REPORT

Embodied Carbon Reduction Study – City of Vancouver

Presented to:

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Project No. 1905470.00 July 4, 2023

Table of Contents

EXECUTIVE SUMMARY

Reducing greenhouse gas (GHG) emissions from buildings has been a long-standing goal in many jurisdictions in North America and around the world. Most of these efforts have been focused on reducing GHG emissions from the operation of buildings, such as local requirements with net-zero ready energy targets in the BC Energy Step Code and Zero Emissions Building plan in the City of Vancouver. As emissions from building operation decreases, greenhouse gas emissions generated from the extraction, production, and disposal of materials, commonly referred to as 'Embodied Carbon' account for a greater portion of the building's overall carbon emissions. While there are a range of options available today to reduce embodied carbon in buildings, there is a lack of information on their effectiveness, cost, and other challenges that are not readily available to the design community. The Embodied Carbon Reduction Study aims to address some of these challenges and present possible solutions that designers could face within the Vancouver market to help the adoption of embodied carbon reduction policy in upcoming versions of the Vancouver Building Bylaw.

The objectives of this study are to:

1. Define locally relevant, standardized, 2018 baselines of construction practice against which to demonstrate reductions in embodied carbon

2. Understand the relative impacts of market-ready solutions available to designers to significantly reduce the embodied carbon of new construction

3. Estimate and present the cost and other barriers to implementing these solutions

To address these objectives parametric analysis of Life Cycle Assessment (LCA) models for three residential building archetypes were performed along with a construction cost analysis. The three archetype buildings were based on typical construction building types commonly found in the City of Vancouver and includes:

- 30-storey high-rise multi-unit residential building
- 6-storey mid-rise multi-unit residential building
- 3-storey low-rise stacked townhome residential building

LCA models were created using the Athena Impact Estimator to calculate embodied carbon emissions via Global Warming Potential (GWP). The scope of the LCA models include:

- Primary structural system of the building including beams, columns, floor slabs, load bearing walls, shear walls foundation walls, and footings

- Exterior walls and windows, including insulation and cladding, roofing membrane, vapour and air barriers, window framing and glazing, parking garages including structure and membranes

- 60-year lifespan

- Life cycle stages A1-A5, B1 to B4, and C1 to C4

The life cycle impact assessment (LCIA) data for most materials used in the study were based on information found in the Athena database built into the Impact Estimator. Supplemental data for other materials such as concrete and insulation referenced industry average and product-specific Environmental Product Declarations (EPDs).

Over 700,000 LCA models were created as part of the parametric analysis. The parametric analysis focused on different building materials and design factors based on research of local and North American building practices which included an industry engagement workshop to discuss embodied carbon strategies relevant to the Vancouver market. The resulting parametric analysis focused on various design factors such as:

- Structure type (concrete, steel, wood, mass timber)
- Building envelope assembly type (curtain wall/ window wall, steel/wood-frame infill, pre-cast concrete, mass timber)
- Insulation type (cellulose, mineral fiber, fiberglass, rigid board)
- Window type (window to wall ratio, window frames, IGU types)
- Parking availability (below grade parkade, surface lots, street parking

Results from the parametric study were also used to develop a public web tool that is accessible to all designers to compare the impacts of various design factors and embodied carbon reduction strategies[1].

The cost analysis of the study was based on typical construction and material costs provided by a local cost consultant, BTY, who provided costs based on the parameters considered for all three archetypes in the study. Some materials and systems were excluded from the cost analysis as they are supplemented by other studies published around the same time. The cost data are based on materials cost from 2020 and typical construction costs from 2021 and Q1 of 2023.

Results from the parametric LCA models produced a range of embodied carbon emissions for each archetype. This range of emissions, measured in kg of equivalent CO_2 per square meter (CO_2e/m^2), was as follows:

- High-Rise Residential: 97-424 kg CO_2e/m^2
- Mid-Rise Residential: 38-349 kg CO_2e/m^2
- Low-Rise Residential Townhomes: 75-571 kg CO_2e/m^2

These ranges show significant reductions in embodied carbon are available and possible ranges differ for each archetype due to different construction practices. This implies various embodied carbon reduction thresholds may result in different impacts on embodied carbon reduction strategies and material choices for each archetype.

[1] The Embodied Carbon Building Pathfinder at www.buildingpathfinder.com

The impacts and consequences of utilizing various embodied carbon thresholds were studied based on these ranges. It was found that most designs can meet the 50th percentile threshold with careful use of concrete and foam insulation for all archetypes. Designs that met the 25th percentile was more challenging since it required eliminating the use of certain high embodied carbon common construction materials such as concrete for most archetypes.

To address perceived cost barriers to meet various embodied carbon reduction targets in Vancouver, estimated construction costs for select building designs that met these targets were calculated. The construction costs of these building designs were compared to a baseline building that is representative of 2018 building construction practices for each archetype. For most designs, most embodied carbon measures resulted in construction cost savings rather than a cost premium. Some of the findings include:

- 2% to 20% estimated construction cost savings for high-rise residential archetype building designs that achieve 10% and 20% embodied carbon reduction over 2018 baseline design

- 0% to 10% estimated construction cost savings for mid-rise residential archetype building designs that achieve 10% and 20% embodied carbon reduction over 2018 baseline design

- Up to 25% estimated construction cost savings for low-rise residential archetype building designs that achieve 10% embodied carbon reduction over 2018 baseline design

- Concrete mixes with higher SCM content are effectively construction cost neutral yet provided embodied carbon reductions up to 10%

- Precast concrete insulated sandwich panels resulted in the greatest estimated construction cost savings over window wall exterior wall systems for the high-rise residential archetype at more than 19% estimated construction cost savings and more than 13% reduction in embodied carbon emissions

- Wood-frame construction resulted in the greatest estimated construction cost savings over poured-in-place concrete for the mid-rise residential archetype at more than 15% estimated construction cost savings and more than 70% reduction in embodied carbon emissions

- EPS roof insulation is construction cost neutral over polyisocyanurate roof insulation for the low-rise residential archetype, yet it provided significant embodied carbon reduction at more than 5%

Based on this study it appears:

1. Embodied carbon of buildings is a significant contributor to climate change.

2. Embodied carbon reductions in buildings are readily available and can result in significant reductions with few impacts on cost and design flexibility.

3. The range of embodied carbon emissions is different between building archetypes. As such, a single numerical target threshold in CO_2e/m^2 may not be appropriate. Multiple targets for different archetypes may be preferred.

4. In general, a target embodied carbon threshold of the 50^{th} percentile of the range of impacts had few limitations on design and no significant impact on cost, but a target of the 25^{th} percentile of the range of impacts placed severe limitations on design and significant impact on cost. As such, a threshold between the 50^{th} and 25^{th} percentile of embodied carbon range may be reasonable.

ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge all individuals and groups who have supported and contributed to this study including:

- The City of Vancouver
- The Athena Institute
- LCA Practitioners Working Group: Vancouver
- Zahra Teshnizi, Mantle
- Ryan Zizzo, Mantle
- Matthew Bowick, NRC
- Panu Pasanen, Bionova
- Zina Berrada, HCMA
- Robert Cooney, NRC
- Phil Northcott, c-change labs
- Manuela Londono, Perkinswill
- Fin Macdonald, CaGBC
- Roderick Bates, Kieran Timberlake
- Helen Goodland, SCIUS Advisory
- Graham Twyford-Miles, Stantec
- Jeremey Field, Integral Group
- Antje Wahl, Forestry Innovation Investment
- Jeremy Caradonna, Government of B.C.

1. INTRODUCTION

1.1 PROJECT BACKGROUND

The Zero Emissions Building Plan (ZEBP1) seeks to reduce the operational emissions of new construction in Vancouver to zero by 2030. This means that the embodied emissions of the building—all the emissions generated by producing the materials and assembling and replacing them on site—will become the only source of emissions from new construction. There are a range of options available today to designers to reduce embodied carbon in construction, but information on those options, including their effectiveness, costs, and other challenges, are not readily available to the design community.

The 2017 Green Buildings Policy for Rezonings requires all new construction undergoing rezoning to estimate their embodied carbon impacts and submit a brief report to the City. This requirement contains standardized methodology for estimating embodied carbon that aligns with the requirements of LEED v4/4.1 for New Construction credits to reduce the embodied carbon impact of new construction. Together these standards have supported a growing body of knowledge and practitioners of Life Cycle Assessment (LCA) practitioners in BC. This has fostered a foundation of industry knowledge that can support a future policy requirement to reduce embodied emissions in construction.

Looking to the future, the City has set a goal of introducing a requirement to reduce embodied carbon in the next version of the Vancouver Building By-law, likely to come into effect in 2023. This study will inform that requirement and potential future targets for the reduction of embodied carbon.

1.2 OBJECTIVES

The objectives of this Embodied Carbon Reduction Study are to:

1. Define locally relevant, standardized, 2018 baselines of construction practice against which to demonstrate reductions in embodied carbon
2. Understand the relative impacts of market-ready solutions available to designers to significantly reduce the embodied carbon of new construction
3. Estimate and present the cost and other barriers to implementing these solutions

2. METHODOLOGY AND APPROACH

The following describes the approach and methodology.

2.1 Archetype Review and 2018 Baseline Development

LCA baselines for building archetypes have been noted as much needed in the industry since the 1990s, but the difficulties in defining the relevant variables (and limits to these variables) become very complicated very quickly. This is of increased importance because the baselines will be the rules by which the industry will measure their performance. One must take into account building code limitations and common regional practices and exclude any very unusual items that might greatly affect the result.

Three separate building archetypes were considered: a high-rise residential building, a mid-rise residential building, and a low-rise residential building (stacked townhome). All archetypes were assumed to be in Vancouver, BC. We began by defining the relevant parameters and limitations of each archetype, including materials that should be excluded from consideration for each type. For example, should wood post and beam construction be included for the various archetypes in the development of the baseline? We documented these assumptions and delivered them to the City for review and comment. Once these "rules" were approved, the project team worked with the City to obtain recent rezoning applications for the building archetypes. Through a combination of drawings obtained through the City and from Morrison Hershfield's past projects, we performed a cursory review of 45 packages and excluded any buildings that were outside of our pre-defined rules. Thereafter, a generic fictional design was developed for each archetype which is believed to be representative of what is expected for these archetypes in the region.

It is difficult to determine a single baseline building for each archetype due to the variability of material types available. Our response to this challenge was to report on the total range of impacts based on the various materials that could be used for each archetype. We developed hundreds of thousands of combinations of building assemblies resulting in every possible combination of common materials and assemblies available. LCA of each of these combinations was performed with a focus on embodied carbon, resulting in a range of possible embodied carbon impacts. This range is presented as the starting point, or baseline, on which to focus possible embodied carbon reduction strategies.

2.2 Vancouver Market Research

This analysis includes web-based research into the following:

- Domestic Market: identify current industry trends, market drivers and policy trends in BC, Ontario, and Canada for green procurement
- International Market: conduct jurisdictional review of industry trends, market drivers, case studies and best practices used in other countries

2.3 Stakeholder Meeting and Review

To further inform the embodied carbon reduction strategies specifically relevant to the local market, an industry engagement workshop was held at the beginning of the project. The feedback received during this workshop and other engagement activities throughout the project with industry groups helped accurately capture any issues or opportunities surrounding implementation of these strategies.

2.4 Athena Impact Estimator

Life cycle assessment (LCA) estimates environmental burden due to a product over its entire life span, from resource extraction to landfilling and beyond. It is a rigorous methodological technique for measuring and rationalizing “green” choices, applying a holistic cradle-to-grave perspective.

As with any cradle-to-grave LCA study, LCA for a building (whole-building LCA) measures all the flows between a building and nature over its lifetime and then estimates the resulting impacts on air, land, and water. The cradle-to-grave lifetime of a building includes manufacturing and transporting of construction materials, the process of construction, a long phase of building occupancy and maintenance, demolition, and removal of waste materials. Resources are consumed and emissions created during every life phase as shown in Figure 2.4.1.

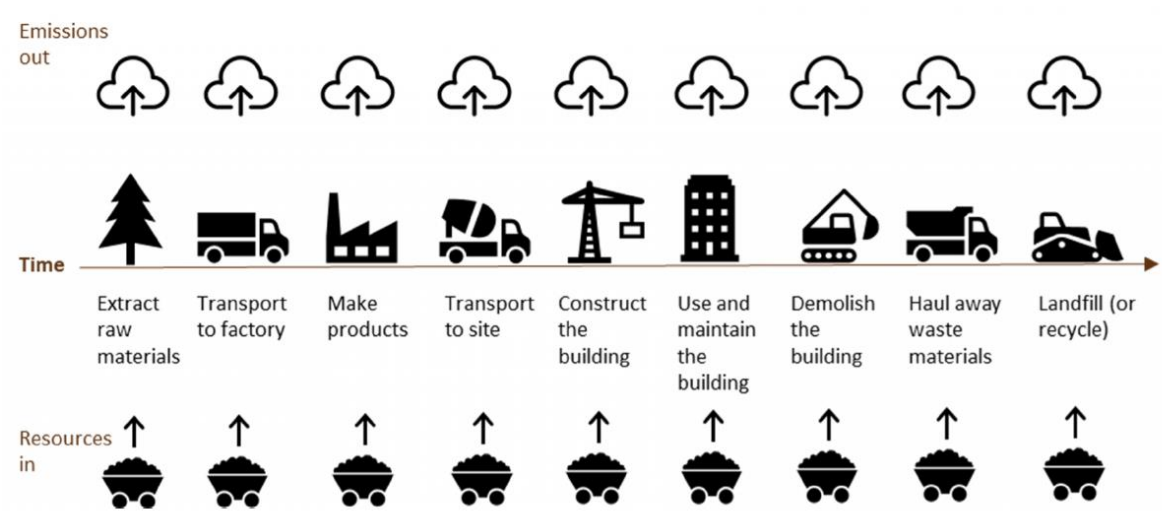


Figure 2.4.1: Life Cycle Phases of a Building (*www.canadianarchitect.com/1003753921-2/cradle-to-grave/*)

Clearly, LCA is a complex process requiring access to extensive data and sophisticated software tools, even when applying LCA to simple products. This is why whole-building LCA software tools are available, to simplify the process for stakeholders in the building industry. For this project we used the Athena Impact Estimator for Buildings software. This is the original simplified whole-building LCA software tool in North America, first released in 2002.

The Athena Impact Estimator for Buildings provides full LCA results across the following impacts:

- Fossil fuel depletion
- Other non-renewable resource use
- Water use
- Global warming potential
- Stratospheric ozone depletion
- Ground level ozone (smog) creation
- Neutrification/eutrophication of water bodies
- Acidification and acid deposition (dry and wet)
- Toxic releases to air, water and land

This study focuses solely on the embodied carbon of buildings, which is simply the global warming potential (GWP) result noted above. The other LCA measures were not considered for this project.

2.5 Life Cycle Assessment Modelling

The lifetime embodied carbon emissions of the evaluated archetypes were based on LCA models developed using the Athena Impact Estimator (Version 5.4.0103). The Athena Impact Estimator includes a database of various construction materials and their environmental impacts in form of life cycle assessment inventory data that considers environmental impacts throughout the life cycle of a product or material. These environmental impacts include Global Warming Potential (GWP).

Supplemental information for materials for which the GWP values are known to be problematic in the Athena database were used based on Environmental Product Declarations (EPDs). Additional assumptions were also made to augment some of the simplifying assumptions made by the Athena Impact Estimator to better align with local construction practices. Examples of these assumptions, work arounds, and EPDs used in the LCA models, are presented in the following subjections for various materials and systems.

2.5.1 Building Model Scope

The LCA models focused on the above and below grade building structure and building envelope. It included the following:

- Primary building structure including beams, columns, floor slabs, load bearing walls, shear walls foundation walls, and footings

- Exterior walls and windows, including insulation and cladding, roofing membrane, vapour and air barriers, window framing and glazing, parking garages including structure and membranes

The LCA model scope did not include ceiling or floor coverings, finish materials, paint, interior walls, mechanical, electrical, or plumbing (MEP) systems, or site components.

2.5.2 System Boundary

The system boundary for the LCA models included the product, construction, use and end of life stages excluding operational energy and water. This includes stages A1-A5, B1 to B4, and C1 to C4 as shown in Figure 2.5.1

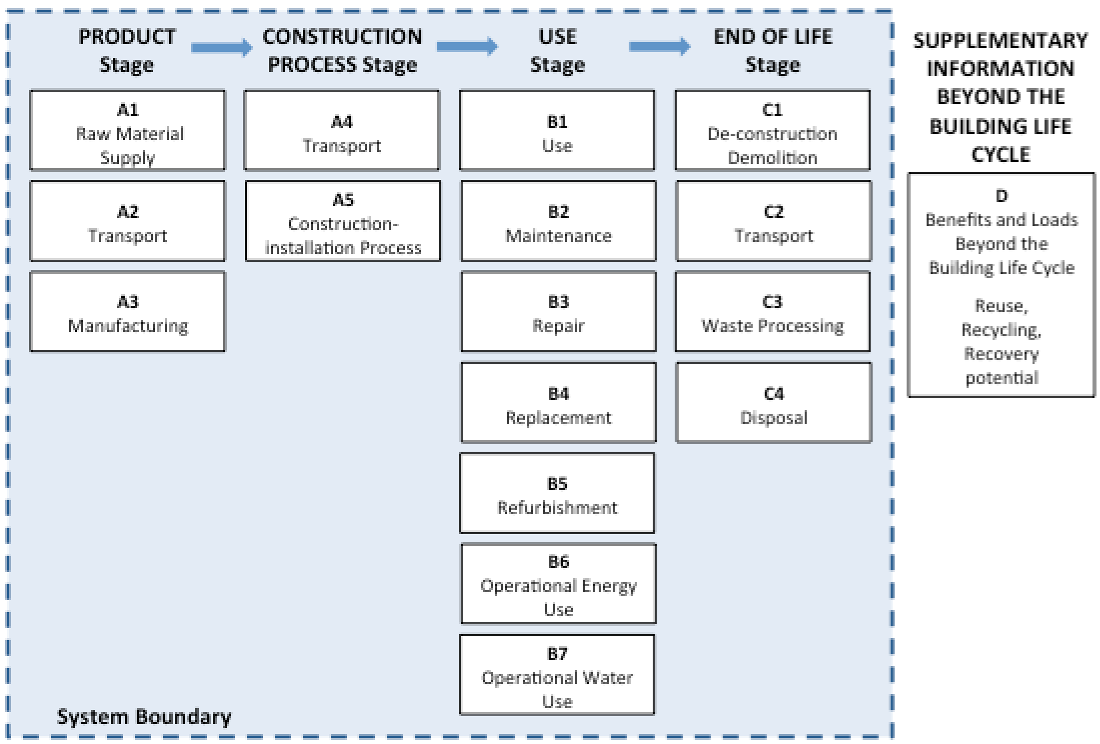


Figure 2.5.1: System Boundary (http://www.athenasmi.org/resources/about-lca/technical-details/)

2.5.3 Insulation

There was some concern that the Athena Impact Estimator would incorrectly estimate the GWP of foam insulations due to the software not fully recognize the impacts of HFC blowing agents in the in the LCA models. The approach to address this issue in this study regarding insulation was as follows:

1. Available EPDs were used to estimate the GWP of all insulation types (not just foam). All insulation types were reviewed to allow a fairer comparison of insulations.

2. For GWP estimates of foam insulation types, only EPDs associated with HFO blowing agents were used given the recent regulatory change in Canada. Any EPDs with HFC blowing agents were not included.

3. Where available, industry wide EPDs were used. Industry wide EPDs were used for polyisocyanurate and loose fill cellulose.

4. When industry wide EPDs were not available, product specific EPDs or averages of product specific EPDs were used.

5. Wall insulation types of fibrous and foam boards were assumed to be medium density, typical for commercial walls.

6. Roof insulation types of fibrous and foam boards were higher density, typical for commercial roofs.

7. EPDs were not available for medium density mineral fiber and medium and high-density fiberglass batt insulation types. For these insulation types GWP was estimated by adjusting the GWP of similar low-density insulation by the differences in density.

8. For all insulation types in the High-rise residential archetype R-15 (2.64 RSI) nominal insulation was assumed and all insulation quantities were adjusted.

9. For all insulation types in the Mid-rise and Low-rise residential archetypes, 4 inches (102 mm) of insulation was assumed.

Note, it is acknowledged that relying on EPD results is not ideal, as the scope and system boundaries may be different and EPDs are often based on singular products that may not represent a typical value. To reduce this risk, each EPD was carefully reviewed to confirm similar the scope and system boundaries are similar to other LCAs in this study. In addition, this methodology was reviewed by various LCA practitioners and specialists in the Vancouver area.

2.5.4 Concrete Mixes and Supplementary Cementitious Materials (SCMs)

GWP values for concrete mixes used in the LCA models were based on mix designs from the Canadian Ready-Mixed Concrete Association (CRMCA). Based on the local construction practices, 35 MPa concrete with Portland Cement without air entrainment and fly ash, with 20% SCM materials was used for the baseline scenario.

SCMs created an issue as a change in SCMs could potentially impact many assemblies within a building. To resolve this issue, the GWP of several different SCM ranges for several different concrete-based building assemblies were compared. More specifically, the following assemblies were reviewed: Slab-on-grade, footings, beams and columns, concrete walls, and concrete in extra basic materials within the software. For each of these assemblies 0, 20%, 30%, and 40% SCM contents were compared. It was found that changing from 0 to 20% SCM content created a GWP reduction between 3.6% and 5.2% for the various assemblies using Mix #21[2] from the CRMCA 2017 concrete EPD. Similarly, increasing the SCM content from 0 to 30% SCM created a GWP reduction between 10.4% and 12.2%, and changing from 0 to 40% SCM content resulted in a 15.5% to 20.1% GWP reduction. For this analysis, the average change of impacts for the different assemblies was used. More specifically, the following factors were applied to all concrete based assemblies to estimate the impact of different SCM contents as outlined in Table 2.5.1.

Table 2.5.1: SCM Content and GWP Reduction Factors

SCM Content	GWP Reduction Factors
0%	1
20%	0.958
30%	0.891
40%	0.822

2.5.5 Concrete Columns

The Athena Impact Estimator did not consider additive loads in the design of column sizes for taller buildings: in a building, columns support not only the floor immediately above, but also the load of a column immediately above. As such, columns effectively support loads from all floors above, so lower floor columns are typically larger than upper floor columns. To determine the real impact on column design, three real designs of tall residential buildings were reviewed (between 30 and 37 stories) and take-offs were performed for concrete columns. These take-offs were factored according to the tributary area that they support and divided into three categories based on floor number (1-10, 11-20, and 21-30). An average of these values resulted in a volume of concrete per m^2 of tributary area. Concrete strength was also factored in by converting all columns to 30 MPa concrete, using a simple multiplication factor (e.g., a 40 MPa concrete volume was multiplied by 40/30 to estimate an equivalent 30 MPa column size).

Reinforcing steel within the columns was assumed to be 1% of the mass of the equivalent 30 MPa concrete.

[2] 30 GU without air 0-14% FA/SC mix in CRMCA 2017 concrete EPD

2.5.6 Load Bearing Wood-Frame Walls

The Athena Impact Estimator also did not factor in the additive load on load bearing walls in multi-story buildings. Similar to columns, the load bearing walls support not only the floor immediately above, but also the load of any load bearing walls above it. This resulted in a significant underestimation of lower-floor load bearing walls in the Mid-rise residential archetype design. To resolve this issue, the wood framing for the bottom three floors of the Mid-rise residential archetype were increased by an additional 25% to account for extra studs at window openings and interior partition walls. Note, this was not considered a significant error in the Low-rise residential (stacked townhome) archetype design as the additive effects are small and it would not be typical to change the stud spacing across the height of this type of building. These decisions were made based on a review of multiple real designs and knowledge of the industry.

2.5.7 Window Wall Systems

GWP values for window wall systems is not available in the Athena Impact Estimator. Instead, the embodied carbon emissions for window wall systems used in the analysis was calculated based on material take-offs of a typical system from Starline Windows, which is commonly found in local new construction projects.

2.6 Parametric Life Cycle Assessment (LCA)

Parametric LCA study was done for all three archetype buildings to help understand the relative impacts of various embodied carbon reduction measures for new construction. This assessment considered different structural materials, supplementary cementitious material (SCM) content for cements, building envelope systems, insulation type, window-to-wall ratio (WWR), and parking levels. A full list of parameters considered is provided in Section 3.1 including parameters for the baseline buildings.

Over 700,000 LCA models were created for all three archetype buildings using GWP data from the Athena Impact Estimator and EPDs. The parametric LCA study considered the compatibility of building materials and excluded material combinations that do not meet code and life safety requirements or may not be durable against environmental conditions. Other material combinations that are not typically seen in local construction practices at this time (e.g., structural steel systems for multi-unit High-rise residential buildings) were also excluded, although these material combinations may be considered in future studies as construction practices evolve.

The results of the 700,000 LCA models have been used to create a free online tool on the Building Pathfinder[3] website that allows designers to quickly evaluate the

[3] https://www.buildingpathfinder.com/

relative impacts of various embodied carbon reduction measures for new construction projects in Vancouver, BC.

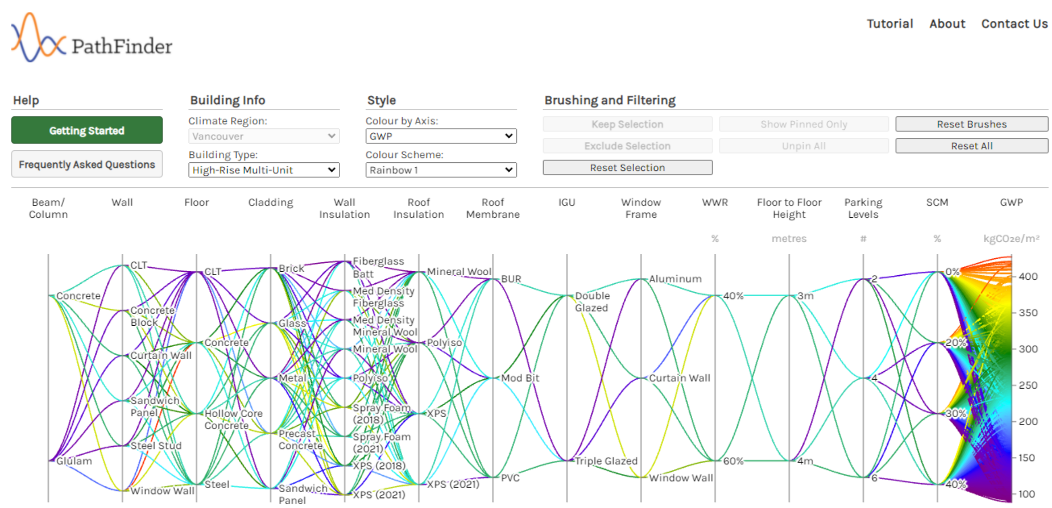


Figure 2.6.1: Embodied Carbon Building Pathfinder Tool (buildingpathfinder.com)

2.7 Embodied Carbon Reduction Thresholds

The embodied carbon reduction thresholds considered in this study were set by the City of Vancouver at 10%, 20%, and 40% when comparing proposed designs to a baseline building. This is consistent with the embodied carbon reduction approach that the City is adopting in upcoming versions of the Vancouver Building Bylaw and the results and will provide insight into how these reduction thresholds may impact future building design of high-rise, mid-rise, and low-rise residential buildings in the City.

More information about the baseline and proposed designs can be found in the Building Archetype Descriptions in Section 3, while information on how certain thresholds may impact design can be found in the LCA and Cost Analysis Results in Section 4.

2.8 Costing

Construction costs of the building designs considered in the parametric LCA study were also calculated. These construction costs were based on typical overall construction cost for each archetype building and material costs of the components for the various designs considered in the parametric LCA study. Construction costs for each design were calculated by prorating the differences in material costs for each design variant relative to the baseline design with the average typical overall construction cost. This helped to find construction cost of different embodied carbon reduction measures.

Results from the cost analysis are presented and discussed in Section 4.2, which provide some insight on the potential cost implications of various embodied carbon reduction measures. The results also show how different design options may impact cost, which could inform designers and policy makers in determining feasible building design and construction strategies.

The costs were determined with consultation from the cost consultant BTY and were based on approximate material quantities provided by MH for the archetype building designs. The costs were provided as material unit costs and typical overall construction costs for each archetype, which were then applied to the archetype building designs. These material costs were based on average material costs from various projects within the lower mainland at the time of this study. Similarly, the overall construction costs were based on typical projects at the time of assessment. Actual costs may vary depending on the project and specific materials procured.

Although the parametric LCA study included many types of materials, the costs for popular materials were only provided. Table 2.8.1 shows a list of components which were included in the cost analysis. Material costs related to mass timber construction were not included in this study as it will be covered by future reports with a deeper focus on mass timber buildings. A full list of the costs of the materials and assemblies are listed in Appendix B.

Table 2.8.2 lists the typical overall construction costs used in the study. Construction costs based on the first quarter of 2023 (Q1 2023) and 2021 are provided to show the range in pricing. While the Q1 2023 costs may be more relevant at the time of the assessment, it may be less indicative of long-term construction costs due to macroeconomic conditions at the time. All costs included in this study excludes general contractor's general conditions, overhead profit and fees, and contingencies.

Table 2.8.1: Materials Included in Cost Analysis

Application	Material/ Assembly
Below Grade Structure	• Reinforced concrete (SCM: 0%, 20%, 30%, 40%)
Parkade	• Reinforced concrete (SCM: 0%, 20%, 30%, 40%)
Beams	• Reinforced concrete (SCM: 0%, 20%, 30%, 40%) • Load bearing wood walls
Columns	• Reinforced concrete (SCM: 0%, 20%, 30%, 40%)
Floors	• Reinforced concrete (SCM: 0%, 20%, 30%, 40%) • Wood parallel chord joist • Wood I-joist with plywood
Exterior Walls	• Steel-frame walls • Wood-frame walls • Window wall spandrels • Pre-cast concrete
Exterior Wall Insulation	• XPS • Mineral wool • Fiberglass batt (R-13) • Blown cellulose
Exterior Wall Cladding	• Metal panel • Glass panel • Fiber cement board • Brick veneer • PVC/Vinyl • EIFS
Windows	• Aluminum frame window walls with double glazing

	• Aluminum frame punched windows with double glazing • Aluminum frame punched windows with triple glazing • Fiberglass frame punched windows with double glazing • Fiberglass frame punched windows with triple glazing • PVC frame punched windows with double glazing • PVC frame punched windows with triple glazing
Roof Insulation	• XPS • EPS • Polyisocyanurate • Mineral wool
Roof Membrane	• PVC • Modified Bitumen/SBS • EPDM

Table 2.8.2: Typical Overall Construction Costs

Archetype	**Q1 2023** $/ft² ($/m²)			**2021** $/ft² ($/m²)		
	Low	High	Average	Low	High	Average
High-Rise MURB	$470 ($5,059)	$500 ($5382)	$485 ($5,220)	$360 ($3,875)	$380 ($4,090)	$428 ($3,983)
Mid-Rise MURB	$510 ($5,490)	$530 ($5,705)	$520 ($5,597)	$380 ($4,090)	$400 ($4,306)	$390 ($4,198)
Low-Rise Stacked-Townhome	$280 ($3,014)	$300 ($3,229)	$290 ($3,122)	$210 ($2,260)	$230 ($2,476)	$220 ($2,368)

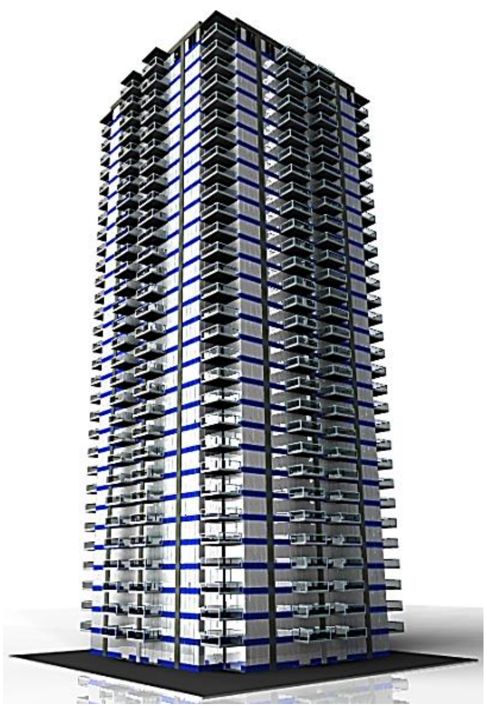
3. BUILDING ARCHETYPE DESCRIPTIONS

3.1 Building Characteristics

The following sections lists the characteristics and parameters considered in the parametric LCA study for the three archetype buildings.

3.1.1 Multi-Unit High-Rise Residential Building

The characteristics of the multi-unit High-rise residential archetype building used in this study is listed in Figure 3.1.1 and the parameters considered in the parametric LCA study is listed in Table 3.1.1 below.



Building Characteristics

- Building Length: 25 m
- Building Width: 25 m
- Floor-to-Floor Height: 3 m
- Number of Floors: 30
- Building Life Span: 60

Building Structure

- Live Load: 2.4 kPa
- Beam Span: 8 m
- Joist Span: 6 m
- Footing: 300 mm x 100 mm below columns and perimeter walls
- Foundation: 100 mm concrete slab on grade
- Below Grade Walls: 200 mm concrete

Figure 3.1.1: Building Characteristics of the Multi-Unit Residential High-Rise Archetype

Table 3.1.1: Parameters of the Multi-unit High-Rise Residential Archetype

Parameters	Components
Structure	• Cast-in-place Concrete (baseline) • Glulam (mass timber)
Floor	• Cast-in-place Concrete (baseline) • Hollow Core Pre-cast Concrete • Steel • Cross Laminated Timber (CLT)
Exterior Wall Assemblies	• Aluminum Window Wall (baseline) • Aluminum Curtain Wall • Steel-Frame

	• Concrete Block (CMU) • Pre-cast Concrete Sandwich Panels • Cross Laminated Timber (CLT)
Exterior Wall Insulation	• Medium Density Mineral Wool (baseline) • Mineral Wool • Fiberglass Batt • Medium Density Fiberglass Batt • Polyisocyanurate • Spray Polyurethane Foam • Extruded Polystyrene (XPS)
Exterior Wall Cladding	• Glass (baseline) • Metal Panel • Brick Veneer • Pre-cast Concrete
Window to Wall Ratio (WWR)	• 40% of Wall Area (baseline) • 60% of Wall Area
Window Vision Glazing	• Double Glazed Low-E Argon Filled • Triple Glazed Low-E Argon Filled
Window Frame	• Aluminum
Roof Insulation	• Polyisocyanurate (baseline) • Mineral Wool • Extruded Polystyrene (XPS)
Roof Membrane	• Modified Bitumen (SBS) (baseline) • Built-up Roofing • PVC
Floor-to-Floor Height	• 3 m (baseline) • 4 m
Parking	• 4 level parkade (baseline) • 2 level parkade • 6 level parkade
SCM Content	• 20% (baseline) • 0% • 30% • 40%

3.1.2 Multi-Unit Mid-Rise Residential Building

The characteristics of the multi-unit Mid-rise residential archetype building used in this study is listed in Figure 3.2.1 and the parameters considered in the parametric LCA study is listed in Table 3.2.1 below.

Building Characteristics

- Building Length: 75 m
- Building Width: 25 m
- Floor-to-Floor Height: 3 m
- Number of Floors: 6
- Building Life Span: 60

Building Structure

- Live Load: 2.4 kPa
- Beam Span: 9 m
- Joist Span: 3 m
- Footing: 300 mm x 100 mm below columns and perimeter walls
- Foundation: 100 mm concrete slab on grade
- Below Grade Walls: 200 mm concrete

Figure 3.2.1: Building Characteristics of the Multi-Unit Mid-Rise Residential Archetype

Table 3.2.1: Parameters of the Multi-unit Mid-Rise Residential Archetype

Parameters	Components
Structure	• Cast-in-place Concrete (baseline) • Steel • Glulam (mass timber) • Wood-Frame
Floor	• Cast-in-place Concrete (baseline) • Steel • Cross Laminated Timber (CLT) • Wood I Joists • Wood Joist
Exterior Wall Assemblies	• Aluminum Window Wall (baseline) • Steel-Frame • Insulated Concrete Forms (ICF) • Cross Laminated Timber (CLT) • Wood-Frame
Exterior Wall Insulation	• Medium Density Mineral Wool (baseline) • Medium Density Fiberglass Batt • Cellulose • Polyisocyanurate • Spray Polyurethane Foam • Extruded Polystyrene (XPS)

Exterior Wall Cladding	• Fiberboard (baseline) • Metal Panel • Brick Veneer • EIFS • PVC (Vinyl)
Window to Wall Ratio (WWR)	• 40% of Wall Area (baseline) • 60% of Wall Area
Window Vision Glazing	• Double Glazed Low-E Argon Filled • Triple Glazed Low-E Argon Filled
Window Frame	• Aluminum (baseline) • Fiberglass • Vinyl
Roof Insulation	• Polyisocyanurate (baseline) • Mineral Wool • Expanded Polystyrene (EPS) • Extruded Polystyrene (XPS)
Roof Membrane	• Modified Bitumen (SBS) (baseline) • Built-up Roofing • PVC
Floor-to-Floor Height	• 3 m (baseline)
Parking	• 1 level parkade (baseline) • Street level
SCM Content	• 20% (baseline) • 0% • 30%

3.1.3 Multi-Unit Low-Rise Residential (Townhome) Building

The characteristics of the multi-unit Low-rise residential townhome archetype building used in this study is listed in Figure 3.3.1 and the parameters considered in the parametric LCA study is listed in Table 3.3.1 below.

Building Characteristics

- Building Length: 12 m
- Building Width: 6 m
- Floor-to-Floor Height: 3 m
- Number of Floors: 3
- Building Life Span: 60

Building Structure

- Live Load: 2.4 kPa
- Beam Span: 6 m
- Joist Span: 3 m
- Footing: 300 mm x 100 mm below columns and perimeter walls
- Foundation: 100 mm concrete slab on grade
- Below Grade Walls: 200 mm concrete

Figure 3.3.1: Building Characteristics of the Multi-Unit Low-Rise Residential Archetype

Table 3.3.1: Parameters of the Multi-unit Low-Rise Residential Archetype

Parameters	Components
Structure	• Wood-Frame (baseline) • Glulam (mass timber)
Floor	• Wood I Joist (baseline) • Cross Laminated Timber (CLT) • Wood Joist
Exterior Wall Assemblies	• Wood-Frame (baseline) • Steel-Frame • Insulated Concrete Forms (ICF) • Cross Laminated Timber (CLT) • Optimum Value Engineered Wood-Frame (OVE)
Exterior Wall Insulation	• Medium Density Mineral Wool (baseline) • Medium Density Fiberglass Batt • Cellulose • Spray Polyurethane Foam • Extruded Polystyrene (XPS)
Exterior Wall Cladding	• Fiberboard (baseline) • Metal Panel • Brick Veneer • EIFS • PVC (Vinyl)
Window to Wall Ratio (WWR)	• 10% of Wall Area (baseline)

	• 25% of Wall Area
Window Vision Glazing	• Double Glazed Low-E Argon Filled • Triple Glazed Low-E Argon Filled
Window Frame	• Fiberglass (baseline) • Aluminum • Vinyl • Wood
Roof Insulation	• Polyisocyanurate (baseline) • Mineral Wool • Expanded Polystyrene (EPS) • Extruded Polystyrene (XPS)
Roof Membrane	• Modified Bitumen (SBS) (baseline) • Built-up Roofing • PVC
Floor-to-Floor Height	• 3 m (baseline)
Parking	• Street Level (baseline)
SCM Content	• 20% (baseline) • 0% • 30%

4. LCA AND COST ANALYSIS RESULTS

4.1 LCA Results

The Athena Building Impact Estimator (Version 5.4.0103) was used to model the impact of most of the various design iterations on embodied carbon (i.e., embodied global warming potential). For more information on the background material data and assumptions, see the Impact Estimator User Manual. The Impact Estimator was used to estimate both material quantities and their embodied impacts. Exceptions and work arounds are presented below.

4.1.1 High-Rise Residential Archetype

The parametric LCA study tool considered various combinations of design factors, resulting in 552,960 unique models. To reduce the number of combinations and make the tool more usable, some combinations of design factors were not considered. These disallowed designs included only combinations that are extremely unlikely to be used, such as a concrete floor slab on a wood column.

The range of GWP for the various combinations was between 97 and 424 kg CO_2e/m^2.

A review of the effect of each variable on the overall range of GWP was performed by declaring a single design factor in most categories. As an example, to explore the effect of different wall insulation types, the following adjustments to the tool were made (wall insulation filter remained open to all five designs and remaining design factors were limited to one selection):

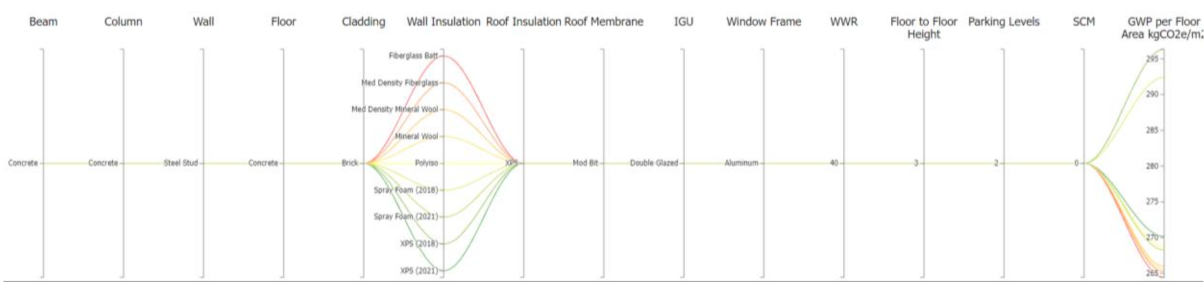
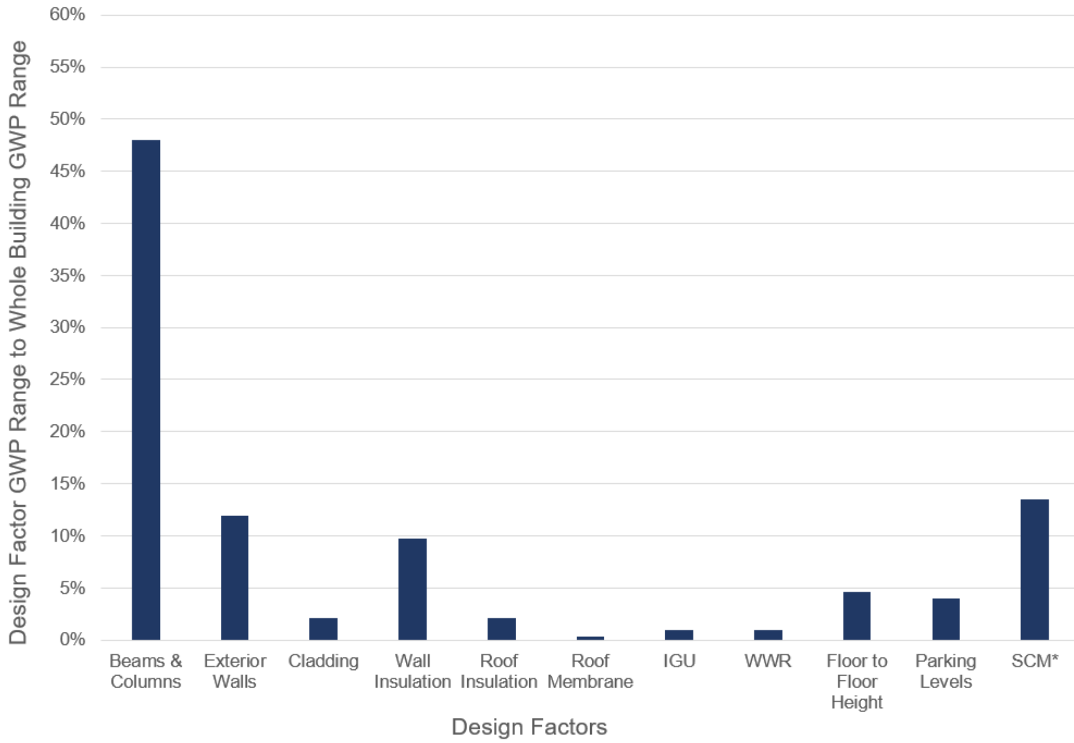


Figure 4.1.1: Performance Map of Wall Insulation Types on Building GWP of the High-Rise Residential Archetype

From Figure 4.1.1 above, the range of GWP is from 264 to 296 kg CO_2e/m^2, or about 10% of the total range of all possible combinations. Accordingly, it can be concluded that wall insulation type does have an impact on total embodied carbon of the building archetype, but perhaps not as large as other design factors. The effect of different variables using a similar methodology is presented in the table below:



* The SCM variable range is developed under the assumption that beams, columns, walls and floors are concrete based.

Figure 4.1.2: Contribution of GWP Reductions of Various Design Factors to the Whole Building GWP Range of the High-Rise Archetype

From Figure 4.1.2, it is apparent which design factors have significant impact on the embodied carbon of the entire building. As such, reduction strategies should focus on the design factors that would have the most impact. It is important to note that many of the design factors are interrelated, so the values given in the graph are approximate in some cases.

In general, there is flexibility when choosing maximum thresholds for embodied carbon reductions. However, some thresholds may have the result of limiting or eliminating the use of certain material types. The implications of choosing different thresholds are presented below.

Threshold of 260 kgCO_2e/m^2: This represents the median value of the total range. It is the 50th percentile. Under this scenario the following observations were made:

- No single design factor was eliminated from the range.
- The use of concrete beams, columns and floors resulted in GWPs in the upper part of the range but still allowed a full range of other design factors.
- The use of concrete beams, columns and floors and at 0 SCMs presented limits on many other design factors. Accordingly, if using concrete systems SCMs would be close to mandatory.

- The use of glulam beams and columns and CLT floors gave results below the threshold for all other design factor combinations. In other words, the use of these wood-based systems would enable full flexibility for other design factors.

Threshold of 179 kgCO_2e/m^2: This represents the lower 25th percentile of the range. Under this scenario the following observations were made:

- Concrete column and beam systems could not be used. Only glulam beams and columns with CLT floor met the criteria.

4.1.2 Mid-Rise Residential Archetype

Similar to the High-rise residential archetype, the parametric LCA study created 935,280 unique LCA models based on combinations of various design factors. Combinations of design factors that are extremely unlikely to be used were excluded from the analysis to reduce the number of LCA models.

The range of global warming potential for the various combinations was between 38 and 349 kg CO_2e/m^2.

A review of the effect of each design factor was performed by declaring a single design factor in most categories. As an example, to explore the effect of different roof membrane systems, all other design factors were limited to one selection and the roof membrane filter remained open:

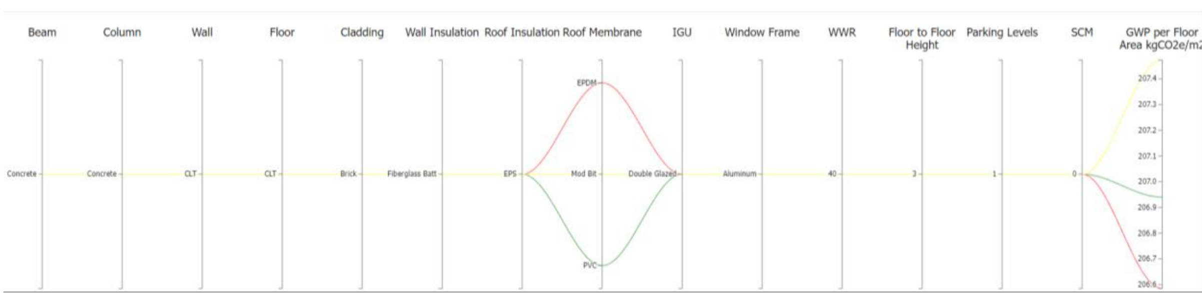
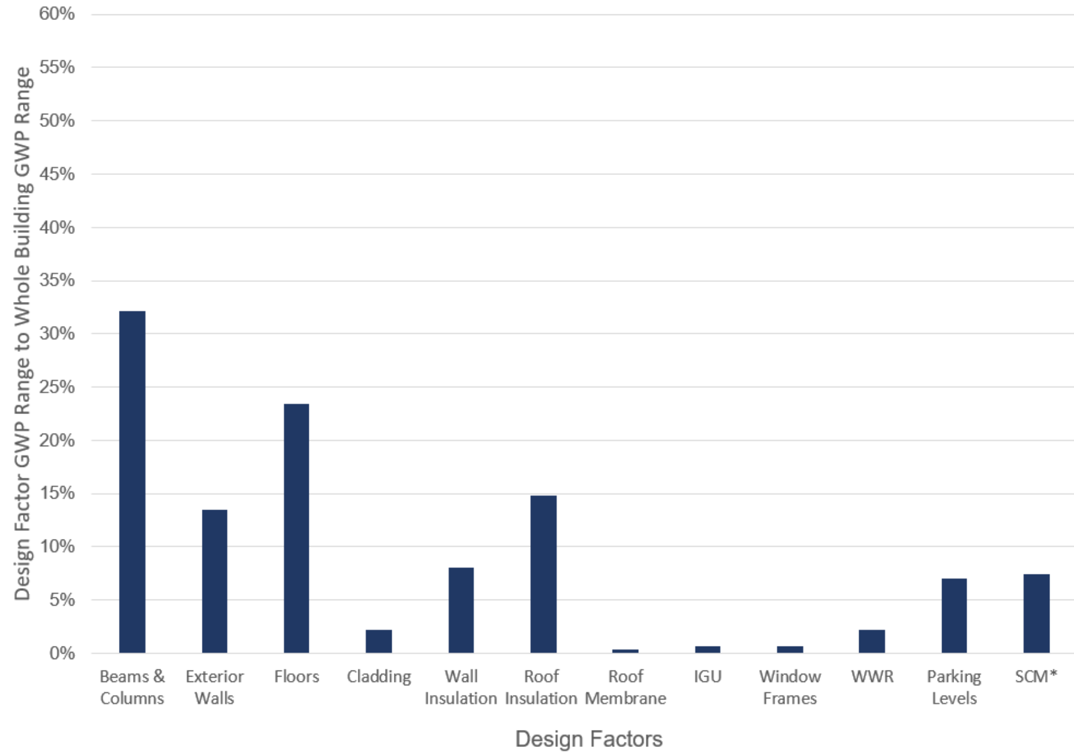


Figure 4.1.3: Performance Map of Roof Membrane Types on Building GWP of the Mid-Rise Residential Archetype

From Figure 4.1.3 above the range of GWP is from 206 to 207 kg CO_2e/m^2, or about 0.3% of the total range of all possible combinations. Accordingly, it can be concluded that roof membrane type has a very small impact on total embodied carbon compared to other design factors. The effect of different design factors using a similar methodology of the Mid-rise residential archetype is presented in Figure 4.1.4.



* The SCM variable range is developed under the assumption that beams, columns, walls and floors are concrete based.

Figure 4.1.4: Contribution of GWP Reductions of Various Design Factors to the Whole Building GWP Range of the Mid-Rise Residential Archetype

From Figure 4.1.4, it is apparent that certain design factors have a larger impact on the embodied carbon of the entire building and reductions should focus on these design factors. Like the High-rise residential archetype, many of the design factors are interrelated so the values shown in Figure 4.1.4 are approximate in some cases.

Setting embodied carbon thresholds may be an effective method to reduce embodied carbon emissions, however, higher thresholds may limit the use of or eliminate certain material types. Below is a summary of how certain thresholds may impact the building design for the Mid-rise residential archetype.

Threshold of 193 $kgCO_2e/m^2$: This represents the median value of the total range. It is the 50th percentile. Under this scenario the following observations were made:

- No single design factor was eliminated from the range.
- The use of concrete beams, columns and floors resulted in several mandatory responses to remain below the threshold. This included the use of 30% SCMs, no underground parking, and wood stud walls.
- The use of steel or wood beams, columns, and floors did not eliminate any additional design factors.

Threshold of 116 $kgCO_2e/m^2$: This represents the lower 25th percentile of the range. Under this scenario the following observations were made:

- Concrete column and beam systems could not be used.
- The use of steel columns and beams required the use of wood-based floor systems.
- The use of wood-based column and beam systems did not eliminate any other design factors.

4.1.3 Low-Rise Residential Archetype

As with the other archetypes, the parametric LCA study evaluated 725,760 unique LCA models based on combinations of various design factors considered in this study. Select combinations of design factors deemed unlikely to be used were excluded from the analysis including ICF walls with batt insulations.

The range of global warming potential for the various combinations was between 75 and 571kg CO_2e/m^2.

Similar to the High-rise and Mid-rise residential archetypes, a review of the effect of each design factor compared to the whole building was performed by declaring a single factor in most categories. As an example, to explore the effect of different roof insulation type, all other design factors were limited to one selection and the roof insulation type filter remained open:

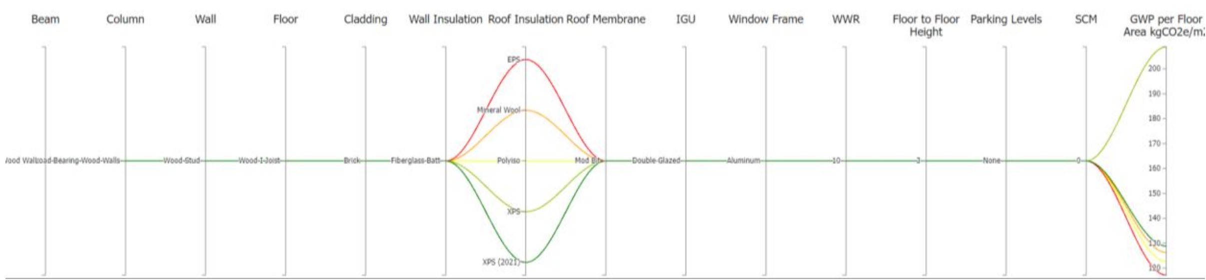
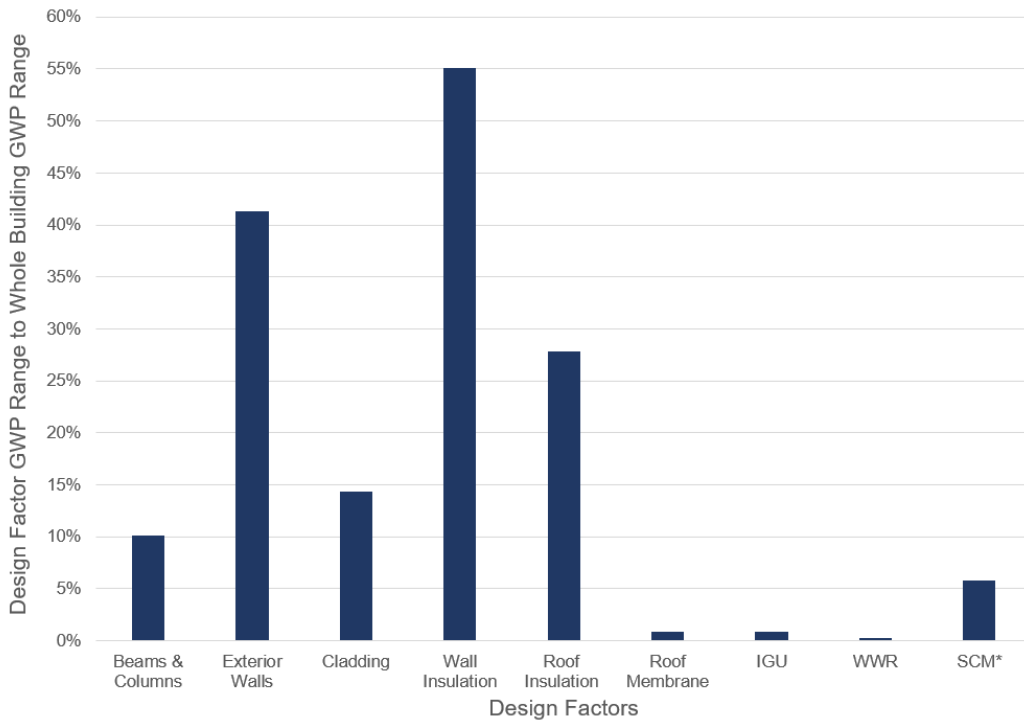


Figure 4.1.5: Performance Map of Roof Membrane Types on Building GWP of the Low-Rise Residential Archetype

From Figure 4.1.5 the range of GWP is from 117 to 209 kg CO_2e/m^2, or about 28% of the total range of all possible combinations. Accordingly, it can be concluded that roof insulation type has a fairly large impact on total embodied carbon compared to other design factors. The effect of different design factors using a similar methodology is shown in Figure 4.1.6.



* The SCM variable range is developed under the assumption that beams, columns, walls and floors are concrete based.

Figure 4.1.6: Contribution of GWP Reductions of Various Design Factors to the Whole Building GWP Range of the Low-Rise Residential Archetype

From Figure 4.1.6, several design factors have a significant impact on the embodied carbon of the entire building and strategies to reduce embodied carbon should focus on these factors. Similar to the other archetypes, many of the design factors are interrelated and the values shown in Figure 4.1.6 are approximate in some cases.

Similar to the High-rise and Mid-rise residential archetypes, higher embodied carbon reduction thresholds may limit the use of or eliminate certain types of materials. Below is a summary of how certain threshold levels may impact design factors for the Low-rise residential archetype.

Threshold of 323 kgCO_2e/m^2: This represents the median value of the total range. It is the 50th percentile. Under this scenario the following observations were made:

- No single design factor was eliminated from the range
- There were some limitations if foam-based wall and roof insulation types were selected

Threshold of 199 kgCO_2e/m^2: This represents the lower 25th percentile of the range. Under this scenario the following observations were made:

- ICF walls could not be used
- CLT walls could not be used with foam-based wall insulation

4.2 Costing Results

Construction costs based on information provided by the cost consultant, BTY, were incorporated into the LCA results for all three archetype buildings to determine the impacts of various embodied carbon reduction measures. The cost analysis was performed by comparing various embodied carbon reduction measures to a baseline design to determine the relative savings in both GWP and costs. These scenarios were grouped based on embodied carbon reduction thresholds of 10%, 20%, 30%, and 40% relative to the baseline design for each archetype building. The results of the costs analysis are presented as both:

- **Individual Embodied Carbon Reduction Measures:** to determine the impact of individual options on GWP and materials cost
- **Bundles of Embodied Carbon Reduction Measures:** to determine the overall impact of a collection of measures that could be used in building design on GWP and materials cost

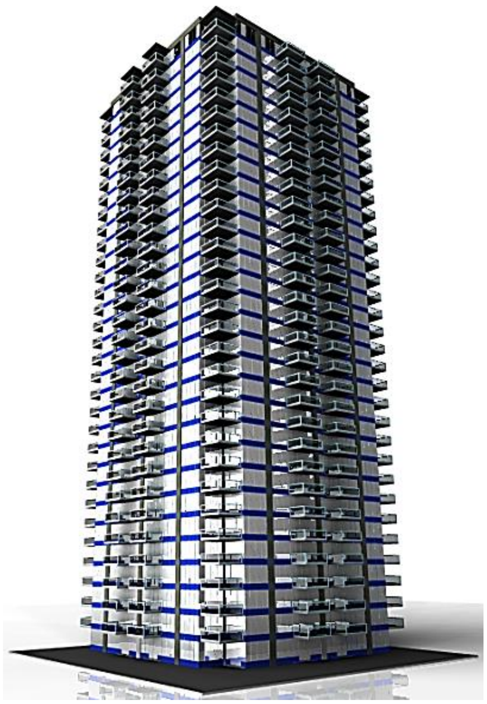
The construction costs for the various design options were based on differences material costs and quantities, which were prorated with the typical overall construction costs for each archetype to find the estimated construction cost of the design. As a result, actual construction cost differences may differ depending on how material choices impact construction labour and schedules.

Due to the recent changes in construction costs, average construction costs based on the first quarter of 2023 (Q1 2023) and 2021 are presented in the report. The Q1 2023 costs may be more representative of the pricing levels at the time of the assessment, while the 2021 costs are more reflective of traditional pricing.

The cost analysis was only performed for select embodied carbon reduction measures that were included in the costing scope of this project. Some reduction measures, such as Mass Timber design options, were beyond the costing scope of this project and were not included in the cost analysis.

4.2.1 High-Rise Residential Archetype

The characteristics of the baseline building design for the cost analysis is listed in Figure 4.2.1. This baseline design represents the typical construction of most multi-unit high-rise residential buildings found in the City of Vancouver built in the late 2010s, which mostly consists of concrete structure and a window wall system as the building envelope. Figure 4.2.2. shows the baseline building design and GWP reduction thresholds in context with the other building designs considered in the parametric LCA study.



Building Structure

- Concrete with 20% SCM
- 3 m floor-to-floor height

Building Envelope

- Aluminum window-wall system with glass spandrel cladding and medium density mineral wool insulation
- 40% Window-to-Wall Ratio (WWR)
- Double glazed low-e, argon filled vision glazing
- SBS roofing membrane
- Polyisocyanurate roof insulation

Parkade

- 4 level concrete structure with 20% SCM

Global Warming Potential (GWP): 311.0 $kgCO_2e/m^2$

Estimated Construction Cost:
(Q1 2023) $120,724,000
(FY 2021) $92, 099,000

Figure 4.2.1: High-Rise Residential Archetype Baseline Building Design GWP and Cost

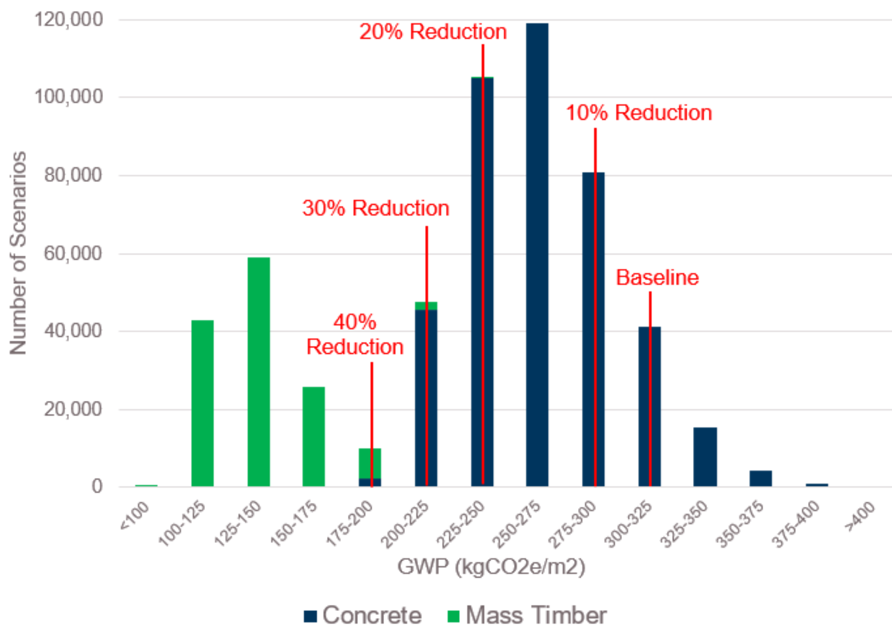


Figure 4.2.2: High-Rise Residential Archetype Baseline Building Design Relative to Parametric LCA Designs

The high-rise baseline design is at the upper end of the spread of designs considered in this study. As such there are many design options that will allow designers to achieve significant GWP savings. Designs that are above the baseline mostly represent building construction that are not typical to practices currently used in Vancouver, such as the use of concrete block in fill walls as listed in Table 4.2.1.

Table 4.2.1: Scenarios above the Baseline Design for the High-Rise Archetype

Scenario	Global Warming Potential	
	$kgCO_2e/m^2$	Percent Difference
Baseline	311.0	-
Concrete Structure, Window Wall with Spray Foam (2018), 40% WWR, 6 Level Parkade, 0% SCM	360.4	15.9%
Concrete Structure, Window Wall with Spray Foam (2018), 40% WWR, 6 Level Parkade, 20% SCM	351.2	12.9%
Concrete Structure, Concrete Block with XPS (2018) and Brick, 40% WWR, 6 Level Parkade, 0% SCM	329.3	5.9%
Concrete Structure, Concrete Block with XPS (2018) and Brick, 40% WWR, 6 Level Parkade, 20% SCM	319.0	2.6%
Concrete Structure, Concrete Block with XPS (2018) and Precast Concrete, 40% WWR, 6 Level Parkade, 0% SCM	337.9	8.7%
Concrete Structure, Concrete Block with XPS (2018) and Precast Concrete, 40% WWR, 6 Level Parkade, 20% SCM	327.6	5.3%

Individual Embodied Carbon Reduction Measures

The GWP and cost reduction impacts of individual measures considered in this study for the High-rise residential archetype are shown in Table 4.2.1. Percent differences listed in Table 4.2.1 were calculated by comparing the GWP and construction costs of the building design with the embodied carbon reduction measure to the baseline building design shown in Figure 4.2.1. These percent differences are also plotted in Figures 4.2.2 and 4.2.3 to show the relative impacts of each measure. Negative percentages shown in Table 4.2.1 and Figures 4.2.2 and 4.2.3 indicate savings, while positive values represent an increase.

Table 4.2.1: Summary of Embodied Carbon Reduction Measures for High-Rise Residential Archetype Building

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline	311.0		$120,724,000	$92,099,00	
Impacts of SCMs					
0% SCM	320.2	3.0%	$121,236,000	$92,489,000	0.4%
30% SCM	296.3	-4.7%	$120,212,000	$91,708,000	-0.4%
40% SCM	281.2	-9.6%	$120,212,000	$91,708,000	-0.4%
Impact of Parkade					
6 Levels, 20% SCM	317.5	2.1%	$123,627,000	$94,313,000	2.4%
6 Levels, 40% SCM	287.7	-7.5%	$123,098,000	$93,910,000	2.0%
2 Levels, 20% SCM	304.5	-2.1%	$118,398,000	$90,324,000	-1.9%
2 Levels, 40% SCM	274.7	-11.7%	$117,903,000	$89,947,000	-2.3%

Impact of Wall Assembly					
Steel Stud	257.8	-17.1%	$114,389,000	$87,265,000	-5.2%
Sandwich Panel with XPS (2021)	270.0	-13.2%	$97,366,000	$74,279,000	-19.3%
Sandwich Panel with Mineral Wool	255.7	-17.8%	$97,383,000	$74,292,000	-19.3%
Impact of Windows					
60% Window-to-Wall Ratio (WWR)	288.0	-7.34%	$112,249,000	$85,633,000	-7.0%

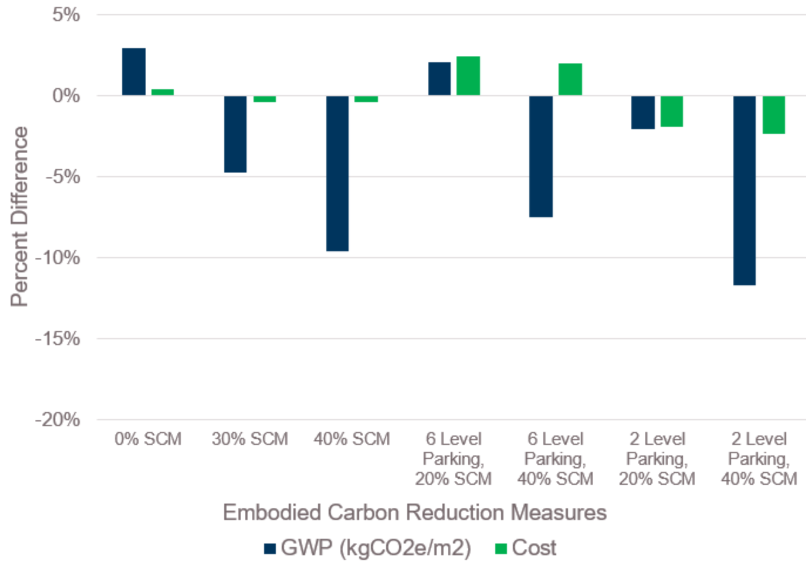


Figure 4.2.2: Percent Difference in GWP and Construction Cost of Structural Related Embodied Carbon Reduction Measures for High-Rise Residential Archetype Relative to Baseline Design

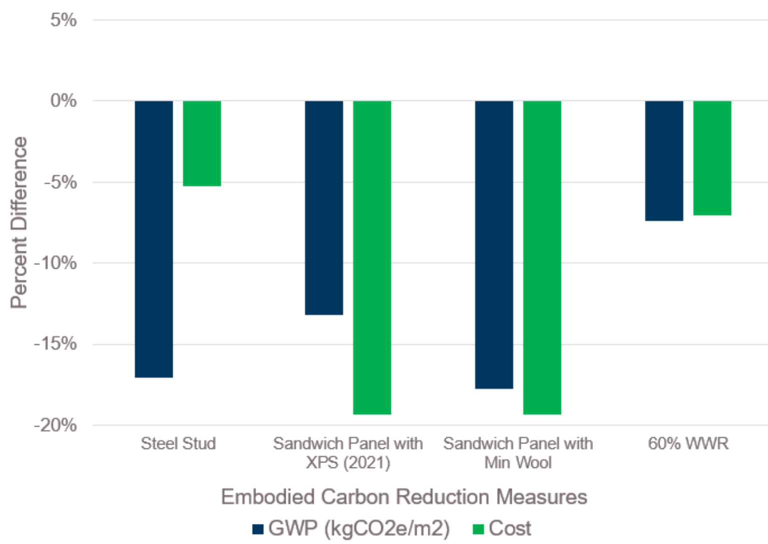


Figure 4.2.3: Percent Difference in GWP and Construction Cost of Building Envelope Related Embodied Carbon Reduction Measures for High-Rise Residential Archetype Relative to Baseline Design

Most of the embodied carbon reduction measures considered produces both GWP and construction cost savings. The only measures that increase cost are removing SCMs from the concrete mix and adding two additional levels to the parkade.

The individual measures that appear to have the biggest impact on GWP and cost are SCM content, reducing parkade levels, and switching building envelope assemblies from a window wall system to steel-frame in fill assemblies or pre-cast concrete sandwich panels.

Bundles of Embodied Carbon Reduction Measures

As seen in the previous section there are various embodied carbon reduction measures that can reduce both the GWP and costs of a typical multi-unit high-rise residential building in Vancouver. Some of these measures can achieve between 2% and 17% in GWP reductions while also reducing construction and construction costs. However, if higher GWP reduction targets, such as 20% to 40%, are desired many of these measures must be used in combination. Below are a few examples of building designs that achieve various GWP reduction targets and their estimated construction costs.

High-Rise Residential Archetype: 10% GWP Reduction

There are many cost-effective strategies available to help achieve 10% GWP reduction over the baseline design. While there are designs that can also achieve 10% GWP reduction with new and innovative materials, many of the strategies presented in this report for the High-rise residential archetype building are based on materials, systems, and assemblies that are commonly used at the time of the assessment. To achieve 10% or greater GWP reductions, many of these typical construction strategies utilize SCMs and substituting carbon intensive building envelope assemblies such as aluminum window wall systems with steel-frame or precast concrete sandwich panel assemblies. Other strategies to reduce GWP is to reduce the amount of parking in the parkade, which not only saves GWP but also construction costs by using less concrete overall. Depending on the design a 19% reduction in GWP may be achieved compared to the baseline design while simultaneously saving over 21% of the estimated construction cost.

Table 4.2.2: Example Design Bundles to Achieve 10% GWP Reduction or Greater over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Window-Wall, 40% WWR, 4 Level Parkade, 20% SCM	311.0	-	$120,724,000	$92,099,000	-
Window Wall, 40% WWR, 2 Level Parkade, 40% SCM	274.7	-11.7%	$117,903,000	$89,947,000	-2.3%
Steel Stud, 40% WWR, 6 Level Parkade, 20% SCM	264.4	-15.-%	$117,291,000	$89,480,000	-2.8%
Steel Stud, 40% WWR, 6 Level Parkade, 30% SCM	249.7	-19.7%	$116,762,000	$89,076,000	-3.3%

Steel Stud, 40% WWR, 4 Level Parkade, 20% SCM	257.8	-17.1%	$114,389,000	$87,265,000	-5.2%
Steel Stud, 40% WWR, 2 Level Parkade, 20% SCM	251.4	-19.2%	$112,063,000	$85,491,000	-7.2%
Sandwich Panel with XPS, 40% WWR, 6 Level Parkade, 20% SCM	266.5	-14.3%	$100,268,000	$76,493,000	-16.9%
Sandwich Panel with XPS, 40% WWR, 4 Level Parkade, 20% SCM	260.0	-16.4%	$97,366,000	$74,279,000	-19.3%
Sandwich Panel with XPS, 40% WWR, 2 Level Parkade, 20% SCM	253.5	-18.85%	$95,040,000	$72,504,000	-21.3%
Sandwich Panel with Mineral Wool, 40% WWR, 4 Level Parkade, 20% SCM	255.7	-17.8%	$97,383,000	$74,292,000	-19.3%

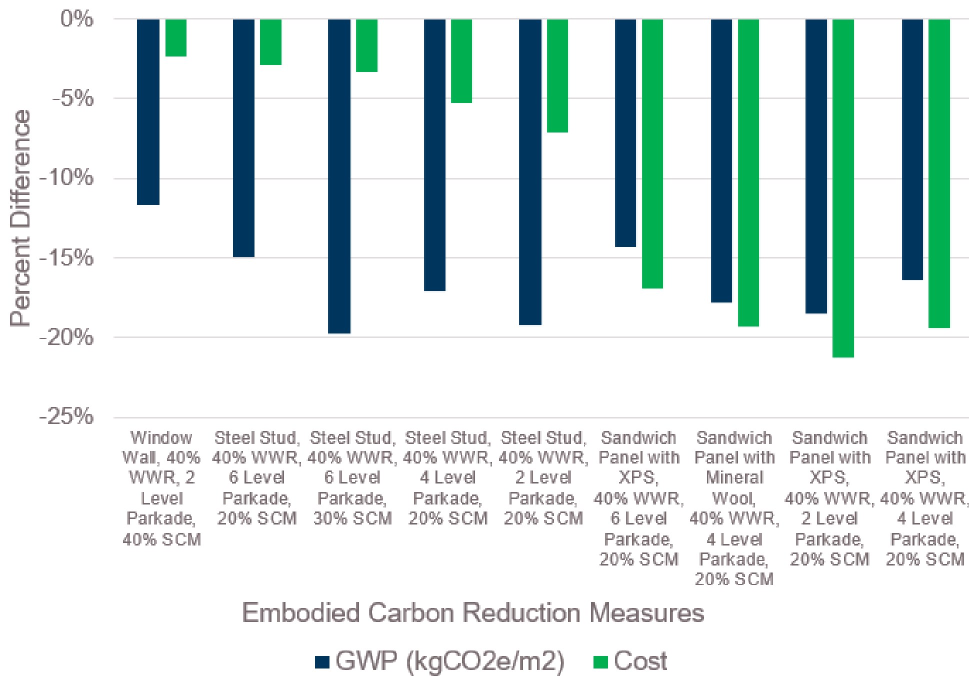


Figure 4.2.4: Percent Differences of Example Design Bundles to Achieve 10% GWP Reduction or Greater over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

High-Rise Residential Archetype: 20% GWP Reduction

Similarly, GWP reductions of 20% or greater can also be achieved using typical concrete structure and building envelope assemblies without necessarily requiring new and innovative systems. Many of these designs require at least 30% SCM and steel-frame or pre-cast sandwich panel wall assemblies as shown in Table 4.2.3.

Table 4.2.3: Example Design Bundles to Achieve 20% GWP Reduction over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Window-Wall, 40% WWR, 4 Level Parkade, 20% SCM	311.0	-	$120,724,000	$92,099,000	-
Steel Stud, 40% WWR, 6 Level Parkade, 40% SCM	234.6	-24.6%	$116,762,000	$89,076,000	-3.3%
Steel Stud, 40% WWR, 4 Level Parkade, 40% SCM	228.0	-26.7%	$113,877,000	$86,875,000	-5.7%
Steel Stud, 40% WWR, 2 Level Parkade, 40% SCM	221.5	-28.8%	$111,567,000	$85,113,000	-7.6%
Sandwich Panel with XPS, 40% WWR, 4 Level Parkade, 40% SCM	227.5	-26.8%	$96,854,000	$73,888,000	-19.8%
Sandwich Panel with XPS, 40% WWR, 2 Level Parkade, 40% SCM	221.1	-28.9%	$94,545,000	$72,127,000	-21.7%
Sandwich Panel with Mineral Wool, 40% WWR, 6 Level Parkade, 30% SCM	246.3	-20.8%	$99,756,000	$76,103,000	-17.4%
Sandwich Panel with Mineral Wool, 40% WWR, 6 Level Parkade, 40% SCM	229.9	-26.1%	$99,756,000	$76,103,000	-17.4%
Sandwich Panel with Mineral Wool, 40% WWR, 4 Level Parkade, 40% SCM	223.3	-28.2%	$96,871,000	$73,901,000	-19.8%

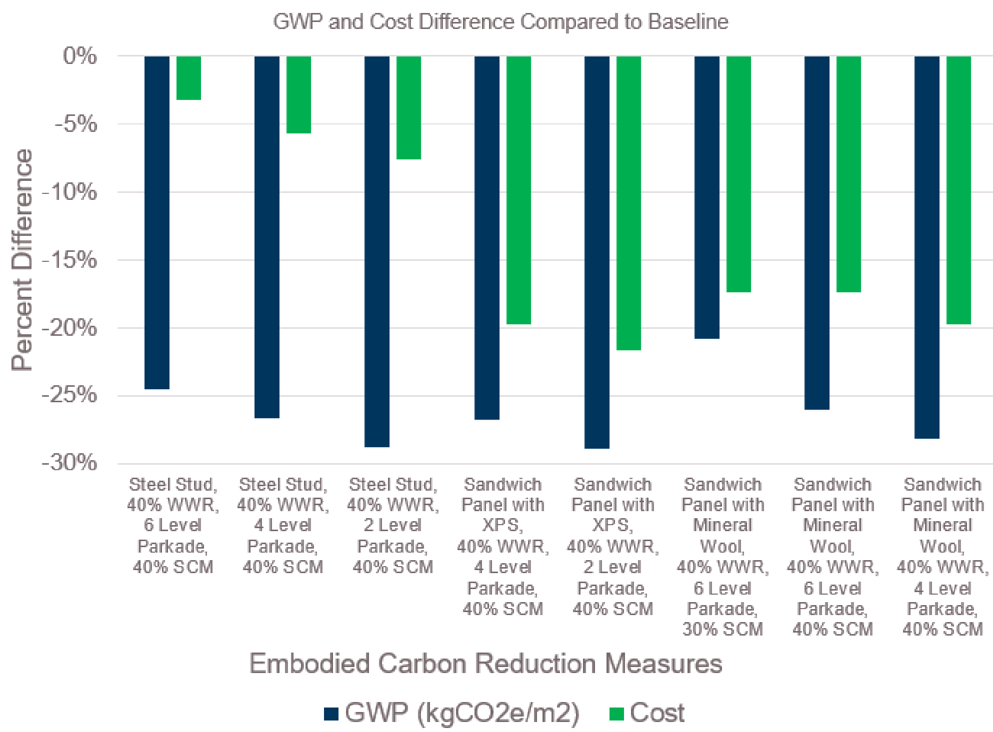


Figure 4.2.5: Percent Differences of Example Design Bundles to Achieve 20% GWP Reduction or Greater over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

High-Rise Residential Archetype: 30% GWP Reductions

There are fewer design options that achieve higher GWP reduction targets. Designs that utilize typical building materials and assemblies, such as concrete beams and columns, and steel frame or precast concrete sandwich panel walls, will require the use of hollow core concrete or steel floors to achieve 30% or greater GWP reductions compared to the baseline. Table 4.2.4 lists some of these design options. Construction cost information for these bundles are not available at this time as they were not included in the cost analysis.

Table 4.2.4: Example Design Bundles to Achieve 30% GWP Reduction over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Window-Wall, 40% WWR, 4 Level Parkade, 20% SCM	311.0	-	$120,724,000	$92,099,000	-
Steel Stud, Hollow Core Concrete Floors, 40% WWR, 4 Level Parkade, 30% SCM	216.4	-30.4%	n/a	n/a	n/a
Sandwich Panel with XPS, Hollow Core Concrete Floors, 40% WWR, 4 Level Parkade, 30% SCM	217.3	-30.1%	n/a	n/a	n/a
Sandwich Panel with Mineral Wool, Hollow Core Concrete Floors, 40% WWR, 4 Level Parkade, 30% SCM	213.0	-31.5%	n/a	n/a	n/a
Steel Stud, Steel Floors, 40% WWR, 4 Level Parkade, 40% SCM	201.4	-35.4%	n/a	n/a	n/a
Sandwich Panel with Mineral Wool, Steel Floors, 40% WWR, 4 Level Parkade, 20% SCM	215.8	-30.6%	n/a	n/a	n/a
Sandwich Panel with Mineral Wool, Steel Floors, 40% WWR, 4 Level Parkade, 40% SCM	196.6	-36.8%	n/a	n/a	n/a

High-Rise Residential Archetype: 40% GWP Reduction

For the design options considered in the analysis, designs that achieve 40% GWP reduction will require the use of mass timber structural systems as shown in Table 4.2.5. The GWP reductions from replacing concrete with mass timber allows for more carbon intensive building envelope assemblies such as window wall systems and sandwich panels with XPS.

Table 4.2.5: Example Design Bundles to Achieve 40% GWP Reduction over Baseline Multi-Unit High-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Window-Wall, 40% WWR, 4 Level Parkade, 20% SCM	311.0	-	$120,724,000	$92,099,000	-

Mass Timber Structure, Window Wall, 40% WWR, 4 Level Parkade, 20% SCM	156.3	-49.7%	n/a	n/a	n/a
Mass Timber Structure, Sandwich Panels with XPS, 40% WWR, 4 Level Parkade, 20% SCM	105.3	-66.1%	n/a	n/a	n/a
Mass Timber Structure, Steel Frame Wall with Mineral Wool, 40% WWR, 4 Level Parkade, 20% SCM	103.2	-66.9%	n/a	n/a	n/a

4.2.2 Mid-Rise Residential Archetype

The characteristics of the baseline building design which the cost analysis was performed with is listed in Figure 4.2.6. The baseline design represents typical construction of most multi-unit mid-rise residential buildings found in the City of Vancouver built in the late 2010s, which consists of concrete structure with a steel-frame infill walls as the building envelope. Figure 4.2.7 shows the baseline design and GWP reduction thresholds in the context of the other building designs considered in the parametric LCA models.

Building Structure

- Concrete with 0% SCM
- 3 m floor-to-floor height

Building Envelope

- Steel-frame wall with fiberglass batt insulation and fiber cement cladding
- 60% Window-to-Wall Ratio (WWR)
- Double glazed low-e, argon filled vision glazing
- Aluminum window frame
- SBS roofing membrane
- Polyisocyanurate roof insulation

Parkade

- 1 level concrete structure with 0% SCM

Global Warming Potential (GWP): 244.7 kgCO$_2$e/m^2

Estimated Construction Costs:
(Q1 2023) $20,150,000
(FY 2021) $15,113,000

Figure 4.2.6: Mid-Rise Baseline Building Design GWP and Construction Cost

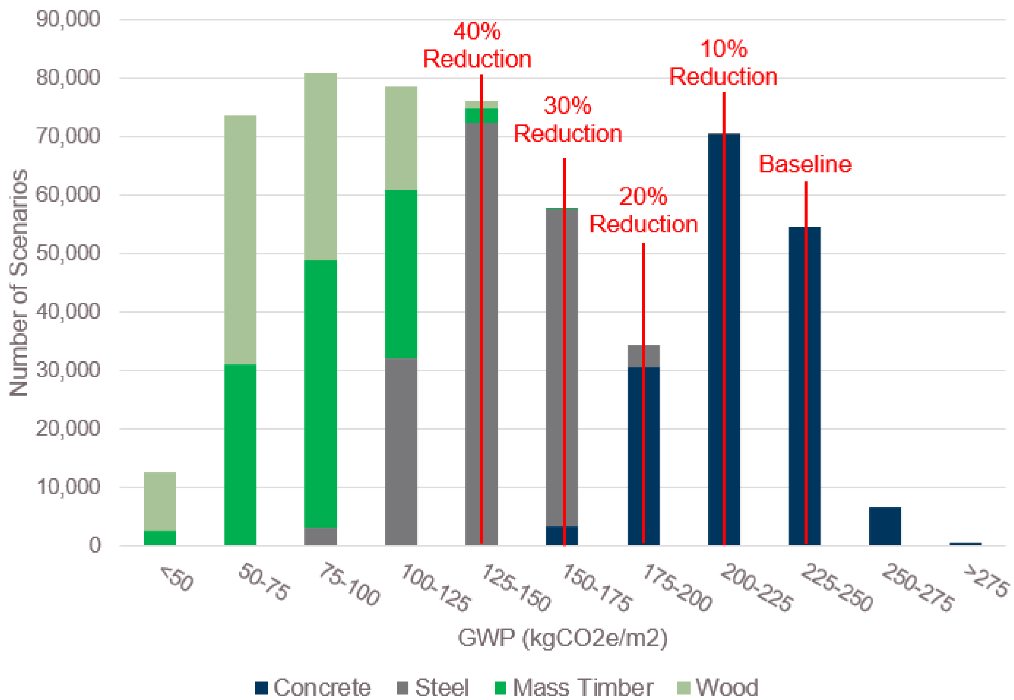


Figure 4.2.7: Mid-Rise Residential Archetype Baseline Building Design Relative to Parametric LCA Designs

Individual Embodied Carbon Reduction Measures

The GWP and cost reductions of individual measures considered in this study for the multi-unit Mid-rise residential archetype building are shown in Table 4.2.6. The percent differences listed in Table 4.2.6 were calculated by comparing the GWP and construction cost of the building design with the embodied carbon reduction measure to the baseline building design shown in Figure 4.2.6. These percent differences are also plotted in Figures 4.2.8 to 4.2.10 to show the relative impacts of each measure. Negative percentages shown in Table 4.2.6 and Figures 4.2.8 to 4.2.10 indicate savings, while positive values represent an increase. Note, there were more GWP reduction measures considered in the parametric LCA study; however, only the measures listed in Table 4.2.6 were included in the cost analysis.

Table 4.2.6: Summary of GWP and Cost Impacts of Embodied Carbon Reduction Measures for Mid-Rise Archetype Building

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline	244.7	-	$20,150,000	$15,113,000	-
Impacts of SCMs					
20% SCM	236.4	-3.4%	$20,055,000	$15,041,000	-0.5%
30% SCM	223.3	-8.7%	$19,959,000	$14,969,000	-0.9%
Impact of Parkade					
Street Parking	222.6	-9.0%	$18,433,000	$13,824,000	-8.5%
Impact of Structure					

Load Bearing Wood Frame Walls with Wood I Joist Floor	74.0	-69.7%	$17,193,000	$12,895,000	-14.7%
Load Bearing Wood Frame Walls with Wood Joist Floor	71.7	-70.7%	$16,994,000	$12,746,000	-15.7%
Impact of Wall Assembly					
Wood Stud	242.6	-0.8%	$20,045,000	$15,034,000	-0.5%
Impact of Wall Insulation					
Mineral Wool Insulation	245.5	0.3%	$20,508,000	$15,381,000	1.8%
Impact of Roof Insulation					
EPS Roof Insulation	241.9	-1.1%	$19,996,000	$14,997,000	-0.8%
Mineral Roof Insulation	246.5	0.8%	$20,288,000	$15,216,000	0.7%
Impact of Roof Membrane					
EPDM Roof Membrane	243.8	-0.4%	$20,298,000	$15,223,000	0.7%
PVC Roof Membrane	244.1	-0.2%	$20,188,000	$15,141,000	0.2%
Impact of Windows					
40% Window-to-Wall Ratio (WWR)	243.9	-0.3%	$20,424,000	$15,318,000	1.4%
Triple Glazed Vision Glazing	248.1	0.8%	$20,548,000	$15,411,000	2.0%
Fiberglass Window Frames	242.7	-0.8%	$21,307,000	$15,980,000	5.7%
PVC Window Frames	245.4	0.3%	$19,318,000	$14,489,000	-4.1%

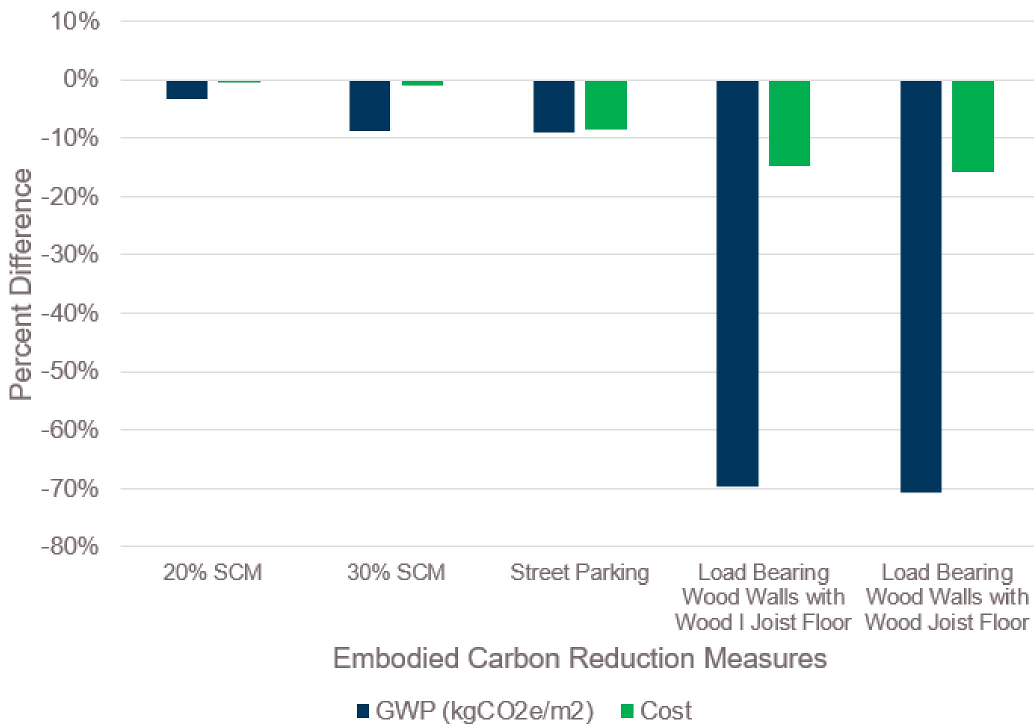


Figure 4.2.8: Percent Difference in GWP and Construction Cost of Structural Related Embodied Carbon Reduction Measures for the Mid-Rise Residential Archetype Relative to Baseline Design

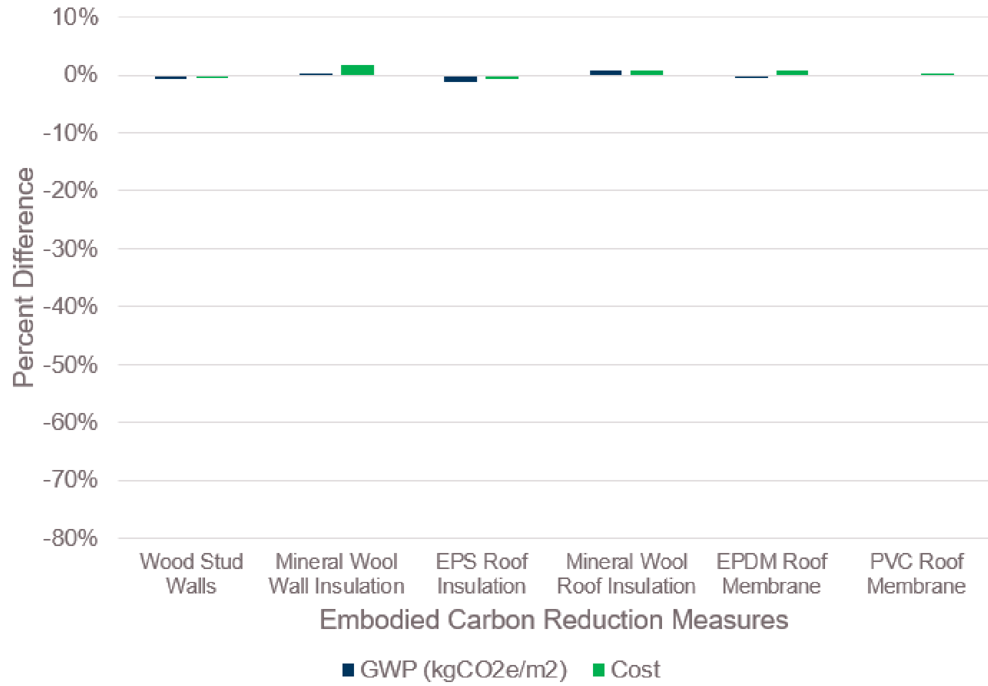


Figure 4.2.9: Percent Difference in GWP and Cost of Building Envelope Related Embodied Carbon Reduction Measures for the Mid-Rise Residential Archetype Relative to Baseline Design

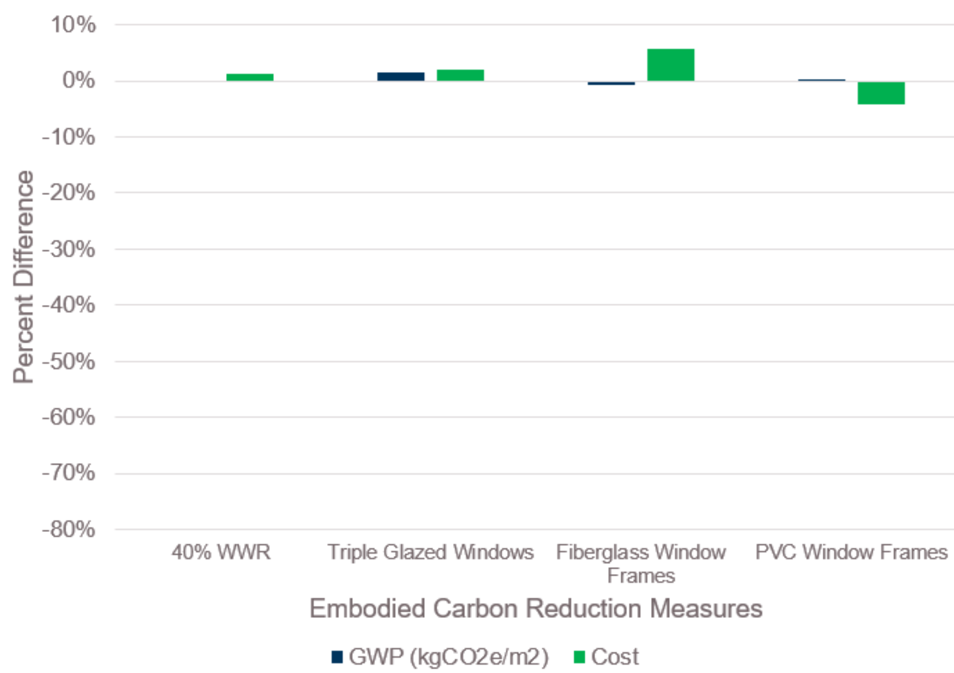


Figure 4.2.10: Percent Difference in GWP and Cost of Window Related Embodied Carbon Reduction Measures for the Mid-Rise Residential Archetype Relative to Baseline Design

From Table 4.2.6 and the associated figures, the majority of GWP reductions considered for this construction cost analysis is from structural related measures. The individual measure with the greatest impact is switching from a reinforced concrete structure to a load-bearing wood frame structure with wood floors. This measure can save up to 71% GWP and more than 15% of the construction cost compared to the baseline design. Other measures such as replacing steel stud walls with wood studs and substituting other roof insulation types resulted in marginal reductions in GWP.

Bundles of Embodied Carbon Reduction Measures

Mid-Rise Residential Archetype: 10% GWP Reduction

As shown in the previous section, structural components account for the greatest impact in GWP reductions. Switching from a reinforced concrete structure to load-bearing wood frame walls alone can reduce GWP by more than 70%. However, for moderate GWP reduction targets between 10% and 20% there are many designs that uses traditional structural materials such as concrete and steel. Table 4.2.7 lists some of the of these design options and their estimated construction costs to achieve 10% GWP reduction following typical building design practices.

Table 4.2.7: Example Design Bundles to Achieve 10% GWP Reduction over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Concrete Structure and Floors, Steel Stud, 60% WWR, Double Glazed Aluminum Windows, Mod Bit with Polyiso Roof, 0% SCM, 1 Level Parkade	244.7	-	$20,150,000	$15,113,000	-
Baseline + 20% SCM, Street Parking	214.4	-12.4%	$20,055,000	$15,041,000	-0.5%
Baseline + 20% SCM, Street Parking, Mod Bit with Mineral Wool Roof	216.3	-11.6%	$18,486,000	$13,864,000	-8.3%
Baseline + 20% SCM, Street Parking, EPDM with Mineral Wool Roof	215.4	-18.6%	$18,338,000	$13,753,000	-9.0%
Baseline + 20% SCM, Street Parking, PVC with Mineral Wool Roof	215.7	-12.0%	$18,376,000	$13,782,000	-8.8%
Baseline + 20% SCM, Street Parking, Mod Bit with EPS Roof	211.6	-13.5%	$18,194,000	$13,645,000	-9.7%
Baseline + Wood Stud, 20% SCM, Street Parking	212.3	-13.2%	$18,243,000	$13,682,000	-9.5%
Baseline + Wood Stud, 20% SCM, Mod Bit with Mineral Wool Roof, Street Parking	214.2	-12.5%	$18,381,000	$13,786,000	-8.8%

Baseline + Wood Stud, 20% SCM, PVC with Mineral Wool Roof, Street Parking	213.3	-12.8%	$18,271,000	$13,703,000	-9.3%
Baseline + Wood Stud, 20% SCM, EPDM with Mineral Wool Roof, Street Parking	213.7	-12.7%	$18,233,000	$13,675,000	-9.5%

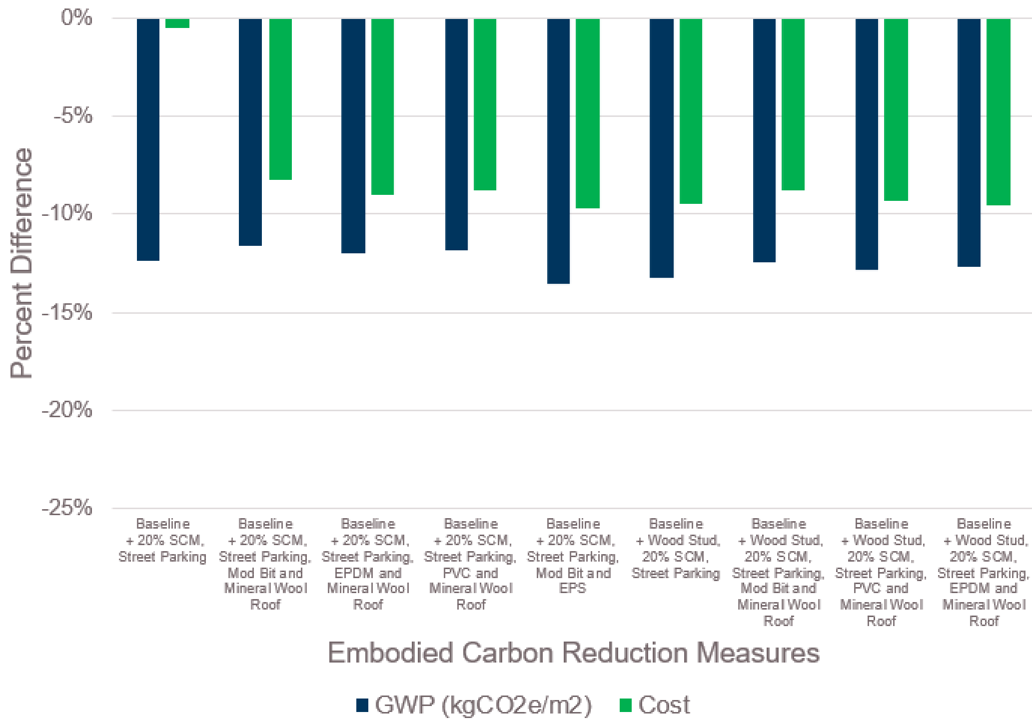


Figure 4.2.11: Percent Differences of Example Design Bundles to Achieve 10% GWP Reduction or Greater over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

The majority of the bundles presented to meet the 10% GWP reduction target may produce between 8% and 10% cost savings.

Mid-Rise Residential Archetype: 20% GWP Reduction

Similar trends were also seen for the evaluated design bundles to meet a 20% GWP reduction target. Building designs from the 10% GWP reduction target with concrete structures and steel stud or wood stud infill exterior walls are still able to achieve over 20% GWP reduction using low-carbon roof assemblies with similar construction cost savings. Unlike the High-rise residential archetype where the roof represents a small portion of the building envelope, the roof of the Mid-rise residential archetype represents a larger portion of the building and can result in a bigger impact on the overall building GWP. Table 4.2.8 lists some of the design bundles that achieves 20% GWP reduction over the baseline for the multi-unit Mid-rise residential archetype building in Vancouver while still using typical construction materials.

Table 4.2.8: Example Design Bundles to Achieve 20% GWP Reduction over Baseline Multi-Unit Mid-Rise Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Concrete Structure and Floors, Steel Stud, 60% WWR, Double Glazed Aluminum Windows, Mod Bit with Polyiso Roof, 0% SCM, 1 Level Parkade	244.7	-	$20,150,000	$15,113,000	-
Baseline + Wood Stud with Cellulose, 30% SCM, Street Parking, Mod Bit and EPS Roof	194.6	-20.5%	$19,427,000	$14,570,000	-3.6%
Baseline + Wood Stud, 30% SCM, Street Parking, Mod Bit and EPS Roof	194.4	-20.5%	$19,162,000	$14,371,000	-4.9%
Baseline + CLT Floor, CLT Wall, 0% SCM, Street Parking	187.2	-23.5%	n/a	n/a	n/a
Baseline + CLT Floor, CLT Wall, 30% SCM, Street Parking	174.5	-28.7%	n/a	n/a	n/a

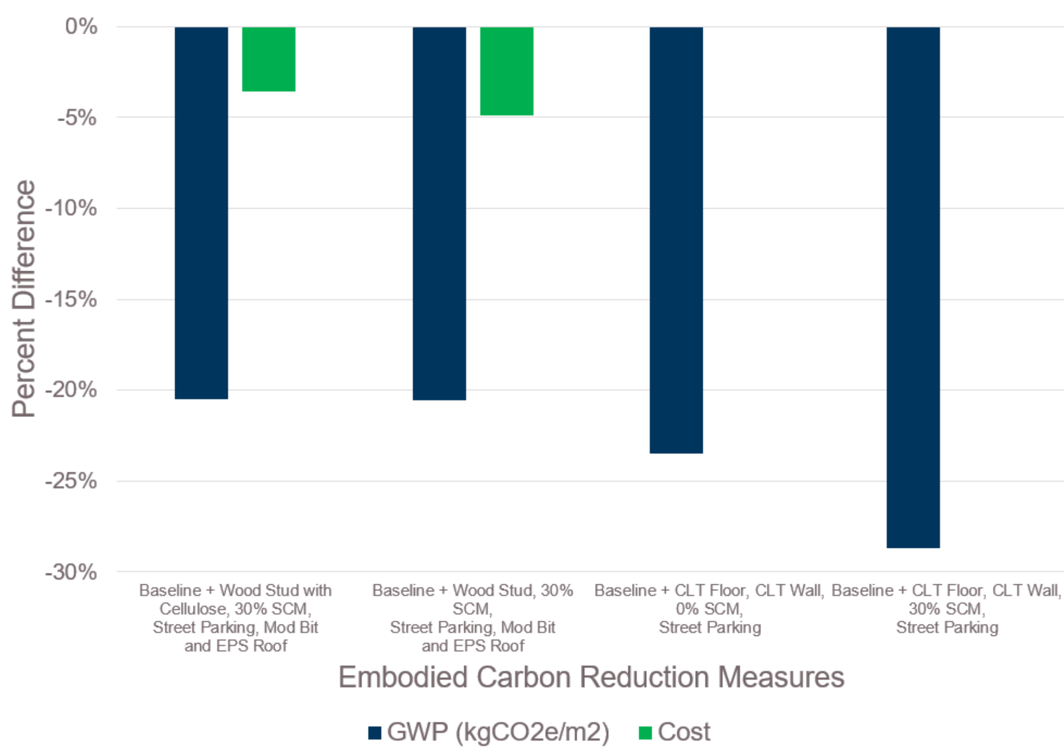


Figure 4.2.12: Percent Differences of Example Design Bundles to Achieve 20% GWP Reduction or Greater over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

Mid-Rise Residential Archetype: 30% GWP Reduction

Mid-rise residential building designs that aim to achieve over 30% GWP savings over the baseline are likely to require switching from a reinforced concrete structure to a steel structure as shown in Table 4.2.9. Since structural steel components were not part of the construction cost analysis, Table 4.2.9 only lists the GWP reductions.

Table 4.2.9: Example Design Bundles to Achieve 30% GWP Reduction over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Concrete Structure and Floors, Steel Stud, 60% WWR, Double Glazed Aluminum Windows, Mod Bit with Polyiso Roof, 0% SCM, 1 Level Parkade	244.7	-	$20,150,000	$15,113,000	-
Baseline + Steel Structure and Floor	156.1	-36.2%	n/a	n/a	n/a
Baseline + Steel Structure and Floor, 30% SCM	154.9	-36.7%	n/a	n/a	n/a
Baseline + Steel Structure, CLT Floor	156.7	-33.3%	n/a	n/a	n/a

Mid-Rise Residential Archetype: 40% GWP Reductions

For design options considered in this study, Mid-rise residential building designs aiming to achieve over 40% GWP reductions will likely need either a mass timber or wood frame structure. Examples of these designs are listed in Table 4.2.10 which includes designs that were included and excluded from the construction cost analysis. These design options are presented to illustrate some of the example buildings that designers may consider for their projects.

Table 4.2.10: Example Design Bundles to Achieve 40% GWP Reduction over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Concrete Structure and Floors, Steel Stud, 60% WWR, Double Glazed Aluminum Windows, Mod Bit with Polyiso Roof, 0% SCM, 1 Level Parkade	244.7	-	$20,150,000	$15,113,000	-
Baseline + Wood Frame Structure, Wood I Joist Floor, Wood Stud, Fiberglass Windows	70.2	-71.3%	$18,246,000	$13,684,000	-9.4%
Baseline + Wood Frame Structure, Wood Joist Floor, Wood Stud, Fiberglass Windows	67.9	-72.3%	$18,047,000	$13,535,000	-10.4%
Baseline + Steel Structure, CLT Floor, CLT Wall	125.7	-48.6%	n/a	n/a	n/a

Baseline + Glulam Structure, CLT Floor, CLT Wall	110.9	-54.7%	n/a	n/a	n/a
Baseline + Glulam Structure, CLT Floor, Wood Stud, Fiberglass Windows	106.2	-56.6%	n/a	n/a	n/a
Baseline + Glulam Structure, Wood I Joist Floor, Wood Stud, Fiberglass Windows	71.6	-70.7%	n/a	n/a	n/a
Baseline + Glulam Structure, Wood I Joist Floor, CLT Wall	76.2	-68.8%	n/a	n/a	n/a

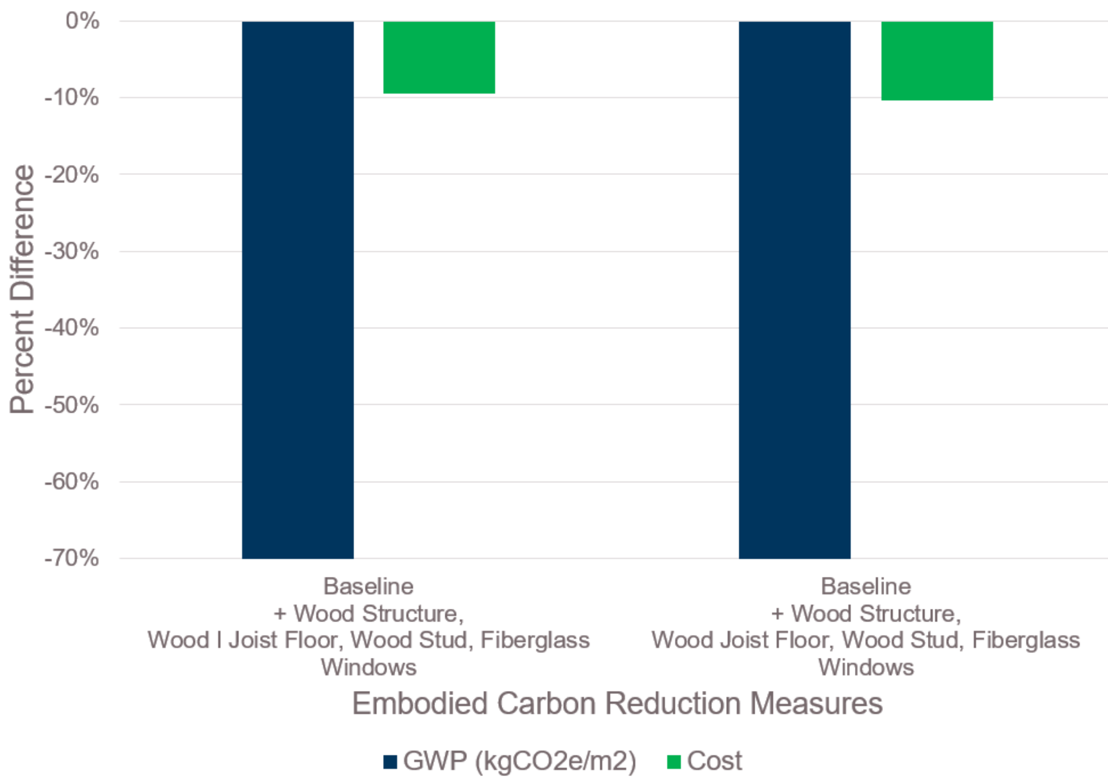


Figure 4.2.13: Percent Differences of Example Design Bundles to Achieve 40% GWP Reduction or Greater over Baseline Multi-Unit Mid-Rise Residential Archetype Building in Vancouver

From the scenarios presented, most of the multi-unit Mid-rise residential building design bundles have approximately 10% construction cost savings; however, many of these bundles have a wide range in GWP reductions. Building designs using lightweight wood framing as the building structure can achieve over 70% GWP reductions over the baseline design for similar costs of designs that achieve approximately 12% GWP reductions with a concrete structure.

4.2.3 Low-Rise Residential Archetype

The characteristics of the baseline building design which the construction cost analysis was performed with is listed in Figure 4.2.14. The baseline design represents typical construction of most Low-rise residential townhome buildings found in the City of Vancouver built in the late 2010s, which consists of light frame wood structure with a wood-frame walls as the building envelope. Other building systems considered for this archetype were mass timber structures and floors. Due to the low GWP of wood, the baseline design is on the low end of designs considered as part of the parametric LCA study as seen in Figure 4.2.15 and does not leave many design options to further reduce GWP with conventional construction practices considered in this study.

Building Structure

- Lightweight wood frame with Wood I Joist Floors
- 3 m floor-to-floor height
- Concrete foundation with 0% SCM

Building Envelope

- Wood-frame wall with fiberglass batt insulation and PVC cladding
- 25% Window-to-Wall Ratio (WWR)
- Double glazed low-e, argon filled vision glazing
- PVC window frame
- SBS roofing membrane
- Polyisocyanurate roof insulation

Parkade

- Street parking

Global Warming Potential (GWP):
98.9 kgCO_2e/m^2

Estimated Construction Costs:
(Q1 2023) $899,000
(FY 2021) $682,000

Figure 4.2.14: Low-Rise Residential Archetype Baseline Building Design GWP and Construction Cost

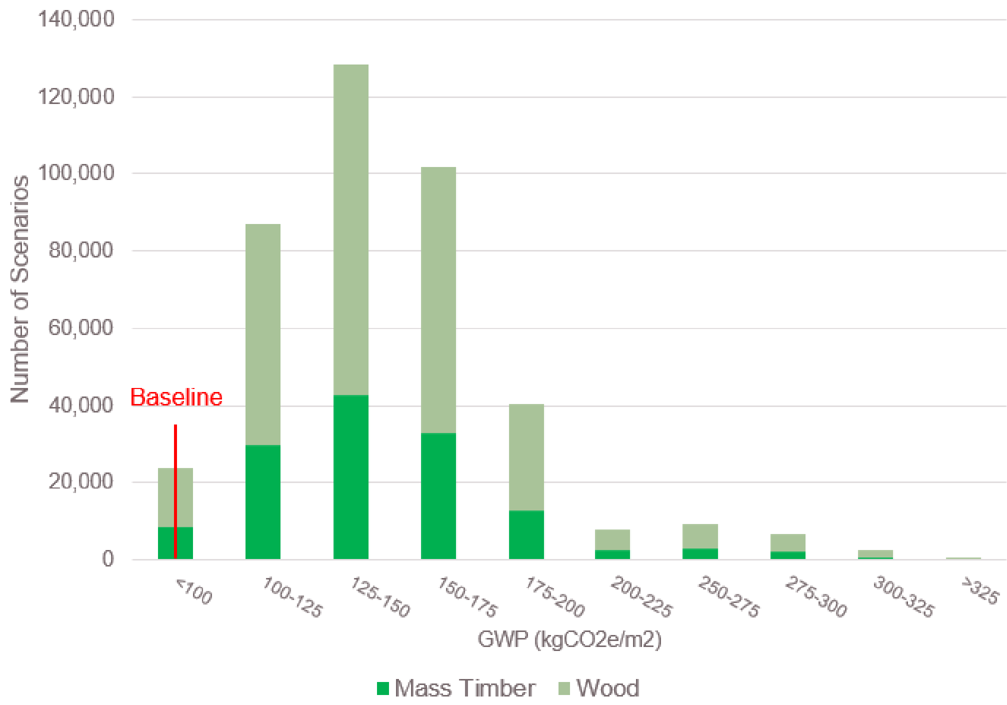


Figure 4.2.15: Low-Rise Residential Archetype Baseline Building Design Relative to Parametric LCA Designs

The GWP and construction cost reductions of individual measures considered in this study for the Low-rise residential townhome archetype building are shown in Table 4.2.11. Similar to the High-rise and Mid-rise residential building archetypes, the percent differences listed in Table 4.2.11 were calculated by comparing the GWP and construction cost of the building design with the embodied carbon reduction measure to the baseline building design shown in Figure 4.2.14. These percent differences are also plotted in Figures 4.2.16 to 4.2.17 to show the relative impacts of each measure. Negative percentages shown in Table 4.2.11 and Figures 4.2.16 to 4.2.17 indicate savings, while positive values represent an increase. Note, there were more GWP reduction measures considered in the parametric LCA study; however, only the measures listed in Table 4.2.11 were included in the cost analysis.

Table 4.2.11: Summary of GWP and Cost Impacts of Embodied Carbon Reduction Measures for Low-Rise Residential Archetype Building

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	2021 CAD	Percent Difference
Baseline	98.9	-	$899,000	$682,000	-
Impacts of SCMs					
20% SCM	97.8	-1.1%	$899,000	$682,000	0.0%
30% SCM	96.0	-2.9 %	$898,000	$681,000	-0.1%
Impact of Structure					
Load Bearing Wood Frame Walls with Wood Joist Floor	96.9	-2.0%	$894,000	$678,000	-0.6%

Impact of Wall Assembly					
Steel Stud	118.7	20.0%	$926,000	$703,000	3.0%
Impact of Wall Cladding					
Brick Cladding	124.8	26.2%	$994,000	$754,000	10.6%
Fiberboard Cladding	103.3	4.5%	$797,000	$604,000	-11.3%
Impact of Wall Insulation					
Cellulose Insulation	100.1	1.2%	$968,000	$734,000	7.7%
Mineral Wool Insulation	106.1	7.3%	$913,000	$693,000	1.6%
Impact of Windows					
10% Window-to-Wall Ratio (WWR)	91.8	-7.1%	$902,000	$685,000	0.3%
Triple Glazed IGU	105.7	6.9%	$927,000	$704,000	3.1%
Fiberglass Windows	96.0	-3.0%	$1,056,000	$801,000	17.5%
Impact of Roof Insulation					
Mineral Roof Insulation	102.6	3.7%	$898,000	$682,000	-0.1%
EPS Roof Insulation	93.4	-5.5%	$890,000	$675,000	-1.0%
XPS Roof Insulation	105.1	6.3%	$896,000	$680,000	-0.3%
Impact of Roof Membrane					
EPDM Roof Membrane	96.1	-2.9%	$908,000	$689,000	1.0%
PVC Roof Membrane	96.9	-2.1%	$901,000	$684,000	0.2%

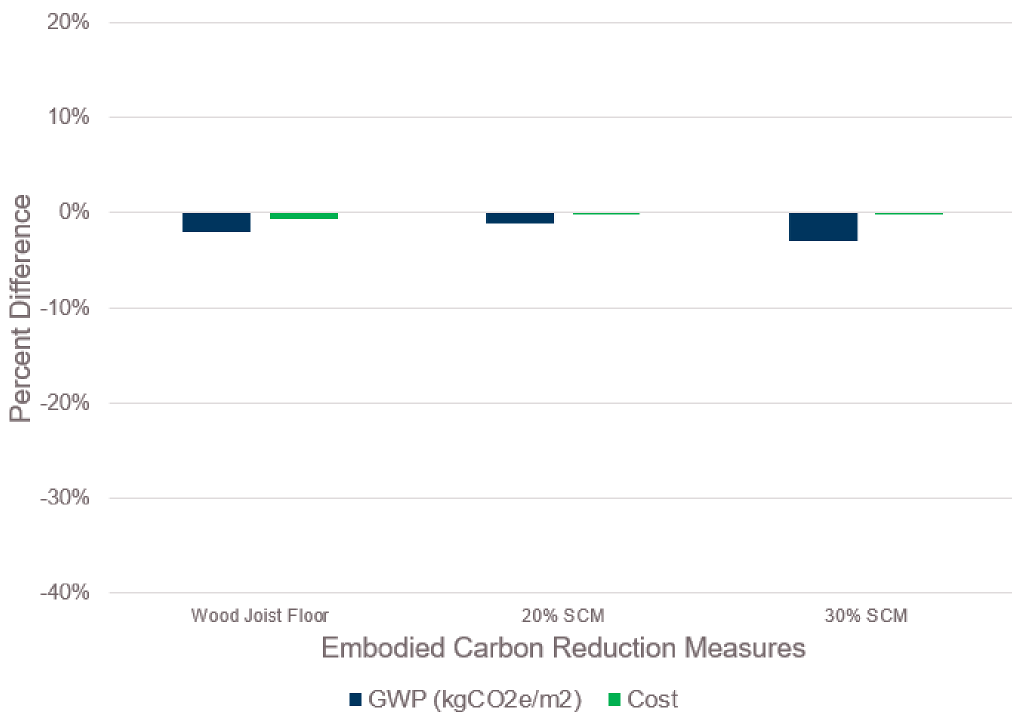


Figure 4.2.16: Percent Difference in GWP and Construction Cost of Structural Related Embodied Carbon Reduction Measures for Low-Rise Residential Archetype Relative to Baseline Design

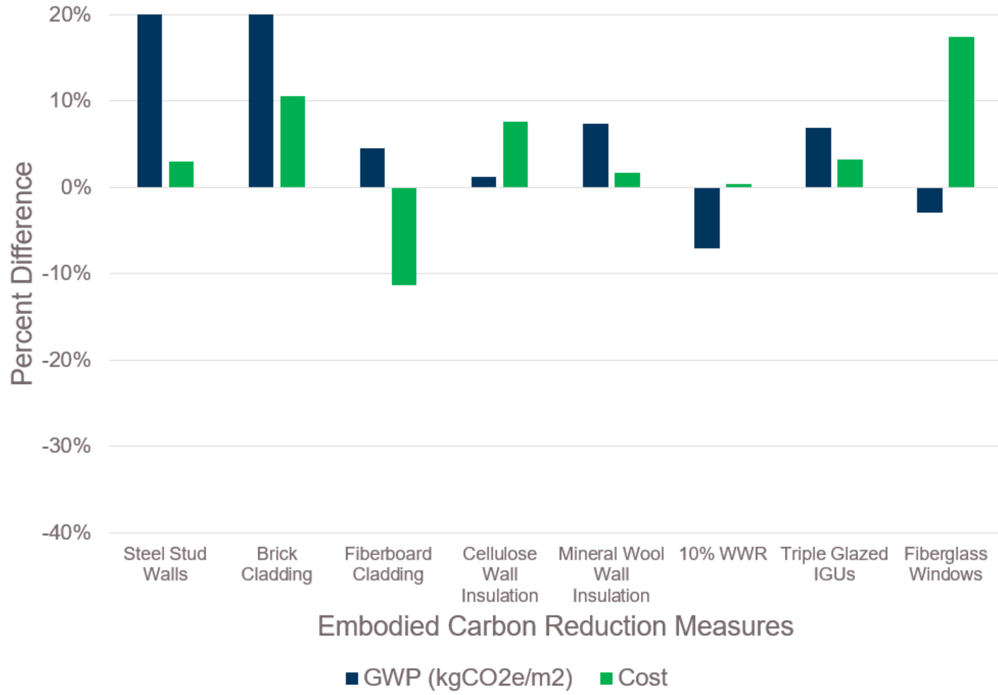


Figure 4.2.17: Percent Difference in GWP and Construction Cost of Building Envelope and Window Related Embodied Carbon Reduction Measures for Low-Rise Residential Archetype Relative to Baseline Design

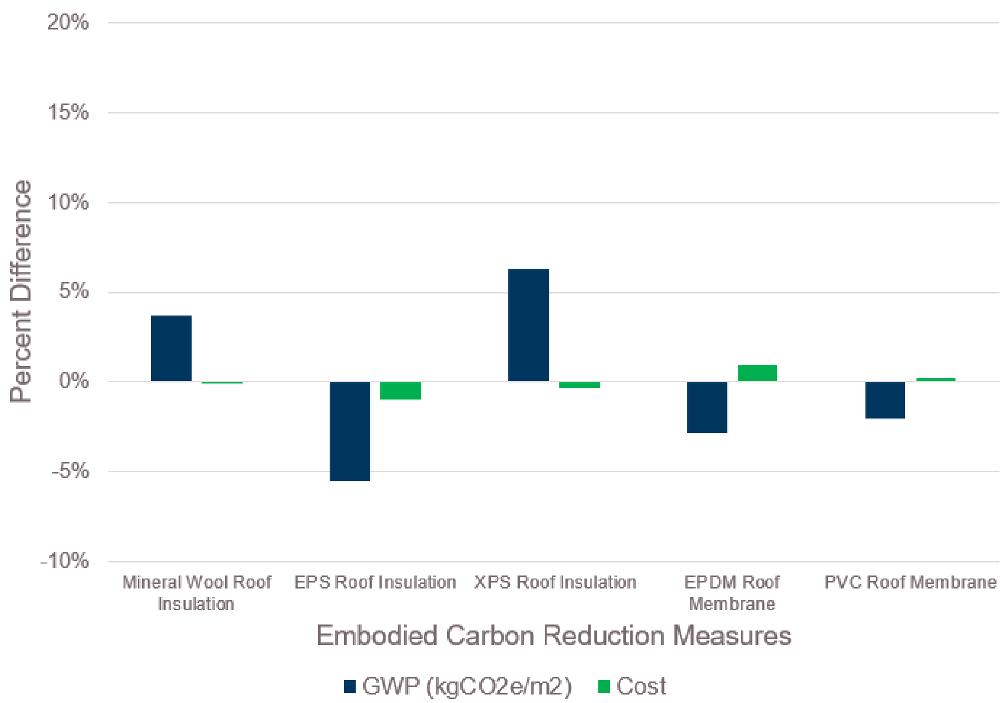


Figure 4.2.18: Percent Difference in GWP and Construction Cost of Roofing Related Embodied Carbon Reduction Measures for Low-Rise Residential Archetype Relative to Baseline Design

Unlike the High-rise and Mid-rise residential archetypes there are very few individual measures that enables significant GWP reductions compared to the baseline. This is due to an already low carbon baseline building design that is commonly found in the City of Vancouver and the lower mainland. Measures such as increasing the SCM content in concrete is only applicable to the foundation which makes up a small part of the overall construction. The most effective measure is to reduce the GWP of the roof insulation. Switching the roof insulation from polyisocyanurate to expanded polystyrene (EPS) results in approximately 5% GWP reduction with marginal cost savings.

Bundles of Embodied Carbon Reduction Measures

For the designs considered in analysis for the Low-rise residential townhome archetype there are relatively fewer options available to reduce GWP of the building. This is already a carbon efficient design that is commonly found for this type of building, which leaves less room for improvement using conventional design strategies and materials. As previously mentioned, most of the GWP reductions for the Low-rise residential archetype comes from using lower carbon insulation materials. This is reflected in the design options listed in Table 4.2.12. Design options to achieve greater than 30% GWP reductions are not listed since there were not any feasible designs that were also cost effective considered in this analysis.

Table 4.2.12: Example Design Bundles to Achieve 20% to 40% GWP Reduction over Baseline Low-Rise Residential Townhome Archetype in Vancouver

Scenario	Global Warming Potential (GWP)		Estimated Construction Cost		
	$kgCO_2e/m^2$	Percent Difference	Q1 2023 CAD	FY 2021 CAD	Percent Difference
Baseline: Lightweight Lumber Structure with Wood I Joist Floors, Wood Stud with Fiberglass Batt, 25% WWR, Double Glazed Vinyl (PVC) Windows, Mod Bit with Polyiso Roof, 0% SCM, Street Parking	98.9	-	$899,000	$682,000	-
Baseline + EPS Roof Insulation and PVC Roof Membrane, 30% SCM	86.6	-12.5%	$668,000	$507,000	-25.7%
Baseline + EPS Roof Insulation and PVC Roof Membrane Roof, 10% WWR, Fiberglass Windows, 30% SCM	79.5	-19.6%	$890,000	$675,000	-1.0%
Baseline + EPS Roof Insulation and PVC Roof Membrane, Fiberglass Windows, 30% SCM	78.3	-20.8%	$952,000	$723,000	5.9%

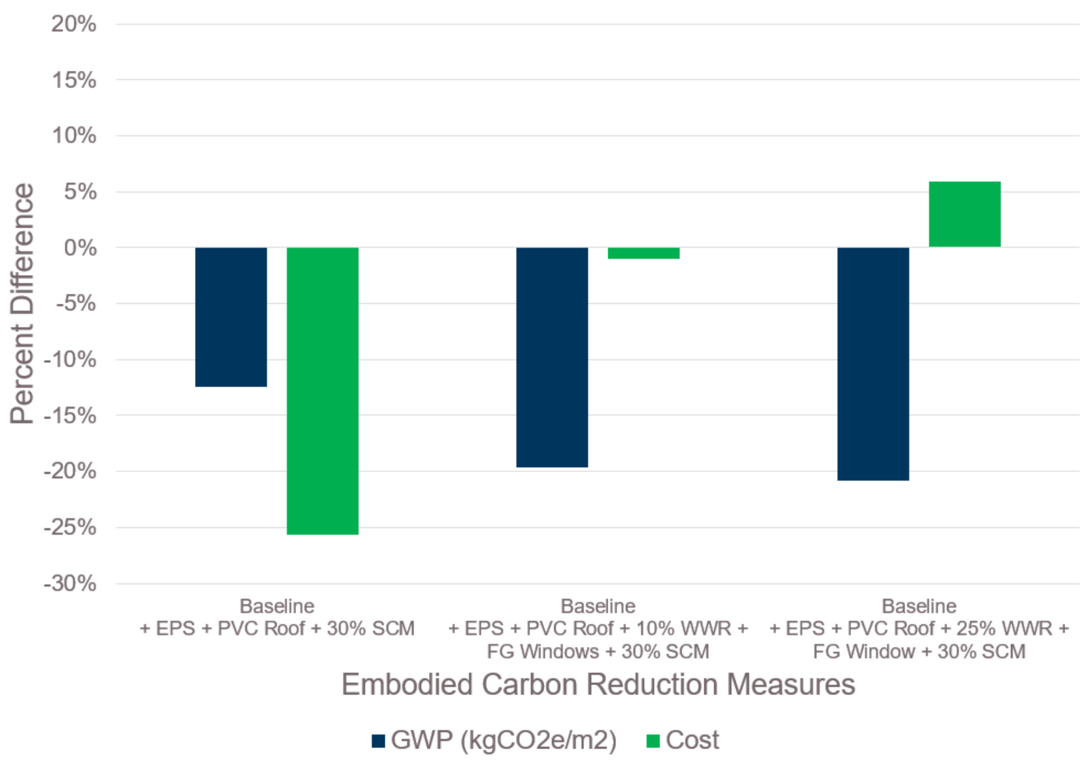


Figure 4.2.19: Percent Differences of Example Design Bundles to Achieve 10% to 20% GWP Reduction or Greater over Baseline Low-Rise Residential Townhome Archetype Building in Vancouver

Most of the example design options listed in Table 4.2.12 and shown in Figure 4.2.19 result in very little construction cost savings and construction cost increases on some occasions. The analysis shows that despite the already low embodied carbon intensive construction practices,10% to 20% GWP reductions can be achieved with townhome designs without additional costs. Costs may rise if GWP reductions around 20% are desired where reductions through other parts of the building such as the window frames are required. In this study fiberglass window frames were considered as a low carbon alternative to vinyl frames. While fiberglass frames can lower a building's GWP, it is currently more expensive than vinyl frames and, in most cases, results in higher construction cost considered in the analysis.

5. SUMMARY AND RECOMMENDATIONS

The study included the definition of baseline construction material and assembly specifications for three building archetypes, a 30-storey high-rise residential, six-storey mid-rise residential and a 3-storey low-rise townhome. These reflect typical 2018 construction practices in Vancouver and were based on both reviews of actual projects and information from local designers and experts.

For each archetype, a list of possible structural and building envelope materials and assemblies was created reflecting typical types of materials and assemblies in Vancouver. The embodied carbon of all possible combinations of materials and assemblies was calculated resulting in a total range of possible embodied carbon impacts from the various archetypes. The possible range of embodied carbon, measured in kg of equivalent CO_2 per square meter (CO_{2e}/m^2), was as follows:

High-Rise Residential:	97 - 424 kg CO_2e/m^2
Mid-Rise Residential:	38 - 349 kg CO_2e/m^2
Low-Rise Residential Townhomes:	75 - 571kg CO_2e/m^2

The ranges above demonstrate both significant reductions in embodied carbon are available for each archetype, and the ranges of embodied carbon are different for each archetype.

The impacts and consequences of utilizing various thresholds were explored. The thresholds were defined as the average of the total range (50th percentile) and a more challenging threshold, the 25th percentile. It was found that the 50th percentile threshold was readily achievable with some care in the design of any concrete used and careful use of foam insulations. The 25th percentile was much more challenging and disallowed use of some common materials such as concrete for most archetypes.

Material costs of various building design combinations considered in the study for each archetype were also calculated to determine the potential costs of various embodied carbon reduction measures. The construction costs of the various building design combinations were compared against a baseline building design that is representative of 2018 construction practices for each archetype. For most building designs, embodied carbon measures resulted in material cost savings rather than a cost premium. Some of the findings include:

- 2% to 20% construction cost savings for High-rise residential archetype building designs that achieve 10% and 20% embodied carbon reduction over 2018 baseline design
- 0% to 10% construction cost savings for Mid-rise residential archetype building designs that achieve 10 and 20% embodied carbon reduction over 2018 baseline design
- Up to 25% construction cost savings for Low-rise residential archetype building designs that achieve 10% embodied carbon reduction over 2018 baseline design

- Concrete mixes with higher SCM content are effectively cost neutral yet provided embodied carbon reductions up to 10%

- Precast concrete insulated sandwich panels resulted in the greatest construction cost savings over window wall exterior wall systems for the High-rise residential archetype at more than 19% cost savings and more than 13% reduction in embodied carbon emissions

- Wood-frame construction resulted in the greatest construction cost savings over poured-in-place concrete for the Mid-rise residential archetype at more than 15% cost savings and more than 70% reduction in embodied carbon emissions

- EPS roof insulation is construction cost neutral over polyisocyanurate roof insulation for the Low-rise residential archetype, yet it provided significant embodied carbon reduction at more than 5%

Based on the results of this study the following are recommended:

1. Embodied carbon of buildings is a significant contributor to climate change.

2. Embodied carbon reductions in buildings are readily available and can result in significant reductions with few impacts on construction cost and design flexibility.

3. The range of embodied carbon is different between building archetypes. As such, a single numerical target threshold in CO_2e/m^2 should not be used. Multiple targets for different archetypes are preferred.

4. In general, a target embodied carbon threshold of the 50th percentile of the range of impacts had few limitations on design and no significant impact on cost, but a target of the 25th percentile of the range of impacts placed severe limitations on design and significant impact on construction cost. As such, a threshold between the 50th and 25th percentile of embodied carbon range may be reasonable.

6. REFERENCES

National Research Council Canada, 2022, National Guidelines for Whole-Building Life Cycle Assessment

BC Housing, 2013, Guide for Designing Energy-Efficient Building Enclosures

BC Ministry of Environment and Climate Change Strategy, 2017, LEED v4 and Low Carbon Building Materials – A Comprehensive Guide

The Carbon Leadership Forum, 2018, Life Cycle Assessment of Buildings: Technical Guidance

CRMCA, 2017, CRMCA Member Industry-Wide EPD for Canadian Ready-Mixed Concrete

City of Vancouver, 2016, Zero Emissions Building Plan

City of Vancouver, 2019, Vancouver Building By-law

City of Vancouver, 2020, Climate Emergency Action Plan Summary 2020-2025

International Energy Agency, 2016, Evaluation of Embodied Energy and GHG Emissions for Building Construction (Annex 57)

International Energy Agency, 2016, Strategies for Reducing Embodied Energy and Embodied GHG Emissions

International Energy Agency, 2016, Guideline for Design Professionals and Consultants – Part 1: Basics for the Assessment of Embodied Energy and Embodied GHG Emissions.

Zera Solutions, 2019, Policy Research on Reducing the Embodied Emissions of New Buildings in Vancouver

https://bylaws.vancouver.ca/Bulletin/bulletin-green-buildings-policy-for-rezoning.pdf

http://www.athenasmi.org/resources/about-lca/technical-details/

7. APPENDIX A – ASSUMPTIONS & METHODOLOGY

Methodology &Assumptions

Methodology

The tool is intended to provide higher level guidance on the potential effect of design choices on embodied carbon. It uses building archetypes and explores variations in design on that archetype.

Building Archetype Selection

Three separate building archetypes were considered: A high-rise residential building, a mid-rise residential building, and a stacked townhome. All archetypes are assumed to be located in Vancouver, B.C. Building archetype designs were selected after review of multiple building permit applications for similar buildings and using our knowledge of the building industry in the region. The designs selected for each archetype are fictional but are believed to be representative of what might be expected for these archetypes in these regions.

Building Variables

Variable types and iterations explored were developed with the intent of achieving realistic possible changes and / or changes that could result in significant change in embodied impact. These were selected based on review of existing building permit applications, using our knowledge of the building industry and embodied impacts, and with the input of others in the LCA and design industries.

Building Archetype Descriptions

A description of the three separate building archetypes and the variables explored are presented below

Description	High-Rise Residential	6-Storey Mid-Rise Residential	Stacked Townhomes
General Information			
Building Length (m)	25	75	12
Building Width (m)	25	25	6
Floor to Floor Height (m)	3	3	3
Number of Floors	30	6	3
Gross floor area (m^2)			
Floor Live Load (kPa)	2.4	2.4	2.4
Service Life (years)	60	60	60
Window to Wall Ratio	40%-60%	30%-60%	10%-25%
Beam Span (m)	8	6	6
Joist Span (m)	6	3	3
Footing	300mm x 100mm below columns and perimeter walls		
Slab on Grade	100mm concrete slab		
Below Grade Walls	200 mm concrete		
Beam Types			
Concrete	Baseline	Baseline	
Steel		x	
Glulam	x	x	
LVL (with load bearing walls)		x	Baseline

Column Types			
Concrete	Baseline	Baseline	
Steel		x	
Glulam	x	x	x
None (load bearing walls)		x	Baseline
Exterior Wall Types			
Steel Stud	x	Baseline	x
Wood Stud (infill)		x	x
Wood Stud (load bearing)		x	Baseline
Wood Stud OVE			x
Curtain Wall	x		
Window Wall	Baseline	x	
Concrete Block	x		
Precast Concrete Sandwich Panel	x		
ICF		x	x
CLT	x	x	x
Floor Type			
Concrete	Baseline	Baseline	
Hollow Core Precast Concrete	x		
OWSJ with Steel Deck and Concrete Topping	x		
Wood Joist with Plywood		x	Baseline
Wood I-Joist with Plywood		x	x
CLT	x	x	x
Exterior Cladding Type			
Brick Veneer	x	x	x
Precast Concrete	x		
Metal Panel	Baseline	x	x
Glass Panel	x		
EIFS	x	x	x
PVC/Vinyl		x	x
Fiber Cement Panel		Baseline	Baseline
Exterior Wall Insulation Type			
XPS	x	x	x
EPS	Included in EIFS	Included in EIFS	Included in EIFS
Polyisocyanurate	x	x	
Mineral Woo Batt	Baseline	x	x
Mineral Wool Batt (medium density)	x		
Fiberglass Batt	x	Baseline	Baseline
Fiberglass Batt (medium density)	x		
Spray Polyurethane Foam	x	x	x
Cellulose		x	x
Roof Insulation Type			
XPS	x	x	x
EPS		x	x
Polyisocyanurate	Baseline	Baseline	Baseline

Mineral Wool (medium density)	x	x	x
Roof Membrane Type			
PVC	X	x	x
Modified Bitumen (SBS)	Baseline	Baseline	Baseline
BUR	x		
EPDM		x	x
Glazing Type			
Double Glazed (low-E, Argon Filled)	Baseline	Baseline	Baseline
Triple Glazed (single low-E, Argon Filled)		x	x
Window Frame Type			
Aluminum	Baseline	Baseline	x
Fiberglass		x	Baseline
PVC		x	x
Parking Type			
None (Street Parking)		x	Baseline
Surface Parking		Baseline	
2 Level Parkade	x		
4 Level Parkade	x		
6 Level Parkade	Baseline		
SCM Content in Concrete			
None	Baseline	Baseline	Baseline
20%	x	x	x
30%	x	x	x
40%	x		

Building Model Scope

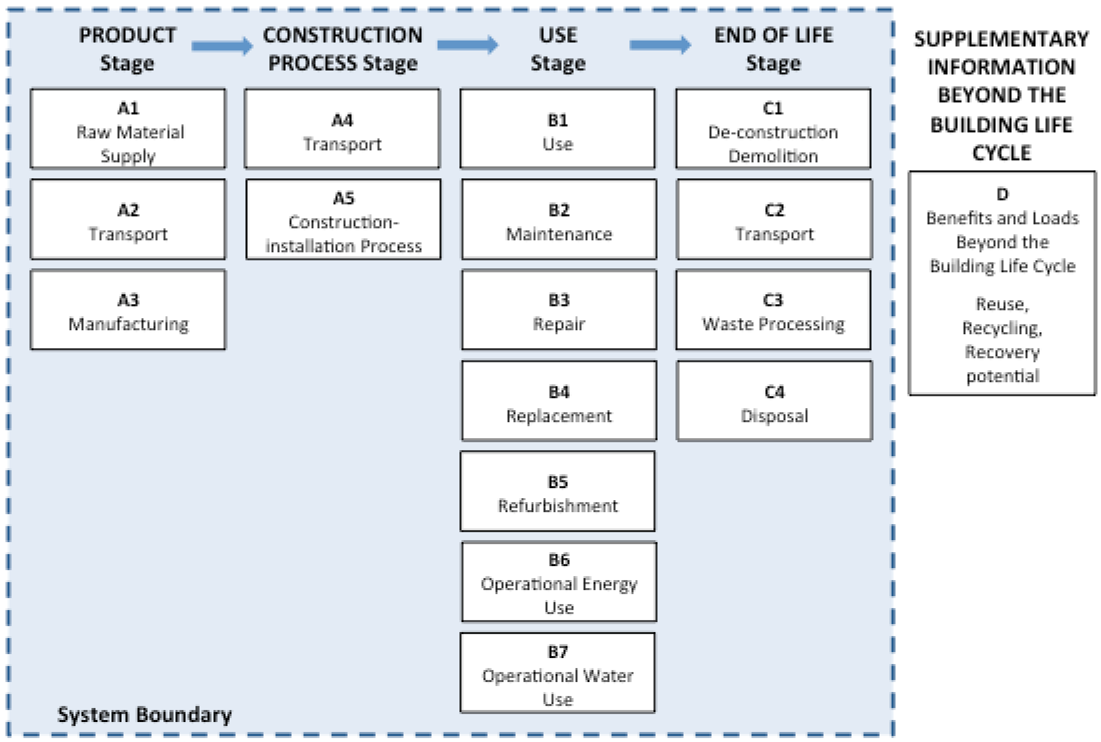
The LCA modelling focused on the building structure and envelope above and below grade. It included the following:

- Main structure including beams, columns, floor slabs, load bearing walls, shear walls foundation walls, and footings,
- exterior walls and windows, including insulation and cladding, roofing membrane, vapour and air barriers, window framing and glazing.
- Parking garages including structure and membranes

It did not include ceiling or floor coverings, finish materials, paint, interior walls, mechanical or electrical systems, or site components.

System Boundary

The system boundary for the LCA models included the product, construction, use and end of life stages excluding operational energy and water. This includes stages A1-A5, B1 to B4, and C1 to C4.



LCA Results

The Athena Building Impact Estimator (Version 5.4.0103) was used to model the impact of most of the various design iterations on embodied carbon (ie. embodied global warming potential). (For more information on the background material data and assumptions, see the Impact Estimator User Manual.) The impact estimator was used to estimate both material quantities and their embodied impacts. Exceptions and work-arounds are presented below:

Insulation: There was some concern that the Athena Impact Estimator would incorrectly estimate the embodied GWP of foam insulations due to the change in blowing agents mandated by recent legislation in Canada. Our approach regarding insulation was as follows:

1. Available EPDs were used to estimate the GWP of all insulations (not just foam). All insulation types were reviewed to allow a more fair comparison of insulations.
2. For GWP estimates of foam insulations, we used only EPDs associated with HFO blowing agents. Any EPDs with HFC blowing agents were not included.
3. Where available, industry wide EPDs were used. Industry wide EPDs were used for polyisocyanurate and loose fill cellulose
4. When industry wide EPDs were not available, product specific EPDs or averages of product specific EPDs were used.
5. Wall insulation fibrous and foam boards were medium density, typical for commercial walls
6. Roof insulation fibrous and foam boards were higher density, typical for commercial roofs
7. EPDs were not available for medium density rock wool and medium and high-density fiberglass. For these insulations GWP was estimated by factoring similar low-density insulation GWP by the differences in density.

8. For all insulation types in the High-Rise archetype R-15 nominal insulation was assumed and all insulation quantities were adjusted
9. For all insulation types in the 6-Storey Mid-Rise and Stacked Townhomes archetypes, 4 inches (102 mm) of insulation was assumed.

Note that it is acknowledged that relying on EPD results is not ideal, as the scope and boundary conditions may be different and EPDs are often based on singular products that may not represent a typical value. To reduce this risk each EPD was carefully reviewed to confirm similar scope and boundary conditions are similar to other LCAs in this tool. In addition, the methodology was provided to a number of LCA practitioners and specialists in the Vancouver area for comment.

Supplementary Cementitious Materials (SCMs): SCMs created an issue as a change in SCMs could potentially impact many assemblies within a building. To resolve this issue, we compared the GWP of several different SCM ranges for several different concrete based building assemblies. More specifically, we reviewed the following assemblies: Slab on grade, footings, beams and columns, concrete walls, and concrete in extra basic materials within the software. For each of these assemblies we compared 0, 20%, 30%, and 40% SCM contents. We found that changing from 0 to 20% SCM content resulting in a reduction in GWP by between 3.6 and 5.2% for the various assemblies. Similarly, changing from 0 to 30% SCM content resulting in a reduction in GWP by between 10.4 and 12.2% and changing from 0 to 40% SCM content resulting in a reduction in GWP by between 15.5 and 20.1%. For this tool, we used the average change of impacts for the different assemblies. More specifically, the following factors that were applied to all concrete based assemblies to estimate the impact of different SCM contents:

SCM content	SCM mult factors from base case
0	1
20	0.957704356
30	0.891212615
40	0.821724451

Concrete Columns: The software did not factor in the additive load on columns in taller buildings: In a building, columns support not only the floor immediately above, but also the load of a column immediately above. As such, columns effectively support loads from all floors above, so lower floor columns are typically larger than upper floor columns. To determine the real impact on column design, three real designs of tall residential buildings were reviewed (between 30 and 37 stories) and take-offs were performed for concrete columns. These take-offs were factored according to the tributary area that they support and into three categories based on floor number (1-10, 11-20, and 21-30). An average of these values resulted in a volume of concrete per m^2 of tributary area. Concrete strength was also factored in by converting all columns to 30 MPa concrete, using a simple multiplication factor (ex. A 40 MPa concrete volume was multiplied by 40/30 to estimate an equivalent 30 MPa column size).

Reinforcing steel within the columns was assumed to be 1% of the mass of the equivalent 30 MPa concrete.

Wood Frame Load Bearing Walls: The software did not factor in the additive load on load bearing walls in multi-story buildings: load bearing walls support not only the floor immediately above, but also the load of any load bearing walls above it. This resulted in a significant underestimation of lower floor load bearing walls in the six-story design. To resolve this issue, the wood framing for the bottom three floors of the 6-storey archetype was increased by an additional 25% to account for extra studs at window openings and interior partition walls. Note this was not considered a significant error in the stacked townhouse design as the additive effects are small and it would not be typical to change the stud spacing across the height of this type of building. These decisions were made based on a review of multiple real designs and our knowledge of the industry.

Project Team

The Morrison Hershfield team involved in the development of the tool, and this document are:

- Mark Lucuik - Director of Sustainability
- Kalum Galle - Team Lead, Sustainability Specialist
- Emma Thomas - Sustainability Analyst
- Ivan Lee - Building Science Consultant

Limitations

By nature, whole-building LCA results are uncertain and should be used as a guidepost and not an absolute. Although the archetype designs are believed to be typical for the region, actual designs will vary. The further a real design strays from the archetype design the less reliable the results.

The LCA results are specific to the region presented. Actual results can vary significantly for other regions, particularly outside of B.C.

For project-specific results, a custom whole-building LCA is needed. Access the free Impact Estimator for Buildings software tool at www.athenasmi.org.

8. APPENDIX B - COSTING

Unit Rates for Residential Buildings in Vancouver Mar-23

	Q1 2023		2021	
	Low	High	Low	High
Residential Building Type	$	$	$	$
30-storey highrise	470	500	360	380
6-storey concrete mid-rise	510	530	380	400
3-storey townhouse, surface parking	280	300	210	230

BTY Group

CoV Embodied Carbon Reduction Study
High Rise Residential
May 26, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Below Grade							
Concrete with 0% SCM	116	m³	250.00	230.02	480.02	55,795	
Concrete with 20% SCM	116	m³	240.00	230.02	470.02	54,633	
Concrete with 30% SCM	116	m³	230.00	230.02	460.02	53,471	
Concrete with 40% SCM	116	m³	230.00	230.02	460.02	53,471	
Rebar	5	Ton	1,938.00	412.00	2,350.00	10,830	
Welded wire mesh	625	m²	2.90	2.60	5.50	3,438	6x6 - W1.4xW1.4 (10x10)
Beams							
Concrete with 0% SCM	2,204	m³	250.00	770.21	1,020.21	2,248,400	assume 2000 x 285mm
Concrete with 20% SCM	2,204	m³	240.00	770.21	1,010.21	2,226,361	
Concrete with 30% SCM	2,204	m³	230.00	770.21	1,000.21	2,204,323	
Concrete with 40% SCM	2,204	m³	230.00	770.21	1,000.21	2,204,323	
Rebar	452	Ton	1,987.00	563.00	2,550.00	1,153,659	
Columns							
Concrete with 0% SCM	2,204	m³	250.00	206.81	456.81	1,006,688	assume size 750mm x 750mm
Concrete with 20% SCM	2,204	m³	240.00	206.81	446.81	984,651	
Concrete with 30% SCM	2,204	m³	230.00	206.81	436.81	962,614	
Concrete with 40% SCM	2,204	m³	230.00	206.81	436.81	962,614	
Rebar	1,021	Ton	2,007.00	668.00	2,675.00	2,732,081	
Floors							
Concrete with 0% SCM	5,065	m³	250.00	693.94	943.94	4,781,206	assume 270mm thick
Concrete with 20% SCM	5,065	m³	240.00	693.94	933.94	4,730,554	
Concrete with 30% SCM	5,065	m³	230.00	693.94	923.94	4,679,903	
Concrete with 40% SCM	5,065	m³	230.00	693.94	923.94	4,679,903	
Rebar	257	Ton	1,977.00	523.00	2,500.00	642,459	

CoV Embodied Carbon Reduction Study
High Rise Residential
May 26, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Exterior Walls							
Steel Stud	9,900	m²	108.45	72.70	181.15	1,793,385	area based on 0% WWR
1/2" Regular Gypsum Board							
1/2" Glass Mat Gypsum Panel							
6 mil Polyethylene							
Air Barrier							
Galvanized Sheet							
39mm x92mm 20ga. Galvanized Steel Studs at 16" o.c.							
Joint Compound							
Nails							
Paper tape							
Screws, Nuts, & Bolts							
Spandrel to Window Walls	9,900	m²	1,016.50	98.50	1,115.00	11,038,500	area based on 0% WWR
1/2" Regular Gypsum Board							
Aluminum Extrusion							
EPDM Membrane (black, 60 mil)							
39mm x92mm 25ga. Galvanized Steel Studs at 24" o.c.							
Glazing Panels							
Joint Compound							
Nails							
Paper Tape							
Screws, Nuts, & Bolts							
Metal Spandrel Panel							

CoV Embodied Carbon Reduction Study
High Rise Residential
May 26, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Precast Concrete	9,900	m²	338.00	64.50	402.50	3,984,750	area based on 0% WWR
1/2" Regular Gypsum Board							
Concrete Benchmark CAN 25 Mpa							Precast insulated concrete panel
EPS (25mm)							
Joint Compound							
Nails							
Paper Tape							
Rebar, Rod, Light Sections							
Exterior Glazing							
Aluminum frame window walls (double glazing)	3,600	m²	851.00	64.00	915.00	3,294,000	area based on 40% WWR
Exterior Cladding							
Metal Panel	9,900	m²	565.00	185.00	750.00	7,425,000	area based on 0% WWR
Aluminum Extrusion							
Metal Spandrel Panel							assume aluminum panel
Glass Panel	9,900	m²	720.00	60.00	780.00	7,722,000	
Glazing Panel							assume single glazing window walls
Exterior Wall Insulation							area based on 0% WWR
XPS (25mm)	28,080	m²	11.40	4.60	16.00	449,279	Roxul semi-rigid insulation
Mineral wool batt R12.6 (25mm)	32,496	m²	12.20	1.80	14.00	454,941	
Roof Insulation							
XPS (25mm)	5,200	m²	18.40	3.10	21.50	111,800	Extruded polystyrene insulation
Polyisocyanurate insulation							
Glass Facer	2,625	m²	21.00	2.50	23.50	61,688	
Polyiso Foam Board (unfaced) (25mm)	5,996	m²	19.50	4.00	23.50	140,912	included tapered for drainage
Mineral Wool Batt (med density)	5,996	m²	40.50	4.50	45.00	269,831	included tapered for drainage

CoV Embodied Carbon Reduction Study
High Rise Residential
May 26, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Mineral wool R-40 (245mm)							
Roof Membrane							
PVC	625	m²	61.93	23.87	85.80	53,625	
6 mil Poly							
Ballast (aggregate stone)							assume 75mm thick
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
PVC Membrane 48 mil							
Small Dimensional Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Mod Bit	625	m²	42.30	33.80	76.10	47,563	
#15 Organic Felt							
1/2" Moisture Resistant Gypsum Board							
Galvanized Steel Sheet							assume 300mm high to roof parapet
Mod Bit Membrane							
Nails							
Roofing Asphalt							
Build Up Roof	625	m²	42.40	20.40	62.80	39,250	
#15 Organic Felt							
Ballast (aggregate stone)							assume 75mm thick
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
Roofing Asphalt							
Type III Glass Felt							

CoV Embodied Carbon Reduction Study
High Rise Residential
May 26, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Parkade							
4 Levels							
Concrete with 0% SCM	676	m^3	250.00	1,184.66	1,434.66	969,400	assume suspended slab 200mm thick
Concrete with 20% SCM	676	m^3	240.00	1,184.66	1,424.66	962,643	assume basement wall 250mm thick
Concrete with 30% SCM	676	m^3	230.00	1,184.66	1,414.66	955,886	
Concrete with 40% SCM	676	m^3	230.00	1,184.66	1,414.66	955,886	
Rebar	34	Ton	1,977.00	523.00	2,500.00	85,705	
6 Levels							
Concrete with 0% SCM	1,014	m^3	250.00	1,241.70	1,491.70	1,511,912	assume suspended slab 200mm thick
Concrete with 20% SCM	1,014	m^3	240.00	1,241.70	1,481.70	1,501,776	assume basement wall 250mm thick
Concrete with 30% SCM	1,014	m^3	230.00	1,241.70	1,471.70	1,491,641	
Concrete with 40% SCM	1,014	m^3	230.00	1,241.70	1,471.70	1,491,641	
Rebar	51	Ton	1,977.00	523.00	2,500.00	128,558	
Note: The above unit rates exclude General Contractor's general conditions, overhead profit & fees, it also excludes any contingencies.							

CoV Embodied Carbon Reduction Study
Mid Rise Residential
July 12, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Below Grade							
Concrete with 0% SCM	291	m³	250.00	199.46	449.46	130,774	
Concrete with 20% SCM	291	m³	240.00	199.46	439.46	127,865	
Concrete with 30% SCM	291	m³	230.00	199.46	429.46	124,955	
Concrete with 40% SCM	291	m³	230.00	199.46	429.46	124,955	
Rebar	9	Ton	1,938.00	412.00	2,350.00	20,151	
Welded wire mesh	1,875	m²	2.90	2.60	5.50	10,313	6x6 - W1.4xW1.4 (10x10)
Beams							
Concrete							
Concrete with 0% SCM	1,377	m³	250.00	770.21	1,020.21	1,405,251	assume 2000 x 285mm
Concrete with 20% SCM	1,377	m³	240.00	770.21	1,010.21	1,391,477	
Concrete with 30% SCM	1,377	m³	230.00	770.21	1,000.21	1,377,703	
Concrete with 40% SCM	1,377	m³	230.00	770.21	1,000.21	1,377,703	
Rebar	283	Ton	1,987.00	563.00	2,550.00	721,037	
Load Bearing Walls	19,858	m²	48.00	56.50	104.50	2,075,202	Full height load bearing walls
Nails							
Screws Nuts & Bolts							
Small Dimension Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Columns							
Concrete							
Concrete with 0% SCM	356	m³	250.00	879.17	1,129.17	402,435	assume size 750mm x 750mm
Concrete with 20% SCM	356	m³	240.00	879.17	1,119.17	398,871	
Concrete with 30% SCM	356	m³	230.00	879.17	1,109.17	395,307	
Concrete with 40% SCM	356	m³	230.00	879.17	1,109.17	395,307	
Rebar	182	Ton	2,007.00	668.00	2,675.00	485,954	
Floors							

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Concrete							
Concrete with 0% SCM	2,003	m³	250.00	1,222.83	1,472.83	2,950,490	assume 270mm thick
Concrete with 20% SCM	2,003	m³	240.00	1,222.83	1,462.83	2,930,458	
Concrete with 30% SCM	2,003	m³	230.00	1,222.83	1,452.83	2,910,425	
Concrete with 40% SCM	2,003	m³	230.00	1,222.83	1,452.83	2,910,425	
Rebar	128	Ton	1,977.00	523.00	2,500.00	319,060	
Wood Parallel Chord Joist (wood joist)	21,758	m²	61.33	62.81	124.14	2,701,087	
Galvanized Sheet							
Large Dimension Softwood Lumber, kiln-dried							
Nails							
Softwood Plywood (9mm)							
Wood I-Joist with Plywood	26,186	m²	48.65	58.13	106.78	2,796,120	
Galvanized Sheet							
Nails							
Small Dimension Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Exterior Walls							
Steel Stud	3,960	m²	108.45	72.70	181.15	717,354	area based on 0% WWR
1/2" Regular Gypsum Board							
1/2" Glass Mat Gypsum Panel							
6 mil Polyethylene							
Air Barrier							
Galvanized Sheet							
39mm x92mm 20ga. Galvanized Steel Studs at 16" o.c.							
Joint Compound							
Nails							
Paper tape							
Screws, Nuts, & Bolts							

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		

CoV Embodied Carbon Reduction Study
Mid Rise Residential
July 12, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Spandrel to Window Walls	3,960	m²	1,016.50	98.50	1,115.00	4,415,400	area based on 0% WWR
1/2" Regular Gypsum Board							
Aluminum Extrusion							
EPDM Membrane (black, 60 mil)							
39mm x92mm 25ga. Galvanized Steel Studs at 24" o.c.							
Glazing Panels							
Joint Compound							
Nails							
Paper Tape							
Screws, Nuts, & Bolts							
Metal Spandrel Panel							
Wood Stud	3,960	m²	68.74	80.75	149.49	591,963	area based on 0% WWR
1/2" Regular Gypsum Board							
6 mil Polyethylene							
Joint Compound							
Nails							
Paper Tape							
Small Dimension Softwood Lumber, kiln-dried							2x6 wood stud
Softwood Plywood (9mm)							
Windows							
Aluminum frame windows (double glazing)	1,440	m²	600.00	130.00	730.00	1,051,200	area based on 40% WWR
Aluminum frame windows (triple glazing)	1,440	m²	710.00	130.00	840.00	1,209,600	area based on 40% WWR
Fibreglass frame windows (double glazing)	1,440	m²	735.00	315.00	1,050.00	1,512,000	area based on 40% WWR
Fibreglass frame windows (triple glazing)	1,440	m²	885.00	315.00	1,200.00	1,728,000	area based on 40% WWR
PVC frame windows (double glazing)	1,440	m²	450.00	50.00	500.00	720,000	area based on 40% WWR
PVC frame windows (triple glazing)	1,440	m²	550.00	50.00	600.00	864,000	area based on 40% WWR

CoV Embodied Carbon Reduction Study
Mid Rise Residential
July 12, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Exterior Cladding							
Metal Panel	7,272	m^2	565.00	185.00	750.00	5,454,000	assume aluminum panel
Metal Wall Cladding (30 ga.)							
Screws, Nuts & Bolts							
Water Based Latex Paint							
Fiber Cement Board	3,600	m^2	190.00	66.00	256.00	921,600	
Fiber Cement (8mm)							
Exterior Wall Insulation							area based on 0% WWR
XPS (25mm)	14,987	m^2	11.40	4.60	16.00	239,795	Roxul semi-rigid insulation
Mineral wool batt R-20 (25mm)	14,866	m^2	8.10	0.90	9.00	133,797	
Fiberglass batt R12.6 (25mm)	14,866	m^2	3.35	1.15	4.50	66,898	
Blown cellulose (25mm)	30,004	m^2	10.00	2.80	12.80	384,047	assume closed cell
Roof Insulation							
XPS (25mm)	11,709	m^2	18.40	3.10	21.50	251,738	Extruded polystyrene insulation
EPS (25mm)	11,668	m^2	14.50	3.00	17.50	204,192	Expanded polystyrene insulation
Polyisocyanurate insulation							
Polyiso Foam Board (unfaced) (25mm)	11,821	m^2	19.50	4.00	23.50	277,802	included tapered for drainage
Mineral Wool Batt (med density)	11,614	m^2	21.00	2.50	23.50	272,937	
Mineral wool R-30 (25mm)							
Roof Membrane							
PVC	1,875	m^2	61.43	23.50	84.93	159,240	
6 mil Poly							
Ballast (aggregate stone)							assume 75mm thick
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
PVC Membrane 48 mil							
Small Dimensional Softwood Lumber, kiln-dried							

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Softwood Plywood (9mm)							
Mod Bit	1,875	m^2	41.80	33.43	75.23	141,053	
#15 Organic Felt							
1/2" Moisture Resistant Gypsum Board							
Galvanized Steel Sheet							assume 300mm high to roof parapet
Mod Bit Membrane							
Nails							
Roofing Asphalt							
EPDM	1,875	m^2	58.43	54.50	112.93	211,740	
6 mil Poly							
Ballast (aggregate stone)							assume 75mm thick
EPDM Membrane (black, 60 mil)							
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
Small Dimensional Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Parkade							
1 Level							
Concrete with 0% SCM	531	m^3	250.00	1,079.92	1,329.92	706,480	assume suspended slab 200mm thick
Concrete with 20% SCM	531	m^3	240.00	1,079.92	1,319.92	701,168	assume basement wall 250mm thick
Concrete with 30% SCM	531	m^3	230.00	1,079.92	1,309.92	695,856	
Concrete with 40% SCM	531	m^3	230.00	1,079.92	1,309.92	695,856	
Rebar	46	Ton	1,977.00	523.00	2,500.00	114,368	
Note: The above unit rates exclude General Contractor's general conditions, overhead profit & fees, it also excludes any contingencies.							

CoV Embodied Carbon Reduction Study
Townhouse
August 11, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Below Grade							
Concrete with 0% SCM	13	m^3	250.00	531.32	781.32	9,990	
Concrete with 20% SCM	13	m^3	240.00	531.32	771.32	9,862	
Concrete with 30% SCM	13	m^3	230.00	531.32	761.32	9,734	
Concrete with 40% SCM	13	m^3	230.00	531.32	761.32	9,734	
Rebar	0.5	Ton	1,938.00	412.00	2,350.00	1,119	
Welded wire mesh	72	m^2	2.90	2.60	5.50	396	6x6 - W1.4xW1.4 (10x10)
Beams							
Load Bearing Walls	226	m^2	48.00	56.50	104.50	23,642	Full height load bearing walls
Nails							
Screws Nuts & Bolts							
Small Dimension Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Columns							
Glulam		excluded					
Glulam Sections							
Floors							
Wood Parallel Chord Joist (wood joist)	358	m^2	61.33	62.81	124.14	44,456	
Galvanized Sheet							
Large Dimension Softwood Lumber, kiln-dried							
Nails							
Softwood Plywood (9mm)							
Wood I-Joist with Plywood	431	m^2	48.65	58.13	106.78	46,020	
Galvanized Sheet							
Nails							
Small Dimension Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							

CoV Embodied Carbon Reduction Study
Townhouse
August 11, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Exterior Walls							
Steel Stud	356	m²	108.45	72.70	181.15	64,562	area based on 0% WWR
1/2" Regular Gypsum Board							
1/2" Glass Mat Gypsum Panel							
6 mil Polyethylene							
Air Barrier							
Galvanized Sheet							
39mm x92mm 20ga. Galvanized Steel Studs at 16" o.c.							
Joint Compound							
Nails							
Paper tape							
Screws, Nuts, & Bolts							
Wood Stud	356	m²	68.74	80.75	149.49	53,277	area based on 0% WWR
1/2" Regular Gypsum Board							
6 mil Polyethylene							
Joint Compound							
Nails							
Paper Tape							
Small Dimension Softwood Lumber, kiln-dried							2x6 wood stud
Softwood Plywood (9mm)							
Windows							
Aluminum frame windows (double glazing)	130	m²	600.00	130.00	730.00	94,608	area based on 40% WWR
Aluminum frame windows (triple glazing)	130	m²	710.00	130.00	840.00	108,864	area based on 40% WWR
Fibreglass frame windows (double glazing)	130	m²	735.00	315.00	1,050.00	136,080	area based on 40% WWR
Fibreglass frame windows (triple glazing)	130	m²	885.00	315.00	1,200.00	155,520	area based on 40% WWR
PVC frame windows (double glazing)	130	m²	450.00	50.00	500.00	64,800	area based on 40% WWR
PVC frame windows (triple glazing)	130	m²	550.00	50.00	600.00	77,760	area based on 40% WWR

CoV Embodied Carbon Reduction Study
Townhouse
August 11, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Exterior Cladding							
Brick Veneer	340	m²	287.00	198.00	485.00	164,997	assume aluminum panel
Cold Rolled Sheet							
Concrete Brick							
Mortar							
PVC/Vinyl	1,108	m²	89.10	24.20	113.30	125,550	assume aluminum panel
#15 Organic Felt							
Aluminum Cold Rolled Sheet							
Nails							
Vinyl Siding							
EIFS	324	m²	61.00	68.50	129.50	41,958	assume aluminum panel
2" EPS							
Fiberglass Mesh							
Adhesive/Basecoat							
Cement							
Water-Resistive Barrier							
Primer							
Finish Topcoat							
Fiber Cement Board	324	m²	190.00	66.00	256.00	82,944	
Fiber Cement (8mm)							
Exterior Wall Insulation							area based on 0% WWR
XPS (25mm)	1,349	m²	11.40	4.60	16.00	21,582	Roxul semi-rigid insulation
Mineral wool batt R-20 (25mm)	1,338	m²	8.10	0.90	9.00	12,042	
Fiberglass batt R12.6 (25mm)	1,338	m²	3.35	1.15	4.50	6,021	
Blown cellulose (25mm)	2,700	m²	10.00	2.80	12.80	34,564	assume closed cell
Roof Insulation							
XPS (25mm)	450	m²	18.40	3.10	21.50	9,667	Extruded polystyrene insulation
EPS (25mm)	448	m²	14.50	3.00	17.50	7,841	Expanded polystyrene insulation

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Polyisocyanurate insulation							
Polyiso Foam Board (unfaced) (25mm)	454	m²	19.50	4.00	23.50	10,668	included tapered for drainage
Mineral Wool Batt (med density)	446	m²	21.00	2.50	23.50	10,481	
Mineral wool R-30 (25mm)							
Roof Membrane							
PVC	72	m²	61.43	23.50	84.93	6,115	
6 mil Poly							
Ballast (aggregate stone)							assume 75mm thick
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
PVC Membrane 48 mil							
Small Dimensional Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							
Mod Bit	72	m²	41.80	33.43	75.23	5,416	
#15 Organic Felt							
1/2" Moisture Resistant Gypsum Board							
Galvanized Steel Sheet							assume 300mm high to roof parapet
Mod Bit Membrane							
Nails							
Roofing Asphalt							
EPDM	72	m²	58.43	54.50	112.93	8,131	
6 mil Poly							
Ballast (aggregate stone)							assume 75mm thick
EPDM Membrane (black, 60 mil)							
Galvanized Steel Sheet							assume 300mm high to roof parapet
Nails							
Small Dimensional Softwood Lumber, kiln-dried							
Softwood Plywood (9mm)							

CoV Embodied Carbon Reduction Study
Townhouse
August 11, 2021

Description	Quantity	Unit	Unit Rate			Amount	Remark
			Material	Install	Total		
Note: The above unit rates exclude General Contractor's general conditions, overhead profit & fees, it also excludes any contingencies.							