Developing an Embodied Carbon Policy Reduction Calculator

Quantifying the embodied emissions reduction potentials of city policies

PROOF-OF-CONCEPT REPORT | APRIL 2022

Carbon Leadership Forum

C40 CITIES

ABOUT THE CARBON LEADERSHIP FORUM

The Carbon Leadership Forum is a non-profit industry-academic collaborative at the University of Washington. We are architects, engineers, contractors, material suppliers, building owners, and policymakers who work collaboratively, pioneering research, creating resources, and incubating member-led initiatives for greatest collective impact. Our goal is to accelerate transformation of the building sector to radically reduce and ultimately eliminate the embodied carbon in building materials and construction.

ABOUT C40

C40 is a network of nearly 100 mayors of the world's leading cities, who are working to deliver the urgent action needed right now to confront the climate crisis, and create a future where everyone, everywhere can thrive. Mayors of C40 cities are committed to using a science-based and people-focused approach to help the world limit global heating to 1.5°C and build healthy, equitable and resilient communities. Through a Global Green New Deal, mayors are working alongside a broad coalition of representatives from labor, business, the youth climate movement and civil society to go further and faster than ever before.

ABOUT THE C40 CLEAN CONSTRUCTION PROGRAMME

The Clean Construction Programme was created in May 2019 at the initiative of the City of Oslo. It supports cities in driving the transition to resource-efficient, resilient, and zero-emission built environment construction systems, which will also deliver decent and green jobs, healthier buildings, and better air quality to millions of residents in cities around the world. It includes a network that brings together over 35 global cities to facilitate peer-to-peer sharing and a forum for city-industry dialogue.

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EXECUTIVE SUMMARY

The buildings and infrastructure that define our cities are also one of the largest sources of greenhouse gas (GHG) emissions. Embodied carbon is the GHG emissions arising from the extraction, manufacturing, transportation, installation, maintenance, and disposal of construction materials. Embodied carbon associated with the construction of our built environment accounts for approximately 20-23% of total global energy-related GHG emissions.[1,2]

A growing number of cities recognize their role and commit to action to tackle the urgent challenge of their built environment carbon footprint through their policies and programs. 110 cities took the Cities Race to Zero Clean Construction pledges to reduce embodied emissions in their policies and programmes in 2021, 40 leading cities are participating in the C40 Clean Construction programme and mayors are setting the direction of travel by signing the Clean Construction Declaration, which requires collective action to halve embodied emissions by 2030.[3]

However, embodied carbon is a new policy area for many cities and the lack of city-level data is a significant barrier for policymakers to gain political support and make informed decisions. Not only do more cities need to adopt policies targeting embodied carbon to reach global decarbonization targets, but cities who have already committed to reducing embodied carbon have to overcome several challenges:

- With limited time to act in the crucial window between now and 2030, pursuing the most impactful strategies is key to maximizing the available political and financial resources.
- Currently, there are tools to measure embodied carbon for a building or product, but there is a lack of tools for modeling embodied carbon impacts at the scale of a city. This limits policymakers' ability to assess which policies will be needed to reach their targets.
- Without data on carbon savings potentials, policymakers are also limited in their ability to communicate why policies must be passed.

The goal of developing an embodied carbon policy reduction calculator is to address these challenges by:

- Modeling the potential embodied carbon reduction of a selected number of policies to give cities the values they need to make informed decisions;
- Allowing for comparison of emissions reduction policies for embodied carbon by key target dates (2030 and 2050) to assess the largest opportunities for impact;
- Evaluating which policies may be required to meet embodied carbon reduction targets, such as those set by city or regional climate action plans; and
- Ultimately enabling cities to make the case for and adopt policies to reduce embodied carbon.

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[1] United Nations Environment Programme. (2021). *2021 Global Status Report for Building and Construction: Toward Zero-emissions, Efficient and Resilient Buildings and Construction Sector*. Nairobi. https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf

[2] Lizhen Huang, Guri Krigsvoll, Fred Johansen, Yongping Liu, Xiaoling Zhang. (2018). *Carbon emission of global construction sector, Renewable and Sustainable Energy Reviews*. Volume 81, Part 2, 2018, ISSN 1364-0321. https://doi.org/10.1016/j.rser.2017.06.001

[3] C40 Cities. (n.d.). *Clean Construction Declaration*. https://www.c40.org/declarations/clean-construction-declaration/

Proof-of-Concept Study

The Carbon Leadership Forum and C40 Clean Construction teams collaborated in 2021 to develop a proof-of-concept for an embodied carbon policy reduction calculator, described in this report. The goal of this study was to:

- Assess the availability of city data and life cycle assessment data required to develop a successful tool;
- Assess tool scope and functionality required to support cities' needs; and
- Demonstrate the tool concept to pilot cities to determine if it would be useful in policymaking.

The team developed four prototype calculators to estimate emissions from four types of embodied carbon policies (summarized in Figure 1):

1. Reducing the embodied carbon footprint of entire buildings
2. Limiting the embodied carbon footprint of concrete
3. Increasing adaptive reuse
4. Evaluating the carbon impact of housing policy

Policymakers using the calculators would need to input data on building use (e.g., multi-family, commercial), building size for that building use (e.g., low-rise, mid-rise), and expected area of growth by 2050. Various percentage (%) reduction targets can then be selected or entered manually. The final output of the calculators provides 1) baseline embodied carbon emissions by 2050, and 2) the various carbon savings potentials of the selected reduction targets.

It is important to note that the calculators described in this report are proof-of-concept: they are still limited in their ability for comparative decision-making at this time due to the gaps in data identified through this initial phase. Appendix B lists the priorities identified by the authors, contributors, and pilot cities necessary for their future development.

Case Studies

The team worked with three C40 North American cities to assess the potential of the prototype calculators:

- **New York City, New York,** using values for growth in projected floor area from New York City's 80x50 Technical Working Group report;
- **Portland, Oregon,** using values for growth in projected floor area from the City of Portland's 2007 analysis of baseline building stock and future growth; and
- **Austin, Texas - South Central Waterfront,** using values for growth in projected floor area from their Vision Framework Plan.

For each city, the CLF used building stock and growth projections noted above as inputs for each prototype calculator to assess the total embodied carbon by 2050 for a baseline scenario and 3-6 reduction scenarios that correlated with the evaluated policy type.

Overall, policies requiring reductions in whole building embodied carbon were found to have the largest impact. The second-most impactful policy type based on the findings from the prototype calculators was incentivizing adaptive reuse, followed by low-carbon concrete and housing size policies. These findings highlight the need for better research and benchmarks on the whole buildings of different building typologies to support more robust estimates of total carbon savings potentials associated with each, but also to enable cities to pass these policies.

The difference in the overall carbon savings potentials of the four different policies highlight the importance of physical scope in determining the impacts of embodied carbon. Whole buildings cover the largest scope in terms of the physical materials and building typologies impacted. They also allow for the largest range of embodied carbon reduction strategies. Other policies, such as the low-carbon concrete policy, impact only a portion of a building (only the concrete), and therefore result in lower overall reductions. Similarly, policies that address only one typology—such as policies targeting housing—resulted in lower overall carbon savings potential, despite multifamily residential being the type with the largest projected growth for some of the cities included in this study.

However, total reductions are not the only relevant policy goals: policymakers must balance political and economic barriers to identify the policy solutions that are feasible in their jurisdictions, and balance social, environmental, and public health co-benefits alongside carbon savings.

Conclusion

The initial results from this proof-of-concept study and feedback from cities indicate that these calculators could be a powerful resource for enabling policymakers to use the carbon savings potential estimates to develop and advocate for the policy solutions that are right for their cities and achieve their cities' goals.

Throughout the study, the authors and contributors sought feedback from the pilot cities on the efficacy and applicability of the selected policy types and calculators. Each city overwhelmingly found that reducing the embodied carbon footprint of entire buildings, limiting the embodied carbon footprint of concrete, and increasing adaptive reuse were the most helpful and useful policy calculators for communicating the importance of embodied carbon and advancing policy development in their city. Additionally, the city feedback reinforced the need for future research development of the calculators. A full list of future priorities is included in Appendix B. High priorities for future work include:

- Developing regionally and typologically specific building embodied carbon intensity values;
- Expanding the physical and temporal scope of the calculators to include infrastructure, parking, and cradle-to-grave impacts;
- Including stepped policy limits to evaluate the impact of incremental phasing over time and the cumulative impact of two or more policies combined;
- Adding additional policy types that could target material reuse, procurement, or other types of planning and zoning strategies.

City policymakers need to have measurable, reliable, and actionable data to support development of their embodied carbon policy strategies. These future research priorities will help refine and expand the calculators in order to provide those metrics and help cities across the globe address the urgent need to decarbonize the built environment.

1 INTRODUCTION

The purpose of this report is to describe the results of a proof-of-concept study for an "Embodied Carbon Policy Reduction Calculator" designed to support city policymakers pursuing policies and programs that aim to reduce embodied carbon.

1.1 Why Embodied Carbon?

The buildings and infrastructure that define our cities are also one of the largest sources of greenhouse gas (GHG) emissions. Embodied carbon is the GHG emissions arising from the extraction, manufacturing, transportation, installation, maintenance, and disposal of construction materials. These emissions are primarily released across building material supply chains before a building even opens. Embodied carbon is measured as **global warming potential (GWP)** using a methodology called **life cycle assessment (LCA)**.

Embodied carbon is significant: embodied carbon associated with the built environment accounts for at least 20% of total global GHG emissions[4]. Additionally, embodied carbon disproportionately impacts frontline communities. When cities work to reduce embodied carbon, they are working to eliminate the environmental and public health burden placed on frontline communities that suffer most from both global impacts related to climate change and local impacts related to fossil fuel use in transportation and manufacturing across construction supply chains, like smog and diesel emissions.

Beyond the direct benefits to the climate and public health due to GHG emissions reductions, policies can have significant potential co-benefits depending on the policy, such as:

Reducing industrial emissions from material manufacturing, resulting in significant environmental and public health co-benefits such as improving air quality in fenceline communities and reducing energy use, water use, ozone depletion, smog formation, and eutrophication;

- Extending the life of existing materials, reducing the environmental damage and community health impacts from landfilling construction materials;
- Incentivizing reuse and material or space efficiency, saving money and reducing waste;
- Rewarding locally sourced materials and products that promote the local economy;
- Creating markets for lower-carbon materials and technologies and signaling manufacturers to decarbonize their products and processes;
- Supporting preservation of cultural resources and heritage through extending the life of existing buildings;
- Discouraging environmental damage from new construction on greenfield (i.e., previously undeveloped) sites by encouraging reuse and increased density in already developed portions of cities; and
- Promoting better access to transit and city services through increased density, resulting in a wide range of environmental and public health benefits from less driving for commuting and other travel.

Global warming potential

The potential climate change impact of a product or process as measured by an LCA, reported in units (typically kg) of carbon dioxide equivalent (CO_2e). This report uses "GWP", "carbon", and "embodied carbon" interchangeably to refer to these impacts.

Life cycle assessment (LCA)

LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a building, infrastructure, product or material throughout its lifecycle (ISO 14040: 2006).

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[4] United Nations Environment Programme. (2021). *2021 Global Status report for Building and Construction: Toward Zero-emissions, Efficient and Resilient Buildings and Construction Sector.* Nairobi. https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf

1.2 Why an Embodied Carbon Policy Calculator?

A handful of cities have already made the commitment to address these emissions through their policies and programs, such as those who have signed on to the Clean Construction Declaration,[5] but more cities will need to adopt a whole life-cycle approach to the built environment that addresses both operational and embodied carbon to reach global decarbonization targets.

A wide variety of paths for reducing embodied carbon are available to cities. For example, the City Policy Framework for Dramatically Reducing Embodied Carbon provides model language for 52 policies to reduce embodied carbon.[6] Similarly, the C40 Clean Construction Policy Explorer[7] and Carbon Leadership Forum Policy Toolkit[8] showcase the many ways in which cities around the world are currently taking action.

Examples of existing policies to reduce embodied carbon include:

- Building reuse and expanded historic preservation incentives;
- Setting life-cycle carbon intensity limits for buildings (i.e., limiting kgCO2e/m2);
- Setting product carbon intensity limits for construction materials, such as concrete or steel;
- Wood or bio-based building material incentives; and
- Deconstruction or salvage requirements for demolition permits.

As more cities take steps towards enacting policies and regulations to reduce embodied carbon for their new buildings, retrofits, and infrastructure, policymakers need tools to estimate the potential impact of different policy opportunities. With limited time to act, pursuing the most impactful strategies to reduce embodied carbon is key, given the limited political will and financial resources available.

Currently, embodied carbon is primarily measured at the scale of a building or project (by design teams) or at the material scale (by manufacturers and construction teams). This has resulted in a plethora of tools for individual projects or products, but a severe lack of tools for considering embodied carbon at the scale of a city. Cities are restricted in their ability to lead this analysis on their own, as data collection and analysis can cost valuable time and resources.

The lack of city-level data on the embodied carbon emission in the built environment is a barrier to action that adds to the typical political and other challenges faced by policymakers. Policymakers can better champion and prioritize embodied carbon policies when they have better data to communicate the magnitude of potential for impact.

The goal of developing an embodied carbon policy reduction calculator for embodied carbon (EC) is to fill this gap by creating a calculator for cities to estimate the carbon reduction potential of embodied carbon policies. This calculator would:

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[5] C40 Cities. (n.d.). *Clean Construction Declaration*. https://www.c40.org/declarations/clean-construction-declaration/

[6] Carbon Neutral Cities Alliance, One Click LCA, Architecture 2030. (2020). *City Policy Framework for Dramatically Reducing Embodied Carbon.* http://carbonneutralcities.org/wp-content/uploads/2021/02/City-Policy-Framework-for-Dramatically-Reducing-Embodied-Carbon.pdf

[7] C40 Clean Construction Team. (October 2021). *C40 Clean Construction Policy Explorer*. https://www.c40knowledgehub.org/s/article/Clean-Construction-Policy-Explorer?language=en_US

[8] Carbon Leadership Forum. (2021). *CLF Embodied Carbon Policy Toolkit.* https://carbonleadershipforum.org/clf-policy-toolkit/

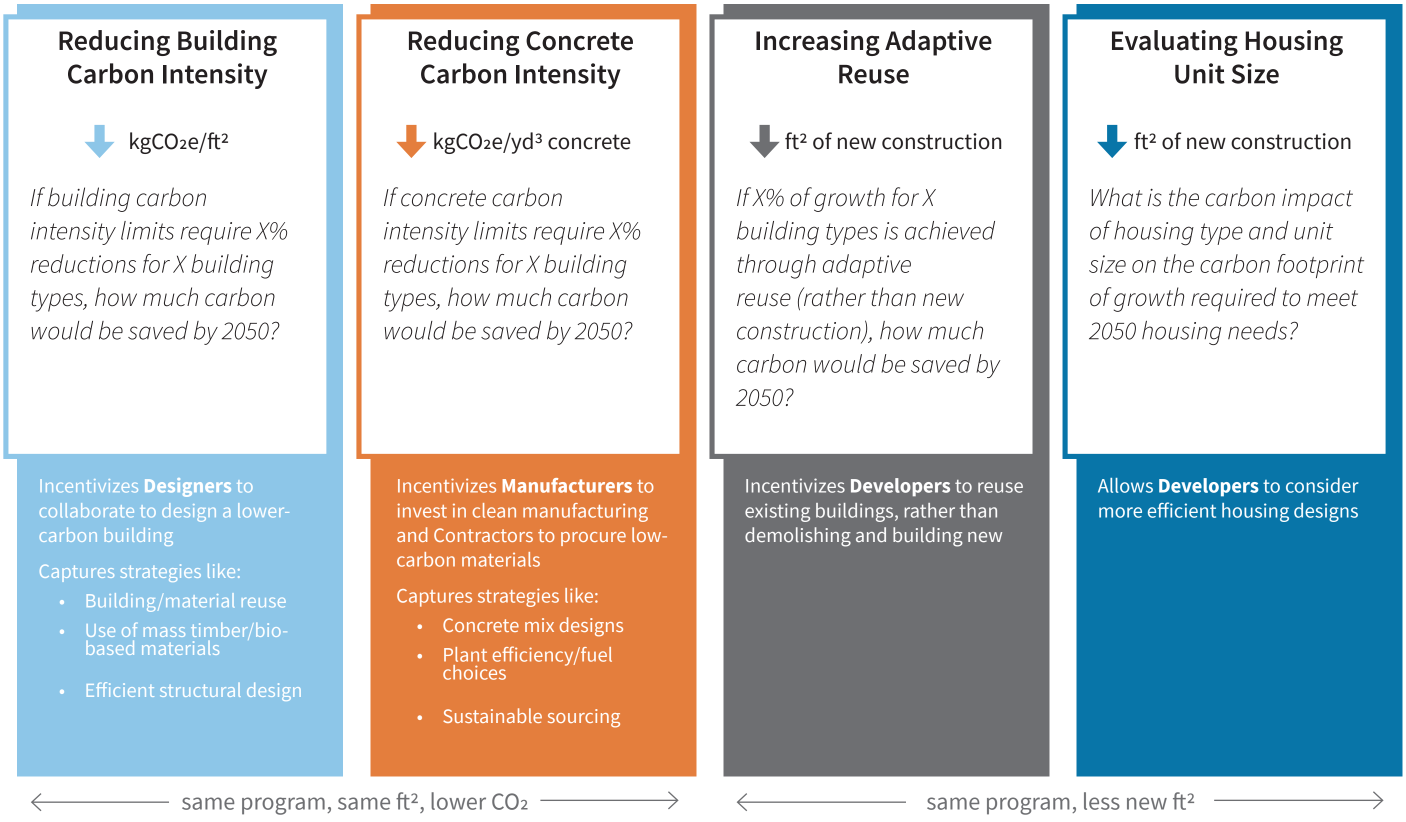
- Establish a simple way for planners and policymakers to model the carbon savings potential of EC policies for a specific city;
- Allow for comparison of emissions reduction policies for EC by key target dates (2030 and 2050) to assess the largest opportunities for impact;
- Provide customized estimates of carbon savings associated with each policy to give cities the values they need to make a case for action;
- Evaluate which policies may be required to meet embodied carbon reduction targets, such as those set by city or regional climate action plans.

1.3 Proof-of-Concept Study

The Carbon Leadership Forum and C40 Clean Construction teams collaborated to develop a proof-of-concept for an embodied carbon policy reduction calculator, described in this report.

The team developed four prototype calculators to estimate emissions from four types of embodied carbon policies (summarized in Figure 1):

1. Reducing the embodied carbon footprint of entire buildings
2. Limiting the embodied carbon footprint of concrete
3. Increasing adaptive reuse
4. Evaluating the carbon impact of housing policy



Reducing Building Carbon Intensity

↓ kgCO_2e/ft^2

If building carbon intensity limits require X% reductions for X building types, how much carbon would be saved by 2050?

Incentivizes **Designers** to collaborate to design a lower-carbon building

Captures strategies like:

- Building/material reuse
- Use of mass timber/bio-based materials
- Efficient structural design

Reducing Concrete Carbon Intensity

↓ kgCO_2e/yd^3 concrete

If concrete carbon intensity limits require X% reductions for X building types, how much carbon would be saved by 2050?

Incentivizes **Manufacturers** to invest in clean manufacturing and Contractors to procure low-carbon materials

Captures strategies like:

- Concrete mix designs
- Plant efficiency/fuel choices
- Sustainable sourcing

Increasing Adaptive Reuse

↓ ft^2 of new construction

If X% of growth for X building types is achieved through adaptive reuse (rather than new construction), how much carbon would be saved by 2050?

Incentivizes **Developers** to reuse existing buildings, rather than demolishing and building new

Evaluating Housing Unit Size

↓ ft^2 of new construction

What is the carbon impact of housing type and unit size on the carbon footprint of growth required to meet 2050 housing needs?

Allows **Developers** to consider more efficient housing designs

Figure 1. Summary of four types of policies assessed by prototype calculators, including primary stakeholders and potential strategies.

These policies were selected for the proof-of-concept because they met multiple or all of the following criteria:

- Policy framework or precedents already exist
- Pilot cities (and other C40 cities) expressed interest in this type of policy
- Adequate preliminary data available to support prototype calculator
- Political priority outside of embodied carbon

To test each prototype calculator, the team worked with three C40 North American cities: New York City, New York; Portland, Oregon; and Austin, Texas. For each city, the CLF used building stock and growth projections provided by the cities to assess the GHG emissions reduction potential for each policy. The findings from each city are shared in Section 3.

This study used many robust and well-researched datasets to determine the growth projections of cities and their resulting embodied carbon impacts. However, multiple assumptions and order-of-magnitude estimates were still required to fill gaps where insufficient data was available. It is important to remember that the calculators were intended as a proof-of-concept only, and not for comparative decision-making at this time. Appendix B lists the priorities identified by the authors, contributors, and pilot cities necessary for their future development.

2 CALCULATING THE EMBODIED CARBON REDUCTION POTENTIAL OF CITY POLICIES

This section provides an overview of four prototype calculators developed to evaluate the impact of the following policies:

1. Requiring reductions in building embodied carbon intensity;
2. Limiting the carbon content of concrete;
3. Increasing **adaptive reuse;** and
4. Evaluating the carbon impact of housing policy.

Adaptive reuse

The renovation and reuse of pre-existing structures for new purposes. In this report, adaptive reuse also refers to the use of a vacant existing building for the same purpose.

Quantifying the embodied carbon of buildings requires multiple sets of data for the physical, temporal, and environmental scales. This pilot study focuses on embodied carbon impacts for a limited scope of building typologies which can be used to estimate the impacts of future growth scenarios.

The prototype calculators rely on currently available life cycle assessment (LCA) data for buildings and products, typical material quantities for certain products per building type, benchmarks for buildings and products, and typical construction type data for North American cities. Appendix A contains a full overview of the methodology, background data, and uncertainties built into the calculators.

While there are many factors that contribute to the carbon impacts of the built environment, this study was limited in its physical, life cycle, and environmental scope:

- **The physical scope** of all calculators is limited to buildings—particularly the structure, enclosure, and interior finishes. The calculators do not include impacts of other systems such as the mechanical, electrical, and plumbing systems (MEP), nor do they include impacts of infrastructure, such as roadways, parking lots, sewer and water systems, and power distribution networks, which can all contribute to the carbon footprint of cities and significantly alter the results of the current calculators.
- **The life cycle scope** is limited to the product stage of a full life cycle (A1-A3) due to the limitations in available data for use across the prototype calculators. This means that impacts from construction operations, use and replacement, demolition, and end-of-life are not included. These stages are critical to include in future stages of developing these calculators to provide cities with estimates that include the entire life cycle. The estimates in Section 3 for each pilot city are therefore conservative, in that they capture reductions from only a portion of the embodied carbon associated growth in each city. The actual emissions are likely to be much higher.
- **The environmental scope** of all calculators is limited to embodied carbon. They do not include other global environmental impacts such as smog or acidification, nor do they include local impacts such as noise, air pollution, or land use changes. The calculators do not measure social, economic, or other non-environmental indicators.

The results from the calculators are intended as a proof-of-concept for functionality, and are directionally accurate but not yet reliable estimates for informing decision-making. Additional research could improve the accuracy, scope, and functionality of the calculators. Appendix B lists the priorities identified by the authors, contributors, and pilot cities for future development.

2.1 Requiring reductions in building embodied carbon intensity

Calculator 1, or the "Building Embodied Carbon Intensity (BECI) Reduction Policy Calculator," was designed to answer the following question:

If a city required **reductions in building embodied carbon intensity for certain building typologies,** what would be the potential carbon savings by 2050 based on their current growth projections?

Answering this question would help policymakers calculate the potential for policies that limit **building embodied carbon intensity (BECI)** through either:

- Requiring percentage (%) reductions in BECI from a baseline over time; or
- Setting maximum allowable BECI values per floor area (kgCO$_2$e/m^2 or similar).

BECI reduction policies allow for the broadest range of embodied carbon reduction strategies of any of the policies explored in this proof-of-concept. For example, a BECI reduction policy would incentivize the following strategies:

- Building and/or material reuse;
- Efficient structural or building design (i.e., using less of a material, rather than choosing the lowest carbon version of a material);
- Selection of lower-carbon systems and materials, such as sustainably sourced mass timber and other bio-based materials; and
- Use of lower-carbon concrete mixes (similar to policies addressed in Section 2.2).

Building embodied carbon intensity (BECI)

Building embodied carbon intensity refers to the typical GWP per floor area (kgCO$_2$e/m^2) for an entire building under typical design and construction practices.

2.1.1 Policy advantages and co-benefits

Requiring reductions in building embodied carbon intensity is a promising policy solution for delivering large savings in embodied carbon across a variety of building typologies. Policies targeting entire buildings have multiple advantages in that they:

- Give architects, engineers, and contractors the most flexibility in meeting reduction targets;
- Allow for capturing reductions from design in addition to material specification, procurement, and construction;
- Can apply to the broadest range of building typologies;
- Can incentivize building and material reuse and efficiency, which can save money and reduce waste;
- Can support the creation of markets for new materials (such as bio-based alternatives to existing materials);
- Can support the creation of city benchmarking databases to support further analysis and identification of the highest-impact opportunity for reductions; and
- Signals manufacturers (indirectly) and supply chains to decarbonize their products and processes.

2.1.2 *Policy precedents*

There are a growing number of policy precedents for limiting a building's embodied carbon intensity. Policies targeting reductions in BECI are best suited to policy levers early in the design process, such as zoning and permitting, to allow for holistic design approaches to carbon reduction. These policies most directly target architects and engineers.

In North America, the first precedent was the Green Building Rezoning Requirements in Vancouver, B.C.,[9] which requires the disclosure of a building's embodied carbon footprint and will soon require percentage reductions in total embodied carbon.

In Europe, the first precedent was the Netherlands' Building Decree established in 2012,[10] which requires new residential and office buildings to meet environmental performance (including embodied carbon) targets per square meter of floor area. Similar policies have now been introduced or planned in many other European countries, including Belgium, Germany, France, Sweden, Denmark, and Finland.[11]

The BECI Reduction Policy Calculator could also help cities estimate the potential impact of requiring projects to meet the building life-cycle impact reduction credit included in LEEDv4 for New Construction, which requires teams to reduce the life cycle impacts of their buildings (including embodied carbon) by 10% from a baseline building.[12]

2.1.3 *Calculator functionality*

To calculate the baseline scenario, the calculator multiplies the BECI values for each **building typology** with the expected building typology growth projected for that city, and then applies the percentage reduction selected by the calculator user. See Appendix A Section A.3 for additional methodology details.

The BECI Reduction Policy Calculator requires users to input **building use**, **building size** for that building use, and expected area of growth by 2050 (in m²) for building typologies being assessed. Then, users can select a percentage (%) embodied carbon reduction requirement.

After entering this information, the calculator provides an estimate of projected embodied carbon by 2050 for a baseline scenario and the selected reduction scenario(s), as well as the total carbon savings potential by 2050. Figure 2 provides an illustrative example of the BECI Reduction Policy Calculator inputs and resulting outputs.

Building typology

In this report, building typology refers to a category of buildings with the same building use and building size. For example, 'commercial' is a building use, whereas 'commercial mid-rise (6-10 stories)' is a building typology.

Building use

Building use refers to the primary function of the building. Examples include commercial, multifamily residential, institutional, or retail. The building use names vary for different cities, and may or may not be tied to specific zoning names.

Building size

Building size refers to the range of building levels. For example, low-rise, mid-rise, 6-10 stories, or very large (>10 stories). The typical range of levels for a building use is typically limited by zoning and varies for each city.

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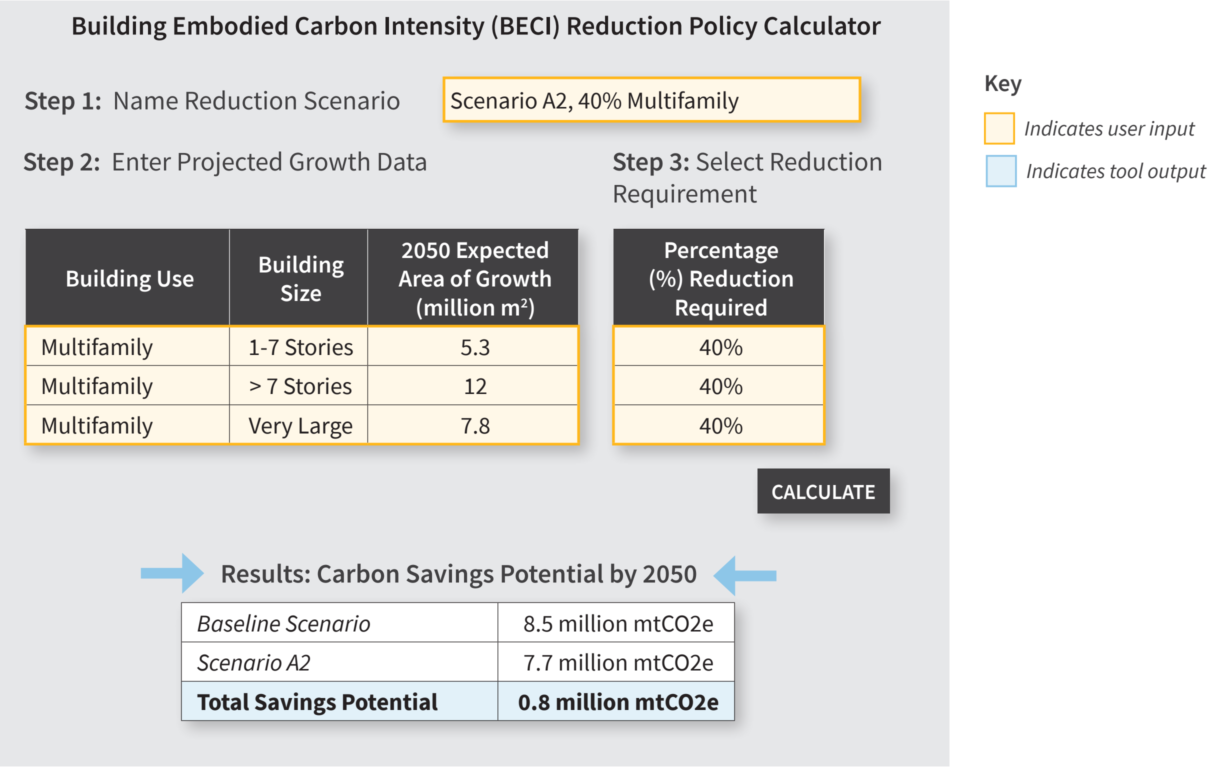
[9] City of Vancouver Planning, Urban Design and Sustainability Department. (2010). *Green Buildings Policy For Rezoning - Process And Requirements*. Available at https://bylaws.vancouver.ca/Bulletin/G002_2017April28.pdf

[10] Netherlands Ministry of the Interior and Kingdom Relations. (2012). *Building Decree 2012.* https://www.rijksoverheid.nl/onderwerpen/bouwregelgeving/bouwbesluit-2012.

[11] WBCSD and OneClickLCA. (2020). *Decarbonizing construction: Guidance for investors and developers to reduce embodied carbon.*

[12] United States Green Building Council. (n.d.). *Building product disclosure and optimization - environmental product declarations.* https://www.usgbc.org/credits/new-construction-schools-new-construction-retail-new-construction-data-centers-new-3?return=/credits/new-construction/v4. Accessed February 2022.



Building Embodied Carbon Intensity (BECI) Reduction Policy Calculator

Step 1: Name Reduction Scenario

Scenario A2, 40% Multifamily

Step 2: Enter Projected Growth Data

Building Use	Building Size	2050 Expected Area of Growth (million m²)
Multifamily	1-7 Stories	5.3
Multifamily	> 7 Stories	12
Multifamily	Very Large	7.8

Step 3: Select Reduction Requirement

Percentage (%) Reduction Required
40%
40%
40%

Results: Carbon Savings Potential by 2050

Baseline Scenario	8.5 million mtCO2e
Scenario A2	7.7 million mtCO2e
Total Savings Potential	**0.8 million mtCO2e**

Key

🟨 *Indicates user input*

🟦 *Indicates tool output*

Figure 2. Illustrative example of the BECI Reduction Policy Calculator demonstrating user inputs and outputs.

2.2 Limiting the Carbon of Concrete

Calculator 2, or the "Low-Carbon Concrete Policy Calculator," was designed to answer the following question:

If a city **limited the maximum allowable embodied carbon intensity of concrete for certain building typologies,** what would be the potential carbon savings by 2050 based on their current growth projections?

Answering this question would help policymakers calculate the potential for policies that limit **concrete embodied carbon intensity (CECI)**. This would also be helpful for cities to understand what magnitude of reduction targets for their policies would result in achieving their carbon reduction goals.

2.2.1 Policy advantages and co-benefits

Cement, a key ingredient of concrete, is responsible for approximately 7% of global greenhouse gas (GHG) emissions, making this a critical sector for GHG reductions.[13] Requiring reductions in concrete embodied carbon intensity is often referred to as "low-hanging fruit" for embodied carbon policies, since there are already a wide range of available strategies for reducing the carbon of concrete.[14,15]

Concrete embodied carbon intensity (CECI)

Concrete embodied carbon intensity refers to the average carbon intensity in kgCO₂e/yd³ of concrete for specific regions of the USA.

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[13] IEA and Cement Sustainability Initiative. (2018). *Technology Roadmap: Low-Carbon Transition in the Cement Industry.* https://www.wbcsd.org/contentwbc/download/4586/61682/1

[14] Cannon, C., Guido, V., and Wright, L. (2021). *Concrete Solutions Guide: Actionable Solutions to Lower the Embodied Carbon of Concrete*. https://rmi.org/insight/concrete-solutions-guide

[15] Fransen, T., Lebling, K., Weyl, D., and Kennedy, K. (2021). *Toward A Tradable, Low-Carbon Cement Standard: Policy Design Considerations For The United States.* https://doi.org/10.46830/wriwp.20.00112

Benefits of policies targeting reduction in the embodied carbon intensity of concrete include:

- Helps create markets for lower-carbon materials and technologies across the concrete supply chain;
- Relative ease of implementation, by focusing on one type of carbon-intensive material;
- Can apply to roads, bridges, and other civil works in addition to buildings;
- Can incentivize material efficiency (e.g., reductions in total cement use), reducing waste;
- Can reward locally sourced materials and products that promote the local economy;
- Signals manufacturers and supply chains to decarbonize their products and processes; and
- Reduces industrial emissions that have significant co-benefits beyond carbon, such as improving air quality in **fenceline communities** and reducing energy use, water use, ozone depletion, smog formation, and eutrophication.

2.2.2 Policy precedents

Low-carbon concrete policies are growing rapidly at the local, state, and federal level across the United States and globally. In the United States, concrete is included in existing state and federal policies targeting procurement—such as the Buy Clean Colorado Act, the New York Low Embodied Carbon Concrete Act, and Executive Order 14057—as well as a growing number of state procurement bills, such as those introduced in 2021 New Jersey, California, Massachusetts, Washington, Minnesota, and Oregon that did not pass. Concrete was also included in the Federal Buy Clean program proposed in the CLEAN Future Act in Congress in March 2021.

At the local level, there are even more examples. Two of the first in the United States are Marin County's Low Carbon Concrete Code, which requires concrete to be below either maximum cement values or maximum GWP values per cubic yard of concrete ($kgCO_2e/yd^3$) by strength class,[16] and the City of Portland's Low Carbon Concrete Purchasing Policy, which will require ready mix concrete products used on city projects to be below a maximum GWP value per cubic yard of concrete ($kgCO_2e/yd^3$) by strength class.[17]

2.2.3 Calculator functionality

To calculate the baseline scenario, the Low Carbon Concrete Policy Calculator uses data on the **construction type**, concrete material quantity per construction type, and regional embodied carbon intensity values for concrete to estimate the embodied carbon associated with the projected growth. Baseline values are representative of typical construction practices and typical concrete production for each region. The percentage reduction selected is then applied to the baselines values to calculate the reduction scenario. See Appendix A Section A.4 for additional methodology details.

While the background calculations are different, the Low Carbon Concrete Policy Calculator requires similar inputs from users as the BECI Reduction Policy Calculator (e.g., building use, size, and expected growth) and communicates results in a similar

Fenceline communities

Fencline communities are communities of increased health risk due to their proximity to a major source of pollution. Fenceline communities are often disproportionately inhabited by people of color and the working poor.

Construction type

In this report, construction type refers to the primary structural system, such as concrete, steel/concrete hybrid, or mass timber. This is important because the structural system of a building, whether it be steel, concrete, or wood, is also an important indicator of the total volume of concrete a building will use.

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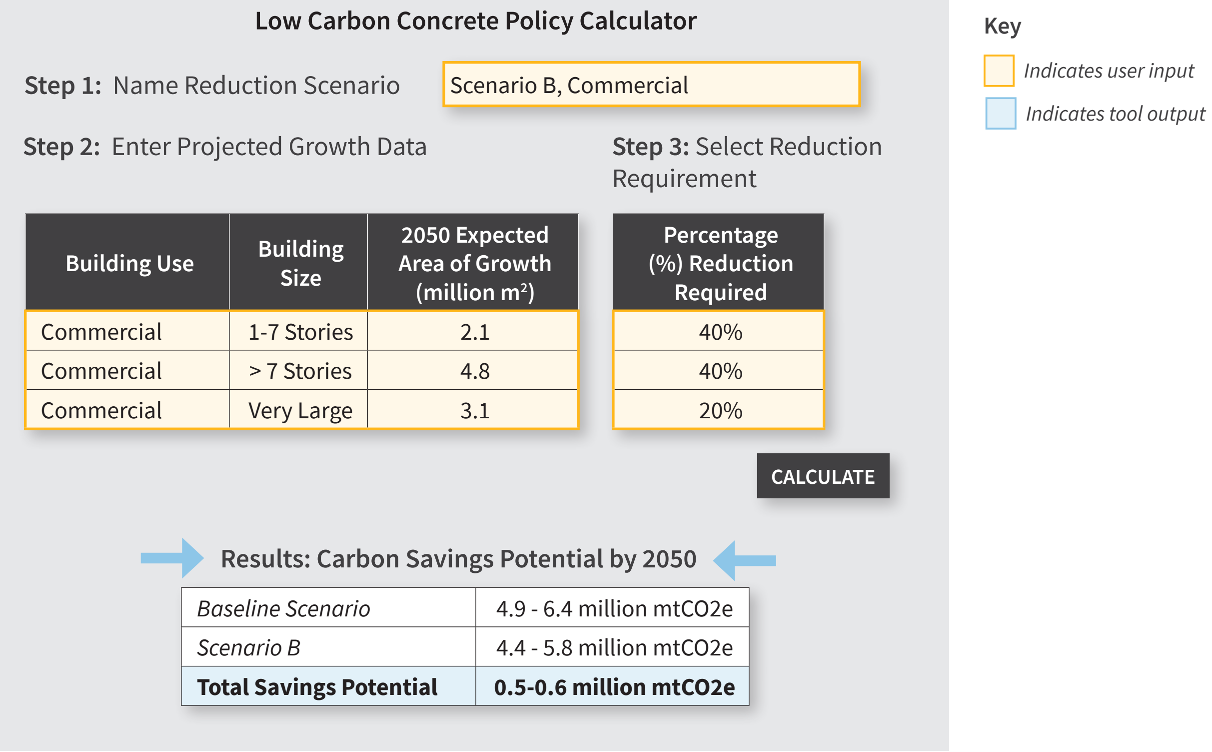
[16] County of Marin Sustainability Department. (2021). *Low-Carbon Concrete Requirements.* https://www.marincounty.org/depts/cd/divisions/sustainability/low-carbon-concrete.

[17] City of Portland Procurement. (n.d.). *Current Sustainable Procurement Initiatives.* https://www.portland.gov/omf/brfs/procurement/sustainable-procurement-program/sp-initiatives#!/

format. This calculator could also be adjusted to allow users to select GWP values, rather than percentage reductions, to more directly match the structure of many policies.

Figure 3 shows an illustrative example of the Low Carbon Concrete Policy calculator inputs and resulting outputs.



Low Carbon Concrete Policy Calculator

Step 1: Name Reduction Scenario: Scenario B, Commercial

Step 2: Enter Projected Growth Data

Building Use	Building Size	2050 Expected Area of Growth (million m²)
Commercial	1-7 Stories	2.1
Commercial	> 7 Stories	4.8
Commercial	Very Large	3.1

Step 3: Select Reduction Requirement

Percentage (%) Reduction Required
40%
40%
20%

Results: Carbon Savings Potential by 2050

Baseline Scenario	4.9 - 6.4 million mtCO2e
Scenario B	4.4 - 5.8 million mtCO2e
Total Savings Potential	**0.5-0.6 million mtCO2e**

Key

🟨 *Indicates user input*

🟦 *Indicates tool output*

Figure 3. Example of the Concrete Embodied Carbon Intensity Calculator inputs and outputs.

2.3 Increasing Adaptive Reuse

Calculator 3, or the "Adaptive Reuse Policy Calculator," was designed to answer the following question:

> If a city **incentivized the adaptive reuse of a percentage of existing building stock** rather than demolishing and building new, what would be the potential carbon savings by 2050 based on their current growth projections?

Answering this question would help policymakers advocate for policies that encourage developers and building owners to extend the life of existing buildings through adaptive reuse rather than building on greenfield sites or demolishing and building new.

2.3.1 Policy advantages and co-benefits

Extending the life of the physical resources already invested in a city's existing buildings and materials through adaptive reuse reduces embodied carbon through avoiding the release of emissions for the manufacturing and construction of new materials. Policies incentivizing adaptive reuse can:

- Avoid carbon emissions from manufacturing new materials for new construction;
- Reduce the environmental damage and community health impacts from landfilling construction materials after demolition;
- Avoid environmental damage from new construction on greenfield (i.e., previously undeveloped) sites by encouraging preservation and increased density in historic portions of cities;
- Preserve cultural resources and heritage, providing economic and social co-benefits;[18]
- Reduce local noise and pollution from demolition activities (depending on the scope of adaptive reuse); and
- Provide an opportunity for energy retrofits of outdated, inefficient, and high-emission MEP systems.

2.3.2 Policy precedents

Relatively few precedents exist for policies that directly encourage adaptive reuse, outside of historic tax credits. While historic tax credits and other historic preservation policies do incentivize building reuse, additional types of policies could apply to a broader range of building reuse, such as preservation of only a building's primary structure, foundation, and/or envelope. Since these types of building reuse may not retain the historic portions of a structure, they may not qualify for a historic tax credit but would still avoid significant carbon emissions.

The Los Angeles Adaptive Reuse Ordinance provides development incentives—such as mezzanines, density bonuses, reduction in off-street parking requirements, and other regulatory exemptions—for adaptive reuse of eligible buildings in the specified downtown project area.[19] Another example is the City of Vancouver's (B.C.) Empty Homes Tax,[20] which encourages empty and under-utilized properties to get back on the rental market.

The adaptive reuse calculator developed for this proof-of-concept focuses exclusively on the carbon savings potential from reusing existing buildings, not on the carbon savings potential of deconstruction for material reuse. Deconstruction policies, such as the Portland Deconstruction of Buildings Law,[21] can also reduce embodied carbon significantly and could be addressed by future versions of the Embodied Carbon Policy Reduction Calculator.

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[18] Historic England. (2020). *Heritage and the Economy 2020*. https://historicengland.org.uk/content/heritage-counts/pub/2020/heritage-and-the-economy-2020/

[19] Los Angeles Department of Building and Safety. (2001). *Adaptive Reuse Ordinance*. https://www.ladbs.org/docs/default-source/publications/ordinances/adaptive-reuse-ordinance---l-a-downtown-incentive-areas.pdf?sfvrsn=7

[20] City of Vancouver. (2022). Empty Homes Tax. https://vancouver.ca/home-property-development/empty-homes-tax.aspx

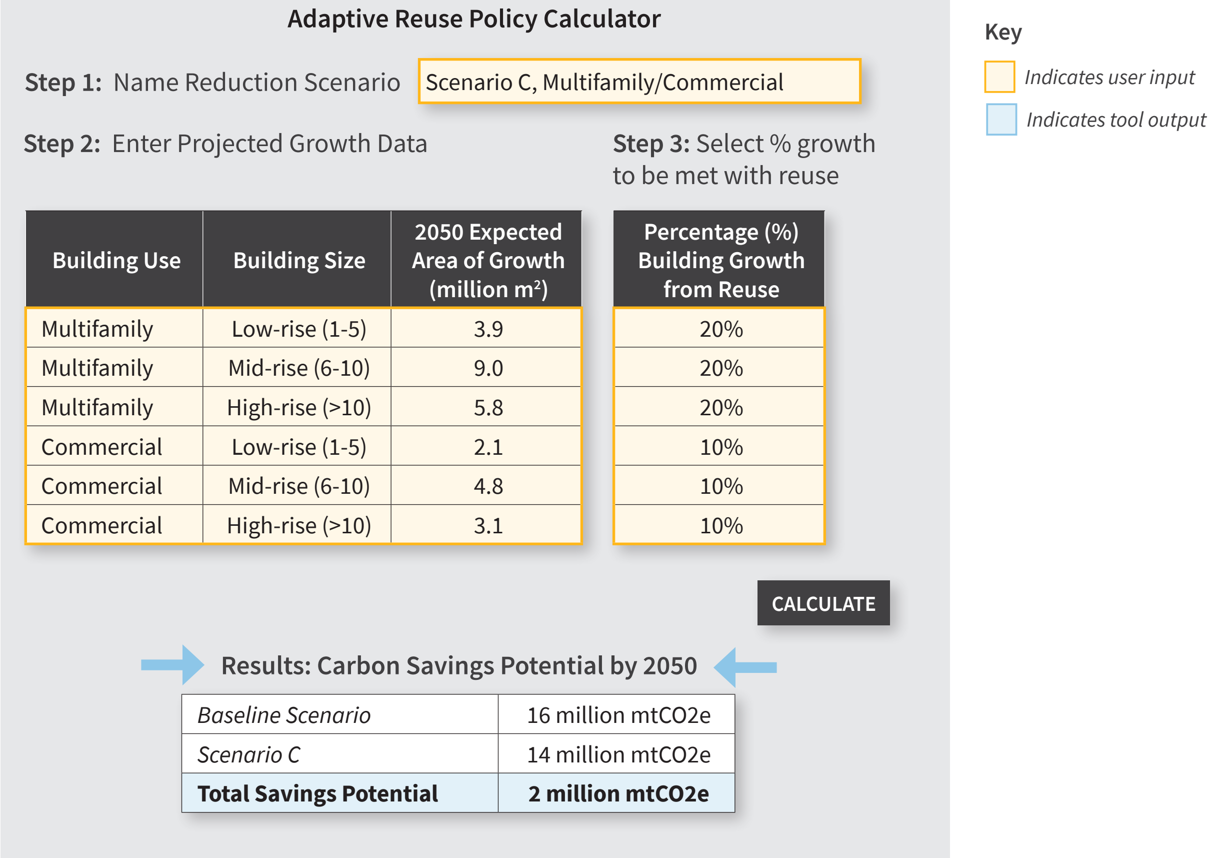
[21] City of Portland. (n.d.) *City Code Chapter 17.106 Deconstruction of Buildings Law*. https://www.portland.gov/code/17/106

2.3.3 Calculator functionality

To calculate a baseline scenario assuming 100% new construction, the calculator multiplies the projected area of growth for each typology by their corresponding BECI values. To calculate the reuse scenarios, the user selects a percentage of the total growth to be achieved through adaptive reuse, rather than new construction. The reuse area is then multiplied by reuse embodied carbon intensities while the remaining new construction area is multiplied by their corresponding BECI values. The impacts from both areas are then combined. See Appendix A Section A.5 for additional methodology details.

Similar to the BECI Reduction Policy and Low Carbon Concrete policy prototype calculators, the Adaptive Reuse Policy Calculator requires users to input building use, building size for that building use, and expected area of growth by 2050 (in m²) for building typologies being assessed. However, rather than selecting a percentage reduction requirement, users enter a percentage of projected growth to be met with adaptive reuse of existing buildings rather than new construction.

After entering this information, the calculator provides an estimate of projected embodied carbon by 2050 for a baseline scenario (e.g., new construction only) and the increased reuse scenario(s), and the total carbon savings potential by 2050. Figure 4 provides an illustrative example of the Adaptive Reuse Policy calculator inputs and resulting outputs.



Adaptive Reuse Policy Calculator

Step 1: Name Reduction Scenario: Scenario C, Multifamily/Commercial

Step 2: Enter Projected Growth Data

Step 3: Select % growth to be met with reuse

Building Use	Building Size	2050 Expected Area of Growth (million m²)	Percentage (%) Building Growth from Reuse
Multifamily	Low-rise (1-5)	3.9	20%
Multifamily	Mid-rise (6-10)	9.0	20%
Multifamily	High-rise (>10)	5.8	20%
Commercial	Low-rise (1-5)	2.1	10%
Commercial	Mid-rise (6-10)	4.8	10%
Commercial	High-rise (>10)	3.1	10%

Results: Carbon Savings Potential by 2050

Baseline Scenario	16 million mtCO2e
Scenario C	14 million mtCO2e
Total Savings Potential	**2 million mtCO2e**

Key

🟨 *Indicates user input*

🟦 *Indicates tool output*

Figure 4. Examples of the Adaptive Reuse Policy Calculator inputs and outputs.

2.4 Evaluating the embodied carbon impact of housing policy

Calculator 4, or the "Housing Size Policy Calculator," was designed to answer the following question:

What is the **impact of housing typology and unit size on the carbon footprint of growth required to meet housing needs** based on a city's current 2050 housing growth goals?

Cities across the globe need to increase their available housing units rapidly to meet the growing and currently unmet needs for housing. Answering the question above would enable policymakers to include embodied carbon as a metric alongside other key metrics for evaluating the impact of land use and zoning decisions related to housing policy.

However, due to the lack of available data on the embodied carbon of specific housing typologies (3-6 story, 6-10 story, etc.) the policy calculator developed for this study currently focuses on housing unit size only. While unit size is a critical factor in understanding the impact on embodied carbon of housing, it is not sufficient for making comparisons at the scales of urban development or zoning. Furthermore, the calculator does not currently take into account infrastructure and parking needs which are also critical for capturing a more holistic scope of housing development.

For these reasons, the housing policy calculator requires the most development and filling of data gaps before it can be usefully deployed at scale (see Appendix B for more information).

2.4.1 Policy advantages and co-benefits

Housing will comprise a large portion of the global construction growth between now and 2050. For example, for New York City and Portland, projected housing growth made up nearly 50% of total citywide growth and accounted for nearly twice the amount of any other building typology. Addressing the embodied carbon associated with housing is therefore critical for making meaningful embodied carbon reductions.

Reducing the size of individual units reduces total embodied carbon by allowing more housing units to be built with the same amount of new materials. Policies dealing with the efficiency of housing units have the following advantages and co-benefits:

- Directly reduces the embodied carbon and other environmental impacts associated with manufacturing new materials for more floor area;
- Increased quantity of affordable housing, as smaller units are typically the lowest-cost option in expensive urban areas;
- Targets the largest growth typology for most cities;
- Avoids environmental damage from construction on greenfield (i.e., previously undeveloped) sites by allowing for more efficient use of land resources in developed urban areas; and
- Can increase access to transit and city services through increased density, resulting in a wide range of environmental and public health benefits from less driving for commuting and other travel.[22]

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[22] C40 Cities Climate Leadership Group and C40 Knowledge Hub. (2021). *Why every city can benefit from a '15-minute city' vision*. https://www.c40knowledgehub.org/s/article/Why-every-city-can-benefit-from-a-15-minute-city-vision

2.4.2 Policy precedents

Restrictions on which housing typologies can be constructed in a particular urban area are typically set by zoning. Therefore, if a particular housing typology was identified as optimized for embodied carbon, no policy precedent would be required aside from zoning. However, there is not currently enough data to determine the relative embodied carbon associated with different housing typologies and building heights to the level of accuracy required to associate different zoning types with relative embodied carbon impacts.

The most relevant policy precedents for the current scope of the housing size policy calculator are those that directly target unit size by removing size minimums or encouraging development of micro units. For example, New York City removed minimum apartment sizes in 2016 to allow for micro units developed under Quality Housing Regulations. Minimum unit sizes still apply for affordable housing, affordable senior housing, and certain zoning districts. This has allowed for the development of projects like Carmel Place, an income-targeted modular development with a high percentage of micro units.[23]

While micro units are seen as a promising opportunity for increasing the quantity of affordable housing units, particularly for first-time renters or to provide housing access in more expensive urban areas, they are not politically feasible in certain cities.

2.4.3 Calculator functionality

Whereas all other prototype calculators assume a fixed area of growth as provided by each city, this reduction scenario instead assumes a fixed number of housing units. For the reduction scenarios run in this report, all numbers of units remained the same between baseline and reduction scenarios.

The Housing Policy EC Calculator requires inputs for building use and size, number of units required by 2050, and baseline average unit size. To calculate the baseline scenario, the calculator multiplies the baseline number of units by the typical unit size and estimated BECI value for each building typology. To calculate the reduction scenario, the calculator does a similar calculation with the custom unit size. Unit size was the only variable used. See Appendix A Section A.6 for additional methodology details.

The calculator provides similar projections to the other prototype calculators (i.e., projected embodied carbon by 2050 for a baseline and reduction scenario(s) and the total carbon savings potential). Figure 5 provides an illustrative example of the Housing Size Policy Calculator inputs and resulting outputs.

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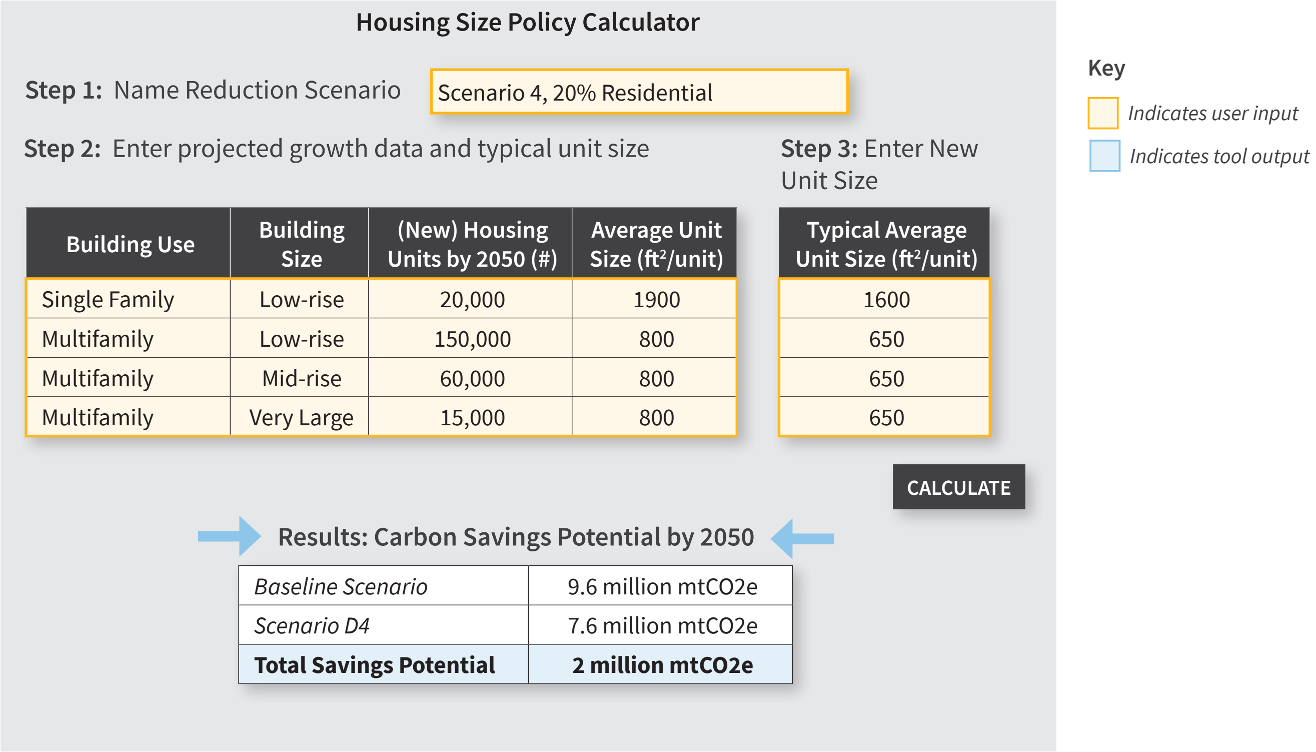
[23] Healthy Materials Lab Parsons School of Design. (2019). *Carmel Place: Innovative Practices for Healthier Homes*. https://prod-hml.s3.amazonaws.com/news/150219_Carmel-Place-Case-Study-Report.pdf



Housing Size Policy Calculator

Step 1: Name Reduction Scenario

Scenario 4, 20% Residential

Step 2: Enter projected growth data and typical unit size

Building Use	Building Size	(New) Housing Units by 2050 (#)	Average Unit Size (ft^2/unit)
Single Family	Low-rise	20,000	1900
Multifamily	Low-rise	150,000	800
Multifamily	Mid-rise	60,000	800
Multifamily	Very Large	15,000	800

Step 3: Enter New Unit Size

Typical Average Unit Size (ft^2/unit)
1600
650
650
650

Results: Carbon Savings Potential by 2050

Baseline Scenario	9.6 million mtCO2e
Scenario D4	7.6 million mtCO2e
Total Savings Potential	**2 million mtCO2e**

Key

- 🟨 *Indicates user input*
- 🟦 *Indicates tool output*

Figure 5. Example of the Housing Size Policy Calculator inputs and outputs.

3 CASE STUDIES

The research team collected projected floor area growth and building typology data from three pilot cities (New York City, Portland, and the Austin South Central Waterfront) to test the potential for use of the Embodied Carbon Policy Reduction Calculator to evaluate embodied carbon policy scenarios. The research team then assessed one baseline scenario and three to six reduction scenarios for each city.

Table 1 summarizes the baseline and reduction scenarios assessed for each city, including the theoretical reduction requirement and which building typologies the reductions were applied to for that scenario.

These scenarios were selected to model a range of reduction scenarios that vary in their ambition and scope (in terms of building typologies targeted). In some cases, reduction scenarios were chosen to reference specific published targets:

- Scenario A1 aligns with the 10% reduction criteria for the building life cycle impact reduction credit in LEEDv4 for New Construction.[24] Similar scenarios could be modeled to understand the potential impact of requiring the Living Building Challenge (requires a 20% reduction) or other certifications.
- Scenarios A2 and A4 align with the 40% reduction target set by Austin's Climate Equity Action Plan.[25]
- Scenarios A5 and B3 align with the 50% reduction targets put forth by the Clean Construction Declaration.[26]
- Research indicates that approximately 30% reductions in the embodied carbon of concrete are possible without additional cost.[27] For this reason, the research team chose 30%, rather than 10% as a conservative percentage reduction requirement for Scenarios B1 and B2.

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[24] United States Green Building Council. (n.d.). *Building product disclosure and optimization - environmental product declarations.* https://www.usgbc.org/credits/new-construction-schools-new-construction-retail-new-construction-data-centers-new-3?return=/credits/new-construction/v4.

[25] City of Austin. (2020). *Austin Climate Equity Action Plan.* https://www.austintexas.gov/page/austin-climate-equity-plan

[26] C40 Cities. (n.d.). *Clean Construction Declaration*. https://www.c40.org/declarations/clean-construction-declaration/.

[27] Esau, R., Jungclaus, M., Olgyay, V., and Rempher, A. (2021). *Reducing Embodied Carbon in Construction: Low Cost-High Value Opportunities*. https://rmi.org/insight/reducing-embodied-carbon-in-buildings/.

Table 1. Baseline and reduction scenarios assessed for each city.

Scenario	Reductions Required	Building typologies included in scope		
		New York City	*Portland*	*Austin*
BECI Reduction Policy Calculator				
A0 Baseline	**0%** reduction (no policy introduced)	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Retail, Multifamily, Hotel
A1	**10%** reduction requirement	Commercial	Commercial	Office, Retail, Hotel
A2	**40%** reduction requirement	Multifamily	Multifamily	Multifamily
A3	**30%** reduction requirement	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Retail, Multifamily, Hotel
A4	**40%** reduction requirement	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Retail, Multifamily, Hotel
A5	**50%** reduction requirement	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Retail, Multifamily, Hotel
Low-Carbon Concrete Policy Calculator				
B0 Baseline	**0%** reduction (no policy introduced)	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Retail, Multifamily, Hotel
B1	**30%** reduction requirement	Commercial	Commercial	Office, Retail, Hotel
B2	**30%** reduction requirement	Multifamily	Multifamily	Multifamily
B3	**50%** reduction requirement	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	Office, Multifamily, Retail, Hotel
Adaptive Reuse Policy Calculator				
C0 Baseline	**100% new construction** (no policy introduced)	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	N/A
C1	**5%** of growth is adaptive reuse	1-4 Family, Commercial, Multifamily, Institutional	Commercial, Multifamily	N/A
C2	**10%** of growth is adaptive reuse	1-4 Family, Commercial, Multifamily, Institutional	Commercial, Multifamily	N/A
C3	**30%** of growth is adaptive reuse	1-4 Family, Commercial, Multifamily, Institutional	Single Family, Commercial, Multifamily	N/A
Housing Size Policy Calculator				
D0 Baseline	**0%** reduction (no policy introduced)	1-4 Family, Multifamily	Single Family, Multifamily	Single Family, Multifamily
D1	**20%** reduction in unit size	1-4 Family	Single Family	N/A
D2	**10%** reduction in unit size	Multifamily	Multifamily	Multifamily
D3	**30%** of units are micro-units	Multifamily	Multifamily	Multifamily
D4	**20%** reduction in unit size	1-4 Family, Multifamily	Single Family, Multifamily	Single Family, Multifamily

3.1 City of New York

The research team used projected floor area growth from the New York City's 80x50 Technical Working Group report[28] to calculate the carbon reduction potential for four types of policies. The data available in the report represented future growth projections for 1-4 family residential, multifamily residential, commercial, and institutional building types by total area. Internal assumptions were used to fill multiple data gaps for the City of New York's growth projections including estimates of typical building heights, construction types, and other variables that affect embodied carbon. To read more about the methodology for Projecting Construction Growth for Pilot Cities, see Appendix A.1.

Figures 6 and 7 show the highest potential carbon saving scenarios from each prototype calculator for New York City.

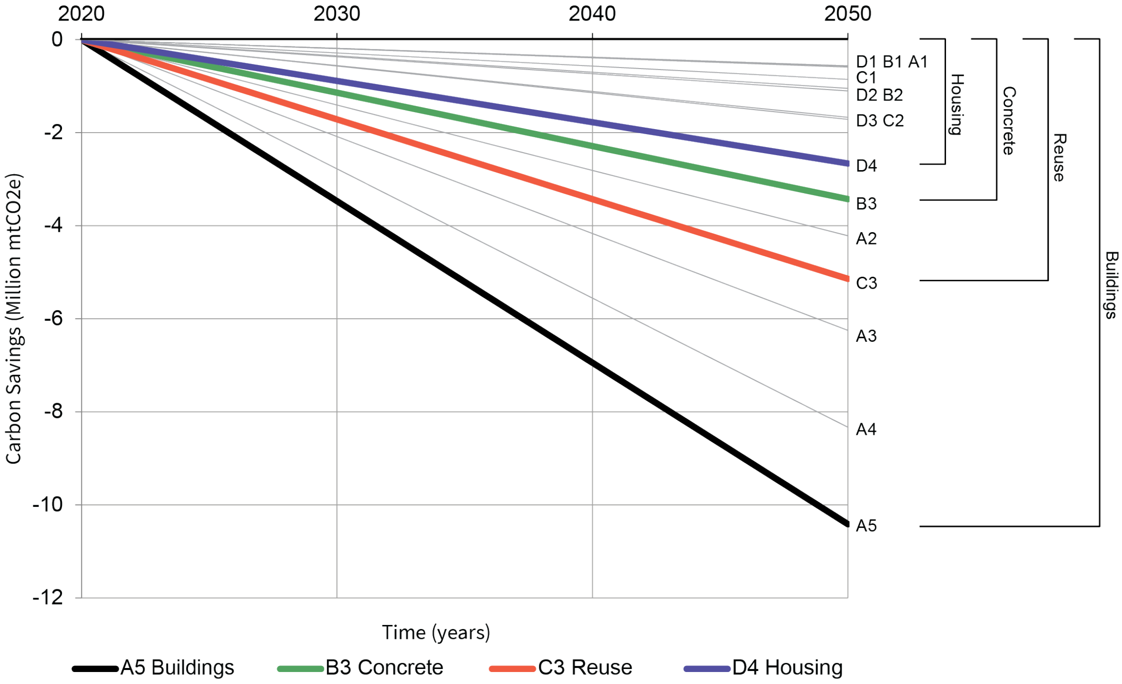

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Figure 6. Preliminary cumulative carbon savings results for City of New York comparing all scenarios studied and illustrating maximum reduction (i.e., the most progressive policy scenario analyzed) from each prototype calculator in bold.

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[28] New York City Mayor's Office of Sustainability. (2016). *One City Built to Last Technical Working Group Report.* http://www.nyc.gov/html/gbee/downloads/pdf/TWGreport_2ndEdition_sm.pdf.

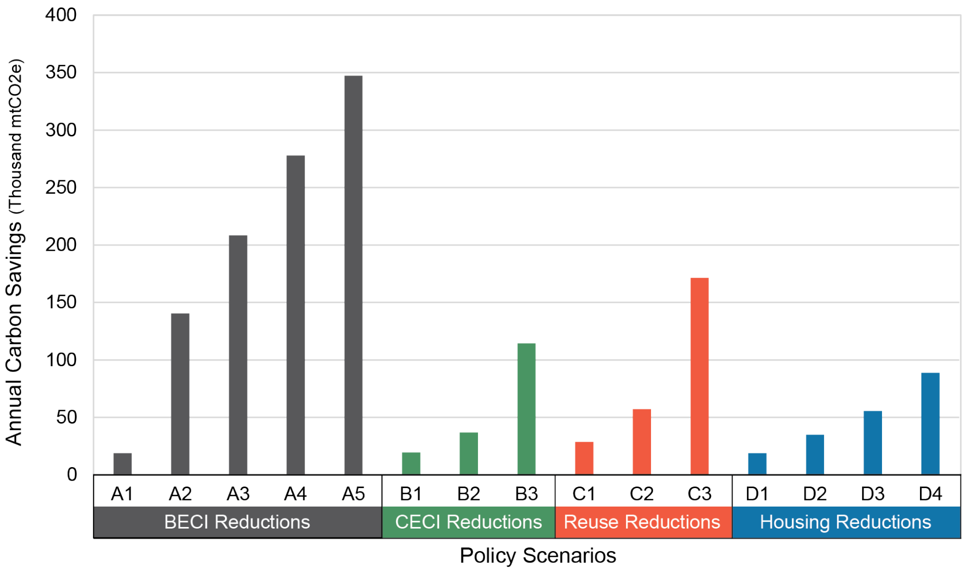

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Figure 7. Preliminary annual carbon savings results for the City of New York comparing all reduction scenarios from each prototype calculator.

This section summarizes initial takeaways that demonstrate the potential of this type of calculator to inform decision-making. However, as these calculators are designed currently as a proof-of-concept, results are directionally accurate and do not yet allow for detailed comparisons. See Appendix B for a discussion of the research and data required to increase the functionality of the calculators for use in decision-making.

Preliminary takeaways include:

- The largest policy opportunity (i.e., largest carbon savings potential) of the scenarios evaluated is requiring reductions in building embodied carbon intensity (BECI)—such as the 50% reduction targets in alignment with the Clean Construction Declaration evaluated in BECI Scenario A5. Even a 30% reduction in BECI (Scenario A3) was still greater than any other scenario from the concrete, reuse, or housing policy calculators.
- The second largest policy opportunity is Reuse. Scenario C3 evaluates the potential of incentivizing adaptive reuse (as opposed to new construction) for about 30% of the growth for commercial, residential, and institutional building stock (approximately 0.23% of the existing building stock area).
- Of the building use types studied, multifamily residential presents the largest opportunity for embodied carbon intensity reduction policies in New York City. This is largely due to multifamily residential having the largest projected growth by 2050. For example, requiring a 40% reduction in BECI for multifamily construction alone has about the same impact as requiring 75% reductions in the embodied carbon of concrete for all commercial, multifamily, and institutional buildings.
- While 1-4 family housing units are the largest unit sizes studied for New York City, they still represent the lowest potential for embodied carbon reductions from unit size changes. This is due to the relatively small amount of projected growth area for 1-4 family houses when compared to multifamily, as well as the less carbon-intensive construction of 1-4 family houses.

- This study only evaluated relatively small percentage reductions in embodied carbon (10-50%). Larger reduction requirements would result in much larger carbon savings potentials.

Figures 8-11 demonstrate the graphic output of each prototype calculator, showing the projected total embodied carbon emissions of the baseline scenario and reduction scenarios from 2020-2050. To see additional results for each city from the prototype calculators, see Appendix C.

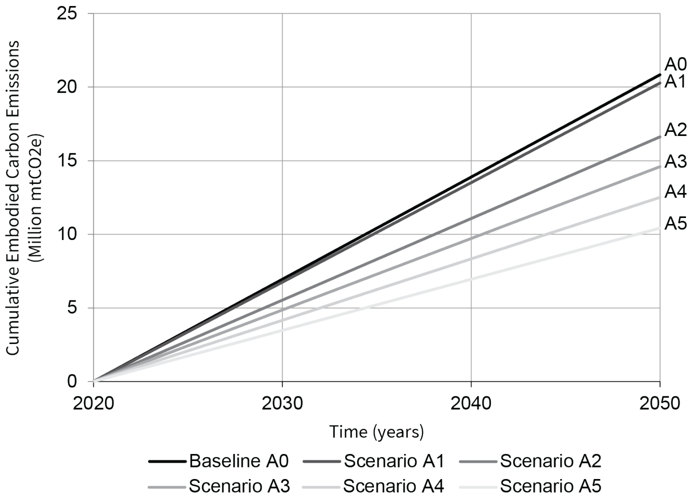

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Figure 8. Preliminary building embodied carbon intensity scenarios for New York City displaying estimates of cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

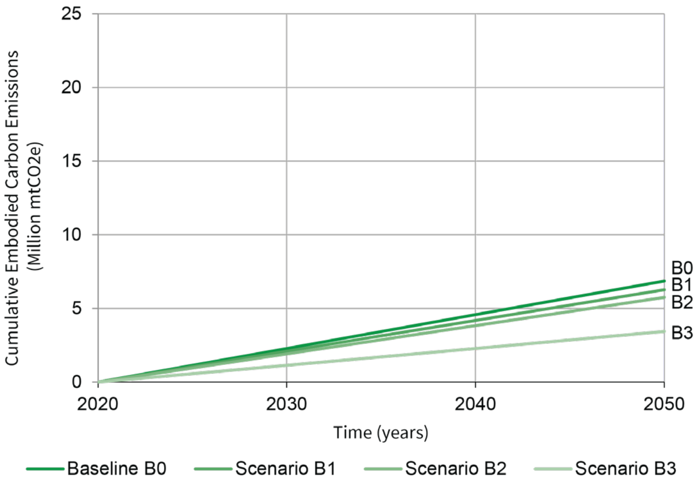

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Figure 9. Preliminary concrete embodied carbon intensity scenarios for New York City displaying estimates of cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050. Results displayed as averages between high and low ranges. Data represents the impacts from concrete only.

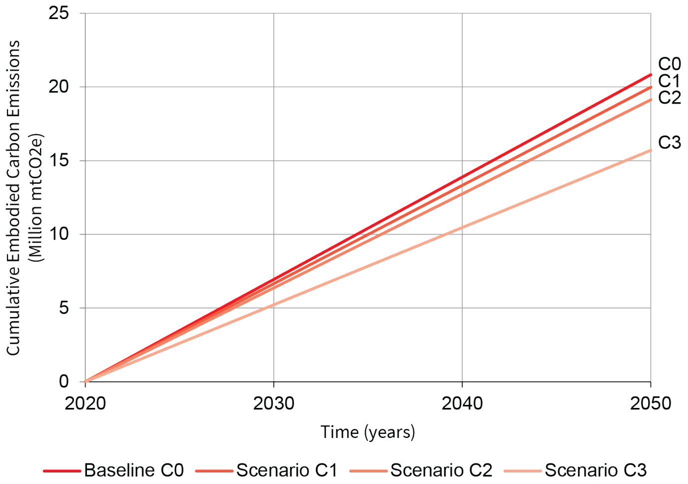

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Figure 10. Preliminary adaptive reuse scenarios for New York City showing estimates of cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

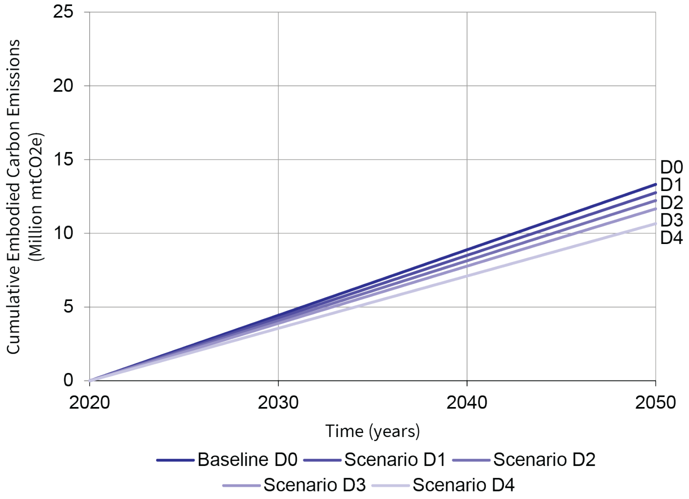

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Figure 11. Preliminary housing policy results scenarios for New York City showing estimates of cumulative embodied carbon emissions of the baseline scenario and four reduction scenarios from 2020-2050.

3.2 City of Portland

The research team used projected floor area growth from the City of Portland's 2007 analysis of baseline building stock and future growth (data provided directly from the City of Portland) to calculate the carbon reduction potential for the four types of policies. The data available in the report represented future growth projections for single family residential, multifamily residential, and commercial building types by total area. Internal assumptions were used to fill multiple data gaps for the City of Portland's growth projections, including estimates of typical building heights, construction types, and other variables that affect embodied carbon. To read more about the methodology for Projecting Construction Growth for Pilot Cities, see Appendix A.1.

Figures 12 and 13 show the highest potential carbon saving scenarios estimated using each prototype calculator for the City of Portland.

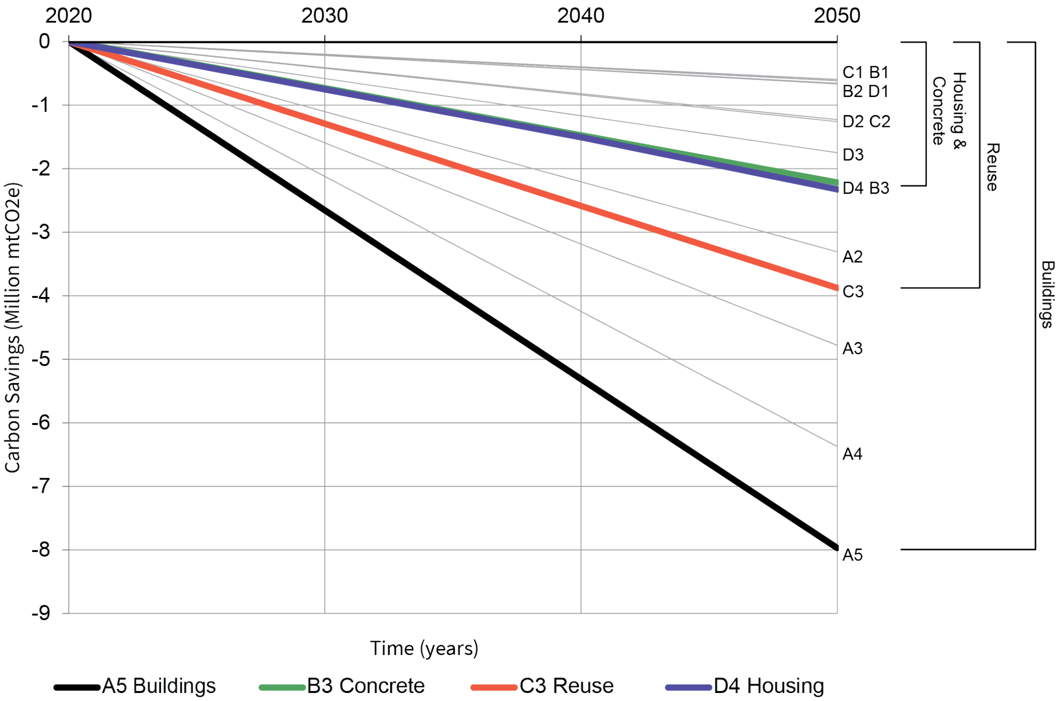

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Figure 12. Preliminary cumulative carbon savings results for City of Portland comparing all scenarios studied and illustrating maximum reduction (i.e., the most progressive policy scenario analyzed) from each prototype calculator in bold.

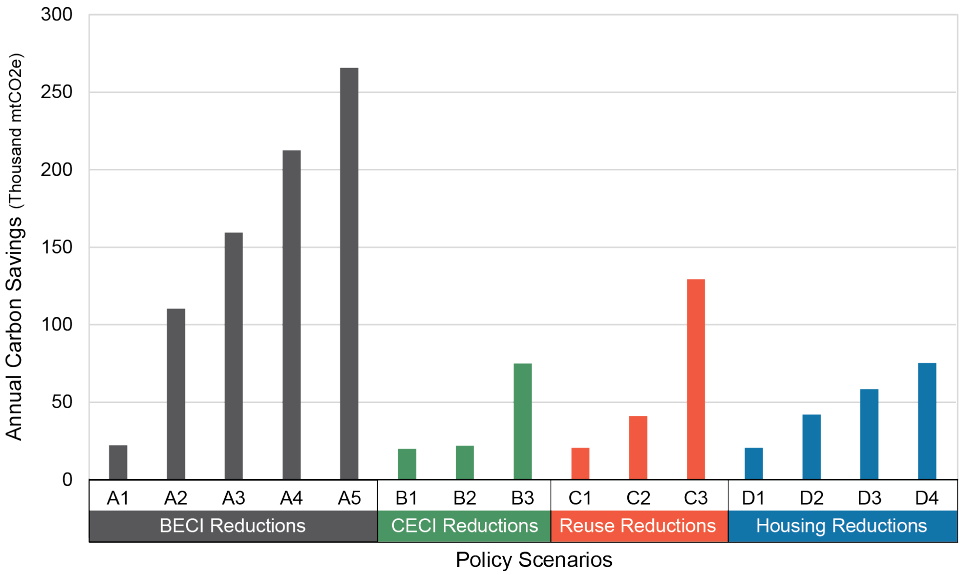

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Figure 13. Preliminary annual carbon savings results for City of Portland comparing all reduction scenarios from each policy calculator.

This section summarizes initial takeaways that demonstrate the potential of this type of calculator to inform decision-making. However, as these calculators are designed currently as a proof-of-concept, results are directionally accurate and do not yet allow for detailed comparisons. See Appendix B for a discussion of the research and data required to increase the functionality of the calculators for use in decision-making.

Preliminary takeaways include:

- Commercial and multifamily residential both represent significant opportunities for embodied carbon policy. For example, Scenarios B1 and B2 have the nearly the same carbon savings potentials.
- The largest policy opportunity (i.e., the largest carbon savings potential) of the scenarios evaluated is requiring reductions in building embodied carbon intensity (BECI), such as the 50% reduction targets in alignment with the Clean Construction Declaration evaluated in Scenario A5. Even a 30% reduction in BECI (Scenario A3) is still greater than any other scenario from the concrete, reuse, or housing policy prototype calculators.
- The second largest policy opportunity is Reuse. Scenario C3 evaluates the potential of incentivizing adaptive reuse (as opposed to new construction) for about 30% of the growth for commercial and residential and building stock (approximately 0.23% of the existing building stock area).
- This study only evaluated relatively small percentage reductions in embodied carbon (10-50%). Larger reduction requirements would result in much larger carbon savings potentials.

Figures 14 - 17 demonstrate the graphic output of each prototype calculator, showing the total embodied carbon emissions of the baseline scenario and reduction scenarios from 2020-2050. For additional results for each city from the prototype calculators, see Appendix C.

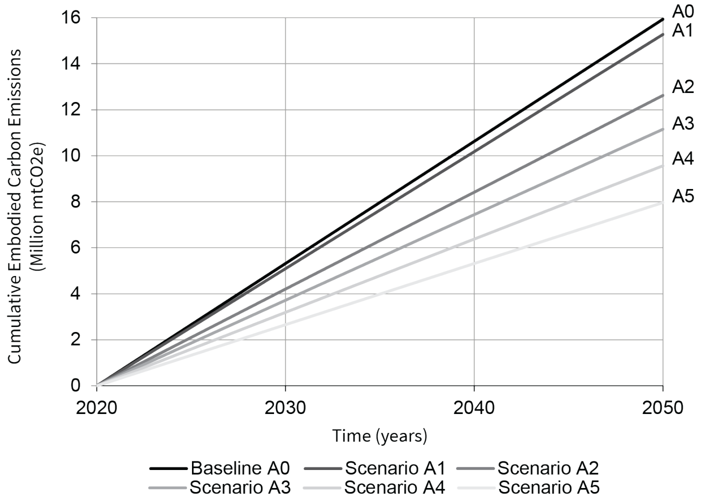

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Figure 14. Preliminary building embodied carbon intensity scenarios for Portland displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

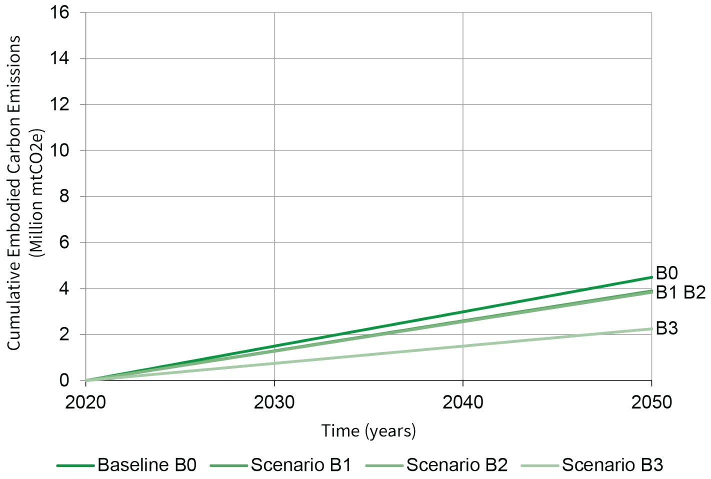

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Figure 15. Preliminary concrete embodied carbon intensity scenarios for Portland displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050. Results displayed as averages between high and low ranges. Data represents the impacts from concrete only.

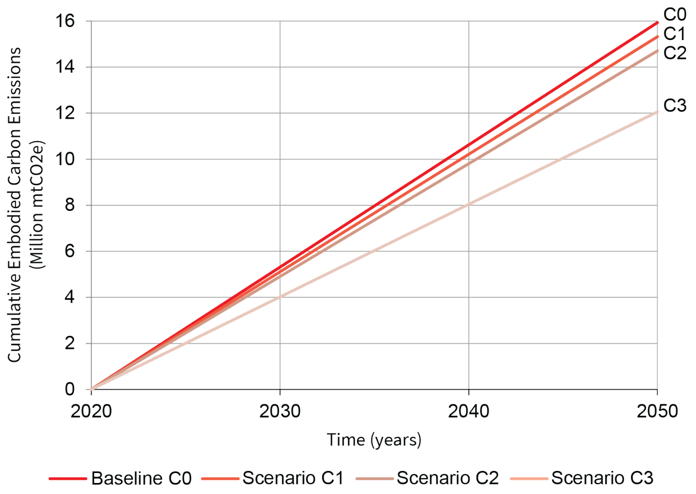

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Figure 16. Preliminary adaptive reuse scenarios for Portland displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

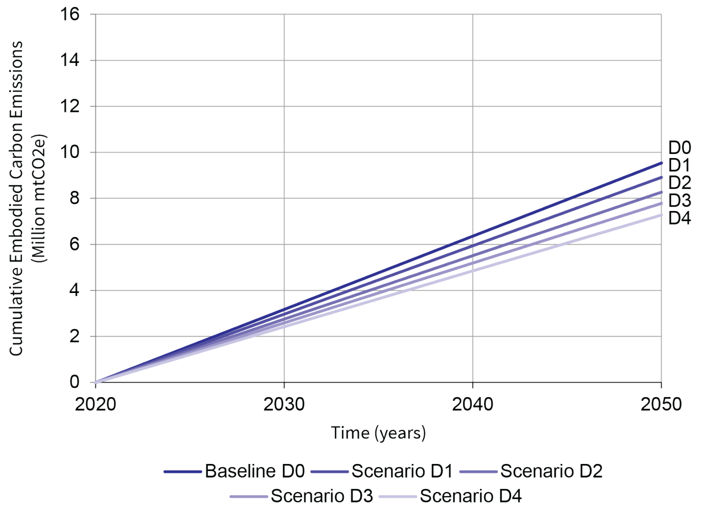

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Figure 17. Preliminary housing policy scenarios for Portland displaying cumulative embodied carbon emissions of the baseline scenario and four reduction scenarios from 2020-2050.

3.3 City of Austin South Central Waterfront (SCW)

The research team used projected floor area growth from the Austin South Central Waterfront (SCW) Vision Framework Plan[29] to calculate the carbon reduction potential for four types of policies. The SCW was used in lieu of available city-wide data to show the potential of the pilot calculator for evaluating planned developments or neighborhood-wide growth plans. The data available in the report represented future growth projections for multifamily residential, retail, office, and hotel building types by total area. Internal assumptions were used to fill multiple data gaps for the City of Austin SCW's growth projections including estimates of typical building heights, construction types, and other variables that affect embodied carbon. To read more about the methodology for Projecting Construction Growth for Pilot Cities, see Appendix A.1.

Figures 18 and 19 show the highest potential carbon saving scenarios estimated with each prototype calculator for the Austin South Central Waterfront.

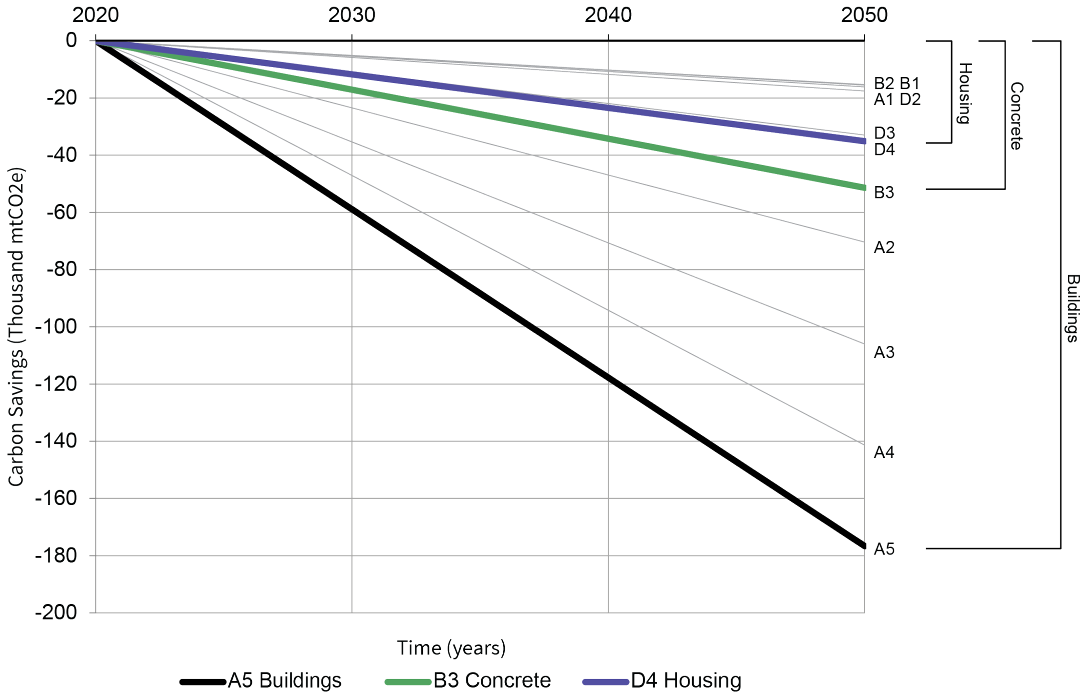

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Figure 18. Preliminary cumulative carbon savings results for the City of Austin SCW comparing all scenarios studied and illustrating maximum reduction (i.e., most progressive policy scenario analyzed) from each policy calculator in bold.

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[29] City of Austin South Central Waterfront (SCW) Project Team. (2016). *South Central Waterfront Vision Framework Plan.* https://www.austintexas.gov/page/south-central-waterfront

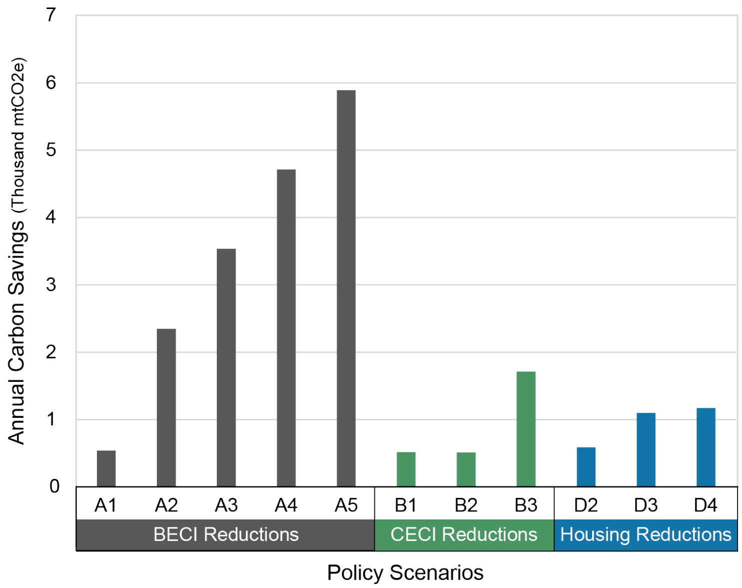

Figure 19. Preliminary annual carbon savings results for the City of Austin SCW comparing all reduction scenarios from each policy calculator.

This section summarizes initial takeaways that demonstrate the potential of this type of calculator to inform decision-making. However, as these calculators are designed currently as a proof-of-concept, results are directionally accurate and do not yet allow for detailed comparisons. See Appendix B for a discussion of the research and data required to increase the functionality of the calculators for use in decision-making.

Preliminary takeaways include:

- Commercial (i.e., office, retail, hotel) is the largest opportunity, closely followed by multifamily residential. Policies targeting multifamily residential and commercial would both be impactful.
- The largest policy opportunity (i.e., the largest carbon savings potential) of the scenarios evaluated is requiring reductions in building embodied carbon intensity (BECI). The 50% reduction targets in alignment with the Clean Construction Declaration evaluated in Scenario A5 is the largest potential studied. However, even a 30% reduction in BECI (Scenario A3) would still be a larger carbon savings than any option from the concrete, reuse, or housing policy calculators.
- A 50% reduction for concrete (Scenario B3) was the largest opportunity for carbon savings outside of the BECI scenarios.
- Reductions in unit size (D3) and 50% reductions in the embodied carbon of concrete for commercial, multifamily, retail, and hotel building uses (B3) resulted in similar carbon savings potentials, with concrete being slightly higher.
- This study only evaluated relatively small percentage reductions in embodied carbon (10-50%). Larger reduction requirements would result in much larger carbon savings potentials.

Figures 20 - 22 demonstrate the graphic output of each prototype calculator, showing the total embodied carbon emissions of the baseline scenario and reduction scenarios from 2020-2050. For additional results for each city from the prototype calculators, see Appendix C.

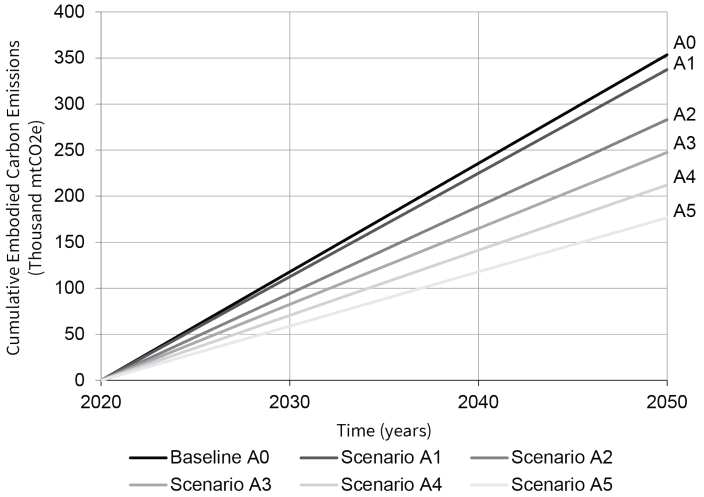

Figure 20. Preliminary building embodied carbon intensity scenarios for Austin SCW displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

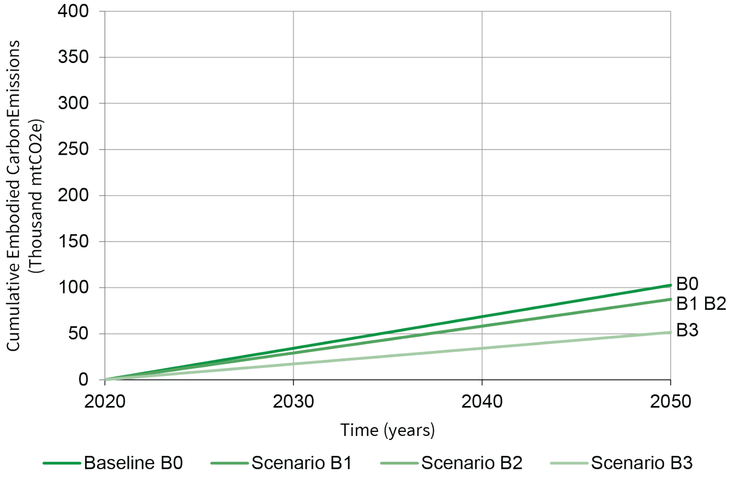

Figure 21. Preliminary concrete embodied carbon intensity scenarios for Austin SCW displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050. Results displayed as averages between high and low ranges. Data represents the impacts from concrete only.

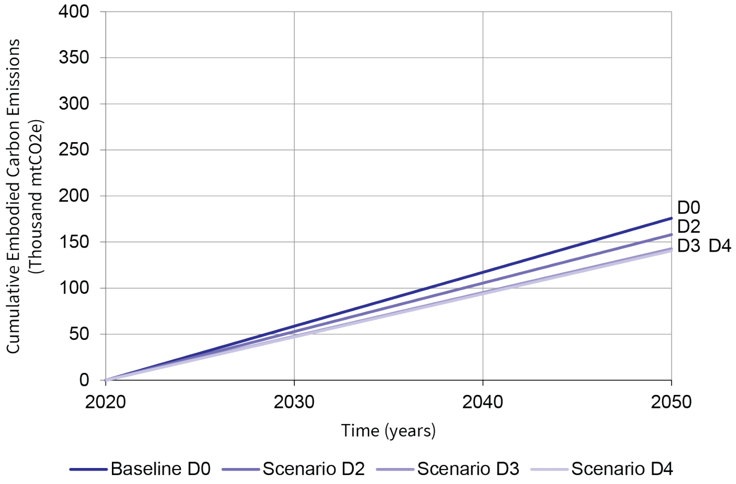

Figure 22. Preliminary housing policy scenarios for Austin SCW displaying cumulative embodied carbon emissions of the baseline scenario and three reduction scenarios from 2020-2050.

3.4 Summary of Feedback from Cities

In January 2022, the CLF and C40 teams presented the results of each case study to individuals from each of the cities in the proof-of-concept study. Overall, each city found the concept helpful and useful for advancing embodied carbon policies within their city. The types of feedback received fell into five major categories:

Use in communicating policies:

The pilot cities all agreed on the value of such a tool. They could see themselves using the calculators for internal discussion with their immediate teams for draft policy development as well as to engage others such as city planners, zoning departments, and other stakeholders. Furthermore, they could envision using the calculators alongside other metrics and benefits of the policies to aid in making political cases for the adoption of embodied carbon reduction policies at Mayoral, City Council, or Commissioner levels.

They also recommended the following additions to the calculators (or calculator interfaces) that could help communicate results and the importance of embodied carbon policies:

- easily shareable or exportable results that could be combined with other analyses;
- communicating co-benefits (in addition to direct embodied carbon benefits) for each policy, such as density, public health impacts, or reduced demolition or other local pollution impacts;
- including comparable carbon metrics as outputs (e.g., coal-fired power plant emissions, cars off the road);
- finding ways to communicate the challenges associated with each policy to non-experts, such as strength or cure-time issues related to low-carbon concrete policies; and
- integrating associated “costs” with each policy.

Use in developing policies:

- All three pilot cities found the building embodied carbon intensity reduction policy, low-carbon concrete policy, and adaptive reuse policy calculators to be most relevant to their work. The housing policy calculator was identified as needing the most future development.
- They thought it was great how the calculators were set up to be able to compare different scenarios and see where the largest opportunities could be achieved.
- In several cases, the scope of the policy calculators (i.e., which policies were being assessed) spurred conversation as to whether the cities should consider new types of policies that they had not previously considered. For example, several teams were surprised to see how impactful the BECI reductions could be and appreciated how a policy could be flexible for architects, engineers, and contractors to achieve the targets, which they had not previously considered. Another team highlighted that the adaptive reuse calculator was exciting to see, given the recent availability of vacant buildings and potential for reuse.

- One team highlighted that the regional baselines and benchmarks the calculators are built with would be very important on their own, and that the ability for users to calibrate these baselines in the tools (i.e., if they had agency-specific data, for example) would be helpful.

Additional functionality and data gaps:

Pilot cities were asked to highlight which additional functionality or data gaps for the calculators would be a high priority for the research team to address in future stages of development for each calculator. The priorities indicated by each pilot city are integrated into Tables B1-B2 in Appendix B.

Pilot cities also highlighted the following opportunities to expand the functionality of the calculators:

- allowing users to modify the global warming potential (GWP) baseline values in the BECI reduction policy and low-carbon concrete policy calculators;
- including more granular building typologies (e.g., hospitals or schools rather than 'institutional') to align with the Commercial Buildings Energy Consumption Survey (CBECS) categories

Political challenges:

While discussing the functionality and potential for each calculator in communicating the importance of embodied carbon policies, the pilot cities shared thoughts related to the political challenges associated with each policy in the scope of this proof-of-concept study.

Although the politics associated with each policy framework are not the focus of these calculators, they are relevant to what type of functionality and user interface could be included to improve the utility for cities. For example, several pilot cities identified low-carbon concrete policies as "low-hanging fruit" that are relatively politically straightforward and feasible, especially with low reductions that don't pose cost or construction challenges. This would influence how quickly that type of policy could be passed, which would in turn impact the total reductions achievable by 2050. This could be addressed by the calculators in the future by:

- allowing users to input the year that a policy is introduced
- allowing for stepped limits
- accounting for the time value of carbon

Some of these comments were related to how the calculators could be framed. For example, one city suggested framing the adaptive reuse calculator as reduced demolition, rather than adaptive reuse. Another city highlighted the political challenges associated with the term "density" in their city.

These framing questions could be addressed by:

- allowing cities to export the data and communicate it with more politically friendly terminology for their local context (assuming that communication did not change the scope of what was actually measured); and

- conducting a survey to a broader range of C40 cities to request feedback on preferred terminology used by the calculators, after additional development of each calculator.

Other comments and suggestions:

Cities were also interested in understanding how the calculator estimates related to consumption-based accounting. This would be a helpful topic to address in educational resources in the future.

Some cities also had additional ideas on how current or future city-specific data sources could be used to fill data gaps, such as typologies, demolition/reuse, unit sizes, and building height. These recommendations have been included in Appendix B.

4 CONCLUSION

In this study, four prototype embodied carbon policy calculators were developed and tested on three different C40 pilot cities including New York City, Portland, and Austin. The intent of the study was to prove the concept and functionality of developing calculators for estimating embodied carbon at the scale of a city and assessing whether this type of data would be useful for developing and communicating embodied carbon policies.

The prototype calculators proved effective for estimating order-of-magnitude embodied carbon impacts of the different policies and were able to generate meaningful outputs that, with additional future research and development, could help inform real-world policy decision-making. For instance, preliminary results from the prototype calculators indicated that requiring reductions in building embodied carbon intensity was the most impactful for making city-scale reductions, followed by incentivizing adaptive reuse. However, multiple significant data and functionality gaps were identified as being critical for future development before the calculators could be applied in a real-world policy setting.

Throughout the study, the authors and contributors sought feedback from the pilot cities on the efficacy and applicability of the selected policy types and calculators. Each city overwhelmingly found the building embodied carbon intensity, limiting carbon content of concrete, and increasing adaptive reuse to be the most helpful and useful policy calculators for communicating the importance of embodied carbon and advancing policy development in their city. Additionally, the city feedback reinforced the need for future research development of the calculators. High priorities for future work include:

- Developing regionally and typologically specific building embodied carbon intensity values;
- Expanding the physical and temporal scope of the calculators to include infrastructure, parking, and cradle-to-grave impacts;
- Including stepped policy limits to evaluate the impact of incremental phasing over time and the cumulative impact of two or more policies combined; and
- Adding additional policy types that could target material reuse, procurement, or other types of planning and zoning strategies.

City policymakers need to have measurable, reliable, and actionable metrics to support their decision-making on embodied carbon policies. These future research priorities, and others listed in Appendix B, will help refine and expand the calculators in order to provide those metrics and help cities across the globe address the urgent need to decarbonize the built environment.

APPENDIX A: METHODOLOGY

This section provides an overview of the assumptions and methodology that were required to develop each calculator.

A.1 Projecting Construction Growth for Pilot Cities

City representatives from New York City, Portland, and Austin provided the CLF team with available reports and data to project construction growth for each city. These datasets were used to calculate estimates of the embodied carbon savings potential associated with each policy scenario.

A.1.1 Area Growth Projections

The pilot cities provided either city-wide or district-wide total square footage projections for new construction. The projections provided by each city were largely based on local building trends and population growth projections derived from recently published comprehensive planning documents. They were adjusted for this study to reflect a 2020 - 2050 growth window.

New York City's 80x50 Technical Working Group report[30] and the City of Portland's 2007 analysis of baseline building stock and future growth[31] included anticipated growth up to the year 2050. City-wide data for anticipated growth by building typology was not available for the City of Austin. As a result, the 2016 district-wide comprehensive plan for South Central Waterfront (SCW) Vision Framework Plan was used for this pilot.[32] The anticipated completion date for the Austin development is unknown, and does not necessarily reflect a 2050 target.

A.1.2 Building Use

The same datasets that were used for the growth projections of each pilot city also contained total growth projections by building use for each city. These included uses such as multifamily residential, commercial, institutional, etc. The building uses reflect key differences in the fabric of each city and were used in the pilot report as provided (see Table A1).

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[30] New York City Mayor's Office of Sustainability. (2016). *One City Built to Last Technical Working Group Report*. http://www.nyc.gov/html/gbee/downloads/pdf/TWGreport_2ndEdition_sm.pdf

[31] City of Portland. (2017). *Baseline & Projections Analysis Scenario Modeling.* [Private data set].

[32] City of Austin. (2016). *South Central Waterfront Vision Framework Plan*. https://www.austintexas.gov/sites/default/files/files/Housing_%26_Planning/South%20Central%20Waterfront/2016%20South%20Central%20Waterfront%20Vision%20Framework.pdf

Table A1. Building uses for each pilot city

City	Building use
New York City	1-4 Family Rowhouse Multifamily Commercial Institutional
Portland	Single-Family Residential Multifamily Commercial
Austin SCW	Office Retail Multifamily Residential Hotel

A.1.3 Linear Growth

The calculators in this study all assume linear growth for each city and building typology. See Appendix B for considerations of the time value of carbon and the potential for future integration of nonlinear growth models.

A.2 Estimating the Embodied Carbon Intensity of Building Typologies

Estimating embodied carbon impacts associated with the future growth of cities requires data on the following variables, which are critical in determining the embodied carbon intensity of a building:

1. Area of growth for each building use (ft² or m²), described in A.1;
2. Range of typical building height for each building use (i.e., whether the growth is of low-rise, mid-rise, or high-rise buildings, and what the typical range of building levels is for that category);
3. Typical construction type(s) for each building use (e.g., light-frame wood vs. metal construction for multi-family residential, etc.)
4. Typical embodied carbon intensity for that building use, height range, and construction type.

While each pilot city provided total projected growth and building use types, it was necessary to make assumptions for variables 2-4 listed above. Sensitivity analyses were conducted for assumptions that were highly variable or sensitive to total carbon impacts.

A.2.1 Building Size

Table A2 summarizes the methods used for each city to estimate what percentages of its growth area projections fall into specific use and height categories.

Table A2. Building size, percentages, and source methodologies used for each pilot city.

City	Source	Building use	Building size	Building size as percentage of total building use
New York City	Aggregated 2021 DOB filings from YIMBY Report[33] into total square footage groupings	1-4 Family	1-4 Family	100%
		Multifamily & Commercial	1-7 Stories	21%
			>7 Stories	48%
			Very Large (buildings > 500,000 ft^2, typically highrises)	31%
		Institutional	1-7 Stories	80%
			> 7 Stories	20%
Portland	Aggregated existing building stock data provided by the City of Portland into total square footage groupings. Heights inferred from square footages	Single Family	Single Family	100%
		Multifamily	Low Rise 1-5 Stories	65%
			Mid Rise 6-10 Stories	26%
			High Rise > 10 Stories	9%
		Commercial	Low Rise 1-5 Stories	38%
			Mid Rise 6-10 Stories	46%
			High Rise > 10 Stories	16%
Austin SCW	All SCW buildings were considered "High Rise >10 Stories." Of the 23 buildings described in the SCW,[34] 19 of them were 100' or taller, while only 3 were less than 100' tall (90', 90', and 60' respectively).	Office	High-rise >10 Stories	100%
		Retail	High-rise >10 Stories	100%
		Multifamily	High-rise >10 Stories	100%
		Hotel	High-rise >10 Stories	100%

A.2.2 Building Typologies

In this report, building typology refers to a category of buildings with the same building use and building size. For example, "commercial" is a building use, whereas "commercial mid-rise (6-10 stories)" is a building typology. When a projected growth area is broken down by building typology it provides the value for building typology growth area (BTGA).

A.2.3 Building Embodied Carbon Intensity (BECI)

BECI is derived from conducting a whole building LCA and varies widely.[35] There are many factors that may influence the total embodied carbon intensity of buildings, such as:

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[33] New York YIMBY. (2021). *YIMBY's 2021 Construction Report Shows 30,036 New Residential Unit Filings In New York City*. https://newyorkyimby.com/2021/01/yimbys-2021-construction-report-shows-30036-new-residential-unit-filings-in-new-york-city.html

[34] City of Austin. (2016). *South Central Waterfront Vision Framework Plan*. https://www.austintexas.gov/sites/default/files/files/Housing_%26_Planning/South%20Central%20Waterfront/2016%20South%20Central%20Waterfront%20Vision%20Framework.pdf

[35] Simonen, K., Rodriguez, B., McDade, E., Strain, L. (2017). *Embodied Carbon Benchmark Study: LCA for Low Carbon Construction*. Available at https://carbonleadershipforum.org/embodied-carbon-benchmark-study-1/

- LCA modeling decisions, such as what building scope was included;
- Building characteristics, such as a primary use, height, structural system, mechanical system, interior finish selection, and aesthetic preferences; and
- Site factors, such as seismic zone, climate zone, and geographic location.

Table A3 shows the BECI factors that were used for this pilot study. The values are based on published research regarding the trends about the carbon intensity of different building typologies from three primary sources:

- CLF Embodied Carbon Benchmark Study[36]
- OneClick European Benchmark[37]
- CLF reference model collection for this study (see A.2.4)

These values are order-of-magnitude estimates, as no available research quantifies the BECI of buildings in the United States with enough regional and typological specificity to provide representative estimates for the building typologies in this study. They are intended to reflect A1-A3 life cycle impacts with a physical scope of primary structure, enclosure, and interiors.

Table A3. Estimated Building Embodied Carbon Intensity in kgCO₂e/m² per building typology. Values listed below are order-of-magnitude only and should not be used outside this study, particularly as baseline BECI to compare against individual buildings.

Building use	**Building size**	**BECI** (kgCO$_2$e/m^2)
Single Family Residential	1-3 stories	200
1-4 Family Rowhouse	1-3 stories	300
Multifamily, Commercial, Institutional	1-7 Stories, >7 Stories, Low Rise 1-5, Mid Rise 6-10,	500
Multifamily, Commercial	Very Large, High Rise >10	700

A.2.4 Reference Model Collection

The CLF collected embodied carbon data on over 70 projects from six architecture firms around the country to help support this study. The reference models cover a wide geography of the United States and are primarily multifamily residential and commercial office buildings. They range from projects early in design all the way to fully constructed buildings and represent a broad range of sizes and structural systems.

The sample size of this database was not large enough and the LCA scope of each project was not consistent enough to provide reliable embodied carbon estimates for any one building typology or location. However, it provided valuable real-world references to compare against other third-party benchmarks and studies. Each reference model was associated with a building use (see Section A.1.2). The embodied carbon intensity data (kgCO₂e/m²) was then used in aggregate to compare against the assumptions and calculations made in this pilot study. The reference model collection also informed the concrete volume factors used for each typology.

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[36] Simonen, K., Rodriguez, B., Barrera, S., Huang, M. (2017). *CLF Embodied Carbon Benchmark Database, database*. Available at https://carbonleadershipforum.org/embodied-carbon-benchmark-study-1/

[37] One Click LCA. (2021). *Embodied Carbon Benchmarks for European Buildings*. Available at https://www.oneclicklca.com/eu-embodied-carbon-benchmarks/

Aggregated BECI values from the reference model collection for each building use and size were on average less than the BECI values used for this study which is likely due to the lack of physical scope for many reference models and the high amount of light wood frame construction types that were included. The aggregated BECI values did, however, reinforce our assumptions about the increase in BECI for building size as well as construction type and concrete volume factors (see Section A.4.1).

A.3 BECI Reduction Policy Calculator Methodology

Baseline Scenario

The baseline scenario is the estimated embodied carbon associated with all new buildings that would be needed to meet the projected growth of each pilot city under typical design and construction practices. The calculator applies a fixed carbon intensity to the total projected area of growth and does not take into consideration accumulative growth over time, or changes in embodied carbon intensity over time.

Baseline Calculation

(BTGA) x (BECI) = (Baseline Scenario)

Where:

- *BTGA* is the Building Typology Growth Area (see A.2.2)
- *BECI* is the Building Embodied Carbon Intensity (see A.2.3)

Reduction Scenario

The reduction scenario is the estimated embodied carbon associated with all new buildings that would be needed to meet the projected growth of each pilot city with a custom reduction percentage applied to the concrete embodied carbon intensity of the baseline scenario. The calculator assumes the reduction percentage (policy) is implemented immediately and in full, rather than slowly integrated over time or in steps.

Reduction Calculation

(Baseline Scenario) x (BECI Reduction) = (Reduction Scenario)

Where: *BECI Reduction* is a reduction percentage selected by the user that is applied to the baseline BECI value.

A.4 Low-Carbon Concrete Policy Calculator Methodology

Baseline Scenario

The baseline scenario is the estimated embodied carbon associated with all concrete that would be needed for new construction to meet the projected growth of each pilot city. Baseline values are representative of typical construction practices and typical concrete production for each region.

The calculator applies a fixed concrete carbon intensity to the total projected area of growth and does not take into consideration accumulative growth over time, or changes in embodied carbon intensity of concrete over time.

Baseline Calculation

(BTGA) x (CT) = (CMQ)

(CMQ) x (CECI) = (Baseline Scenario)

Where:

- *BTGA* is the Building Typology Growth Area (see A.2.2)
- *CT* is the Construction Type (see A.4.1)
- *CMQ* is the Concrete Material Quantity (see A.4.1)
- *CECI* is the Concrete Embodied Carbon Intensity (see A.4.2)

Reduction Scenario

The reduction scenario is the estimated embodied carbon associated with all concrete that would be needed for new construction to meet the projected growth of each pilot city with a custom reduction percentage applied to the concrete embodied carbon intensity. The calculator assumes the reduction percentage (policy) is implemented immediately and in full, rather than slowly integrated over time or in steps.

Reduction Calculation

(Baseline Scenario) x (Reduction %) = (Reduction Scenario)

A.4.1 Construction Type (CT)

Construction type (CT) refers to the assumed percentage of buildings from any one building typology that share the same primary structural system. The structural system of a building, whether it be steel, concrete, or wood, is also an important indicator of the total volume of concrete a building will use. Estimating total embodied carbon of a city's growth thus requires assumptions about the type of structural systems that will be used.

Each construction type corresponds to a unique concrete volume factor that was used to determine the total concrete material quantity per building typology.

Table A4 lists the construction types and concrete volume factors that were used in this study. The concrete volume factors represent the total volume of concrete (yd3) per unit of area (m2) for each construction type. Steel/Concrete Hybrid (High Rise) contains the most volume of concrete per area, whereas Wood: Light Frame contains the least volume of concrete per area. The factors were derived by equally averaging steel, concrete, and steel/concrete hybrids by the values from two primary sources listed below.

- Background Data from the Early Phase Integrated Carbon (EPIC) Calculator[38]
- CLF Reference Model Database from this study (see Section A.2.4)

The values for both wood type constructions were weighted by 75% towards the reference model database.

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[38] EHDD Architects. (2021). *Early-Phase Integrated Carbon EPIC (Summer 2021 BETA Version)*. [Spreadsheet] https://epic-documentation.gitbook.io/epic/

Table A4. Construction Type and Concrete Volume Factors used for determining the total material quantity of concrete for each building typology.

Construction Type	Concrete Volume Factor (yd^3 concrete/m^2 area)
Steel/Concrete Hybrid (High Rise)	0.78
Concrete	0.75
Steel	0.48
Wood: Mass Timber	0.39
Wood: Light Frame	0.24

For each city and building typology a set of assumptions was created for both a "low range" and "high range" of construction types. The assumptions took into consideration local building practices, markets, seismic concerns, and future growth projections.

Low Range represents a reasonable construction type mix for the building typology that would be built with less concrete-intensive construction types (more Steel and Wood buildings).

High Range represents a reasonable construction type mix for the building typology that would be built with more concrete-intensive construction types (more Steel/Concrete Hybrid and Concrete structural systems).

Multiplying a building typology growth area by its construction type will yield an estimate of the total Concrete Material Quantity (CMQ) for that building typology.

The low-rise building categories (NYC 1-7 Stories, Portland 1-5 Stories) represented the widest range of concrete material quantities. Both the 2012 and 2015 International Building Code allows for the construction of wood-frame structures up to five stories for many residential occupancy groups, and six stories for office buildings. This means that a hypothetical "low range" construction type for low-rise buildings could be almost entirely light-wood framed, using very little concrete or steel for their construction. The "high range" assumptions for the low-rise category included upwards of 50% steel, or steel/concrete-framed structures.

Alternatively, high-rise buildings showed the narrowest range of concrete material quantities. This is due to the fact that these size types, regardless of their location, tend to be built almost exclusively with steel, concrete, or steel/concrete hybrid structural systems. Mid-rise buildings were assumed to still be largely made up of steel and concrete structural systems, but with a smaller percentage of steel/concrete hybrids. The "low range" for mid-rise buildings also included a small percentage of mass timber buildings. Table A5 lists all construction types and percentages assumed for each pilot city. They were derived from assumptions about local construction requirements and markets. Estimated percentages are orders of magnitude, and intended to be replaced with city-provided data in the future (see Appendix B, Opportunities for Expanding Research).

Table A5. All construction type percentages used for each pilot city and building typology. Estimated percentages are order-of-magnitude, and are intended to be replaced with city-provided data in the future.

New York Multifamily, Commercial, and Institutional

	1-7 Stories		>7 Stories		Very Large	
	Low Range	High Range	Low Range	High Range	Low Range	High Range
Steel Framed	25.00%	50.00%	55.00%	30.00%	50.00%	0.00%
Concrete	20.00%	45.00%	30.00%	60.00%	25.00%	0.00%
Hybrid (High Rise)	0.00%	0.00%	0.00%	10.00%	25.00%	100.00%
Wood Light Frame	50.00%	5.00%	0.00%	0.00%	0.00%	0.00%
Wood Mass Timber	5.00%	0.00%	15.00%	0.00%	0.00%	0.00%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Portland Multifamily and Commercial

	Low Rise 1-5		Mid Rise 6-10		High Rise >10	
	Low Range	High Range	Low Range	High Range	Low Range	High Range
Steel Framed	10.00%	35.00%	35.00%	50.00%	50.00%	20.00%
Concrete	5.00%	20.00%	25.00%	40.00%	25.00%	30.00%
Hybrid (High Rise)	0.00%	0.00%	0.00%	0.00%	15.00%	50.00%
Wood Light Frame	80.00%	45.00%	25.00%	5.00%	0.00%	0.00%
Wood Mass Timber	5.00%	0.00%	15.00%	5.00%	10.00%	0.00%
Total	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Austin SCW All Typologies

	All > 10 stories	
	Low Range	High Range
Steel Framed	50.00%	20.00%
Concrete	25.00%	30.00%
Hybrid (High Rise)	15.00%	50.00%
Wood Light Frame	0.00%	0.00%
Wood Mass Timber	10.00%	0.00%
Total	100.00%	100.00%

A.4.2 Concrete Embodied Carbon Intensity (CECI)

Concrete embodied carbon intensity refers to the average carbon intensity in $kgCO_2e/yd^3$ of concrete for specific regions of the USA. The source data used for CECI values is the National Ready-Mix Concrete Association (NRMCA) regional baselines[39] which were adjusted for this study. The NRMCA embodied carbon intensities cover cradle-to-gate life cycle impacts and NRMCA provides multiple carbon intensities for a range of concrete strengths in pounds per square inch (psi).

Table A6 lists the concrete embodied carbon intensities used in this report, which were averaged for multiple concrete strengths to represent the mixes of concrete that are commonly used for each building size type. Because embodied carbon intensities of concrete for real-world individual projects can vary greatly, the values used for this study are only intended to represent reasonable averages for current typical construction practices, concrete specification, and concrete production of each region based on the best available data.

Table A6. Concrete Embodied Carbon Intensities per building size type. Based on NRCMA regional baselines that were averaged across anticipated strengths for each building size type.

Building Typologies	Concrete strengths (psi)	Average Concrete Embodied Carbon Intensities ($kgCO_2e/yd^3$)		
		Eastern Region (New York City)	PNW Region (Portland)	South Central Region (Austin)
1-4 Family Row Houses; Single Family Residential	3000, 4000	240	252	218
1-7 Story; 1-5 Story	4000, 5000	288	304	257
>7 Story; 6-10 Story	4000, 5000, 6000	304	321	270
Very Large; High Rise >10	4000, 5000, 6000, 8000, 4000 LW	351	371	313

A.5 Adaptive Reuse Policy Calculator Methodology

Baseline Scenario

The baseline scenario is the estimated embodied carbon associated with all new buildings that would be needed to meet the projected growth of each pilot city under typical design and construction. The calculator assumes 100% new construction and zero reuse. Calculator does not take into account demolition rates or carbon impacts from demolition, waste disposal, or reuse/recycling.

Baseline Calculation

(BTGA) x (BECI) = Baseline Scenario

Where:

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[39] Athena Sustainable Materials Institute. (2019). *A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members Version 3.0 - Appendix D: NRMCA Member National and Regional LCA Benchmark (Industry Average) Report – Version 3.* https://www.nrmca.org/wp-content/uploads/2020/02/NRMCA_LCA_ReportV3_20200416.pdf

- BTGA is the Building Typology Growth Area (see A.2.2)
- BECI is the Building Embodied Carbon Intensity (see A.2.3)

Reduction Scenario

The reduction scenario is the estimated embodied carbon associated with all new built area that would be needed to meet the projected growth of each pilot city with a custom percentage of built area being achieved through adaptive reuse/renovation rather than brand new construction. Scenario assumes there are enough existing buildings available to be reused to meet the reuse percentage. Calculator does not take into account demolition rates or carbon impacts from demolition.

Reduction Calculation

BTGA x RP = Reuse Area

Reuse Area x RT x RECI = Reuse EC

(BTGA - Reuse Area) x BECI = EC New Construction

EC New Construction + Reuse EC = Reduction Scenario

Where:

- *BTGA* is the Building Typology Growth Area (see A.2.2)
- *RP* is the Reuse Percentage of each typology (see A.5.1)
- *Reuse Area* is the total area (m2) of reuse
- *RT* is the Reuse Type (see A.5.2)
- *RECI* is the Reuse Embodied Carbon Intensity (see A.5.2)
- *Reuse EC* is the embodied carbon impacts from all reuse area
- *BECI* is the Building Embodied Carbon Intensity (see A.2.3)
- *EC New Construction* is the embodied carbon impact from the area of construction (not reuse) that still would need to occur to meet the city's growth area projections.

A.5.1 Reuse percentage

Reuse percentage (RP) is the percentage of total area from a building typology that would be expected to be achieved through reusing or renovating existing buildings, rather than constructing new buildings. This percentage is customizable by the user of the calculator to test different impacts of varying levels of reuse.

A.5.2 Reuse type (RT) and reuse embodied carbon intensity (RECI)

Reuse type (RT) is a percentage breakdown that indicates what level of reuse and/or renovation of a hypothetical existing building would need to occur to meet the reuse percentage. Examples of reuse types include interior remodels, envelope replacement, or substantial structural modifications. Reuse embodied carbon intensity (RECI) refers to the embodied carbon intensity associated with each reuse type definition based on background data and carbon intensity factors from the Carbon Avoided Retrofit

Calculator[40] which were averaged and adjusted to fit the typologies of this study. Table A7 lists both the reuse types, their definitions, and the reuse embodied carbon intensity factors used for each.

Table A7. Reuse type definitions and their associated reuse embodied carbon intensity (RECI) based on adjusted and averaged data from the Carbon Avoided Retrofit Calculator.

Reuse Type	Definition	RECI ($kgCO_2e/m^2$)
Minor	50-100% of interior replaced with new	38
Moderate	50-100% of interior and exterior envelope replaced with new	98
Major - Light	50-100% of interior, envelope, and light structural system replaced with new (applies to 1-4 Family Row Houses and Single Family Residential typologies)	123
Major - Heavy	50-100% of interior, envelope, and heavy structural system replaced with new (applies to Multifamily, Commercial, and Institutional typologies)	198

The following reuse type percentages that were used for the Adaptive Reuse Policy Calculator based on CLF assumptions about typical types of reuse:

- Minor: 50%
- Moderate: 25%
- Major - Light / Major - Heavy: 25%.

A.6 Housing Policy EC Calculator Methodology

Baseline Scenario

The baseline scenario is the estimated embodied carbon associated with all new residential buildings that would be needed to meet the approximate projected growth of each pilot city assuming typical unit sizes.

Baseline Calculation

Baseline Number of Units x Unit Size x BECI = Baseline Scenario EC

Where:

- *Baseline Number of Units* is the estimated units of growth to meet total projected growth area (see A.6.2)
- *Unit Size* is the average unit size for each typology (see A.6.1)
- *BECI* is the building embodied carbon intensity (see A.2.3)

Reduction Scenario

The reduction scenario is the estimated embodied carbon associated with all new residential buildings that would be needed to construct a custom number of units with a

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[40] Net Zero Carbon Collaboration. (2021). Carbon Avoided: Retrofit Calculator (CARE) (Summer 2021 BETA Version). [Spreadsheet Calculator]

custom unit size. Whereas all other calculators assume a fixed area of growth as provided by each city, the reduction scenario for housing policy allows users to test different growth scenarios for each typology based on unit size and number of units and see the potential impacts against the baseline. For the reduction scenarios run in this report, all numbers of units remained the same between baseline scenarios and reduction scenarios. Unit size was the only variable used.

Reduction Calculation

Custom Number Units x Custom Unit Size x BECI = Reduction Scenario

Where:

- *Custom Number of Units* is a user-entered number of units of growth to test against the baseline.
- *Custom Unit Size* is a user-entered unit size to test against the baseline.
- *BECI* is the building embodied carbon intensity (see A.2.3)

A.6.1 Unit Size

Unit size indicates the average area per dwelling unit for residential properties. Unit sizes are typically derived from averaging the sizes of all residential units of a specific type across an entire city or region, regardless of number of bedrooms or occupants living in the unit. Baseline unit sizes were provided for the calculator, whereas custom unit sizes are to be manually entered by users.

Table A8 shows the unit sizes for the baseline scenario of each city and typology that were used for this study. Values listed are in square feet per unit and based on CLF assumptions. Real estate market data and average unit sizes for cities are available from multiple online sources such as Rentcafe.[41] However, due to the sensitivity of unit size for the housing policy calculator, this pilot study uses CLF assumptions about generic and typical unit sizes with the intention that they would be replaced by the best available up-to-date data from each pilot city in future versions of the calculators.

Table A8. Baseline unit sizes for each city and typology that were used for this study. Values listed are in square feet per unit and based on CLF assumptions and intended to be placeholder values only.

City	Typology	Average Unit Size (sqft per unit)
New York City	1-4 Family Row House	1200
New York City	Multifamily 1-7 Stories, > 7 Stories, Very Large	800
Portland	Single Family	1900
Portland	Multifamily Low Rise 1-5, Mid Rise 6-10, High Rise >10	800
Austin SCW	Residential	1000

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[41] Balint, Nadia. (2018 November 30th). *As Apartments Are Shrinking, Seattle Tops New York with the Smallest Rentals in the U.S. Rent Cafe.* https://www.rentcafe.com/blog/rental-market/real-estate-news/us-average-apartment-size-trends-downward/

The unit size for the reduction scenario is a custom unit size that is intended to be a user-entered value to test against the embodied carbon impacts against the baseline.

A.6.2 Number of Units

"Number of units" refers to the anticipated growth in residential dwelling units for each city and typology. For New York City and Portland the baseline number of units were calculated by dividing the BTGA by the baseline unit size and rounding to the nearest five thousand units. This produces a number of units for the baseline that closely aligns with the projected growth in area for each city and building typology. For Austin SCW the baseline units of growth were provided and used as-is. Future versions of this calculator could allow cities to manually enter the number of units they expect to be required by a given date.

The number of units for the reduction scenario are intended to be a user-entered number of units to test against the baseline scenario.

Table A9 lists the baseline number of units of growth for each city and typology that were used in the housing policy calculator. Estimates of growth by units were only provided in the Austin SCW. All others are based on CLF assumptions and are intended to be placeholder values until city specific data can be acquired.

Table A9. Baseline number of units of growth used for the housing policy calculator based on CLF assumptions and as placeholder values until city-specific data can be acquired.

City	Typology	Baseline # of Units
New York City	1-4 Family Row House	85,000
	Multifamily 1-7	50,000
	Multifamily >7	120,000
	Multifamily Very Large	80,000
Portland	Single Family	25,000
	Multifamily Low Rise 1-5	140,000
	Multifamily Mid Rise 6-10	60,000
	Multifamily High Rise >10	15,000
Austin SCW	Residential (all)	2,702

APPENDIX B: OPPORTUNITIES FOR EXPANDING RESEARCH

Throughout this pilot study the authors, contributors, and pilot cities identified multiple opportunities to expand the accuracy, scope, and functionality of the calculators. The types of future research and developments identified fall into two primary categories:

1. **Additional Research Required:** For some gaps in data, there is simply not adequate research currently available. This type of gap will require more significant research, time, and funding to address.
2. **Expanding Calculator Functionality:** Due to the short timeline of this proof-of-concept study, the research team had to prioritize which functionality could be built into the tool. Functionality of the calculators could be expanded with currently available data in many cases if additional time and funding were secured.

B.1 Additional Research Required

While this proof-of-concept study proved the concept and potential of the calculators, additional research is critical before they can be used at scale to support policy decision-making. Sensitivity analyses revealed that the following factors in Table B1 are the most urgent to address with additional research to develop future versions of the calculators and move beyond the proof of concept phase.

Table B1. Gaps in data identified to reduce uncertainty around results of prototype calculators.

Data Gap	Priority	Potential Data Sources
Regionally and typologically specific BECI values Additional research is urgently needed to provide regionally specific embodied carbon values for BECI that reflect the construction typologies of each city as well as capture the missing physical scopes of the calculators and provide a more accurate and comprehensive picture of the total embodied carbon impacts of buildings. The BECI values used in this study are order-of-magnitude estimates for each building typology. No available research quantifies the BECI of buildings in the United States with enough regional and typological specificity to provide representative estimates for the building typologies in this study. Most current BECI benchmarks also exclude physical scope beyond structure, enclosure, and interiors, such as mechanical, electrical, and plumbing systems (MEP).	High	Building benchmarking studies by building typology by the Carbon Leadership Forum and other research organizations Benchmarks collected by governments that have policy requirements to disclose whole building life cycle assessment results. In the future, this may be a larger dataset, but currently this data source does not exist and/or is not publicly available.

Inclusion of life cycle stages beyond A1-A3 The scope of the prototype calculators is limited to A1-A3, which is indicative of the scale of life cycle impacts but excludes key life cycle stages for decision-making. This also means that the projections included in Section 3 may be low (i.e., they underestimate the baseline and potential carbon savings of policies). If this data is used alongside other metrics related to carbon to communicate the importance of policies, it is important that the scale of emissions is appropriately communicated. Pilot cities highlighted that impacts from other life cycle impacts, such as construction equipment (A5), local transportation (A4), and replacement/end-of-life (stages B and C), would be helpful, but did not highlight as a high priority.	High/ Medium	Requires additional data, most of which is readily available.
City data on building size Differences in building height and size can dictate multiple variables that have significant ramifications for total embodied carbon such as structural system, foundation design, level of interior finishes, and MEP system selection. This data would help provide more accurate calculations across all calculators. This item is a 'medium/low' rather than high priority because this may be difficult to integrate, depending on the scope of future versions of the calculators. This would potentially require pre-determining which cities could use the calculators, so that appropriate building size data could be included.	Medium/ Low	City building permit databases City LIDAR and other GIS building data layers by local cities
City-specific data on construction type Construction type varies widely due to regional structural necessities, preferences, and market factors. This would indicate the structural system typical for each building typology, which would influence the volume of concrete assumed for each building typology for the Low Carbon Concrete Calculator. This item is a 'medium/low' rather than high priority because this may be difficult to integrate, depending on the scope of future versions of the calculators. This would potentially require pre-determining which cities could use the calculators, so that appropriate construction type mix data could be included.	Medium/ Low	City building permit databases, taxlot information, or GIS data

B.2 Expanding Calculator Functionality

There are multiple ways the calculators could be expanded both in terms of scope and functionality that improve their utility for policymakers in developing and communicating embodied carbon policies. Table B2 lists additional features identified by the authors, contributors, and pilot cities and their priority for future work.

Table B2. Additional functionality that could be added to the calculators to expand their utility for policymakers and better reflect policy mechanisms.

Additional Function	Priority	Requires New Data Sources
Stepped Policy Limits All reduction scenarios modeled for this study assume that a policy (reduction strategy) is immediately passed or implemented, rather than phased in over time.	High	No
Infrastructure and Parking The impacts from infrastructure were not included in any of the calculators for this pilot study. Physical buildings only represent a portion of the total embodied carbon impacts of the larger built environment. The embodied carbon impacts from constructing roadways, parking lots, sewer and water systems, and power distribution networks, contribute significantly to the carbon footprint of cities. Furthermore, the demands for infrastructure typically increase as cities grow. Parking spaces, for instance, are often required by law for certain types of housing developments. Future versions of this calculator could attempt to capture the embodied carbon impacts from the associated infrastructure that would be required for additional growth in buildings	High	Yes
Demolition impacts The adaptive reuse calculator does not capture the impacts from demolishing existing buildings, disposing of their materials, or any reuse/recycling. Including these end-of-life impacts could have substantial effects on the total carbon savings potentials of the reuse calculator.	Medium	Yes
Adding additional policies These calculators can estimate the impacts of only 4 types of embodied carbon policies. There are many additional policy paths that could be modeled, each of which have their own data availability challenges. For example, pilot cities highlighted that other material-specific policies (such as wood, steel, insulation, etc.) would be interesting to see results from, in addition to concrete. Also of interest were policies targeting material reuse, procurement, and others targeting additional planning and zoning measures.	Medium	Yes
Time Value of Carbon and Nonlinear Growth Near-term reductions in carbon emissions are critical for meeting larger climate change targets because carbon emitted today has more potential for amplifying the negative effects of climate change than emitting the same amount of carbon in the future[42]. However, this report does not attempt to apply numerical value factors to carbon emitted either in the near-term or long-term. All carbon emissions are treated equally. Furthermore, all calculators in the pilot study apply embodied carbon intensities to the total projected growth assuming a linear growth rate for cities, which does not capture the potential nonlinear climate change impacts of cities that grow faster in the near term. Future versions of these calculators could integrate both predictions about the fluctuations of growth that cities might experience over time, as well as the time-dependent values of those carbon emissions.	Medium/Low	No

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[42] Council of Economic Advisors. (July 2014). *The Cost of Delaying Action to Stem Climate Change.* https://scholar.harvard.edu/files/stock/files/cost_of_delaying_action.pdf

APPENDIX C: PILOT CITY RESULTS TABLES

Tables C1-C3 summarize the carbon savings potential estimated by the prototype calculators for each pilot city. The results from the calculators are intended as a proof of concept for functionality, and are directionally accurate but not yet reliable estimates for informing decision-making. Additional research, as described in Appendix B, would increase the utility of these prototypes for decision-making.

Table C1. Summary of preliminary carbon impacts and savings potentials for the City of New York for policy scenarios evaluated with the BECI Reduction Policy Calculator (A0-A3), Low-Carbon Concrete Policy Calculator (B0-B3), Adaptive Reuse Calculator (C0-C3) and Housing Size Policy Calculator (D0-D4).

Scenario	Carbon emissions by 2050 (MmtCO2e)	Carbon savings by 2050 (Mmt-CO2e)	Annual carbon savings (Thousand mtCO2e)	Percent reduction from Baseline
Requiring reductions in building embodied carbon intensity (City of New York)				
Baseline Scenario A0 (No reduction for 1-4 Family, Commercial, Multifamily, Institutional)	20.8	0	0	0
Scenario A1 (10%, Commercial)	20.2	0.6	19	3%
Scenario A2 (40%, Multifamily)	16.6	4.2	141	20%
Scenario A3 (30%, 1-4 Family, Commercial, Multifamily, Institutional)	14.6	6.3	208	30%
Scenario A4 (40%, 1-4 Family, Commercial, Multifamily, Institutional)	12.5	8.3	278	40%
Scenario A5 (50%, 1-4 Family, Commercial, Multifamily, Institutional)	10.4	10.4	347	50%
Limiting the carbon of concrete (City of New York)				
Baseline Scenario B0 (No reduction for 1-4 Family, Commercial, Multifamily, Institutional)	6.9	0	0	0
Scenario B1 (30%, Commercial)	6.3	0.6	20	9%
Scenario B2 (30%, Multifamily)	5.8	1.1	37	16%
Scenario B3 (50%, 1-4 Family Commercial, Multifamily, Institutional)	3.4	3.4	114	50%
Increasing adaptive reuse (City of New York)				
Baseline Scenario C0 (No reduction for 1-4 Family, Commercial, Multifamily, Institutional)	20.8	0	0	0
Scenario C1 (5%, Commercial, Multifamily, 1-4 Family, Institutional *- preserves approximately 0.04% of existing building stock area)*	20.0	0.9	29	4%
Scenario C2 (10%, Commercial, Multifamily, 1-4 Family, Institutional *- preserves approximately 0.08% of existing building stock area)*	19.1	1.7	57	8%

Scenario C3 (30%, Commercial, Multifamily, 1-4 Family, Institutional *- preserves approximately 0.23% of existing building stock area)*	15.7	5.1	171	25%
Reducing typical housing unit size (City of New York)				
Baseline Scenario D0 (No reduction for 1-4 Family, Multifamily)	13.3	0	0	0
Scenario D1 (-20% unit size 1-4 Family)	12.8	0.6	19	4%
Scenario D2 (-10% unit size Multifamily)	12.2	1.0	35	8%
Scenario D3 (30% of Multifamily units to be micro)	11.7	1.7	56	13%
Scenario D4 (-20% unit size Multifamily, 1-4 Family)	10.7	2.7	89	20%

Table C2. Summary of preliminary carbon impacts and savings potentials for the City of Portland for policy scenarios evaluated with the BECI Reduction Policy Calculator (A0-A3), Low Carbon Concrete Policy Calculator (B0-B3), Adaptive Reuse Calculator (C0-C3) and Housing Size Policy Calculator (D0-D4).

Scenario	Cumulative carbon emissions by 2050 (in million mtCO2e)	Cumulative carbon savings by 2050 (in million mtCO2e)	Annual carbon savings (Thousand mtCO2e)	Overall percent reduction from Baseline
Requiring reductions in building embodied carbon intensity (City of Portland)				
Baseline Scenario A0 (No reduction for Single Family, Commercial, Multifamily)	16.0	0	0	0
Scenario A1 (10%, Commercial)	15.3	0.7	22	4%
Scenario A2 (40%, Multifamily)	12.6	3.3	110	21%
Scenario A3 (30%, Single Family, Commercial, Multifamily)	11.2	4.8	159	30%
Scenario A4 (40%, Single Family, Commercial, Multifamily)	9.6	6.4	213	40%
Scenario A5 (50%, Single Family, Commercial, Multifamily)	8.0	8.0	265	50%
Limiting the carbon of concrete (City of Portland)				
Baseline Scenario B0 (No reduction for Single Family, Commercial, Multifamily)	4.5	0	0	0
Scenario B1 (30%, Commercial)	3.9	0.6	20	13%
Scenario B2 (30%, Multifamily)	3.8	0.7	22	15%
Scenario B3 (50%, Single Family, Commercial, Multifamily)	2.2	2.2	75	50%

Increasing adaptive reuse (City of Portland)				
Baseline Scenario C0 (No reduction for Single Family, Commercial, Multifamily)	15.9	0	0	0
Scenario C1 (5%, Commercial, Multifamily - *preserves approximately 0.2% of existing building stock area)*	15.3	0.6	21	4%
Scenario C2 (10%, Commercial, Multifamily - *preserves approximately 0.4% of existing building stock area)*	14.7	1.2	41	8%
Scenario C3 (30%, Commercial, Multifamily, Single Family - *preserves approximately 1.4% of existing building stock area)*	12.0	3.9	129	24%
Reducing typical housing unit size (City of Portland)				
Baseline Scenario D0 (No reduction for Single Family, Multifamily)	9.5	0	0	0
Scenario D1 (-20% unit size Single Family)	8.9	0.6	21	6%
Scenario D2 (-10% unit size Multifamily)	8.3	1.3	42	13%
Scenario D3 (30% of Multifamily units to be micro)	7.8	1.7	58	18%
Scenario D4 (-20% unit size Multifamily, Single Family)	7.3	2.3	75	24%

Table C3. Summary of preliminary carbon impacts and savings potentials for the Austin SCW for policy scenarios evaluated with the BECI Reduction Policy Calculator (A0-A3), Low-Carbon Concrete Policy Calculator (B0-B3), and Housing Size Policy Calculator (D0-D4).

Scenario	Approximate carbon emissions by 2050 (in thousand mtCO2e)	Approximate carbon savings by 2050 (in thousand mtCO2e)	Annual carbon savings (Thousand mtCO2e)	Overall percent reduction from Baseline
Requiring reductions in building embodied carbon intensity (Austin SCW)				
Baseline Scenario A0 (No reduction for Office, Retail, Multifamily, Hotel)	353	0	0	0
Scenario A1 (10%, Office, Retail, Hotel)	337	16	0.5	5%
Scenario A2 (40%, Multifamily)	283	70	2	20%
Scenario A3 (30%, Office, Multifamily, Retail, Hotel)	247	106	4	30%

Scenario A4 (40%, Office, Multi-family, Retail, Hotel)	212	141	5	40%
Scenario A5 (50%, Office, Multi-family, Retail, Hotel)	176	176	6	50%
Limiting the carbon of concrete (Austin SCW)				
Baseline Scenario B0 (No reduction for Office, Retail, Multifamily, Hotel)	103	0	0	0
Scenario B1 (30%, Office, Retail, Hotel)	87	15	0.5	15%
Scenario B2 (40%, Office, Multi-family, Retail, Hotel)	62	41	0.5	40%
Scenario B3 (50%, Office, Multi-family, Retail, Hotel)	51	51	2	50%
Reducing typical housing unit size (Austin SCW)				
Baseline Scenario D0	176	0	0	0
Scenario D1 (-20% unit size Single Family)	N/A	N/A	N/A	N/A
Scenario D2 (-10% unit size Multifamily)	158	17	0.5	10%
Scenario D3 (30% of Multifamily units to be micro)	143	33	1	19%
Scenario D4 (-20% unit size Multifamily)	141	35	1	20%

CLF Carbon Leadership Forum

C40 CITIES