, the model captures uncertainty and variability in building and infrastructure design by employing a random sampling procedure on these datasets. The model considers city planning choices in future construction by simulating infill versus greenfield construction and circularity (e.g. the degree to which existing buildings/units are maintained and/or building materials are reused). FIG forecasts material emissions at a national-level while still facilitating detailed geographic breakdown, captures the interaction of multiple infrastructure systems together, and is applicable to any country where input data is available or can be approximated. The scope of life-cycle stages included in FIG depend on resource use and associated embodied emissions data available for the infrastructure studied (E.g. A0, A1-A3, A4, A5, B2, B5, C1-C4)[24].

To demonstrate an implementation of the FIG model, we analyze and forecast future A1-A3 [24] life-cycle embodied construction emissions in Canada. The Federal Government of Canada has committed to reducing emissions 40% below 2005 levels by 2030 [25] and achieving net-zero by 2050 [26]. At the same time, the government has pledged to build more homes in hopes of alleviating the country's ongoing housing crisis. Canada's national housing agency estimates that that the country will require 5.8 million new units by 2030 [27] to restore housing affordability, which is more than double Canada's current annual housing construction rate [27]. As such, Canada exemplifies a country that must emit less while building much more. By applying the FIG model in this case study, we calculate the equivalent modern embodied emissions for tens of thousands of neighbourhoods in Canada, quantify future growth and find effective strategies for reducing future embodied emission. Finally, we identify a possible, but narrow, pathway where Canada can simultaneously provide adequate housing and infrastructure while reducing embodied emissions according to its international climate commitments.

2. Methods

2.1. Future Infrastructure Growth Model

FIG quantifies and forecasts neighbourhood-level embodied emissions in houses, roads, and local water, waste-water, and storm-sewers (referred to hereafter as “water infrastructure”). FIG does not include non-local infrastructure such as major highways, rail, schools, hospitals, water treatment facilities or non-residential buildings and as such calculates a lower bound of emissions. FIG uses open data on housing/infrastructure types and location, modern architectural and structural material quantities used to build housing/infrastructure, and present-day GHG intensity of materials[28–30] (using a 0/0 approach for biogenic carbon [31]). The model begins by simulating the embodied emissions associated with all neighbourhoods in the study area using existing urban form (e.g. arrangement of buildings and infrastructure, types of buildings) and modern material intensities and embodied GHG emissions. Here FIG diverges from other city or regional-scale material stock and urban metabolism studies: it calculates the embodied GHG required to build neighbourhoods as if they were constructed now, rather than determine the emissions from their actual construction. In this way, FIG generates a dataset of thousands of neighbourhoods for use in modelling future growth, rather than back-calculating accumulated embodied GHG.

We model future construction and embodied GHG one of two ways: 1) by sampling from existing neighbourhoods and ‘building’ them again on greenfield land or 2) by retrofitting existing lower density neighbourhoods into higher density neighbourhoods with more housing units. This forecasting method aligns future construction within the range of neighbourhoods that already exist somewhere in the study area and approximates norms and codes without needing to model them directly. With a sufficiently large starting area (in this case all of Canada), the samples cover a large range of neighbourhood, building, and infrastructure forms, from dense, tall downtowns to suburban and rural neighbourhoods. We modify future growth sampling within scenarios based on the density and type of housing being modelled (e.g. when modelling future mid/high rise construction, sampling is limited to current mid/high rise neighbourhoods).

Figure 1 illustrates the main steps of the FIG model: 1) importing, cleaning, and transforming data 2) bottom-up quantification and Monte Carlo sampling and 3) scenario-based forecasting of future construction. The major components of FIG and their implementation in the Canadian case study are discussed below in sections 2.1.1 and 2.1.2. Supplementary Information (SI) sections 1-3 provide further detail on the modelling and data sources.

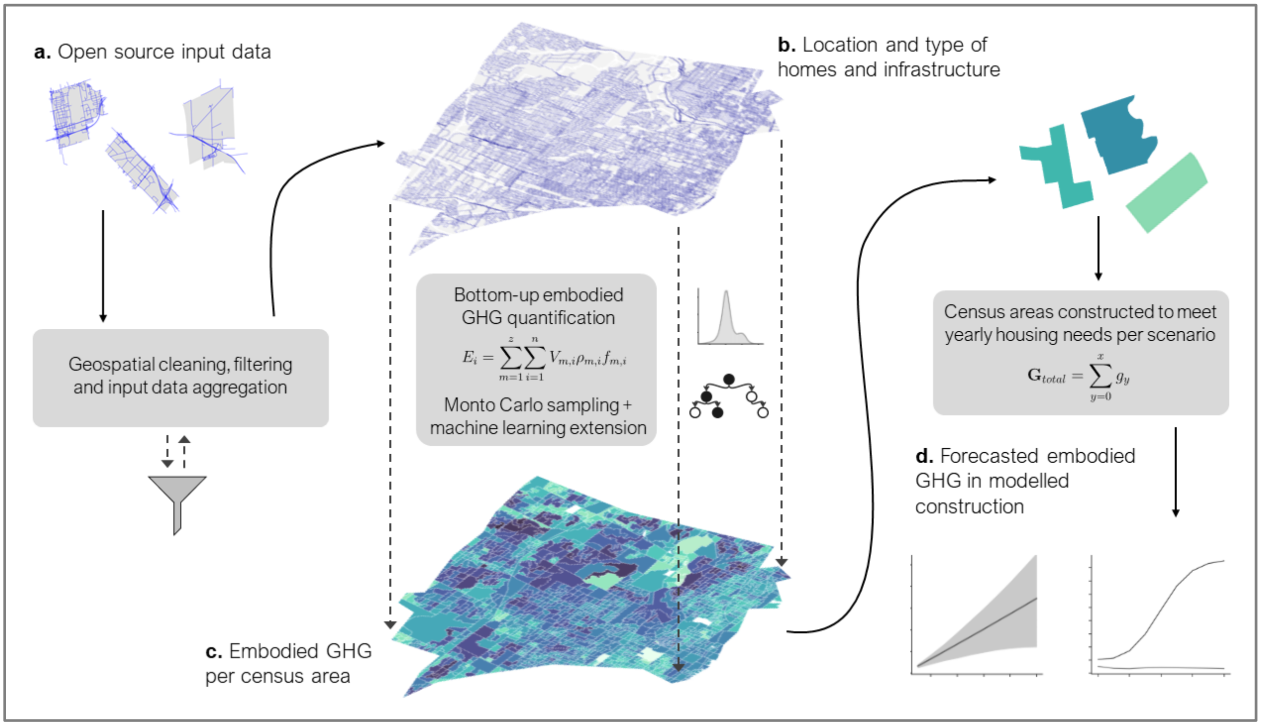

Figure 1: Overview of the Future Infrastructure Growth (FIG) model – **a.** FIG uses open data on materials in housing and related infrastructure. **b.** Open data is processed and organized into census regions. **c.** FIG quantifies the distribution of embodied emissions in infrastructure for each census area as if it were built today using Monte Carlo sampling. Emissions in census areas which lack some data (e.g. water infrastructure locations and sizes) are predicted using machine learning. **d.** Future construction is simulated by sampling many quantified census areas.

2.1.1. Housing and Infrastructure Embodied Emissions Quantification

FIG starts with the assumption that future neighbourhoods will be built in a form similar to that of at least one currently existing standard geographic area somewhere in the overall study area. In the Canadian case study, this calculation is done at the census Dissemination Area (DA) level. DAs are small geographic units within Canada defined to have a population between 400 – 700 people [32]; there are 57932 dissemination areas which include residential building across Canada. For each standard geographic area, FIG quantifies the mass and embodied emissions of materials for all residential buildings, roads, and water infrastructure in that region as if they were built in the present (using material intensity data for modern buildings, modern infrastructure, and present day or future embodied GHG factors). Equation 1 contains a simplified representation of the bottom-up quantification procedure used to determine embodied emissions E (in $kgCO_2eq$) for an infrastructure system I:

$$E_I = \sum_{m=1}^{z}\sum_{i=1}^{n} V_{m,i}\,\rho_{m,i}f_{m,i} \qquad (1)$$

Where V is the volume (in m^3), ρ is the density (in kg/m^3) and f is the present-day or future A1-A3 material emission factor (100-year global warming potential [33] in $kgCO_2eq/kg$) for infrastructure element *i* and material *m*. FIG calculates the embodied emissions of residential buildings and roads over the entire geographic region using existing quantification methods [28–30] for material takeoffs of buildings and horizontal infrastructure, following the procedure laid out in Equation 1. However, there are few examples of comprehensive bottom-up material quantifications in real water infrastructure systems [34,35], and open data on these systems is sparse. FIG uses the procedure in Equation 1 to quantify material mass and embodied emissions in water infrastructure where data is available, and then uses machine learning regression to predict emissions embodied of water infrastructure in geographic areas that lack public data (see SI section 1). Once all infrastructure has been quantified, FIG records the embodied GHG and number of homes for each geographic area. Critically, all of the inputs to FIG's bottom-up quantification contain uncertainty. FIG fits bounded distributions to all uncertain parameters or takes distributions from references if available, and then uses Monte Carlo sampling to propagate the uncertainty through the calculation process [36–38] (see SI section 1.2).

For the Canadian case study, FIG uses Canadian census data [39] on the number and types of residential units in each neighbourhood (DA) as inputs to calculate modern embodied GHG in housing. The model estimates the distributions of material volumes and densities in housing using public data on construction material use in North American buildings [40,41] built between 2009-2025. This material use data focuses on architectural and structural components and does not include mechanical, electrical, or plumping (see SI section 1.4 for more details on exclusions). FIG calculates the material mass in standard road cross-sections using a semi-archetypal approach [29]. To diminish archetype bias, we tune the quantification to the local context using detailed bottom-up data from Toronto, Canada's largest city [30] (see SI section 1.1). FIG then multiplies road cross sections over the length of all of Canada's roads using federal geospatial data [42]. For water infrastructure, we newly quantify material volume and mass in water distribution, stormwater, and sewer systems of 7 Canadian cities (see SI section 1.1), and the model extends the quantification to the rest of Canada using a random forest regression. For all buildings and infrastructure, we convert material mass to CO_2eq mass using Canada-specific, system-specific, present-day GHG emission factors [38,43]. Final embodied emissions are agglomerated by DAs, where they are paired with population data.

The scope (A1-A3 lifecycle processes), bottom-up approach, and exclusion of MEP in FIG should be kept in mind when reviewing numerical emissions calculated in the Canadian case study. Transport (A4) and onsite construction (A5) processes add ~15% upfront embodied GHG emissions [44]. Bottom-up methodology may leave a portion impacts out of an analysis depending on the defined scope of the assessment [45]. FIG's quantification should be taken as a lower bound on true embodied emissions in newly-built neighbourhoods.

2.1.2. Future Construction Simulation

FIG forecasts new construction by using the existing form of infrastructure systems (both vertical and horizontal) as a best guess for what forms will be built in the future. The model simulates a given year of new construction by sampling (representing the construction of) a geographic area (e.g. a neighbourhood) repeatedly until the quantity of new housing construction meets an assigned annual target. For example, the Canadian case study is based on future need for housing in the 10 Canadian provinces (the territories are excluded because there is a lack of future growth data [27]). In a given year, FIG loops through each individual province and samples DAs until the number of houses 'built' is equal to the future housing projections for that year ± an allowed error (1000 per province for this case study). In the high growth scenario, this equals a total of 5,794,483 new housing units built between 2023-2030. Neighbourhood sampling is limited within each province (e.g. neighbourhoods 'built' in Alberta are sampled from existing neighbourhoods in Alberta, not other provinces). The sampling process is then repeated and modified to consider different future scenarios with embodied emission reduction strategies, such as building denser housing, or reducing material emission factors to represent reductions in the GHG intensity of material manufacturing.

FIG simulates infill construction (construction in an existing built-up area) by setting new embodied emissions of road and water infrastructure to zero in a redeveloped neighbourhood (simulating retaining the existing infrastructure and avoiding new infrastructure development associated with greenfield development) and reducing housing emissions by circularity factor k. The circularity factor is a multiplier $\in [0,1]$ that represents of emissions required to create the new residential infill housing units compared to building equivalent units entirely anew. For example, a future neighbourhood made up of new buildings that reuse the foundation of previous structures, or new apartments created by subdividing an existing building, will have a lower k than infill which reuses no existing structures or recycled materials. Unless otherwise noted, the factor k is assumed to be 0.8 based on engineering judgement regarding current construction norms in Canada. FIG assumes that infilled housing units are added in a built-up area somewhere within the study geography (the province in the case of Canada) rather than assigning them a specific spatial location. For the Canadian case study, we used infill rates from the last decade in each province as a baseline for the forecast, and these rates were modified when modelling emission reduction strategies (see SI section 3 for more detail).

2.2. Emission Reduction Strategies

Inputs and variables in the FIG model can be modified to simulate the effects of different embodied emission reduction strategies. The Canadian case study specifically investigates five main strategies for reducing embodied emissions in future construction. Table 1 describes each reduction strategy.

Table 1: FIG model embodied emissions reduction strategies. SI Table 4.1 summarizes which strategies were used for the analysis in section 3

Emission Reduction Strategy	Description
Urban form	Limiting construction to neighbourhoods defined by their percentage of certain housing forms. Form is broken down into three general types: 1) single family homes, 2) mid/high rise construction and, 3) low-rise multi-unit buildings. For example, in one scenario only neighbourhoods with the highest proportion (95th percentile) of single-family homes in their respective Canadian provinces are sampled for future construction. The percentile is set by province. In New Brunswick (a rural province), the neighbourhoods with the most mid/high rise building (95th percentile) include areas that are only <1% mid/high rise. Whereas in Ontario (a province with taller neighbourhoods) the 95th percentile cut off is 76% mid/high rise.
Best-in-class building design	Best-in-class design; specifically, this strategy limits housing construction to well-designed, lightweight buildings in the 1st quartile of $kgCO_2eq$/unit for their given form. Examples of best-in-class design include single-family homes with lower gross floor area, low-rise multi-unit buildings with wooden structural elements and non-metal cladding, mid/high rise buildings with less slab volume (e.g. avoiding transfer slabs), and a decrease in substructure size across the all buildings [46].
Material technology improvements (leading to reductions in material GHG intensity)	The potential of embodied emission reductions through improved material production and technology (e.g. carbon capture). In the Canadian study these improvements are applied as percentage reductions to the emission factor every year based on expected future reductions from literature [25,47–52]. The model defines specific reductions for 6 major materials (concrete, lumber, insulation, asphalt, steel, plastic). Remaining materials are assumed to achieve 20% reductions by 2030 and decay to net zero

	exponentially in line with existing projections thereafter [53]
Infill rate	The relative percentages of housing built within existing built-up areas vs. greenfield land. This influences most directly the amount of new horizontal infrastructure needed (roads and water). The FIG model does not include land use change and forestry impacts from greenfield development.
Circularity (*k*)	(100% – *X)*, where *X* is the percentage of housing units and/or material retained during infill development (e.g. is a new building built in place of an old one or beside the old one with no units lost? Are existing buildings subdivided or do new units require new buildings? Are the bricks from a demolished building reused?)

SI section 2 provides further details on the development of reduction strategies. Yearly emission reductions in 2030 are compared to allowable emissions based on a proportionally-downscaled version of the Canada's economy-wide commitment to reduce GHG emissions by 40% below 2005 levels by 2030 [25]. This downscaling holds the amount of yearly emissions allowed to new construction equal to their current proportion of Canada's overall emissions.

2.3. Future Housing Growth

In the Canadian case study, we project housing starts from 2023 to 2030 in two scenarios taken from national economic research conducted by the Canadian Mortgage and Housing Corporation (CMHC) [27]:

1. **Business-as-usual (BAU) Growth** – this first scenario assumes BAU growth equating to ~2.3 million additional housing units by 2030, with yearly growth staying relatively constant.
2. **Affordability Growth** – This second scenario assumes construction experiences the increased growth (starting in 2023) required to restore housing affordability and that 5.8 million additional housing units are built by 2030.

Affordability growth is modelled using a logistic function, following the common growth curve that occurs under new market pressures [54]. This approximates growth in housing delivery capacity that could result from growing the work force (e.g. targeted immigration) [55] or the introduction of new construction technologies, techniques, and designs that make housing delivery more efficient. Beyond 2030, the Canadian case study estimates yearly housing starts by converting the government's projected population growth scenarios [56] to new housing stock using fixed, provincial household formation rates from the 2021 census [57]. SI section 3 provides further detail on projections, along with an analysis of time-series forecasting models that are fit to historic housing start data.

3. Canadian Case Study Results

3.1. Drivers of Neighbourhood-Scale Emissions

Neighbourhood-level embodied emissions calculated by FIG in the Canadian case study are governed by residential buildings. Embodied emissions from residential buildings range from 345-46,700 kgCO_2eq per capita (median 21,000 kgCO_2eq) across 500 Monte Carlo samples. On average, residential building emissions are an order of magnitude higher than embodied emissions in a neighbourhood's roads (median 1390 kgCO_2eq), which in turn are nearly an order of magnitude higher than the embodied emissions in the neighbourhood's water infrastructure (median 260 kgCO_2eq) (Figure 2a). Some rural neighbourhoods and those near critical non-residential infrastructure (e.g. an airport) have embodied road emissions that are equal to or exceed their housing emissions. More rural regions of Canada (e.g. Atlantic Canada) tend to have neighbourhoods with higher road emissions compared to more urban provinces (e.g. Ontario, Quebec). The highest embodied water emissions per capita are found in neighbourhoods at the rural periphery of cities.

Single-family homes are more GHG-intensive than other forms of housing, and neighbourhoods dominated by single-family housing have higher embodied emissions across all studied infrastructure systems. Figure 2b contains a principle component analysis (PCA; a low-dimensional representation of data where the axes are uninformative) of neighbourhood properties for every DA in Canada. A gradient of single-family home percentage and embodied emissions are overlaid on the data. The analysis shows that percentage of single-homes is a large driver of the variance between neighbourhoods. It also shows that a higher percentage of single-family homes in a neighbourhood increases the per-capita embodied emissions in all infrastructure systems. Compared to low-rise multi-unit and mid/high rise buildings, the percentage of single-family homes in a neighbourhood is a strong predictor (linear fit R^2=0.87, p=0.00) of embodied residential building emissions per capita. Neighbourhoods with a high percentage of single-family homes also have higher road (linear log-transform, R^2=0.82, p=0.00) and water infrastructure (linear log-transform, R^2=0.81, p=0.00) embodied emissions because their less dense layouts have higher horizontal infrastructure requirements and house fewer people. Lower log population density is also a predictor of increased building and infrastructure emissions (R^2=0.77-0.87, p=0.00) as is mean household size in a neighbourhood (R^2=0.92-0.96, p=0.00) (Figure 2c). Denser neighbourhoods with <10% single-family buildings, whether they are composed of taller mid/high rise or dense low-rise buildings, reduce embodied emissions by 19600 kgCO_2eq per person (56.8%) on average compared to neighbourhoods which are made up exclusively or almost exclusively (>90%) of single-family homes.

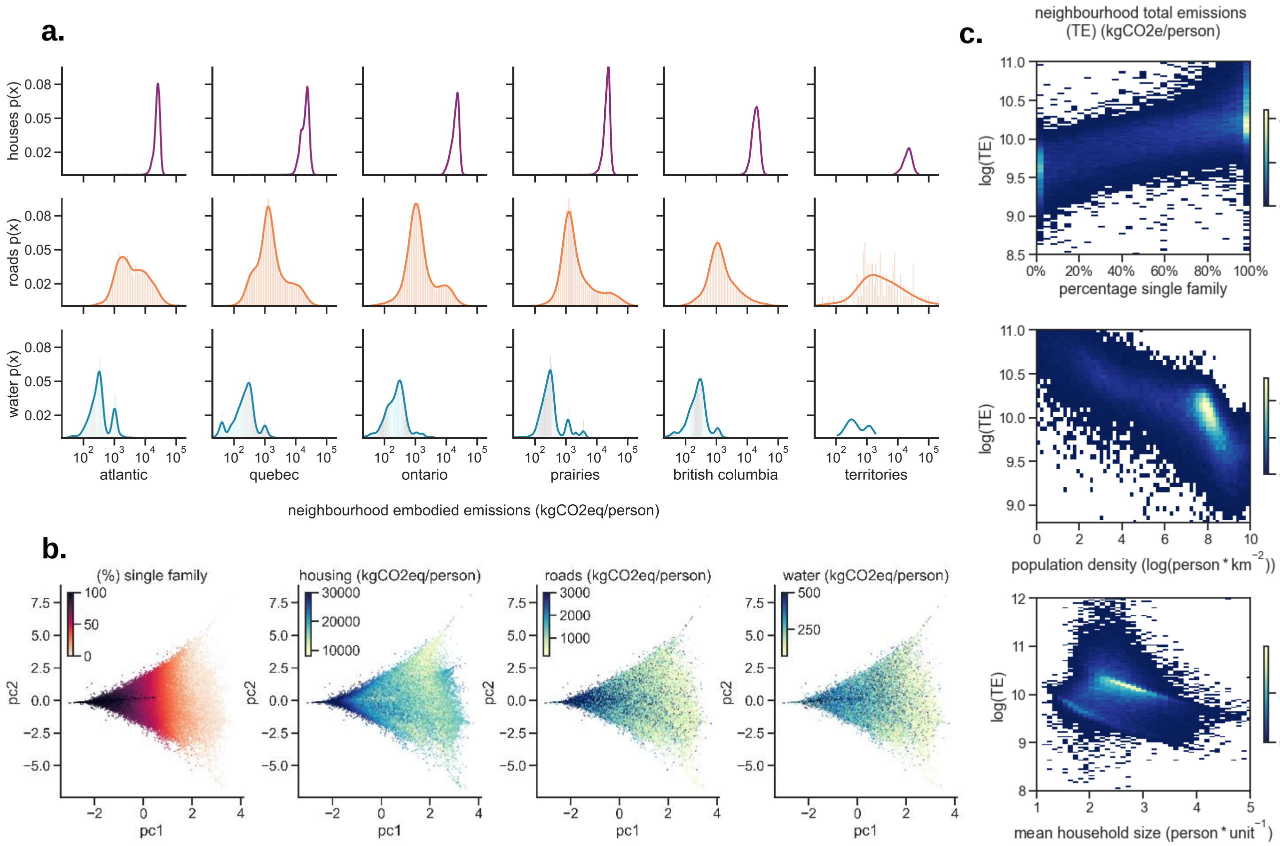

Figure 2: Neighbourhood-level analysis of embodied emissions – **a.** Probability distribution of per-capita A1-A3 embodied emissions (kgCO_2eq/person) of the median sample for neighbourhoods in regions of Canada if they were built with current material intensities and emission factors. The horizontal axis is log-transformed. **b.** Principle component analysis of houses per person of all neighbourhood configurations in Canada. Each datapoint is a neighbourhood. The gradients on the plots show the share of single-family homes and per-capita embodied emissions of different infrastructure systems. The number of single-family homes per capita is the largest driver of variance and emissions in neighbourhoods across the country. **c.** Relationship between neighbourhood properties and total per-capita embodied emissions. Each count is a neighbourhood. Plots showing distributions across the Monte Carlo samples and individual infrastructure relationships can be found in SI section 4 Figures 4.1-4.2

3.2. 2030 growth forecasts and reduction of embodied emissions

We analyzed the effect of the reduction strategies from Table 1 on future embodied emissions in two stages. First, we isolated the effects of changing urban form, improving material technology, and building best-in-class buildings in future neighbourhoods while maintaining current infill and circularity rates. We then analyzed the combined reduction potential of these strategies together with changing infill and circularity percentages. Finally, we looked at how future embodied emission vary geographically across Canada. SI Table 4.2 summarizes key results from this section.

3.2.1. Impact of Reduction Strategies

When analyzing the effect of urban form, material technology, and best-in-class design in the affordability (high-growth) scenarios, total cumulative A1 to A3 embodied emissions through

2030 range between 178-418 $MtCO_2eq$ (Figure 3a). This range is largely dependant on choices related to housing form (e.g. reductions in the share of single-family homes and improving building design to the 1st quartile). Shifting construction away from single-family urban forms to neighbourhoods made up almost entirely of mid/high rise and/or low-rise multi-unit buildings reduces cumulative embodied emission by up to 57.5% (240 $MtCO_2e$) in the affordability growth scenario. By itself, 1st quartile best-in-class design can achieve cumulative reductions of up to 38.0% (158 $MtCO_2e$). Conversely, improvements in material technology and production, even when in line with government net-zero pledges, only have an up to 9.05% (37.8 $MtCO_2e$) cumulative reduction potential by 2030. Best-in-class design provides at least double the embodied emission reductions compared to material technology improvements in each urban form scenario.

If current construction practices continue, yearly A1 to A3 embodied emissions in 2030 exceed Canada's 2030 emission reduction target by 35.1% (3.26 $MtCO_2e$) and 376% (35.0 $MtCO_2e$) in the BAU growth and affordability growth scenarios, respectively (Figure 3b and 3c). Forecasts of yearly emissions in 2030 with affordability growth and without reductions strategies have an uncertain sample range between 44.0-44.7 $MtCO_2eq$, with a median value of 44.3 $MtCO_2e$. Figure 3b shows that reducing these emissions below the 2030 emission target requires all of the reduction strategies from Table 1: single-family urban form must be almost completely eliminated, material technology must be improved, all buildings must follow best-in-class designs, the infill rate must be nearly 100% and circularity must be doubled. Collectively these reduce future emissions 3.12 $MtCO_2eq$ below the target in 2030. Achieving sufficient reductions with BAU growth is much easier but would leave Canada's growing housing crisis unaddressed. Figure 3c shows that with BAU growth, a subset of reduction strategies or a single aggressive strategy, such as changing urban form or pursuing best-in-class design, is sufficient to reach the reduction target.

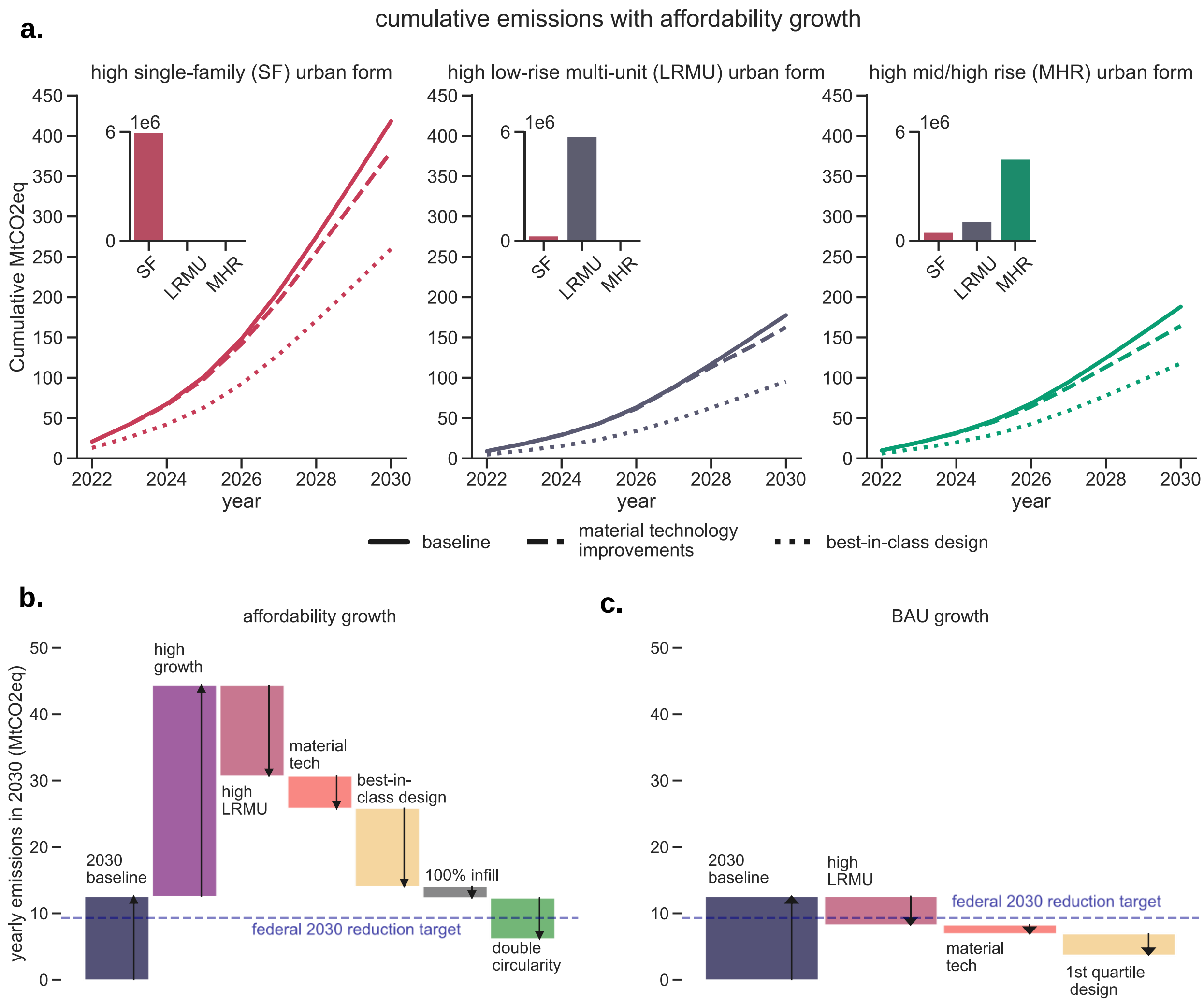

Figure 3: 2030 embodied emissions from neighbourhood construction and effect of embodied emission reduction strategies – **a.** Cumulative emissions in the affordability growth scenario simulated with different urban forms. The two dotted lines show the reduction potential of a single strategy: material technology improvements or best-in-class design. The embedded bar plot shows the total number of residential units built in the mix, broken down by single-family, low-rise multi-unit, and mid/high-rise houses. The bottom plots show median forecasted emissions in the year 2030 plotted against a linearly-downscaled federal budget. **b.** shows the reduction potential of strategies in the median affordability growth scenario. **c.** shows emissions in the median BAU growth scenario. The 2030 baseline is calculated by running the construction simulation with single-family, low-rise multi-unit, and mid/high-rise unit proportions equal to the historic ten-year average in each province. SI Figures 4.3-4.4 show the sampling uncertainty for these results.

Figure 4 further explores the sensitivity of infill and circularity savings from Figure 3a. When all other strategies are applied, the impact of changes in the circularity constant k increases as national infill rate increases. At the current national infill rate of 31%, increasing circularity from $k = 0.8$ to $k = 0.4$ results in 1.94 $MtCO_2eq$ yearly savings in 2030. At a double national infill rate of 62%, the shift from $k = 0.8$ to $k = 0.4$ results in 3.85 $MtCO_2eq$ yearly savings. Without increasing circularity of residential building construction, increasing infill rates have minimal savings potential, due to the order of magnitude difference between the embodied GHG of buildings and infrastructure in most neighbourhoods. FIG assumes a shift to 100% infill only eliminates construction of horizontal infrastructure, reducing yearly emissions by a maximum of 1.48 $MtCO_2eq$ without simultaneous increases in circularity. Accordingly, these approaches are complimentary. Other environmental impacts of infill development (e.g. reduction in driving distances and associated emissions) are outside the scope of this analysis.

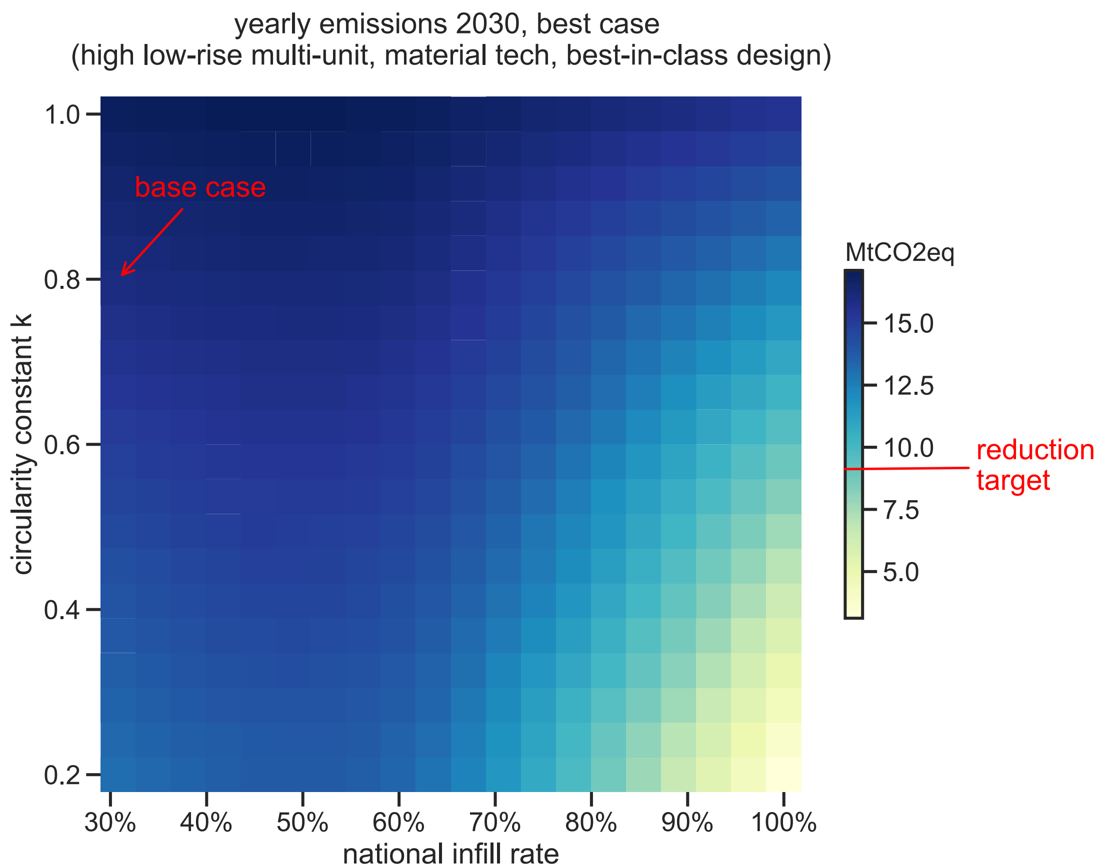

Figure 4 Circularity and infill sensitivity – Embodied emissions reductions analyzed for a range of infill and circularity strategies. The plot values show yearly emissions for 2030 when the other tested embodied emission reduction strategies have already been applied (high LRMU, improved material technology and best-in-class design as per Figure 3b). The "base case" denotes the assumption of infill rate and circularity factor for other forecasts in the Canadian case study (the bottom of the yellow bar in Figure 3b). The reduction target labels Canada's 2030 goal (same as Figure 3b/c).

The quantification above excludes ~15% [44] of emissions from A4-A5 lifecycle processes and up to ~20% [71] from building components not quantified in the input data (like mechanical, electrical, and plumbing) plus major infrastructure which is unevenly distributed between neighbourhoods (e.g. water treatment plants) (see SI section 1.4 for a full list of excluded elements) [44]. These exclusions are mostly proportional across forms (e.g. construction energy), and the inclusion of major infrastructure would reinforce the findings in results (e.g. more highways are built to serve lower density development than higher density). For example, within the affordability growth scenario where 5.8 million homes are constructed, adding 30% factors to the calculated A1-A3 numbers (to adjust for MEP, A4 and A5 exclusions) leads to an estimate of embodied emissions for housing and neighbourhood scale infrastructure of 94.2 MtCO2eq/year in 2030 if future housing construction is 100% single family homes (the worst case modelled). If current housing norms around building types, design, infill and circularity persist we estimate 57.6 $MtCO_2eq$ per year in 2030. In the best case modelled, where future housing construction is entirely in multi-unit buildings using best-in-class design with high infill rates and circularity, A1 to A5 emissions for housing and neighbourhood infrastructure is estimated at 8.04 $MtCO_2eq$ per year in 2030. Cumulatively each would lead to 544 $MtCO_2eq$ through 2030 in the worst case, 333 $MtCO_2eq$ if current norms continue and 70.9 $MtCO_2eq$ in the best case modelled. Major infrastructure would add further emissions on top of these estimates.

3.2.2 Geographic Variability

FIG supports regional analysis. In the Canada case study, each province samples only their respective DAs when modeling future growth, so the analysis captures variations in built form (and likely future form) between provinces. Figure 5 breaks down forecasted embodied emissions and the effect of urban form by province (smaller neighbouring provinces are grouped, e.g. Atlantic Canada). Increased embodied emissions are not evenly distributed across the country in the affordability growth scenario. Ontario sees the largest increase by far compared to BAU growth, with a maximum of 127 $MtCO_2eq$ additional cumulative emissions by 2030 (Figure 5b). Alberta sees only 1.41 $MtCO_2eq$ in cumulative emissions difference between the two growth scenarios due to very small differences in projected housing units between the scenarios.

The effectiveness of urban form as an embodied emissions reduction strategy also varies by province. Figure 5b compares changes in urban form to a base case where future construction has a similar urban form as historic construction within the province. Shifts towards low-rise multi-unit and mid/high rise urban forms have similar saving potential in most provinces, but some benefit less when switching to mid/high rise construction. Prince Edward Island and Saskatchewan specifically see a 6.85% and 8.65% increase in embodied emissions when shifting towards mid/high rise urban forms in the affordability growth scenario. Because there are so few mid/high rise buildings in these provinces (Prince Edward Island only has 120), and neighbourhoods with mid/high rise buildings tend to also have many single-family homes, a 'shift to mid/high rise' scenario actually results in the construction of a few mid/high rise buildings and many single-family buildings/neighbourhoods and associated infrastructure. These results are dependent the continued construction of low-density neighbourhoods forms within these rural provinces. To gain the GHG reduction advantages of mid/high rise buildings, Prince Edward Island and Saskatchewan will need to adopt neighbourhood forms extant in other Canadian provinces (e.g. narrower streets, denser, higher percentage of multi-unit buildings per neighbourhood).

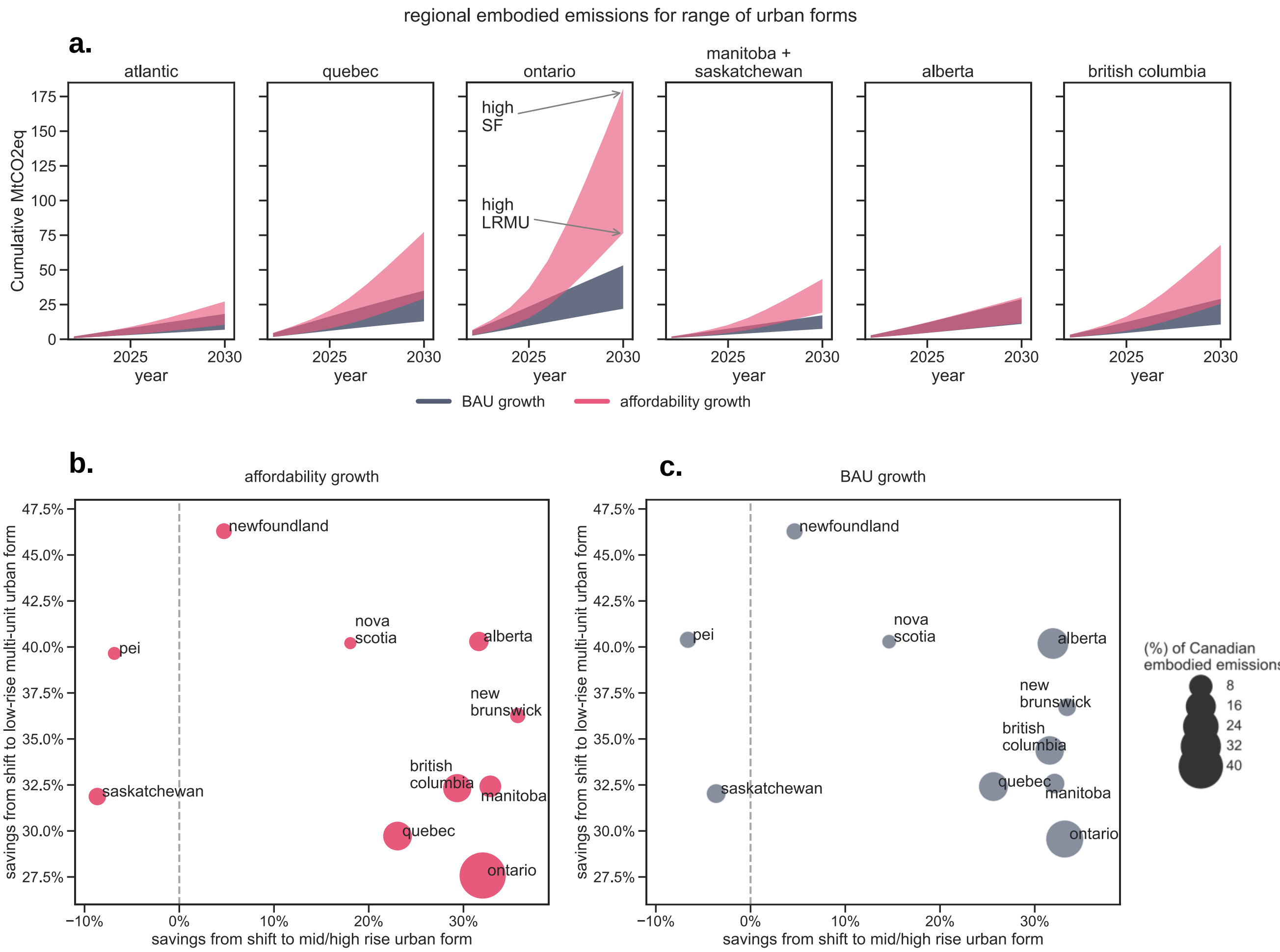

Figure 5 Geographic breakdown of future Canadian emissions – **a.** Cumulative embodied emissions by grouped regions in Canada under the two growth scenarios. The only strategy applied in this forecast is change in urban form. The top of the band shows high single-family (SF) construction, and the bottom shows high low-rise multi-unit (LRMU) construction. The bottom plots show effectiveness of urban form changes by province under **b.** affordability growth and **c.** BAU growth. Provinces like Saskatchewan and PEI would need to copy urban denser urban forms from other provinces to achieve form-related savings. Savings are calculated based on yearly embodied emissions in 2030. Each data point is sized based on its relative contribution to overall embodied emissions in their respective scenarios.

3.3. Net-zero under housing and infrastructure requirements to 2050

Beyond 2030, Canada has committed to achieving net-zero emissions by 2050. Achieving net-zero embodied emissions for construction materials requires large improvements in material production technology and large-scale deployment of carbon capture and storage [58]. SI Figure 4.6 shows three potential embodied emissions scenarios through 2050 in Canada forecasted using FIG. In the scenario where material technology and carbon capture are the only strategies employed and follow best-case, net-zero predictions [53], A1-A3 embodied emissions modelled by FIG reach zero by 2050, but yearly embodied emissions remain higher than if other strategies (changing urban form, best-in-class design, increased infill/circularity) were employed without technology improvements until 2036.

In a scenario where material technology and carbon capture is the only strategy employed embodied emissions associated with future housing and infrastructure construction becomes very sensitive to the timeline and scale of technology deployment (e.g. widescale deployment of carbon capture starting in 2030). If this technology is delayed or does not scale as planned, Canada sees growing embodied emissions from construction in 2050 – up to 18.8 $MtCO_2eq$ per year in 2050 if population growth is high. Employing other reduction strategies will be critical for delivering low embodied GHG housing and infrastructure as they can greatly reduce the risk of relying solely on material technology and carbon capture; combined use of the strategies from Figure 3b can decrease year embodied emissions in 2050 to as low as 0.595-3.15 $MtCO_2eq$ depending on population growth.

4. Discussion

4.1. Model-driven insights for neighbourhood-scale infrastructure systems

When applied in the Canadian case study, FIG highlights that business-as-usual construction methods and urban form norms in Canada are incompatible with meeting long-term climate goals. If enough housing is built by 2030 to restore affordability, using current approaches to form, infill and circularity will lead to a 376% (35.0 $MtCO_2e$ in 2030) increase in A1-A3 (or 45.5 $MtCO_2e$ when factoring to include MEP, A4 and A5) emissions above a proportional allocation of Canada GHG reduction commitments.

By calculating the embodied GHG of 57,932 DAs in Canada, the FIG model generates a large dataset of neighbourhood forms and their associated embodied GHG emissions. We find that housing form and design drive variance in embodied emissions at a neighbourhood level. Beyond just reducing the size of new homes [6,59,60] or extending the lifetime of existing ones [9,61], the difference between building single-family neighbourhoods using average design practices and building dense, multi-unit neighbourhoods with best-in-class designs (e.g. reducing substructure size [62], avoiding transfer slabs) can reduce cumulative embodied emissions by up to 77.2% in the affordability growth scenario without having to hedge on future technological changes. Savings from design choices are also conservative compared to what is technically possible; FIG uses the top 25% of existing building designs, which is not particularly strict and does not account for future improvements in design such as structural light weighting [63]. The results further previous work on the sustainability of different neighbourhood forms [64,65], showing that denser neighbourhood layouts have predictably lower (0.838-1.16 $kgCO_2eq/km^2$ less GHG for every person added) embodied emissions in houses, roads, and water infrastructure across Canada's varied geography. Embodied emissions savings from denser urban environments also coincide with reductions in transportation [66,67] and operational energy use and emissions [68–70] not modelled here.

Methodologically, FIG presents one of the first detailed bottom-up quantifications of embodied emissions in water infrastructure and introduces a machine-learning tool for predicting embodied emissions in neighbourhoods/regions where data on infrastructure is sparse. Critically, the model provides a new approach for projecting future housing and infrastructure growth based on combining existing neighbourhood forms with modern building and infrastructure material intensities and modern/future GHG factors. This is an effective method for capturing variability in neighbourhood forms that could be built in the future while retaining the detail of bottom-up modelling.

The embodied emissions quantified by FIG are a lower bound on actual future $kgCO_2eq$ of embodied emissions given housing and infrastructure growth. Bottom-up methods systematically underestimate emissions because they exclude the quantification of some elements and lifecycle processes. FIG quantification in the Canadian case study does not include some infrastructure elements, such as mechanical, electrical, and plumbing in buildings or service lines in water infrastructure – though this is only a limit of the case study as the FIG model could account for these elements if given bottom-up data. Due to the focus on new construction, embodied emissions are quantified for cradle-to-gate (A1-A3) lifecycle stages and do not include later life stages, though again this can be included in FIG with the appropriate baseline data. Some major infrastructure like large highways and water treatment facilities are excluded from forecasted emissions due to the focus on residential emissions and the one-off/few-off nature of major infrastructure.

4.2. Reduction strategies for achieving both adequate housing and emission goals

The effectiveness of the analyzed embodied emission reduction strategies is highly dependent on growth scenarios and the time of deployment. In 2030, the potential for reductions via improvements in material production and technology is lower than the reduction required for Canada's 2030 target with both BAU and affordability growth. Achieving this target requires relying more on non-technology strategies like shifting away from single-family neighbourhood construction, building best-in-class designs, and providing new housing units using infill construction that reuses/maintains existing housing stock and materials.

While there is near-term potential for form and design optimization to greatly reduce cumulative embodied emissions in high-growth scenarios, getting new construction to net-zero will ultimately rely on some large-scale deployment of new materials technology and production improvements (e.g. carbon capture) before 2050. Without these technologies, the model forecasts a mitigation gap of ~0.5-9 $MtCO_2eq$ embodied per year regardless of the growth scenario. Other construction of infrastructure and buildings not addressed here, such as commercial buildings, major infrastructure projects, investment demand for housing, and major renovations, will add further emissions over the coming decades. At the same time, major construction materials are persistently difficult to decarbonize [58]. As shown by FIG, reliance on the emergence of new material technologies and carbon capture [72] to reduce emissions from materials can lead to pathways with higher and potentially growing embodied emissions in 2050 compared to scenarios where a suite of strategies is deployed. Employing many reduction strategies reduces the risk of relying on future material technology and carbon capture scaling.

Given the results of the FIG-Canada forecasts, it will be difficult to meet the demand for housing and infrastructure while also reducing embodied emissions in line with promised reductions goals, even with the aggressive implementation of multiple strategies. The increase in housing supply required to address affordability makes meeting sustainability goals challenging. A decrease in demand for new construction and the associated embodied emissions by 2050 is unlikely in Canada and other countries with similar growing population trends [73,74]. Changes at the neighbourhood, building and materials scale are critical to a sustainable future. This will require culturally challenging changes, such as shifting away from the construction of single-family neighbourhoods. It also challenges design and construction practitioners to immediately move towards only designing and building best-in-class buildings and urban forms.

There are variables and policies which would increase the likelihood of achieving emission reduction commitments under high growth scenarios outside of choices on how to build housing and supporting infrastructure. Delaying increases in housing production would result in more housing and infrastructure built in the future using better material technologies (assuming material technology improve as projected), though it would exacerbate the ongoing housing affordability crisis. Greater-than-expected emission reductions in other sectors (e.g. transportation, energy) could give the construction sector a greater share of the overall sectoral carbon budget on the way to net-zero [13]. Demand-side changes, such as increasing average household size (which has been studied previously [59] and is explore briefly in SI section 4.2), reducing floor space per capita (e.g. by building smaller homes) [75], extending the lifetime of housing units that would otherwise come off the market, or reducing in the demand for second homes and housing as an investment [15] , could lower the total demand for housing supply and associated embodied emissions required to achieve affordability. Overall, the social need for housing and related infrastructure and the need to reduce embodied emissions for sustainability goals are two closely-linked problems that will require careful choices around what we build and how we build it.

5. Conclusions

This paper presented a new model for calculating future embodied emissions due to housing and supporting infrastructure construction at the neighbourhood scale, and it analyzed strategies for reducing future embodied emissions while still meeting demand for housing. It introduced the bottom-up FIG model, which captures variability in house and infrastructure design across an entire country at a detailed level. As a case study, we applied the model to Canada in order to analyze embodied emissions through 2030 and 2050.

In Canada, residential buildings have on average one and two orders of magnitude more embodied emissions per capita at a neighbourhood level compared to roads and water infrastructure, respectively. The percentage of single-family homes in a neighbourhood is a significant and strong (R^2 = 0.81-0.87, p = 0.00) predictor of higher embodied emissions in all infrastructure systems, and dense neighbourhoods made up almost entirely of low-rise multi-unit or mid/high rise buildings had 56.8% less (19600kgCO_2eq/person) embodied emissions than single-family neighbourhoods.

The model found that if Canada were to build enough housing to restore affordability using current construction norms, it would exceed its 2030 emission reduction commitment by 376%. Shifting away from single-family urban forms, designing best-in-class residential buildings, and increasing the circularity of construction were found to have high emission reduction potential (38.0-57.5%) this decade. These strategies were more effective through 2030 than improvements in material product and technology, which had minimal reduction potential (9.05%). Between 2030 and 2050, rapid decreases in projected GHG intensity of materials lead to increasing savings as long as CCS and manufacturing improvements scale up in the 2030s.

In the meantime, reaching Canada's reduction targets by 2030 will require ambitious roll out of a mix of strategies, including a rapid shift to multi-family buildings for nearly all new housing, top quartile or better design of new buildings, near 100% infill rates and doubling circularity in parallel with material GHG intensity improvements. By 2050, achieving net-zero embodied emissions from new construction in Canada is not possible without large reduction in emissions from the manufacturing of materials (e.g. through carbon capture and storage); however, relying largely on these technologies to reduce the emissions burden from new housing is risky as it could lead to growing embodied emissions from new construction in 2050 if optimistic technological improvements are not achieved.

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Author contributions: K.H.R. and S.S. conceptualized research, developed the methodology, created scenarios, validated results, and wrote the paper. K.H.R. collected and cleaned data, coded the model, and created visualizations.

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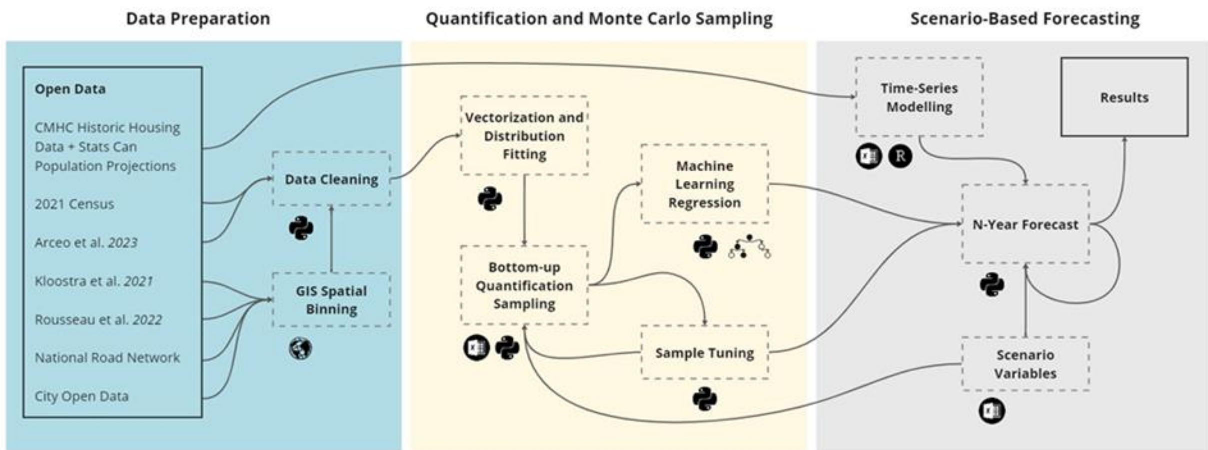
Supporting Information

1. **Future Infrastructure Growth Model Details**

SI Figure 1.1 below presents a high-level overview of the FIG model and its computational components, which are expanded on in the next three sections (1.1-1.3).



SI Figure 1. 1 Future infrastructure growth model overview – the three major steps of the model are bounded by different colours. Icons denote the software used in different parts of the model (Python 3.9 with machine-learning extensions, ArcGIS, Excel, and R programming language).

1.1 Housing, road, and water infrastructure quantification details

We sourced housing quantifications from a public dataset developed in previous studies [40,41] which used material quantification software to determine the material volume and mass in residential buildings to Masterformat and Uniformat level 5 detail [76,77]. The dataset contains material quantities and embodied emissions for 102 North American residential buildings of varying forms that are used as inputs to the FIG model. The embodied emissions in each residential building are normalized by the number of housing units in the building. Full details on residential building quantification are too extensive to include in this SI and can be found in the cited studies. One limitation of the public dataset is that only three residential mid/high rise buildings are fully quantified. The remaining buildings only have data for concrete and steel emissions and are missing other wood, masonry and architectural elements quantified in the other buildings. A linear regression (shown in Equation S1.1) based on the embodied emissions from concrete per floor ($\boldsymbol{CF}$) is fit to the fully quantified buildings and used to estimate the unquantified architectural and structural embodied ($\boldsymbol{G}_{highrise}$) emissions in the remaining buildings:

$$\boldsymbol{G}_{highrise} = 4.1568\boldsymbol{CF} + 3.392 * 10^3 \quad \text{(S1.1)}$$

Canadian census data counts and classifies every dwelling units in the country into six forms: single detached, semi detached, rowhouses, plexes, low-rise apartments, and high-rise apartments. Each dwelling unit was drawn from a distribution of embodied emissions per unit values from their corresponding form in the dataset during the sampling process (see SI section

1.2), and then multiplied by the number of dwelling units to get embodied housing emissions, $\boldsymbol{G}_{houses}$. Put simply in Equation S1.2:

$$\boldsymbol{G}_{houses} = \boldsymbol{g}_{\boldsymbol{\omega}}\boldsymbol{U} \quad \text{(S1.2)}$$

Where g is the embodied emissions per housing unit of form *ω* and *U* is a vector of housing units of the corresponding form. The model performed calculations of house, road and water embodied emissions using elementwise operations on vectorized input data for each province in Canada (hence the bold highlighting of vector variables in the previous and following equations).

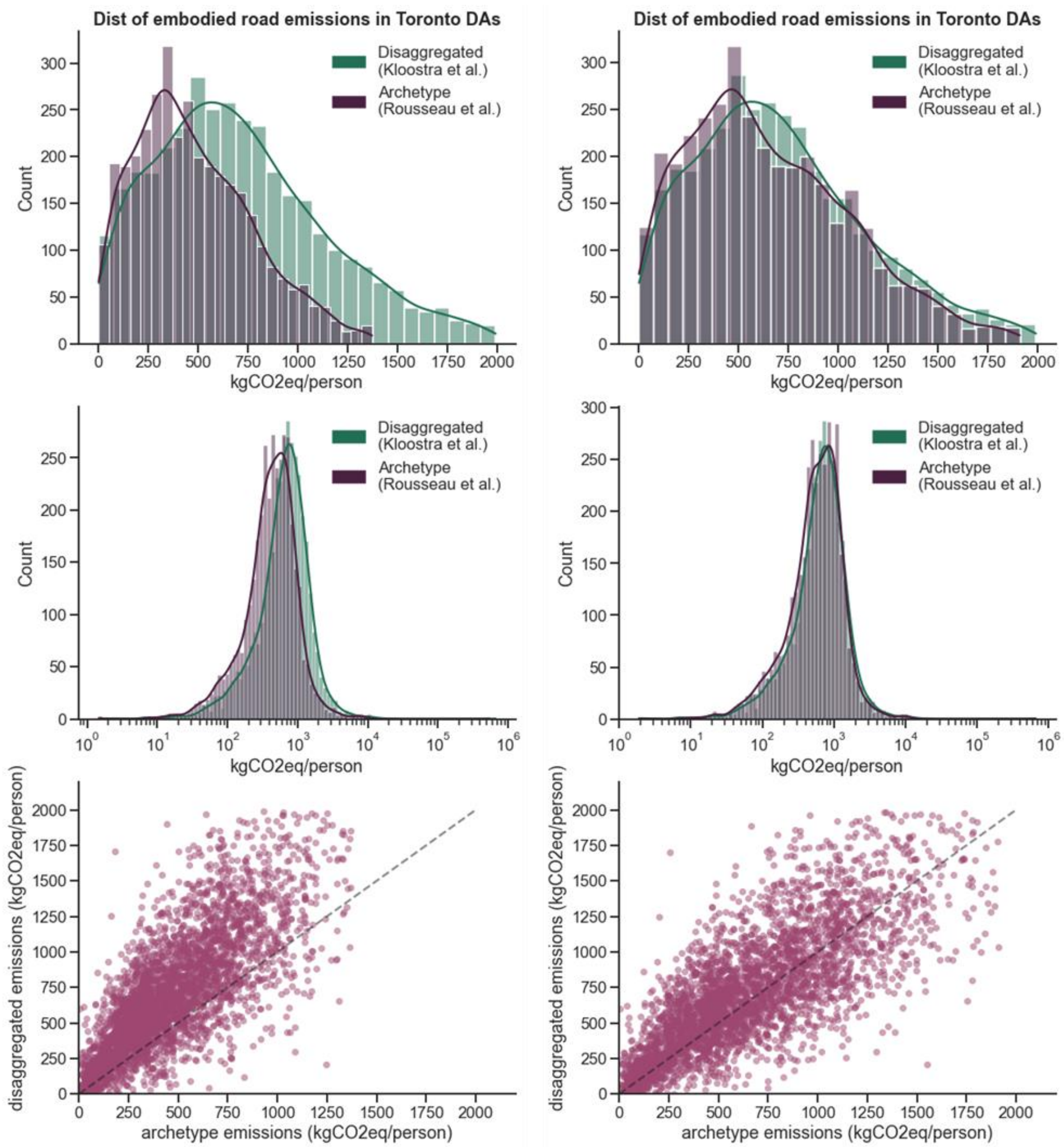
Equation S1.3 shows the formula used to quantify material mass *M* of every road for a given road class *r* and material type *m*:

$$\boldsymbol{M}_{r,m} = \boldsymbol{t}_{r,m}\boldsymbol{w}_{r}\boldsymbol{ln} * \rho_{m} \quad \text{(S1.3)}$$

Where *t* is thickness, *w* is width, and *l* is length in metres; *n* is number of lanes; and *ρ* is material density. Material mass is converted to embodied emissions *G* by multiplying by emission factor *f* (Equation S1.4):

$$\boldsymbol{G}_{roads,\ r} = \boldsymbol{M}_{r,m} * f_{m} \quad \text{(S1.4)}$$

The quantification method came from a published study [78] which used the GRIP [79] dataset and road classes in combination with Canadian highway design standards to determine the width and thickness of different materials based on whether on a given road's class (e.g. primary, secondary, freeway) and whether it used rigid (concrete) or flexible (asphalt) pavement. The model mapped the GRIP road classes from the previous study to road classes in the Canadian National Road Network dataset used in this chapter, which supplied lane counts and road lengths. To make the road quantification more location-specific and reduce bias in the thicknesses and widths chosen in the previous study, the model tuned the road classifications to match our results to a more detailed bottom-up study of embodied road emissions in the city of Toronto, Canada [80]. The thickness and width of each road class were varied until the outputs of the FIG model in Toronto matched those of the detailed study (see SI Figure 1.2). These new thicknesses and widths were used going forward.



SI Figure 1. 2 Visualizing the tuning procedure for the road quantification – the three plots on the left show the results in Toronto when using thicknesses and widths from the previous study. The three plots on the right show the results after inputs were tuned to the disaggregated, detailed quantification of Toronto.

Equation S1.3-S1.7 show the procedure used to calculate embodied emissions *G* in water infrastructure for all census regions where data was available. Water infrastructure is split into three components: watermains, stormwater, and sewer (or combined stormwater-sewer when present). For a given pipe *p*:

$$\boldsymbol{G}_{water} = (\boldsymbol{M}_{mains} + \boldsymbol{M}_{storm} + \boldsymbol{M}_{sewer})\boldsymbol{f} \tag{S1.5}$$

Where,

$$\boldsymbol{M}_{mains} = \boldsymbol{M}_g \tag{S1.6}$$

$$\boldsymbol{M}_{sewer} = \boldsymbol{M}_g \tag{S1.7}$$

$$\boldsymbol{M}_{storm} = \boldsymbol{M}_g + \boldsymbol{V}_{catch} * \rho_{catch} \tag{S1.8}$$

$$\boldsymbol{M}_g = \begin{cases} \left(\frac{\boldsymbol{d_p}}{2}^2 - \frac{\boldsymbol{d_{po}}}{2}^2\right)\pi \boldsymbol{l}_p \boldsymbol{n}_p * \rho_m \;\; if\ circular \\ (\boldsymbol{L_o} - \boldsymbol{L_i})(\boldsymbol{w_o} - \boldsymbol{w_i})\boldsymbol{l}_p \boldsymbol{n}_p * \rho_m \;\; if\ rectangular \end{cases} \tag{S1.9}$$

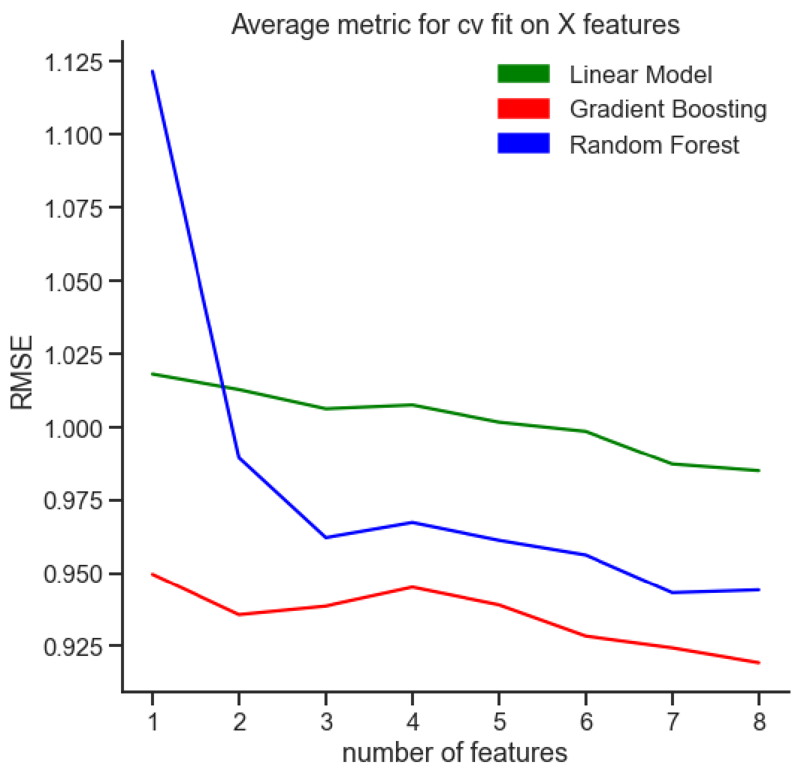
Equation S1.7 represents a volume calculation for a hollow pipe, where *d* is diameter, *L* is cross-section length, *w* is cross-section width, *l* Is pipe length, *n* is the number of pipes, ρ is material density, and *f* is matrix map of emission factor for any given pipe material. The material mass of watermains and sewers are simply the pipe mass M_g, whereas the stormwater system has the addition of reinforced concrete catch basins, which are quantified using standard designs [81].

We collected water infrastructure data for 7 different municipalities in the province of Ontario: Brampton, Mississauga, Kingston, London, Durham, Kitchener, and Waterloo [82–89]. The model cleaned, standardized, and combined open datasets maintained by the municipalities into a single data table for input into the above equations. When the thickness or diameter of a pipe was unknown, the model imputed the median thickness or diameter of pipes with the same material. When material was unknown, the model assigned the most common material for the given pipe in the city (Polyvinyl Chloride in most cases).

The FIG model uses a random forest regression to predict the embodied emissions of water infrastructure outside of the 7 cities. The random forest model was compared with gradient boosting and linear regression models in training. Though the gradient boosting model outperformed the random forest in cross validation (see SI Figure 1.3), the random forest regression generalized better on the test set after random-search hyperparameter tuning and a further qualitative analysis of predictions to the city of Toronto. Six features were chosen from cross validation: population density, secondary road length in metres, primary road length in metres, number of primary lanes, number of mid/high rise buildings per capita, and number of single-family homes per capita. Many of the road features have skewed, long-tailed distributions, and some parameter values may be zero, so the regression transformed features using a hyperbolic sine function. The regression achieved an R^2 value of just over 0.3 on the test set. Model hyperparameters chosen using random search are summarized in SI Table 1.1. The random forest was fit at model runtime.

SI Table 1. 1 Hyperparameter values for water infrastructure random forest regression

Hyper-parameter	**Value**
Split criterion	Friedman mean square error
Maximum tree depth	None
Minimum samples to split	2
Minimum samples for leaf	4
Maximum features for split	6
Max samples for bootstrap	87.8% of total
# Of decision tree estimators	1000



SI Figure 1. 3 Cross validation results for water infrastructure machine learning regression – the vertical axis shows the machine learning model’s average root mean square error of cross validation for the number of features on the horizontal axis. Cross validation was completed using k folds. Given that input data corresponds to a given neighbourhood, cross validation is essentially a spatial CV that accounts for geographic correlation.

The final embodied emissions for some given census area *s* are calculated in Equation S1.10 as the sum of the emissions in the three quantified infrastructure systems:

$$\boldsymbol{G}_s = \boldsymbol{G}_{houses} + \boldsymbol{G}_{roads} + \boldsymbol{G}_{water} \tag{S1.10}$$

1.2 Monte Carlo sampling procedure and sample size experiment

The FIG model uses Monte Carlo sampling to propagate uncertainty through the quantification of embodied emissions in infrastructure. SI Table 1.2 organizes each input variable from the quantification procedure described in SI section 1.1, along with the distribution type (if the input data was uncertain) and data source used in the Canadian case study.

To avoid infinite and negative values in our samples, the model fit uncertain variables to three bounded distributions: the PERT risk (modified beta or smooth triangular) distribution, the triangular distribution, and the uniform (uninformative) distribution. If possible, distributions were chosen based on previous studies and data sources (e.g. GHG emission factors were taken to be PERT distributed from Arceo et al.). The FIG model has a built-in distribution fitting procedure for distributions not specified in previous studies [38]. The model fits the data to each of the three bounded distributions using maximum likelihood estimation (MLE). It then puts these candidate distributions through a Kolmogorov–Smirnov test, and the distribution which minimizes the test p-value is chosen. Equations S1.11-S1.14 describe this process mathematically given a distributions probability density function *f(x)* defined by parameters θ in parameter space Θ:

$$\mathcal{L}_n(\theta|x) = f_n(x|\theta) \tag{S1.11}$$

For each candidate distributions f_n:

$$\hat{\theta} = \underset{\theta \in \Theta}{arg\ max}\, \mathcal{L}_n(\theta|x) \tag{S1.12}$$

Take candidate distribution with largest K_n given:

$$K_n = \sup_x \left|F_n(x) - F\left(x\middle|\hat{\theta}\right)\right| \tag{S1.13}$$

$$F_n(x) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{S1.14}$$

For dataset *x* with *n* independent and identically distributed samples. The fitting procedure has a fail-safe: if the MLE fails to converge, or if the number of observations is below a certain threshold, the data is automatically fit to a uniform distribution. The distribution-fitting procedure is performed at runtime to dynamically update samples if input data is modified. The only exception to the use of the three bounded distributions is the assumption of flexible vs. rigid pavement. The quantification method for Canadian roads assumed 100% of local roads used flexible pavement, with 68% of remaining roads being flexible [78,90]. When the pavement type of a road was not given in the data, the model sampled non-local roads from a Binomial distribution fit to the 68% assumption.

SI Table 1. 2 Quantification variables, distributions, and source

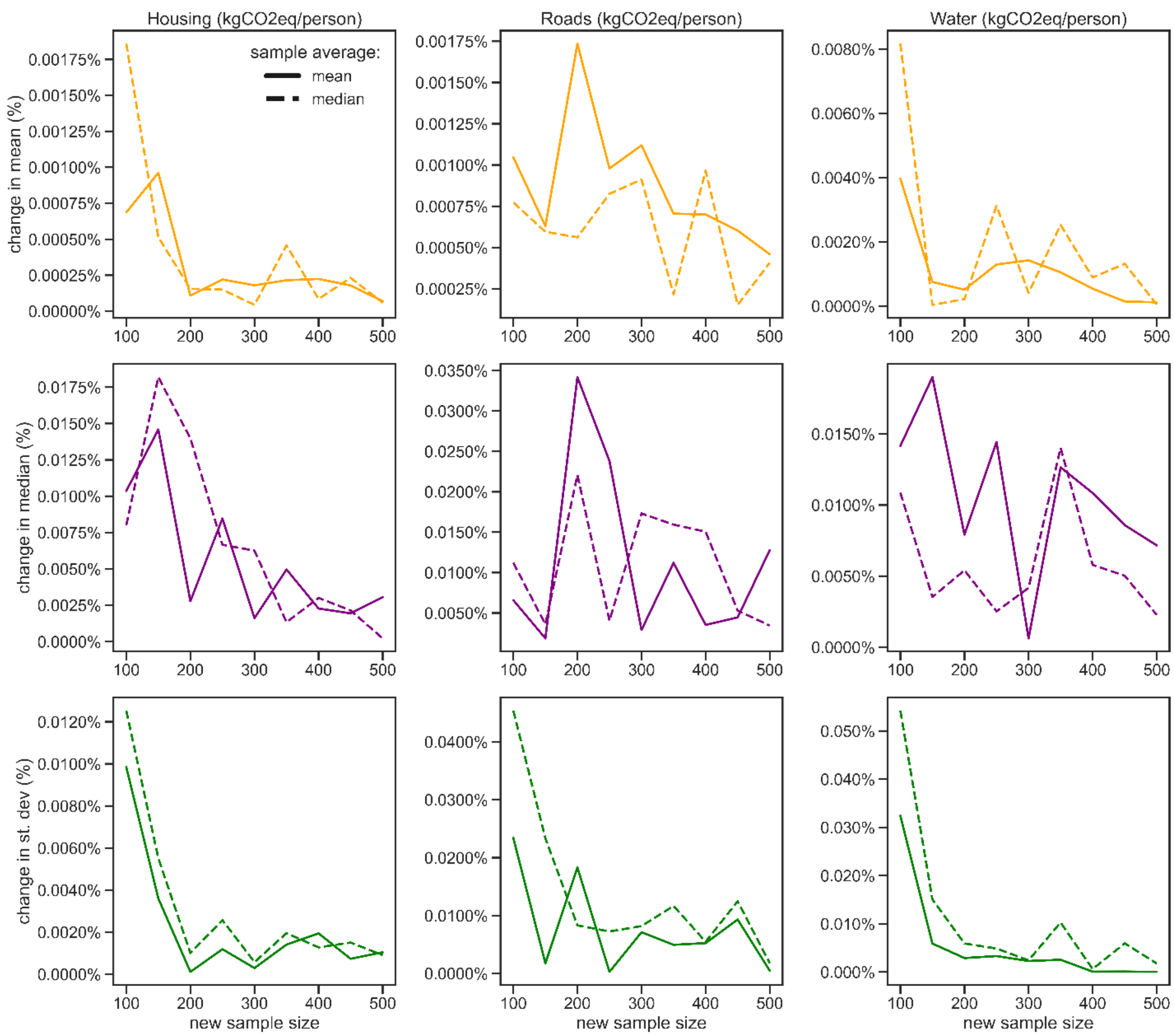
Quantification variable (symbol)	Distribution/value	Input source
Houses:		
GHG emission factors (f)	Absolute or pert	Arceo et al 2023 [62]
Number and type of residential dwelling units in a neighbourhood (u)	Absolute	Statistics Canada 2022b [57]
Embodied emissions per unit for any given residential building of some form in a neighbourhood (g_ω)	Variable (FIG fitting procedure)	Arceo et al. 2020 [40]
Roads:		
Road class	Absolute	Statistics Canada 2022d [42]
Number of lanes (n)	Absolute	Statistics Canada 2022d [42]
Lane width ($w_{r,m}$)	Uniform (dependent on road class, pavement type)	Rousseau et al. 2022a [78]
Material thickness ($t_{r,m}$)	Uniform (dependent on road class, pavement type)	Rousseau et al. 2022a [78]
Material density (ρ_m)	Absolute	Circular Ecology 2019 [43]
GHG emission factors (f_m)	Pert/uniform	Arceo et al. 2020, Rousseau et al 20221a [40,78]
Unknown, non-local road pavement type	Binomial (p=0.68)	EAPA and NAPA 2011 [90]
Water:		

Pipe material volume parameters (n, d, l, n, l)	Absolute	7 Ontario Cities
Catch basin depth (component of v_{catch})	Discrete uniform with values: 1980mm, 1830mm, 1520mm, 1380mm, 1680mm	The Road Authority 2019 [81]
Other catch basin parameters	Absolute	The Road Authority 2019 [81]
Material density (ρ_m)	Absolute	Circular Ecology [43]
Ghg emission factors (f)	Pert	Arceo et al 2020, Circular Ecology 2019[40,43]

The Monte Carlo simulation is applied to equations from SI section 1.1 in order to produce samples from some empirical distribution ψ. Mathematically, this means that every sample from the model is derived from the distribution described in Equation S1.11 – a probabilistic form of Equation S1.15:

$$\psi(\boldsymbol{G}_s) = \psi(\boldsymbol{G}_{houses}) + \psi(\boldsymbol{G}_{roads}) + \psi(\boldsymbol{G}_{water}) \qquad (S1.15)$$

A sampling experiment was performed in order to determine reasonable sample sizes required for the Monte Carlo simulation. The experiment used the baseline embodied emissions per capita of every neighbourhood in Canada. At every step, the experiment increased the sample size by 50, took the average sample (both mean and median) for each neighbourhood, and then calculated the percent difference in summary statistics (mean, median, and standard deviation) off all Canadian neighbourhoods compared to the previous sample size. SI Figure 1.4 shows the results. Percent change is quite low due to the large sample size, with the largest value observed being a 0.05% change in the standard deviation of embodied emissions in water infrastructure when increasing the sample size from 50 to 100. Also, some of the results seem to suggest a plateau in the decrease of percent change around the change from 150 to 200 samples. The mean and median sample have similar percent differences, indicating robustness to outliers. To get best results from the simulation, the analyses in the main text uses 500 Monte Carlo samples for figures and median results wherever possible. In more sample-intensive analysis such as the 2050 forecast with material reductions (which requires new samples for each year that emission factors are reduced), The model used 50-100 samples.



SI Figure 1. 4 Monte Carlo sampling experiment results – the horizontal axis value denotes the sample size being compare its sample size less 50.

1.3 *Forecasting construction and embodied emissions*

The final embodied emissions for each year and the overall embodied emissions for a simulation is found by summing up the emissions in the census areas built to meet the future construction growth. Given $b_{p,y}$ is the number of houses to be built in province p in year y, then the construction forecast proceeds as follows for each Monte Carlo run from SI section 1.2:

Sample n neighbourhoods from the set of census areas A_{census} according to some prior (we base the initial sample off the average number of houses per DA in a province). Also extract the embodied emissions $g_{p,y}$ as per Equation S1.16.

$$\{A_{census}\} \xrightarrow{n} b_{p,y}\,,g_{p,y} \qquad (S1.16)$$

If $b_{p,y}$ is not within the set tolerance (±1000), sample or drop some number of neighbourhoods (we found 5 neighbourhoods to be a reasonable value for this hyper parameter).

Determine the total embodied emissions at the end of the simulation by summing $g_{p,y}$ according to Equation S1.17.

$$G_{p,total} = \sum_{y=0}^{x} g_y \tag{S1.17}$$

1.4 Model exclusions and comparison with top-down methodology

Below is a list of all infrastructure elements and life-cycle processes that the current iteration of the Canadian run of the FIG model excludes (and other assumptions made). The FIG framework theoretically allows for the addition of these missing elements; this chapter mainly makes these omissions due to data constraints and time feasibility.

- Housing elements: the public housing dataset excludes some elements, such as structural connections and landscaping elements; see the dataset and related papers for a comprehensive list of exclusions [40,41]. The Canadian case study does not consider temporary or "other" dwellings [57], which make up a small part of Canada's housing stock.
- Road elements: does not include bridges or other interchange structures. Does not include unusually large granular fill. The forecasts for the Canadian case study include only local infrastructure, not major highways or interchanges outside of residential/urban areas. Does not include signage.
- Water elements: does not include major water infrastructure like large water treatment plants. Does not include sidings that connect houses to watermains, fire hydrants, grates, or manholes.
- Emission factors: does not include construction energy use or end of life emissions (A1-A3 life cycle stages only [24]). Biogenic carbon quantification follows the 0/0 approach [31].
- Renovations outside of unit count conversions: the current FIG framework does not account for maintenance of new or existing infrastructure.
- Other infrastructure: Due to the focus on housing, the current version of the FIG model does not include commercial buildings, industrial buildings, rail infrastructure, energy infrastructure, oil & gas, etc.

The Canadian case study specifically excludes future forecasting of housing infrastructure in Yukon, Nunavut and the Northwest Territories. The Canadian Housing and Mortgage Corporation lacks future construction data for these territories [27], and FIG's housing and GHG factor data is probably not representative of construction materials used in Northern/Arctic Canadian climate.

The Canadian case study results from the FIG model were compared to downscaled, top-down sectoral emissions calculated using an environmentally-extended input-output (EEIO) model [91].

This comparison found that the results from FIG were 15% than the EEIO model results (as expected from bottom-up modelling), depending on what was defined as the residential construction sector.

2. Reduction Strategy Details

2.1 Low embodied emissions building design

This strategy limited the data samples used to fit the embodied emissions per unit distribution for each of the housing forms defined by in Canadian census (single-detached, semi-detached, rowhouses, plexes, low-rise apartments, and high-rise apartments) [92] to quantified houses in lowest quartile of $kgCO_2eq$/unit (described in Equation S2.1; the model uses data only up to rank-ordered index *j* for the dataset with length *n*):

$$j \leq \frac{1}{4}(n+1) \tag{S2.1}$$

The 1st quartile is chosen because it represents a change in building design which could be adopted quickly, and because some forms of housing have limited sample sizes (particularly in rowhouses and plexes). Choosing housing only in the 10th quantile or below had little marginal reductions compared to the 1st quartile, likely due to these limited sample sizes. More data could identify further potential savings from existing design variation.

2.2 Changing future housing form

Limiting of construction to only certain neighbourhood forms worked similarly to the limits on building design choices. For forecasted scenarios labelled "high single-family" (see main text Figure 2), for example, neighbourhoods built in the simulation were limited to those in 95th quantile (replace ¼ with 0.95 in Equation S2.1) of percentage of homes in that neighbourhood being single family. This method was chosen over simply picking a certain housing mix because some more rural provinces have different housing profiles than the more urban ones. Provinces like Prince Edward Island have few to no mid/high rise buildings, and it would be unlikely to see neighbourhoods with the density of Canada's large cities to be built in this region by 2030. Neighbourhood construction is therefore limited to the housing mixes of each individual province.

2.3 Infill construction and circularity constant

The embodied emissions of neighbourhoods sampled for infill construction are modified according to Equation S2.2:

$$G_s = k * G_{houses} + 0 * (G_{roads} + G_{water}) \tag{S2.2}$$

The circularity constant *k* is set to a value of 0.8 for results outside of the sensitivity analysis in the main text. This value was chosen using engineering judgement based on our knowledge of construction in Canada and the rarity of *k* values near zero (which would imply adding infill housing units with very little new materials) and a k value of one (all infill construction being completely new, which is known to not be the case from city development applications).

Some assumptions are also made when determining the infill rate for each province. SI Table 2.1 summarizes the infill rates used in the different forecast scenarios. There is minimal information of infill rates in provinces outside of Ontario (the most populace province in Canada and the area where the most future growth is predicted by Canada's National Housing Corporation). Infill percentages in cities around Ontario were determined using municipal data and provincial legislation [93–97], and then historic census construction data was used to calculate an overall 35% infill rate for the province. The two other most populated and densely built provinces – Quebec and British Columbia – were assumed to have the same infill rate, and the remaining, less-dense provinces were assumed to have half of Ontario's infill rate. These assumptions resulted in a 30.8% national average infill rate in the baseline results. While this infill rate has a high degree of uncertainty, it should be noted that the main text Figure 4 shows that results do not vary significantly at the assumed k value unless the national infill rate is more than doubled.

SI Table 2. 1 Infill rate for provinces in different projection scenarios

Provinces	**Baseline Scenarios** (historic infill rate)	**Scenarios with increased infill** (doubled historic rate)
Newfoundland, Nova Scotia, Prince Edward Island, Manitoba, Saskatchewan, Alberta	17.5%	35%
Ontario, Quebec, British Columbia	35%	70%

2.4 Material technology and production improvements

Yearly reductions in the material emission factors come from literature. The analysis assumed specific reductions for five major materials: concrete, steel, asphalt, PVC/plastics, lumber, and insulation and assumed reductions for other materials from an industry-scale study [25,47–53]. Sources generally split material reductions into two parts: reductions to 2030, and reductions from 2031 to 2050. Broad studies generally assume near-linear reductions in material production emissions until 2030. Studies looking at emissions after 2030 project rapidly decaying emissions towards net zero in 2050. Some materials have more short-term emissions reduction potential than others. For example, multiple studies project a 25% decrease in concrete and cement production emissions by 2030, whereas the plastics industry has very little short-term reduction potential. The analysis assumed linear reductions to 2030 for all materials, and fit 2031-2050 reductions to the exponential decay formula in Equations S2.3-S2.5:

$$f(x) = c + \theta_1 e^{-\theta_2 x} \tag{S2.3}$$

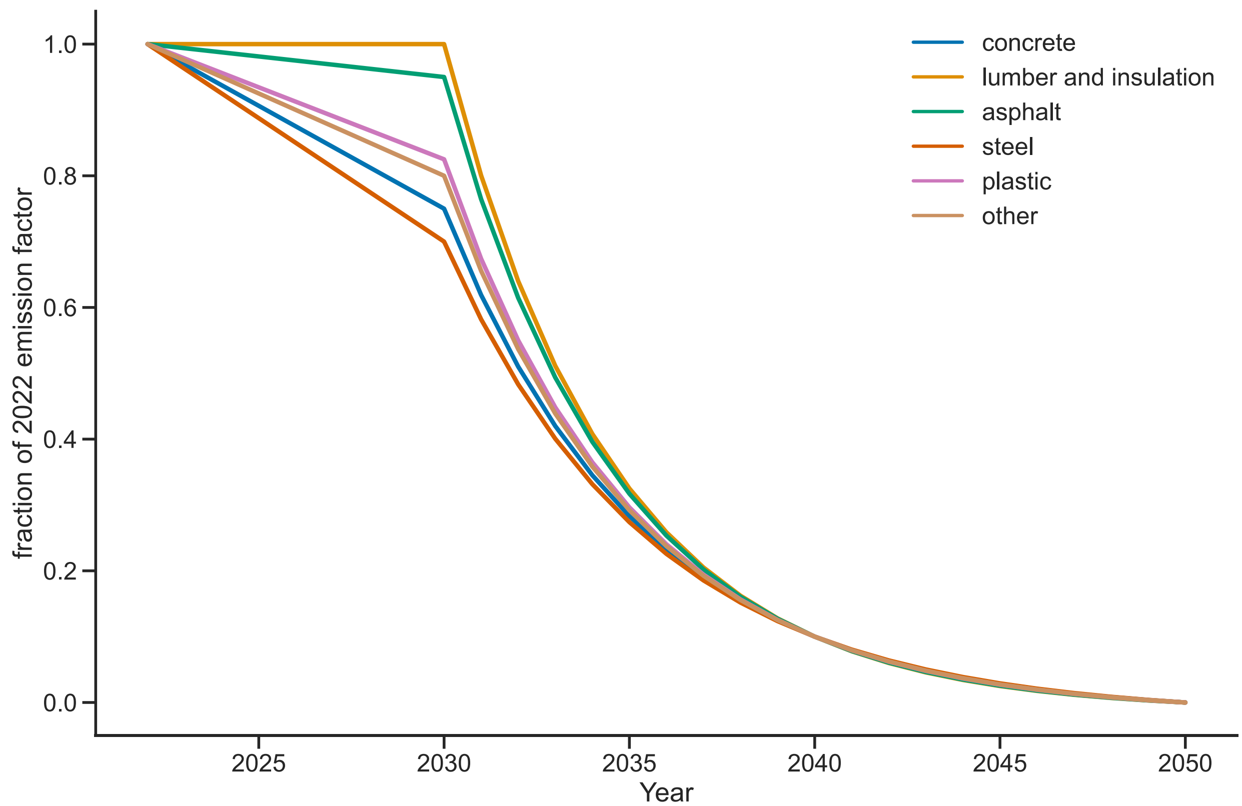
Subject to constraints,

$$f(2030) = rm_{2030} \tag{S2.4}$$

$$f(2040) = 0.1 \tag{S2.5}$$

Where rm_{2030} is the percentage reduction applied to a given materials emission factor in 2030. SI Figure 2.1 plots the reduction percentage for each material. Remaining assumptions are below:

- Assumed the steel industry continues to reduce production emissions at the rate they did between 1990 and 2020 [51].
- Assumed lumber and insulation producers achieve insignificant reductions until 2030. There are few-if-any comprehensive emission reduction plans for these industries.



SI Figure 2. 1 Reduction in material emission factors over time

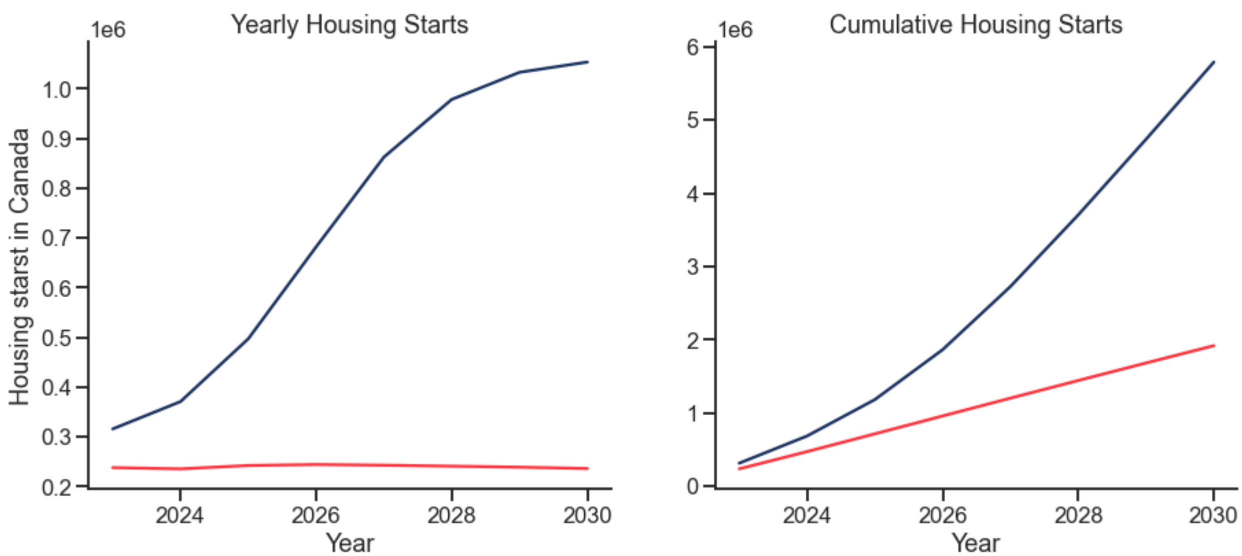
3. Future Construction Projections

3.1 Short-term: business-as-usual and affordability growth

The analysis derived construction of houses in the BAU and affordability growth scenarios from a recent Canadian Mortgage and Housing Corporation report [27]. The CMHC gives time-series projections for BAU construction, but only provides aggregate extra units required for affordability. The analysis assumed these extra units start getting added in 2023 and that construction grows logistically in every province until 2030, according to Equation S3.1:

$$\int_{2023}^{2030} \frac{L_p}{1 + e^{-k_p(t-c_p)}} = b_p + \delta_p \tag{S3.1}$$

Where t is time in years, b is BAU, δ is additionally units for affordability, and L, k, c are function parameters specific to province p. SI Figure 3.1 shows national-housing growth as a result of this assumption.



SI Figure 3. 1 Business-as-usual (red) and high-housing growth (blue) that restores affordability by 2030.

3.2 Long-term growth based on population projections

The analysis estimated housing construction past 2030 by assuming housing growth proportional to Canada's population according to Equation S3.2:

$$S_y = \frac{pp_{y,s}}{HF_{2021}} \tag{S3.2}$$

Where S is the number of housing starts in year y, pp is the yearly projected population growth in scenario s, and HF is the average household formation rate (number of residents per housing unit) for the given province from the 2021 census. The government of Canada forecasts 10 separate population growth scenarios generally categorized under low, medium, and high growth [56]. In growth scenarios where the population decreases (which happens in some provinces but never at an aggregated national level), the analysis assumes no new housing is constructed.

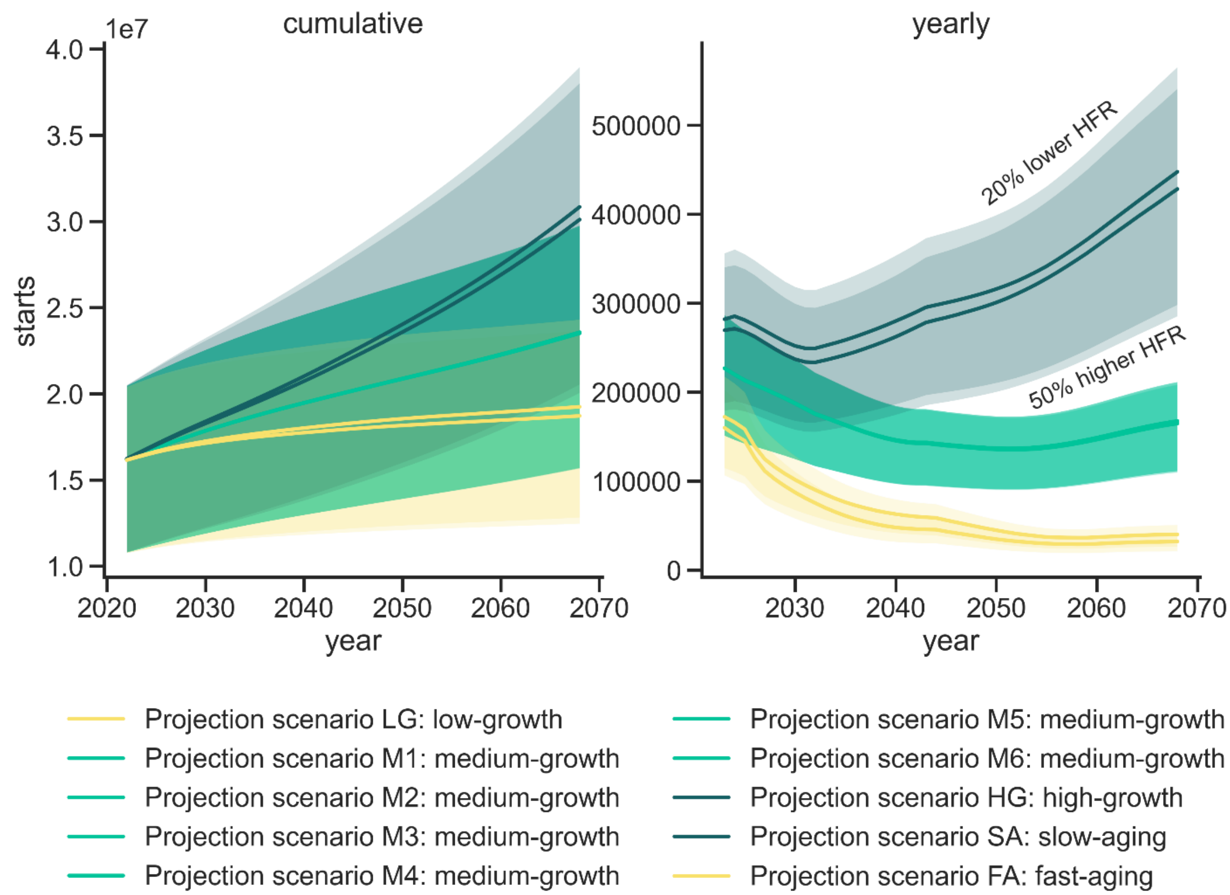
In the main text, household formation rate is assumed to be fixed between 2030 and 2050 (see SI Table 3.1), but demographic and economic pressures may push the average number of occupants in a unit up (such as increasing housing prices) or down (such as smaller families). SI Figure 3.2 shows how future housing starts may vary if national average household formation rate increases by 50% to 3.6 people per unit (to the approximate rate in the 1970) or decreases by 20% to 1.9 people per unit (following the current trend of smaller households) [98]. The cumulative variation in housing starts is significant, showing that increasing the future average household size in Canada may be a way to mitigate demand for housing as shelter. It also shows how uncertainty projections of housing construction can be beyond the near term.

The country-level population projection extends to 2068, but province-level projections only extends to 2043; the analysis assumed that the rate of change between 2042 and 2043 is constant until 2050.

There are some limitations to using population as a proxy for housing growth. The most important is that it ignores economic factors that drive housing growth like interest rates (factors that cannot be accurately estimated as far out as 2050), and the demand for housing as an appreciating asset.

SI Table 3. 1 Average provincial household size in Canada in 2021

Province	**2021 average household size** (people/housing unit)
Ontario	2.6
Quebec	2.2
British Columbia	2.4
Manitoba	2.5
Saskatchewan	2.5
Newfoundland	2.3
Nova Scotia	2.2
Alberta	2.6
New Brunswick	2.3
Prince Edward Island	2.3

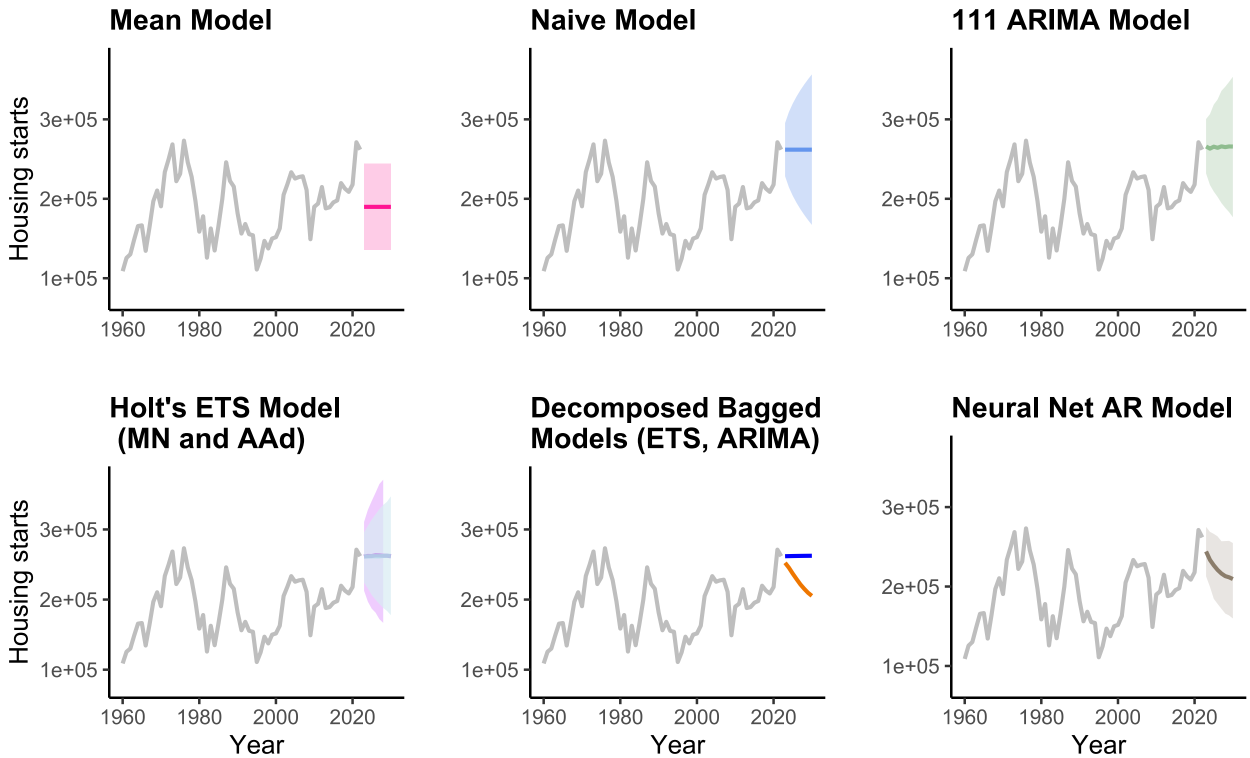


SI Figure 3. 2 Population-based yearly housing starts under different household formation rates – the top of the coloured bands shows the 20% average household size decreases, thus increases the total housing requirements for the growing population. The bottom bands show the 50% average household size increase. The solid lines show the fixed household formation projection referred to in the main text.

3.3 Time-series modelling and probability of future high growth

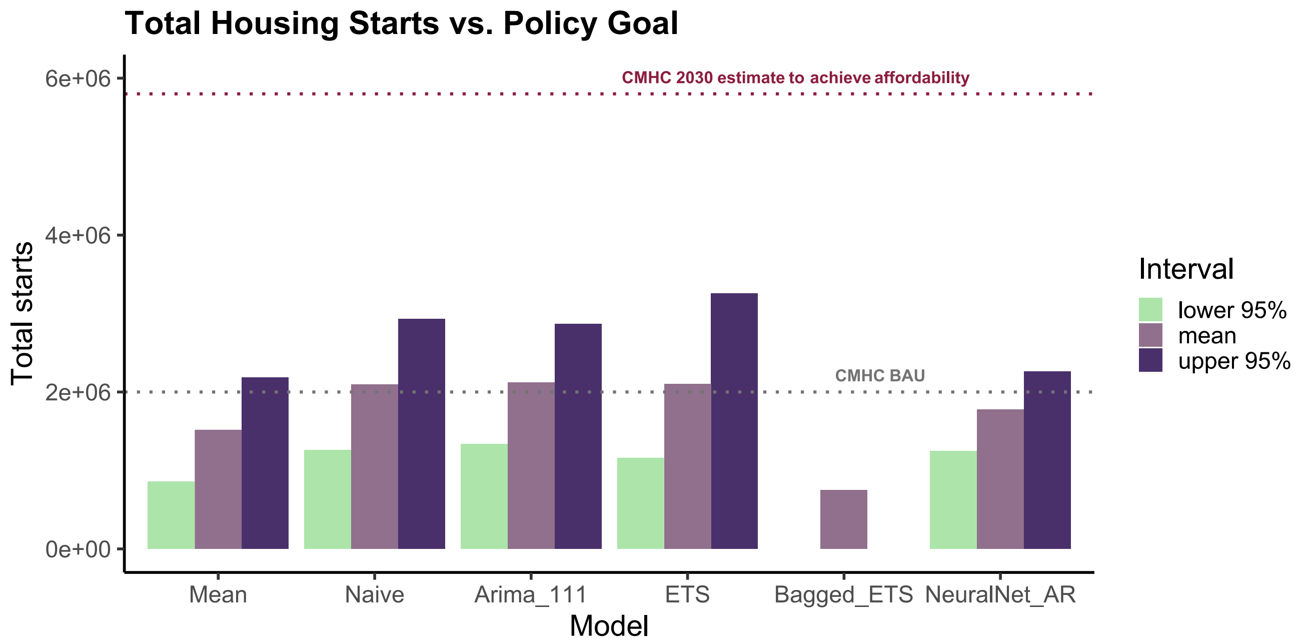
This appendix includes supplementary study of historic housing starts to determine the feasibility of the high growth construction scenario. The results below show a set of best-fit time-series models that were fit to the historic housing start data in Canada, and it shows the prediction interval for these models to 2030.

SI Figure 3.3 shows the various time-series models fit to the historic data. The ARIMA and exponential smoothing models performed best on the test set. Other models either had lower RMSEs (e.g. the small, single-layer neural network), had autocorrelated residuals (Drift Model), or failed a Ljung-Box test (naïve model). The plot shows the 80% confidence interval (bootstrapped for most models).



SI Figure 3. 3 Time-series forecasting models fit to historic housing start data in Canada. Decomposed bagged models show the bagged mean for ETS (blue) and ARIMA (orange)

SI Figure 3.4 shows the prediction interval of cumulative starts for each model. When compared to BAU and high construction growth. The means of the best models line up with the BAU case. The high-growth goal of 5.8 million homes is more than 2 million homes above the 95% confidence interval for the best-fit models. This indicates that it is unlikely, based on historical data, that Canada will build enough housing by 2030 to restore affordability, which would result in less future embodied emissions. Nevertheless, there are still reasons to believe that housing construction could grow significantly. Increases in efficiency through the emergence of construction technology could increase yearly housing starts. Technology improvements and political pressure due to unaffordability in Canada could cause historically unprecedent restructuring of the economy and corresponding growth in housing construction. Finally, scenarios which do lie within a reasonable confidence interval still see millions of more units than the BAU case, which would greatly increase embodied emissions beyond the country's reduction goals.



SI Figure 3. 4 Prediction interval of cumulative housing starts from time-series models compared to BAU and high growth

4. Supplementary Results

This section contains additional figures/tables referred to in the text (primarily in the main text Figure annotations).

SI Table 4.1 Summary of embodied emission reduction strategies and growth scenarios explored in the main text

Summary of forecast scenarios:

Reduction Strategies

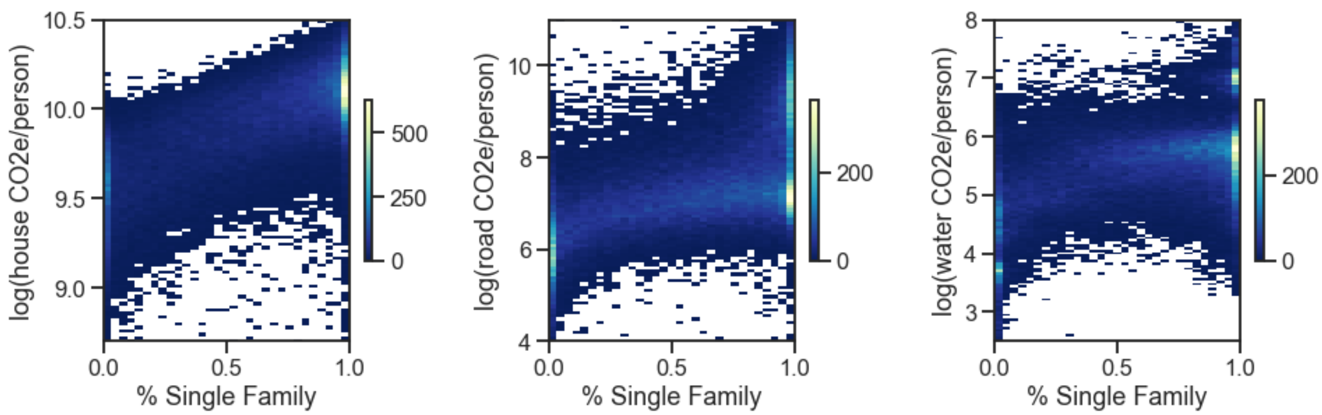
- Urban form
- Best-in-class design
- Material technology improvements
- Increased infill rate
- Increased circularity

Growth Scenarios

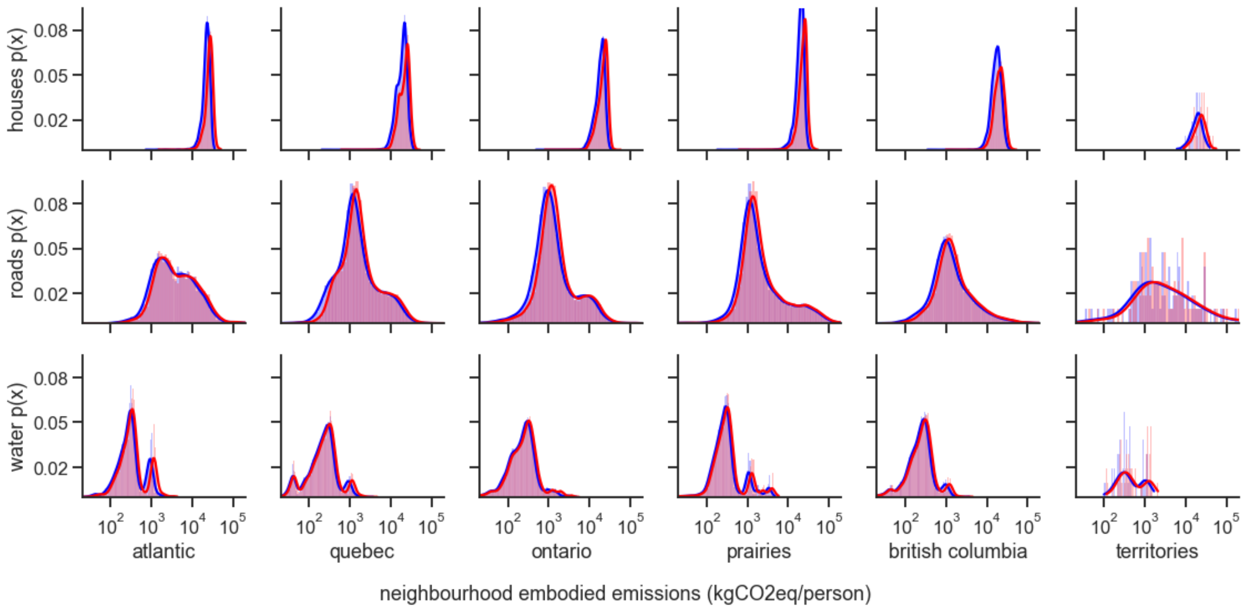
- BAU Growth
- Affordability Growth

Different scenarios in the paper analysis:

Analysis/Figure	Sub	Growth Scenario	Strategies
Figure 3	a	Affordability Growth	Urban form, best-in-class design, material technology
	b	Affordability Growth	All
	c	BAU Growth	Urban form, best-in-class design, material technology
Figure 4	a	Affordability Growth	All (sensitivity looks specifically at infill and circularity)
Figure 5		BAU + Affordability Growth	Urban form



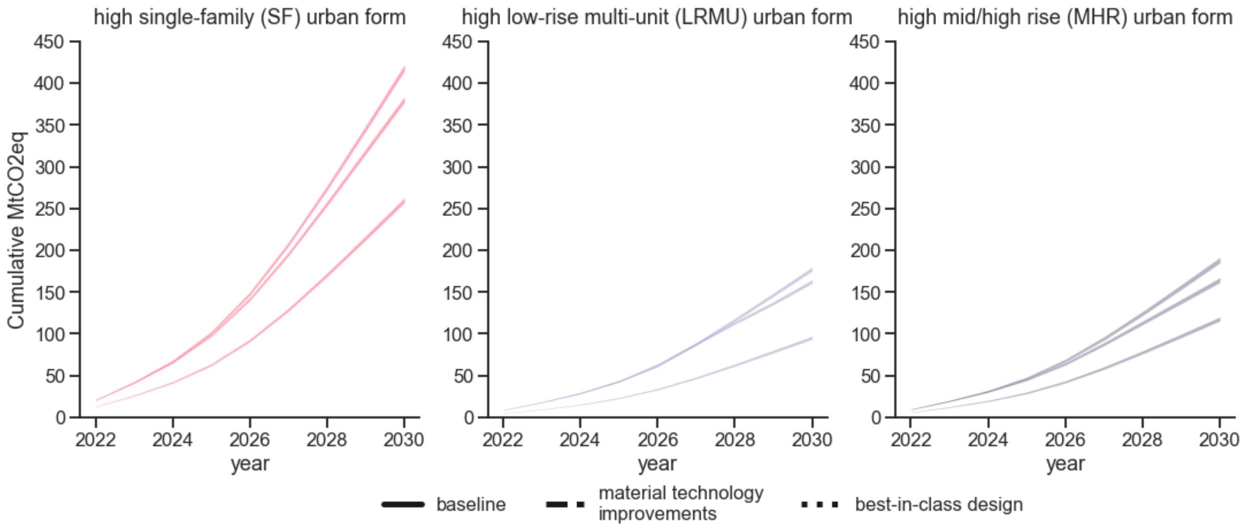
SI Figure 4.1 Relationship between **a.** building, **b.** road, and **c.** water embodied emissions and the percentage of single-family buildings in a Canadian neighbourhood.



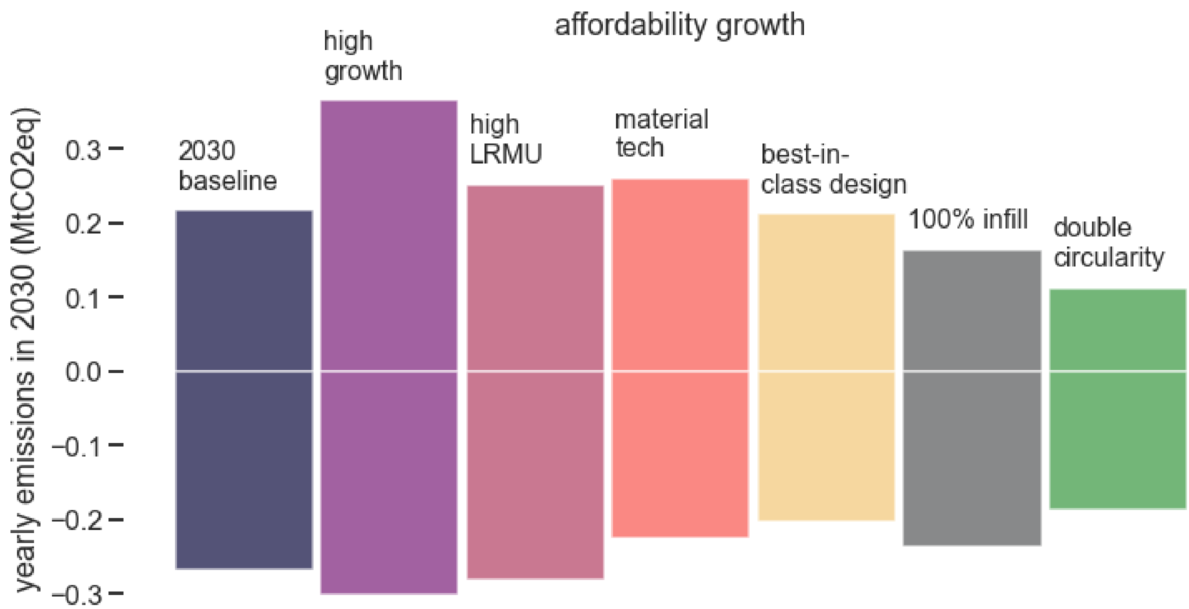
SI Figure 4.2 Main text Figure 2a distribution of embodied emissions in neighbourhood infrastructure with sampling uncertainty. The minimum (blue) and maximum (red) out of the 500 Monte Carlo samples are shown.

SI Table 4.2 Key results from 2030 forecast of embodied emissions under different scenarios

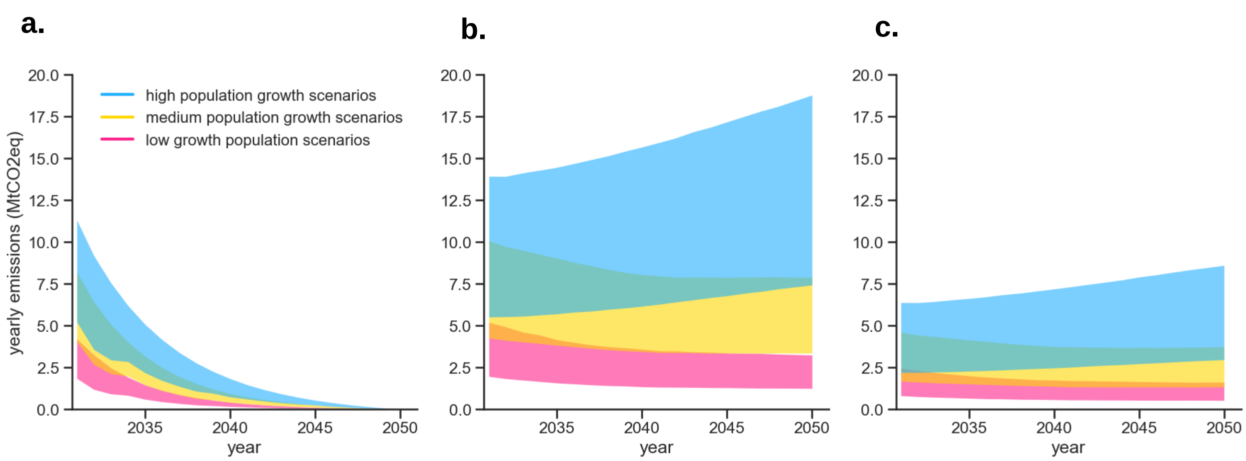
Housing Growth Scenario	Housing mix	Other strategies	Yearly emissions in 2030 (MtCO2eq)	Cumulative emissions 2022-2030 (MtCO2eq)
BAU (2.3 million homes)	High single family	None	19.2	174
	Historic (baseline)	None	12.6	107
	High mid/high rise	None	9.14	82.7
	High low-rise multi-unit	None	8.26	74.9
	High low-rise multi-unit	material technology + best-in-class design	3.74	36.9
Affordability (5.8 million homes)	High single family	None	72.5	418
	Historic (baseline)	None	44.3	256
	High mid/high rise	None	32.2	188
	High low-rise multi-unit	None	30.7	178
	High low-rise multi-unit	material technology + best-in-class design	14.1	86.5
	High low-rise multi-unit	material technology + best-in-class design + 100% infill + double circularity	6.19	54.5



SI Figure 4.3 Main text Figure 3a showing the range including sampling uncertainty. Sampling uncertainty for cumulative emissions in 2030 is around 5 $MtCO_2eq$ in each scenario.



SI Figure 4.4 Sampling uncertainty in Figure 3b. Uncertainty between the minimum and maximum Monte Carlo sample too small to show in error bars. The top of the plot shows the maximum sample, while the bottom shows the minimum for each additive strategy.



SI Figure 4.5 Net zero prospects of new construction under different strategies – a. Shows the range of forecasted yearly emissions between 100% single family (SF) (top of coloured bands) and 100% low-rise multi-unit (LRMU) (bottom of coloured bands) if material technologies improve in line with net-zero policies. **b.** shows average pathways if production emissions cannot be lowered below 2030 levels. **c.** shows the range of forecasted emissions if production emissions cannot be lowered below 2030 levels but other reduction strategies are also deployed: infill rate is doubled, circularity is increased from k = 0.8 to k = 0.5, and buildings are built using 1st quartile designs.

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