Low Carbon Solutions for Multi-Unit Residential Buildings

BC HOUSING
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Chapter 1: Introduction and Embodied Carbon Primer

Introduction

Canadian policy is focusing on increasing energy efficiency for both new and existing buildings to help meet Canada's commitments to reducing carbon emissions in the next decade and beyond. Focusing on both new and existing buildings recognizes the widening gap between new building regulations and the performance of the existing building stock. Housing authorities, like BC Housing, are leading the market transformation for multi-unit residential buildings (MURBs) to meet net-zero energy targets by 2032 for new construction and piloting deep energy retrofits (Morrison Hershfield 2018a, 2018b, Pembina Institute 2024, RDH 2012).

There is growing evidence that embodied carbon is as important as operational emissions. Embodied carbon emissions are becoming a bigger portion of overall building emissions in British Columbia for new construction because of regulations targeting low-energy buildings and a low carbon-intensive gird. However, there are knowledge gaps on how to minimize embodied carbon for both new construction and existing MURBs including:

1. The optimal strategies to capture maximum energy efficiency gains and overall carbon emission reductions during manufacturing, construction, operation, and deconstruction,
2. How to reduce embodied carbon of the building envelope, and
3. How to accurately determine building embodied carbon in an efficient and consistent manner.

The objective of this study is to provide the building industry with resources addressing these knowledge gaps. The study focuses on building envelope design guidance, while also showing relative impact of the embodied carbon for the building structure. The aim is to demonstrate analysis with enough detail and transparency to provide practical guidance and illustrated solutions to support the building industry. The aim is also to provide valuable insights for policy makers that are introducing project embodied carbon calculation and performance requirements.

Carbon Emissions Background

Building operational carbon emissions are those from consumption of utilities (gas and electricity) to heat, cool, ventilate, light, and provide services to buildings. Reduction of operational carbon emissions are achieved by energy efficiency measures and through electrification in low-carbon grids, such as British Columbia's power grid. Operational emissions are regulated through energy efficiency codes and standards, such as the National Energy Code for Buildings (NECB) and the BC Energy and Zero Carbon Step Codes. However, buildings also have embodied carbon emissions from the consumed materials and activities that happen during the construction, maintenance, retrofitting, demolition and transportation of building materials.

The UNEP 2022 Global Status Report for Building and Construction examined operational and embodied carbon as part of total global emissions. This report estimates that the average contribution from building operation (direct and indirect) is 28%. Embodied carbon (interpreted here as building construction industry materials and other emissions) is 12%, as seen is **Figure 1**. Such global statistics are commonly referenced when discussing the significance of embodied carbon (Heritage BC 2022, ZEBX 2021, CaGBC 2020, and Teicher 2021).

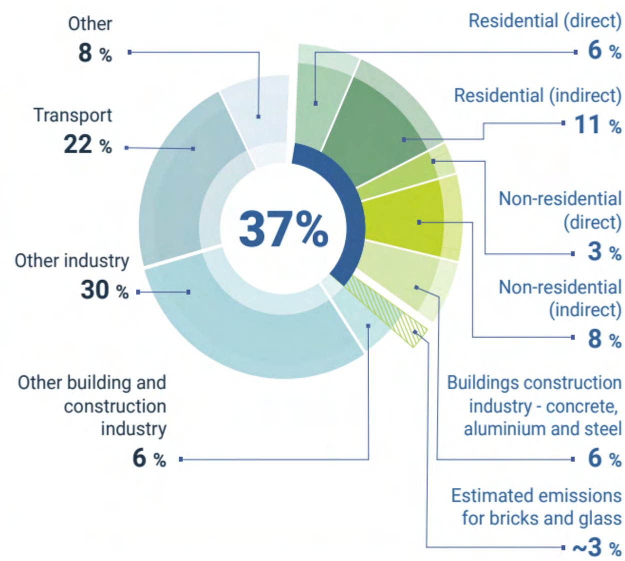


Figure 1: Breakdown of Global Emissions based on IEA World Energy Statistics and Balances (graphic from UNEP 2022)

In a 2019 report prepared for the City of Vancouver, Zera Solutions estimated embodied carbon emissions between 145 and 543 kg eCO_2/m^2 for the residential buildings detailed in **Table 1**. They found that embodied carbon emissions in newer energy efficient Vancouver buildings surpassed 50% of lifetime operating emissions. Embodied carbon is expected to be a large proportion of carbon emissions as buildings increase energy efficiency, electrify space heating, and domestic hot water heating. Hence, reducing embodied carbon in jurisdictions with low carbon electricity grids is a logical next step for further reducing greenhouse gas emissions.

Table 1. **Embodied Carbon of Vancouver Residential Buildings (Zera Solutions 2019)**

Location	Structure	Building Envelope	Gross Floor Area (GTA) (m^2)	Embodied Carbon, excluding Parkade (eCO_2/m^2)	Parkade Area (m^2)	Total Embodied Carbon (eCO_2/m^2)
Low-Rise Buildings						
4575 Granville St.	Concrete	Wood Studs	2,228	458	NA	280
2601-2619 E Hastings	Concrete	Concrete panels	5,618	295	1,860	222
686 E 22nd Ave, 3811-3833 Fraser St., 679 E 23rd Ave	Hybrid wood	Wood Studs	9,550	177	1,620	151
441-463 West 59th Ave	Concrete	Steel Studs	5,730	524	NA	NA
1535-1557 Grant St.	Hybrid wood	Wood Studs	2,982	185	NA	NA
2715 West 12th Ave	Hybrid wood	Wood Studs	1,273	145	54	139
8636-8656 Oak St	Hybrid wood	Wood Studs	5,871	330	NA	NA
High-Rise Buildings						
1668-1684 Alberni St.	Concrete	Steel Studs	21,564	270	8,029	197
1068-1080 Burnaby St, 1318 Thurlow St	Concrete	Steel Studs	14,403	336	4,837	252
2218 Main St.	Concrete	Steel Studs	6,526	434	4,856	249
1070 Barclay St.	Concrete	Curtain wall	64,710	543	NA	NA
950 W 41st Ave	Concrete	Steel Studs	59,370	423	27,775	288
2218 Main	Concrete	Steel Studs	6,526	434	4,856	248
			Average	**350**		**225**

The City of Vancouver approved the Climate Emergency Action Plan in 2020 to reduce carbon emissions by 50% by 2030 as part of six big moves as illustrated in Figure 2. The policy includes several measures to reduce emissions related to embodied carbon by 40% by 2030 relative to a 2018 baseline. These measures include the following:

- Set embodied carbon limits for new buildings.
- Make it easier and less expensive to use lower impact carbon materials in new construction.
- Support the people using low-carbon materials in new buildings.
- Low-carbon planning and strategies.

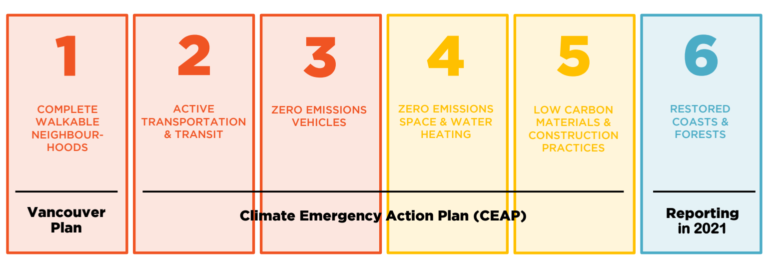


Figure 2: Vancouver's Climate Emergency Action Plan Includes Reducing Measures to address Embodied Carbon (Vancouver City Council, 2020)

Some practitioners may overlook the importance of energy efficiency in reducing emissions in BC and focus solely on the need for electrification and reducing embodied carbon. However, energy efficiency measures and demand side management enable a plan like the Climate Energy Action Plan to work.

There are several reasons why energy efficiency cannot be ignored, which include:

1. **Resiliency**: energy efficiency increases the passive ability of buildings to maintain habitable conditions in the event of a heating or cooling system loss, forest fire, or other outdoor pollutants.
2. **Occupant comfort:** well insulated buildings, quality ventilation, and good quality windows translate to a healthy indoor environment for acoustics, air quality, temperature control, and overall satisfaction.
3. **Affordable housing**: reduce the overall need for energy and related costs for the future electricity grid and demand.
4. **Avoid electrical upgrades**: upgrading the electrical infrastructure for existing buildings is costly and invasive. Electrical upgrades can be triggered by building electrification and sometimes avoided by applying comprehensive energy efficiency measures through a deep energy retrofit.
5. **Demand side management**: reducing energy demand in buildings is important to maintain a clean and affordable power grid while there is aggressive electrification across many industry sectors.

Recent development in codes and energy standards that are aimed at transitioning industry to net-zero emission buildings have addressed most of these items by introducing requirements for both total energy-use intensity (TEUI) and thermal energy demand intensity (TEDI). Example codes and standards include the Vancouver Building Bylaw, the BC Energy Step Code, and the Toronto Green Standard. Reducing TEDI is a key consideration for reducing heating demand and all the items listed above.

This study puts these concepts into perspective by exploring how energy efficiency measures are critical to reducing overall carbon emissions for three archetype buildings. Chapters 2 and 3 present an evaluation of several case study buildings where the impact of various energy efficiency measures are presented for the operational and embodied carbon emissions.

The remainder of this chapter presents background information on life cycle assessment (LCA) of buildings and recommendations for LCA evaluations and policy. Recommendations are primarily related to embodied carbon.

Embodied Carbon Review

Embodied carbon impacts are calculated based on LCA calculations for stages defined in EN 15978 (2011) and illustrated in **Figure 3**. The basis for the embodied carbon calculations in this study are outlined in the following subsections.

Embodied carbon performance requirements can be based on either:

1. Normalized emissions intensity targets or limits, or
2. A percent reduction relative to a baseline.

Building Life Cycle Stages

Product			Construction Process		Use							End of Life				Supplementary Information
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational energy use	Operational water use	Deconstructural/demolition	Transport	Waste Processing	Disposal	Benefits and loads beyond the system boundary (Reuse, Recovery, Recycling)
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

Figure 3: Building Life Cycle Stages (Bowick et al., 2022)

Percent reduction using a baseline offers a simple and flexible way to address:

1. Wide ranges of building types, and
2. Evolving calculation methodologies, where absolute limits can be problematic for ensuring compliance.

However, metrics relying on precent reductions can lead teams to focus on defining unrealistically poor baselines to boost reported percent reduction in lieu of reducing actual project emissions.

To encourage consistency and set expectations, the City of Vancouver developed Embodied Carbon Guidelines v1 (2023) to guide compliance for part 3 buildings. The City of Vancouver guideline requires Embodied carbon calculations to cover substructure, superstructure, building envelope and interiors. The calculations are for cradle-to-grave and cover A1-A5, B1-B5, and C1-C4 life cycle stages and does not allow D stage emissions to be included in compliance calculations. Guidance for Stage D calculations are provided for users to refer to for non-compliance calculations.

Quantity data collection options in the guide follow the National Research Council of Canada's National Guideline (2022) for whole-building life cycle assessment including:

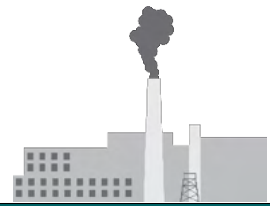
- building information models (BIM),
- cost estimate analysis, and
- takeoffs from drawings.

Key considerations for the calculation of emissions for each life cycle stage and the methodology utilized in this study follows.

Production (stages A1 to A3)

The production stages consist of the carbon emissions that are associated with the cradle-to-gate processes, including raw material supply, transport, and manufacturing. Production impacts are the minimum scope of embodied carbon calculations and are commonly drawn from Environmental Product Declarations (EPDs).

Table 2. **LCA Production Stages**

		
Raw material (A1) extraction and processing material inputs (raw and recycled)	**Transport (A2)** of materials to and between manufacturing facilities	**Manufacturing (A3)** processing of materials and products to create new products

A rough range for A1-A3 emissions values is between 0.9 to 2.5 kg eCO_2/kg, which is drawn from the 2017 Buy Clean California Act for key building materials and is plotted in Figure 4. The mineral wool values are provided in kg CO_2e/m^2 RSI that have been converted for comparison purposes and are based on EPD data referenced in Appendix B.

A1 emissions are from extracting and processing raw materials for products, which can vary greatly.

A2 transport emissions can be significant when these materials are sourced from across the globe and involve manufacturing processes that have far-apart facilities.

Figure 4: Maximum A1-A3 Embodied Carbon Allowances in 2017

A3 manufacturing emissions are dramatically affected by the electrical grid in which they are produced due to high use of electricity for mechanical and heating processes. EPDs can provide this data as industry data for groups of manufactures per regions or specific product EPDs for manufacturers and sometimes manufacturing locations.

British Columbia's grid is amongst the lowest intensity in the world as explained in Chapter 2 of this study. Specifying and accounting for locally produced materials on B.C. projects has potential for reducing A3 embodied carbon dramatically. These advantages, however, are not typically captured due to few EPDs being currently available for specific plant locations.

Adjustments for "Regionalization" are possible with some LCA analysis software, where the emissions from the electricity use component of a product's A1-A3 emissions are adjusted based on associated manufacturing electrical grid. Nevertheless, more consistent outcomes will be provided if more manufacturers provide plant specific data in EPDs.

Version 1.0 of the City of Vancouver Embodied Carbon Guidelines requires using the industry wide EPDs for baseline definitions and for project calculation when product specific data is not available or multiple manufacturers are permitted in design specifications. If industry wide EPDs are not available, an appropriate benchmark, such as the Carbon Leadership Forum's (CLF) Material Baselines Report, or default data in calculation software, may be used. These are discussed in greater detail in Appendix B.

Reporting of calculation uncertainty in embodied carbon analysis is recommended as a good practice in some guides (ISE 2022) but is not required by the current City of Vancouver guidelines. A simple methodology for estimating uncertainty for stage A1-A3 was put forth by the CLF (2019) as follows:

- ±2% for emissions for specific products, ±2% for specific manufacturing process and ±2% for specific manufacturing location, or
- ±20% each when not known.

Given these are random errors (and not bias to being consistently high or low), the total uncertainty can be reasonably summed using the square root sum as shown below. The resulting range of total uncertainty is ±3.5% to ±35% based on the three uncertainty sources in product, manufacturing process, and manufacturing location. This methodology seems reasonable given industry's limited understanding of associated uncertainties, but the values used are crude estimates.

$$Total\ Uncertainty = \sqrt{uncertainty1^2 + uncertainty2^2 + uncertainty3^2}$$

Some uncertainties have a bias in lieu of a random error. For example, determining the material quantities for the building envelope based the clear field assemblies (Walter P Moore 2021) underestimates the quantity of supporting elements. The underestimation is because the additional quantities at component interfaces are unaccounted for in this approach. Such interfaces include window-to-wall, intermediate floors, and roof-to-wall. This and other biases are not yet well understood by industry.

Several broad industry recommendations for supporting reductions related to A1-A3 emissions are:

1. Encourage and support the generation of EPDs from B.C. suppliers and manufacturers to help practitioners to specify and accurately account for local products that benefit from a low carbon grid intensity.
2. Given that EPDs currently take significant time and expense to generate, provide guidance to professionals on best practices for adjusting for project specific emissions where innovative product modifications are implemented.
3. Encourage reporting and further study of uncertainty and develop effective and consistent calculation methodologies.

Transport (A4)

A4 Transport covers transportation from the manufacturing facilities to the construction site. These emissions are reported in some EPDs based on default values given in Product Category Rules (PCRs) or based on plant shipping surveys. These EPD reported A4 emissions are of little relevance to project calculations because the assumed shipping distances can vary greatly from actual distances to project sites. However, determining the actual manufacturing plant locations and mode of transportation can be cumbersome for detailed A4 emissions calculations.

The City of Vancouver Embodied Carbon Guidelines allow for the use of a simplified method that assumes a combined A4 assumption at four percent of the A1-A3 emissions. Alternatively, the

Institution of Structural Engineer's guide for embodied carbon calculations (2022) includes a simplified method of determining A4 transportation emissions based on carbon intensity values as summarized in **Table 3**. This method adjusts for transport to site by selecting the sourcing location based on broad ranges and does not require detailed calculations.

Table 3. ISE United Kingdom Transportation A4 Values

Location	Distance Travelled by Road (km)	Distance Travelled by Sea (km)	GWP Intensity ($kg\ eCO_2/kg$)
Local	50 km	N/A	0.005
National	300 km		0.032
Europe	1500 km		0.161
Global	200 km	10,000	0.183

To estimate A4 emissions for B.C. projects we have applied a similar method as given in the ISE guide using the following equation:

$$A4\ Carbon\ Intensity = \frac{Vehicle\ Carbon\ Intensity \times Shipping\ Distance}{Capacity\ Utilization}$$

Discussion on assumptions for each of these variables follows.

Vehicle carbon intensity is based on the emissions from fuel use per distance and weight. The vehicle carbon intensity is dependent on vehicle type (including type of fuel) and the fill capacity.

One-Click LCA (2017) provides factors for vehicle carbon intensities as summarized in **Figure 5**. Carbon emissions are strongly dependent on shipping mode; ocean going container ships have an order of magnitude less emissions per km ton than shipping with small road vehicles. Furthermore, shipping with partially loaded road vehicles have greater emissions than with fully loaded vehicles.

Road **shipping distances** from major Canadian and US cities to our study's B.C. locations are given in **Figure 6**. The distances between Vancouver and Prince George are similar to the distances between Seattle or Calgary to B.C. Cities and are less than 1000 km. Eastern Canada and US cities are less than 5000 km from B.C. Cities and the destination within B.C. has little relative impact on this distance.

Road shipping distances used in the North American EPDs considered in this study range from 250 to 1200 km. As such, many products used in B.C. projects can be expected to have a much greater A4 emissions than those available in EPDs.

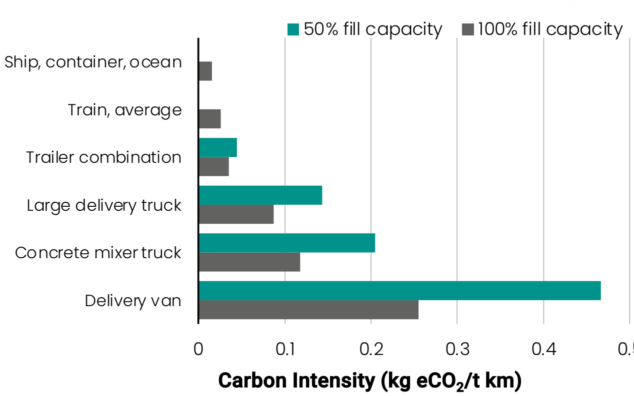


Figure 5: Vehicle Carbon Intensity

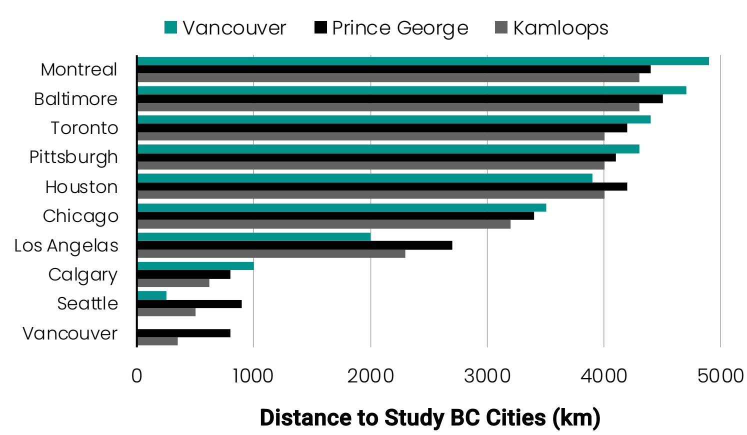


Figure 6: Road Distances to Study Locations

The transportation of building materials sourced from overseas will involve both land transportation to and from port and shipping by sea.

Figure 7 lists sea **shipping distances** (taken from sea-distances.org) ranging from about 10,000 to 20,000 km for East Asian and Oceanic locations to the Port of Vancouver and 7000 to 10,000 for Europe and South America to the Port of Baltimore (which would then be trucked to Vancouver). Many products imported from Europe can be expected to use the route through east coast ports.

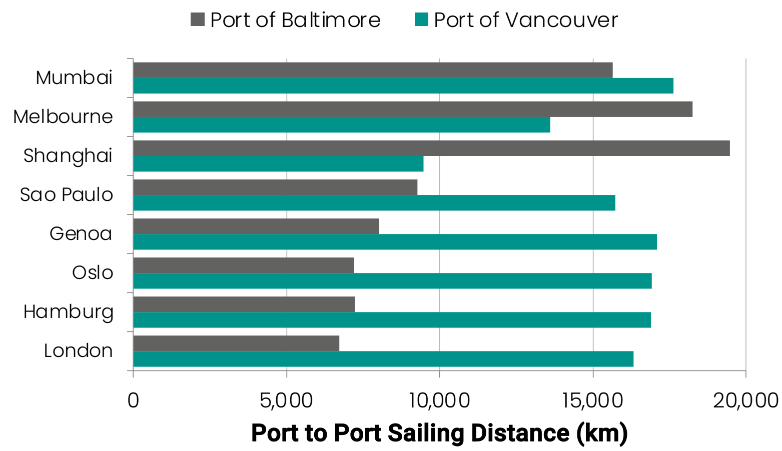


Figure 7: Sea Distances to Port of Vancouver and Baltimore (seadistances.org)

Capacity utilization captures a multitude of transportation factors. The use of online mapping software to estimate shipping distances provide minimum shipping distances and underestimate LCA impacts (a bias error) because:

1. deliveries may stop at several locations off the minimum distance route,
2. materials may be shipped to distributors or temporary storage locations off the minimum distance route, and
3. return journeys of empty and partial loaded vehicles limit capacity utilization since carbon intensity is lower for fully loaded shipments.

To account for these effects, this study uses a capacity utilization of 65% based on a survey of values reported in insulation EPDs as plotted in **Figure 8**. Regional A4 transportation values have been calculated using:

- trailer combination and container ship vehicle carbon intensities (Figure 5),
- conservative distances (Figures 6 and 7),
- 65% capacity utilization (Figure 8), and
- regional transportation values (Table 3).

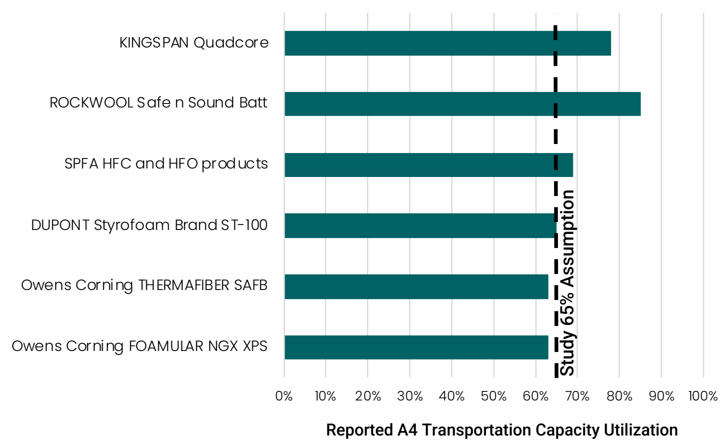


Figure 8: Reported Utilization Capacity Values in EPDs for Insulation Products

Transportation A4 emissions have large uncertainties when the source location is unknown. Uncertainties remain when source locations are known due to vehicle carbon intensities, shipping distances, and capacity utilization assumptions. All these factors are subject to bias when project specific calculations are applied. One-Click LCA recommends a 28% uncertainty for A4 transportation emissions where source location is not specified. This value seems suitable when source location is known to address other uncertainties. When source locations are unknown then the A4 emissions could vary by two orders of magnitude as demonstrated by the carbon intensity presented in **table 4**.

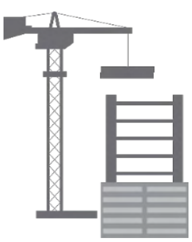
Table 4. **Calculated Reginal Transportation A4 Values for BC Study Locations**

Location	**Distance Travelled by Road** (km)	**Distance Travelled by Sea** (km)	**GWP Intensity** (kg eCO_2/kg)
Local	100	N/A	0.005
BC, Alberta, Washington	1000		0.053
Eastern North America, Mexico	5000		0.267
Overseas direct to Vancouver	1000	10,000	0.429
Overseas through East Coast ports	5000	10,000	0.643

We recommend using simple regional A4 emissions such as those provided in Table 4. Materials and product type assumptions can be reasonably made with more information provided in Appendix B. For example, cast-in-place concrete can be sourced locally because it is cost-prohibitive or impractical to ship from further locations.

Further evaluation is needed to outline when the 4% assumption for A4 is appropriate since the value is clearly too low for some materials and products transported to site from outside of B.C.

Construction Activities (A5c) and Wastage (A5w)

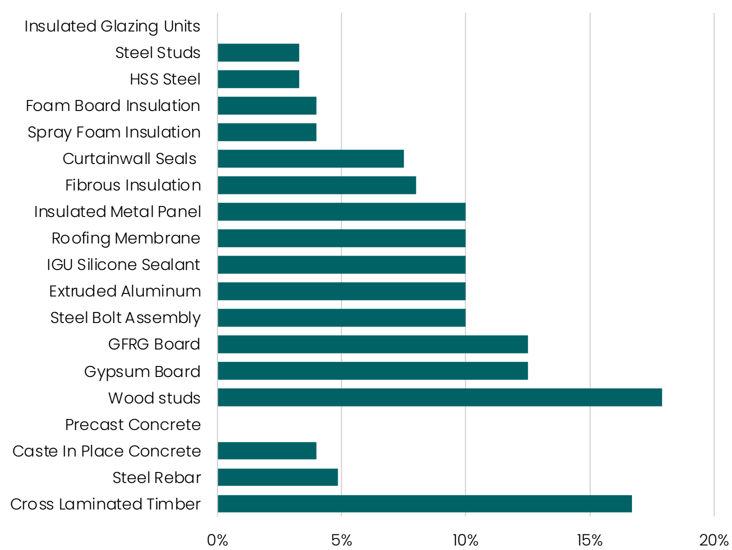


Construction A5 stage emissions are comprised of two parts: A5c which is site activity emissions and can be estimated from on-site electricity and fuel consumption. A5w refers to emissions associated with construction material waste.

For **A5c Construction Activities** emissions, software such as One-Click LCA accepts data for energy and water consumption on site. For design projects without construction emission information, One-Click LCA offers some average scenarios. Scenarios include average impacts per climate region for electricity, fuel consumption and waste production. Emissions associated with excavations can also be calculated and added to the model. It can be either per m^3 of removed mass or fuel consumption. In contrast, the current version of EC3 only accepts electricity and field consumption.

Yue et al. (2019) recommend 9 kg/m^2 to account for new building construction activity emissions. Assuming a building weight of 1000 kg/m^2 of GFA would result in an impact of 0.009 kg eCO_2/kg. It is reasonable to allow use of such a simple assumption for construction projects to avoid cumbersome tracking and calculations because the impact is quite low.

A5w Construction Waste emissions capture emissions due to materials and product wastes. Standard construction waste values from One-Click LCA for a range of building material types are included in **Figure 9**. Rates are low for concrete and steel structural materials, around 10% for several building envelope materials, and over 15% for wood materials.



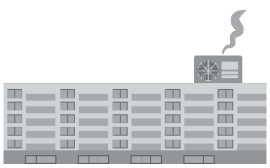
Default A5 Construction Site Material Wastage Rates

A5c emissions for construction activities are small and while uncertainty may be significant it seems unlikely to be significant relative to construction project emissions. A5w emissions for construction waste may add 10 to 17% to project emissions and are likely to be of that order of magnitude for building envelopes. Therefore, associated uncertainties for construction wastage rates are important to consider in lieu of a default assumption.

This study determined values for components of the construction emissions. A5a emissions are calculated using area-based factor. A5w is calculated using material waste rate depending on the material type as shown in Figure 10 and further discussed in Appendix B.

Zera Solutions (2019) recommended collecting data to assemble default values for Vancouver construction. This will be valuable information and useful to verify the A5 assumptions presented in this study.

Usage (stages B1 to B5)



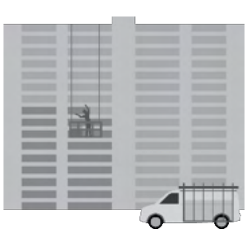
Use (B1): Refers to the emissions during the use of the installed product, often refrigerants leaking from mechanical systems or gas leaking from foam insulation materials.

Carbonization of the outer layer of cementitious materials during the life of buildings absorbs carbon dioxide from the air. This results in negative B1 emissions. This process is the chemical reversal of the cement production process calcination phase. The amount of carbon dioxide absorbed depends on exposure of the material, the duration of the exposure and the initial amount of cement. Our assumption is that these effects are negligible, which is aligned with the City of Vancouver Embodied Carbon Guidelines, and not included in calculations.

Maintenance (B2): Refers to the activities undertaken to maintain the facility. Maintenance and renewal work is required for the building envelope to function as intended. This work includes cleaning, replacement of weather components, and recoating.

Renewal of coatings and sealants is included as maintenance and can dominate the B2 related emissions.

Repair (B3): Work and component replacement that is performed to return equipment to service after a failure or vandalism. Some failure rates can be reasonably set based on historical precedent (e.g., window breakage) but other repair needs are more difficult to predict and often unanticipated (e.g. masonry decay due to freeze-thaw).



Replacement & Refurbishment (B4 & B5): Replacement and refurbishment of materials and components at the end of their service life.

Service life values for materials and products can significantly impact analysis and replacement essentially repeats the A1-A5 emissions for each occurrence.

In this study we will refer to these impacts as B4 impacts assuming end of life components are replaced. This is significant for insulated glazing units, roofing systems, and some cladding systems that are replaced one or more times during the life of the building.

Figure 10 presents service life predictions for building envelope components provided in City of Vancouver Embodied Carbon Guidelines. Such values are hotly debated in the building industry and component level discussion is provided in Appendix B.

Service life is affected by premature component decay and failures due to design detailing, construction, and maintenance issues. The impact of such issues and varying recommendations for component service life values results in significant uncertainty for B4 calculations.

The draft City of Vancouver Embodied Carbon Guidelines further allow users to assume B1-B4 impacts of 10% of the A1-A3 impacts of the baseline. We recommend that this default not be applied on a component-by-component basis or to envelope retrofit projects.

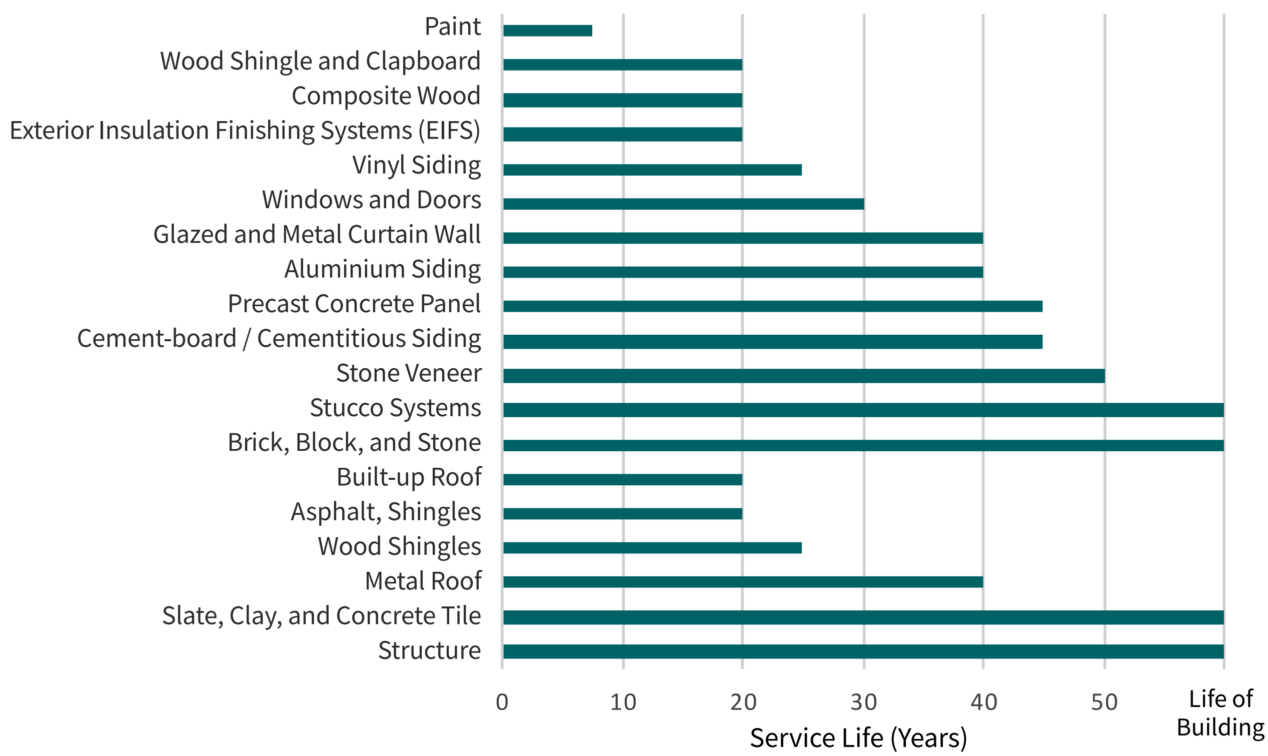
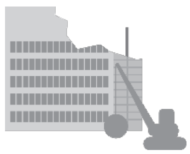


Figure 10: Building Envelope Components Service Life taken from City of Vancouver Embodied Carbon Guidelines

Operation (stages B6 to B7)

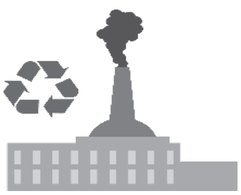
B6 Energy Usage and B7 Water Usage emissions constitute the operational emissions for project over the building's life. These emissions are typically determined from utility meters for existing buildings and predicted using energy models and other calculations.

End of Life (stages C1 to C4)

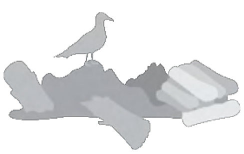


C1 Deconstruction Demolition are emissions due to machine-use to demolish the building. RICS (2017) includes a default value of 3.4 kg eCO_2/m^2 for gross floor area. To compare to other impacts, assume a building weight of 100 kg/m^2 of GFA, which results in an impact of 0.034 kg eCO_2/kg which is used in this study.

C2 Transport involves the transportation of the same materials included in A4 emissions to waste processing or disposal sites over a short distance. Assume local transport with an impact of 0.005 kg eCO_2/kg.



C3 Waste Processing is typically processes performed for reuse, recycling, and/or incineration. More details for specific products can be found in Appendix B. The total of end-of-life C1-C4 values summarized above are approximately 0.05 kg eCO_2/kg.



C4 Disposal captures processes of decay and machine work at the landfill disposal location. For inert landfilling processes a value of 0.0026 kg eCO_2/kg is used. The release of blowing agents from foam-based insulations is significant for some products and is captured in the study based on product EPDs.

The City of Vancouver guidelines allow C1-C4 emissions to be assumed to 5% of A1-A3 emissions. Similar to other applications of such broad simplifications we recommend that this default not be applied on a component-by-component basis or to envelope retrofit projects.

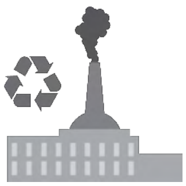
Zera Solutions (2019) recommends developing default values for end-of-life phases for Vancouver projects. This will reduce uncertainty in LCA calculations and is recommended.

Despite the relatively small quantity of emissions involved, reductions should be encouraged to promote carbon reductions and simultaneously provide environmental advantages. A recent report from the Pacific Institute for Climate Solutions (Teicher 2021) further recommended developing improved construction waste diversion regulations including putting a price on waste where there is none. Such measures should continue to be explored.

Other Impacts (D)

Recycling (D1) captures the carbon emissions which are avoided when construction materials are recycled into new products. Metals are often considered carbon intensive but their EPDs report 20% to 65% reductions when end of life recycling is considered. Whether or not these benefits are included in analysis can significantly affect comparisons between systems.

Reuse (D2) capture the emission savings from refurbishing salvage building components.



Energy Recover (D3) capture the avoided carbon emission from use of energy recovered from the incineration or end of life processing of building materials.

Exported Energy (D4) are emissions avoided from export of excessive site energy production in energy positive constructions. These emissions are handled similarly to B6 Energy Use and not part of embodied carbon.

Biogenic impacts capture carbon sequestration benefits of materials. Organic-based materials and organic packaging (cardboard and paper packaging as well as wood skids) have a small impact. The most commonly considered contributions for construction projects are use of wood-based products. Based on their EPDs, wood products (discussed in Appendix B) are shown to store 2 to 11 times more carbon for these materials through sequestration and their A1-A3 emissions

These other impacts involve significant uncertainty. While such beneficial uses of building materials should be encouraged and can be likely to occur for many materials, the intensity of the materials and/or electricity they are displacing is difficult to project accurately. Most wood product EPDs are from industry averages which do not reflect the specific impacts of the source forest which are understood to vary significantly. Hence, these impacts also have a high degree of uncertainty.

The City of Vancouver Embodied Carbon Guidelines and CaGBC Zero Carbon Building Design Standard do not include Module D or Biogenic impacts in compliance calculations. Nevertheless, results from Module D may be calculated and reported separately. This is reasonable considering the uncertainty inherent within the calculation of such impact including the actual treatment of the materials at end of life.

Module D and Biogenic impacts are key components to the Impact and Innovation credit for CaGBC's Zero Carbon standard and commonly claimed for advocates of wood buildings. Hence, guidance is needed to ensure the robustness of these calculations. Specific recommendations are provided in Appendix B.

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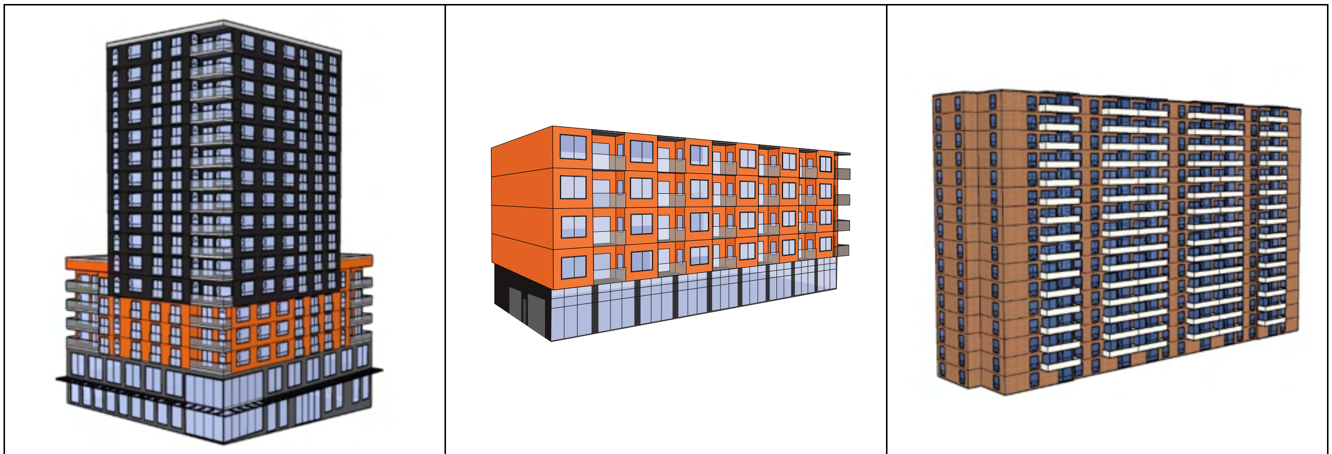
Chapter 2: Methodology for Life Cycle Assessment of Archetype Buildings

Life Cycle Assessment Approach

This study explores the knowledge gaps on how to reduce overall carbon emissions by maximizing energy efficiency gains and minimizing embodied carbon for multi-unit residential buildings (MURBs). This study focuses on building envelope design guidance, while also showing the relative impact of the structures for perspective.

This chapter outlines the methodology used in the life cycle assessment (LCA) of three building archetypes. A variety of energy efficiency measures are assessed to benchmark the impact in terms of operational and embodied carbon emissions. Three building archetypes are considered in this study as outlined in Figure 1.



Building 1: 17-Storey mix-use Building with hybrid structure	**Building 2:** 5-Storey wood-frame Mix-use building	**Building 3:** 16-Storey existing multi-unit residential building

Figure 1: Building Archetype Buildings for the Study Life Cycle Assessment

For the embodied carbon analysis, only the residential portions of buildings 1 and 2 were considered. These were levels 3 to 17 for building 1, and levels 2 to 5 for building 2.

The following sections provide an overview of the methodology and assumptions for determining the embodied carbon and operational emissions for this study. Additional detailed information can be found in the appendices as follows:

- Appendix A provides the detailed quantity take-off of the buildings, assemblies, and structure that is used in the embodied carbon analysis.
- Appendix B provides the detailed assumptions of the global warming potential (GWP) for the products and materials that were applied in the embodied carbon analysis.
- Appendix C provides the detailed assumptions for the various energy efficiency measures that were included in the operational energy analysis of the buildings.

Chapter 3 presents the results of the LCA for both operational and embodied carbon emissions. Chapter 3 explores the relative impact of various energy efficiency measures, provides building envelope design guidance, and recommendations for further development of LCA analysis.

Operating Greenhouse Gas Emissions

The operational emissions of this study explored three B.C. locations (Kamloops, Prince George, Vancouver) in climate zones 4 to 6[1] using an archetype energy modelling approach for MURBs. Specific building designs and occupancies may vary from the findings of these archetypes. Nevertheless, the intent of the findings is to provide good benchmarks and starting points that maximize energy efficiency gains and minimize embodied carbon emissions.

In this section, we discuss the annual energy use of the building in operation, and how that energy use translates to greenhouse gas (GHG) emissions. The operating GHGs in this section is only for building energy use due to operation. Emissions related to maintenance or replacement of equipment or systems and car charging are not included.

Electricity and conventional natural gas are the only fuel sources considered in this study. Fuel sources such as other fossil fuels (e.g. propane), renewable natural gas, on-site renewables such as photovoltaics (PV), and various sources of district energy, are not considered.

Buildings 1 and 2 utilize results from Building Pathfinder[2] to explore the impact of energy conservation measures. Additional analysis using end-use breakdowns and calculations further align the results to the archetype buildings used in this study. The results for Building 3 were developed from a custom energy model using EnergyPlus v9.6.

This study explored a broad range of energy conservation measures to assess the following:

1. Operational emissions for gas and electric heating and domestic hot water compared to embodied carbon emissions for a low-carbon electricity grid.
2. The impact of various energy efficiency measures compared to embodied carbon emissions.
3. The impact of grid emission factors on operating GHG emissions.

Energy Model Inputs

Tables 1 to 3 outline the baseline and energy conservation measures that were explored for each building. The baseline scenario assumptions are highlighted in bold.

The baseline scenario varies between buildings to account for typical construction practices in mid-rise wood framed buildings, Part 3 high-rise buildings, and "typical" existing MURBs. In general, the baseline scenario is intended to meet Step 2 of the BC Energy Step Code, or Step 3 if it does not require energy conservation measures significantly beyond what is considered common.

Electric domestic hot water is post-processed for Buildings 1 and 2 as Building Pathfinder does not include an electric domestic hot water option.

[1] The Fort Nelson grid is not specifically considered, although a high-carbon grid is included in the operating carbon analysis for context.

[2] www.buildingpathfinder.com

Table 1. Building 1 Energy Efficiency Measures

Variable	Range of Efficiency Measures
Location	Vancouver, Kamloops, Prince George
Vertical Surface Area to Floor Area Ratio (VFAR)	**0.5** (aligned with embodied carbon archetype) 0.7 ("Complex" in Building Pathfinder to test sensitivity) 0.9 ("Narrow" in Building Pathfinder to test sensitivity)
Window system	**Typical Double Glazing**: USI-2.0 (U-0.35), SHGC-0.35 Better Double Glazing: USI-1.7 (U-0.3), SHGC-0.3 Triple Glazing: USI-1.1 (U-0.2), SHGC-0.25 Better Triple Glazing: USI-0.9 (U-0.15), SHGC-0.2
Window to Wall Ratio	30%, **40%**, 50%, 60%
Wall R (effective)	RSI-0.9, **1.8**, 2.6, 3.5, 4.4, 5.3, 6.2 (IP units R-5, **10**, 15, 20, 25, 30, 35)
Mech System Type	Electric Resistance, **Natural Gas Hydronic**
DHW Fuel Source	Electric Resistance, **Natural Gas**
Heat Recovery	**60%**, 80% Base case improved to **70% in Prince George** to meet Step 2
Airtightness (modeled)	**0.2**, 0.08 L/s/m^2 at 5 Pa typical operating pressure
Inputs held constant	RSI-7.0 (IP units R-40 Roof) Occupant density and airflow per Building Pathfinder defaults

Table 2. Building 2 Energy Efficiency Measures

Variable	Range of Efficiency Measures
Location	Vancouver, Kamloops, Prince George
Vertical Surface Area to Floor Area Ratio (VFAR)	**0.5** (aligned with embodied carbon archetype) 0.7 ("Complex" in Building Pathfinder to test sensitivity) 0.9 ("Narrow" in Building Pathfinder to test sensitivity)
Window system	Typical metal framed double Glazing: USI-2.0 (U-0.35), SHGC-0.35 **Vinyl or Fiberglass Double Glazing:** USI-1.7 (U-0.3), SHGC-0.35 Better Double Glazing: USI-1.4 (U(IP)-0.25), SHGC-0.3 Vinyl or Fiberglass Triple Glazing: USI-1.0 (U(IP)-0.17), SHGC-0.25
Window to Wall Ratio	30%, **40%**, 50%, 60%
Wall R (effective)	RSI- **2.6**, 3.5, 4.4, 5.3, 6.2 (IP units **R-15**, 20, 25, 30, 35)
Mech System Type	Electric Resistance, **Natural Gas Hydronic**
DHW Fuel Source	Electric Resistance, **Natural Gas**
Heat Recovery	**60%**, 80%
Airtightness (modelled)	**0.2**, 0.08 L/s/m^2 at 5 Pa typical operating pressure
Inputs held constant	RSI-7.0 (IP units R-40 Roof) Occupant density and airflow per Building Pathfinder defaults

Table 3. Building 3 Energy Efficiency Measures

Variable	Typical Existing Building Assumption	Range of Efficiency Measures for Retrofit
Location	Vancouver, Kamloops, Prince George	
Vertical Surface Area to Floor Area Ratio (VFAR)	0.45 VFAR	
Window system	Single-glazed metal framed, USI-4.5, SHGC 0.55	Typical Double Glazing: USI-2.0 (U(IP)-0.35), SHGC-0.35 Better Double Glazing: USI-1.7 (U(IP)-0.3), SHGC-0.3 Triple Glazing: USI-1.1 (U(IP)-0.2), SHGC-0.25 Better Triple Glazing: USI-0.9 (U(IP)-0.15), SHGC-0.2
Window to Wall Ratio	28%	28%, 40%, 50%
Wall R (effective)	Interior insulated steel framed wall RSI-0.8 (R-4.5)	RSI-0.9, 1.8, 2.6, 3.5, 4.4, 5.3, 6.2 (IP units R-5, 10, 15, 20, 25, 30, 35)
Mech System Type	Natural gas hydronic	Electric Resistance, Natural Gas Hydronic
DHW Fuel Source	Natural gas	Electric Resistance, Natural Gas
Heat Recovery	None	60%, 80%
Airtightness (modelled)	0.5 L/s/m^2 at 5 Pa	0.2, 0.08 L/s/m^2 at 5 Pa typical operating pressure
Inputs held constant	RSI-3.5 (IP units R-20 Roof)	

The existing building has been benchmarked against BenchmarkBC data for existing multi-family buildings, as well as against past projects for similar buildings as follows:

- Benchmark BC 2020 Multifamily[3]: mean EUI is 240 kWh/m^2.
- RDH Report (2012): Energy Consumption and Conservation in Mid-and High-Rise Residential Buildings in British Columbia (all Vancouver buildings); Mean EUI is 220 kWh/m^2.

The Vancouver baseline was adjusted to be within the range of 220 to 240 kWh/m^2 and then utilized for Kamloops and Prince George for the regional baselines.

Energy Use and GHG Emissions

Building energy use and GHG emissions are not correlated on a 1:1 basis. Buildings often use more than one fuel source, which can have significantly different emission factors. The B.C. electricity grid has much lower carbon than a grid with conventional natural gas. Regardless of actual energy use or implemented conservation measures, a fully electric building in B.C. will have much lower GHG emissions than one heated by natural gas.

Varying utility or grid emission factors must be kept in mind when comparing operational emissions to embodied carbon emissions. For example, a fully electric building on B.C.'s low-carbon grid will have significantly lower GHG emissions than a fully electric building in Alberta using the same amount of energy.

[3] buildingbenchmarkbc.ca

There is a great deal of nuance to emission factors because grids are interconnected and peak demand may have significantly different emissions profiles than typical baseload. Adding significant electric loads in the form of new or retrofitted buildings also impacts the grid over time, particularly in the form of potentially increased peak demand. The sources of electricity production also shift over time, impacting grid emission factors. For example, the Alberta Electric System Operator (AESO) notes that "Alberta's power system is changing rapidly", and that in 2022, renewables supplied more power to the grid than coal. In fact, as of June 2024, Alberta's last dedicated coal plant is now offline. This has not been accounted for in the Alberta emission factors used in this report, which are intended to consider the potential tradeoffs in a higher-carbon grid. Future electricity factors for Alberta are expected to be lower than currently given recent developments.

Several studies[4] have gone into extensive detail on the question of accounting for GHG emissions of electrical grids that provide guidance on how to approach emission factors. In this study, a range of factors from these sources have been considered to test the sensitivity of the emission factors on the overall operational emissions as outlined in Table 4.

Table 4. Emission Factors for Converting Energy Use into Greenhouse Gas Emissions

Scenario	Source for Electricity Emission Factor	Electricity Emission Factor ($kgCO_2e$/ kWh)	Natural Gas Emission Factor ($kgCO_2e$/ ekWh)
Baseline (B.C. 2022)	Ministry of Environment and Climate Change Strategy, B.C. Electricity emission intensity factors for grid-connected entities for 2022	0.0115	0.185[5]
Last 5 years B.C. high (B.C. 2020)	Ministry of Environment and Climate Change Strategy, B.C. Electricity emission intensity factors for grid-connected entities for 2020	0.0401	
High Carbon Grid	Portfolio Manager Technical Reference, Greenhouse Gas Emissions (August 2021) - Alberta Indirect emissions	0.690	

Synergies of Energy Conservation Measures

Beyond GHG emission savings, energy conservation measures have a number of co-benefits that should not be ignored. Some decarbonization measures may in fact require certain energy conservation measures to be implemented.

Co-benefits or synergies of energy conservation measures include:

1. Resiliency
    a. In the event of a power outage, a building with an improved envelope will remain habitable for much longer.
    b. Using heat recovery ventilators (HRVs) to supply ventilation air to suites also filters the air, improving indoor air quality, e.g. when there are forest fires in the area, or if the building is near traffic pollution.
    c. Similarly, improved envelope airtightness reduces infiltration of pollutants from outdoors.

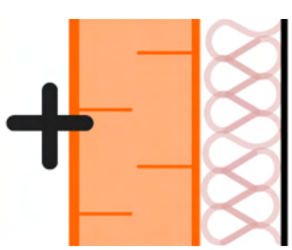
[4] Refer to appendix C for referenced emission factors.
[5] The natural gas emission factor is applied to all scenarios from the City of Vancouver Energy Modeling Guidelines v2.

2. Occupant Comfort
    a. Improved building envelope reduces localized discomfort effects.
    b. Passive cooling measures, such as operable windows and shading, can:
        i. reduce glare,
        ii. localized discomfort effects, and
        iii. are a benefit during prolonged power outages that coincide with extreme heat events.
    c. Improved acoustics
3. Affordable Housing
    a. Reducing residents' long term energy costs can improve financial stability, and reduce exposure to rising costs and carbon taxes.
4. Synergies with Decarbonization
    a. Heat pumps are a highly efficient, low-carbon source of heating, with increasing adoption in B.C. as well as worldwide. However, heat pumps provide heat at lower temperatures than conventional fossil fuel based systems, meaning they cannot provide the same capacity per flow. Lowering the heating load improves the case for using heat pumps as a decarbonization measure, since the required heating capacity is reduced.
    b. Costly and invasive electrical upgrades can be triggered by building electrification. Upgrades can sometimes be avoided by comprehensive energy efficiency measures through a deep energy retrofit.
5. Demand Side Management
    a. Reducing energy demand in buildings is important to maintain a clean and affordable power grid while there is aggressive electrification across many industry sectors.

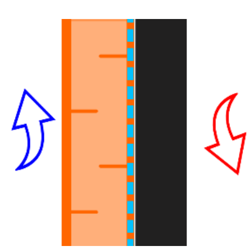
The synergies of energy conservation measures are further explored in Chapter 3 alongside the findings of the study for both operational and embodied carbon emissions.

Building Envelope Energy Conversation Measures

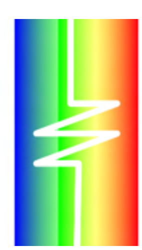
High performance buildings require more insulation, mitigation of thermal bridging, increased airtightness, and better windows and glass to meet net-zero standards compared to conventional practice. Insulation thickness, thermal bridging, and type of glazing impact embodied carbon and are explored in detail as part of this study.



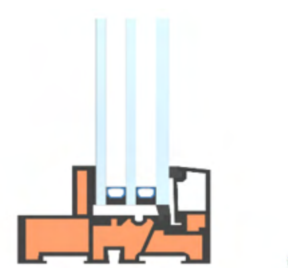
more insulation and structural optimization



increased airtightness



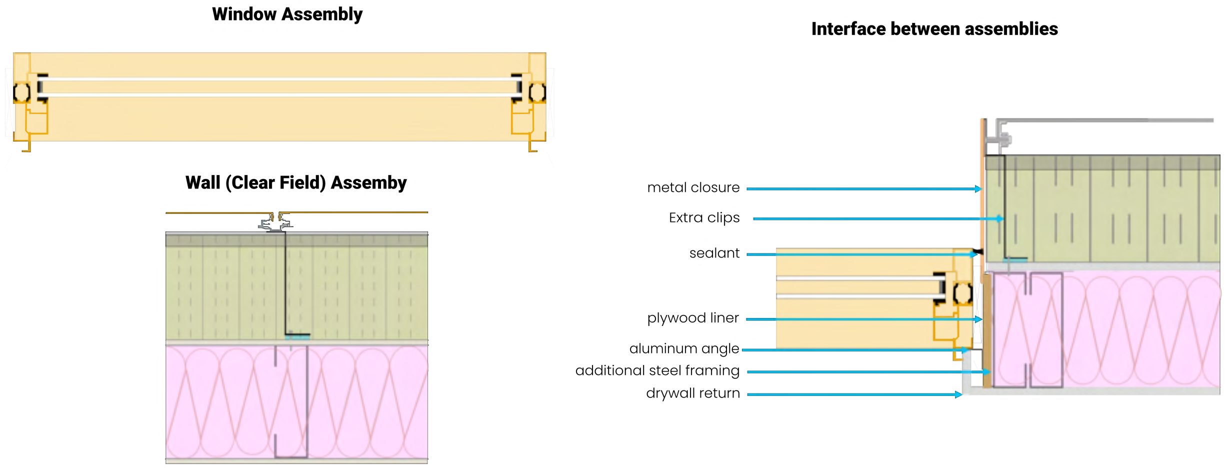
thermal bridging mitigation



better windows and glass

The process of accounting for the impact of thermal bridging in thermal transmittance calculations has a direct analogy to accounting for embodied carbon at the interface details. Secondary structural components that contribute to thermal bridging also have a significant impact on embodied carbon calculations relative to the clear field assembly.

Accounting for the extra materials at the interfaces for embodied carbon can be done in a similar manner as accounting for the extra heat flow at interfaces using linear transmittances. Figure 2 illustrates this concept for a window-to-wall interface.



$$\text{Overall Thermal Transmittance } (W/m^2\,K) \;\Big|\; U_o \text{ - clear field U-value } (W/m^2\,K) + \frac{\Psi \text{ - linear transmittance (W/m K) x length of detail (m)}}{\text{Area of Opaque Wall } (m^2)}$$

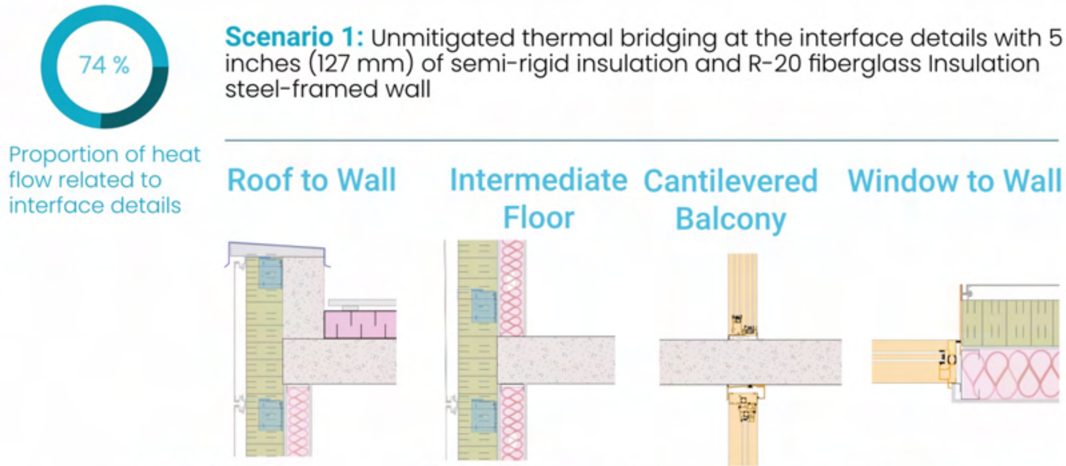
$$\text{Overall Embodied Carbon } (kg\,CO_2\,e/m^2) \;\Big|\; \text{Global Warming Potential per material } (kg\,CO_2\,e/kg) \times \left[\text{Quantity of Material in assembly per tributary area } (kg/m^2) \times \text{Opaque area } (m^2) + \text{weight of material (kg/m) x length of detail (m)} \right]$$

Figure 2: Accounting for Heat Flow and Embodied Carbon at Interface Details

Thermal transmittance (overall effective R-value) calculations were performed for varying levels of thermal bridging mitigation for the archetype buildings. This was done to explore the correlation to insulation thickness, embodied carbon, and operational emissions.

From a high-level perspective, unmitigated thermal bridging is when the impact of interface details is 60% or higher and mitigated thermal bridging is 35% or lower. Figures 3 and 4 illustrate example calculations for building 1 for the residential levels, if the structure were entirely concrete.

A summary of the thermal transmittance calculations for all the buildings can be found in Appendix C.



	Roof to Wall	Intermediate Floor	Cantilevered Balcony	Window to Wall
Linear Transmittance	0.67 W/ m K	0.07 W/ m K	1.78 W/ m K	0.18 to 0.53 W/ m K
Length	195 m	591 m	338 m	3275 m
% Contribution to Overall Heat Flow	6%	2%	22%	44%

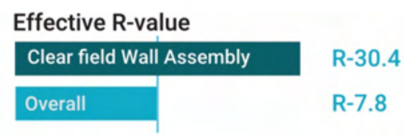
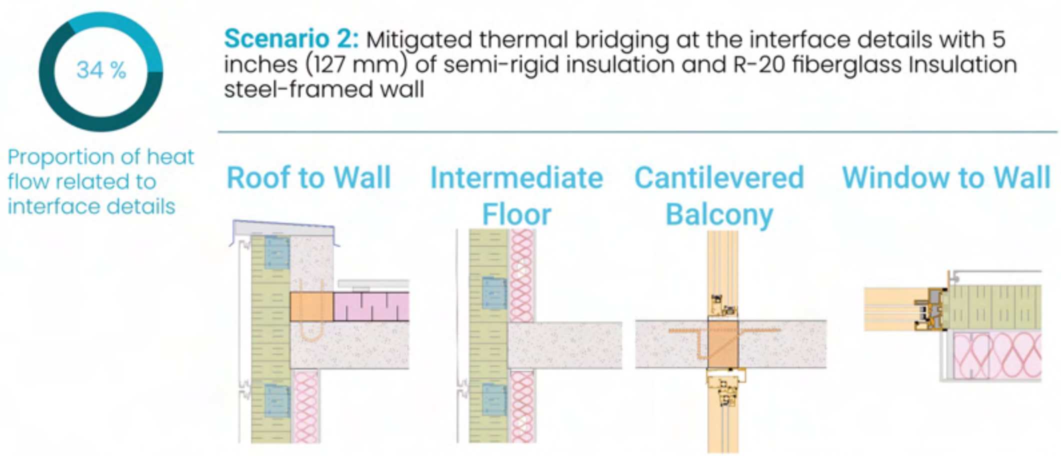


Figure 3: Impact of Unmitigated Thermal Bridging on Overall Effective R-Value for the Residential Walls of Building



	Roof to Wall	Intermediate Floor	Cantilevered Balcony	Window to Wall
Linear Transmittance	0.21 W/ m K	0.07 W/ m K	0.33 W/ m K	0.02 to 0.03 W/ m K
Length	195 m	591 m	338 m	3275 m
% Contribution to Overall Heat Flow	5%	5%	14%	11%

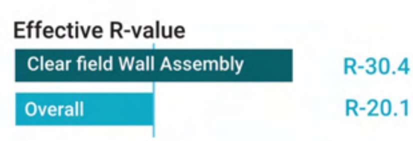


Figure 4: Impact of Mitigated Thermal Bridging on Overall Effective R-Value for the Residential Walls of Building

Embodied Carbon Emissions of Materials and Products

The embodied carbon calculations for this study are generally aligned with EN 15978 (2011) and the City of Vancouver Embodied Carbon Guidelines (2023), with the deviations and general assumptions that are identified in Chapter 1.

Detailed quantities for the archetype buildings that were utilized for the embodied carbon calculations are presented in Appendix A.

Detailed Assumptions for the embodied carbon emissions of products and materials for currently available data utilized in this study is presented in Appendix B. Comparisons of data from various sources and products are presented and discussed.

All the scenarios for the embodied carbon calculations presented in Chapter 3, with assumptions for quantities and global warming potential (GWP), are summarized in spreadsheets that accompany this report.

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Chapter 3: Findings, Insights, and Guidance

Operational Emissions

Impact of Step, Fuel, and Emissions Factors

This section presents generalized results to set expectations for operational emissions before individual energy conservation measures for each archetype are explored in the Life Cycle Assessment section later in this Chapter.

These findings identify patterns at a high level and compare the greenhouse gas intensity (GHGI) impacts of:

1. **BC Energy Step Code level,** in conjunction to typical existing building benchmarks and buildings designed to the Passive House Institute standard. This is an indication of the expected GHGs as a function of the overall energy efficiency level of the building.
2. **Fuel Source** for heating and domestic hot water (either electric resistance or condensing natural gas).[1]
3. **Emission factors**
    a. City of Vancouver Energy Modelling Guidelines (electricity = 0.011 $kgCO_2e/kWh$)
    b. BC 2020 Emission Factors (electricity = 0.040 $kgCO_2e/kWh$)
    c. Non-baseload avoided emissions from Portfolio Manager (electricity = 0.419 $kgCO_2e/kWh$)
    d. High-Carbon Grid emission factors (electricity = 0.690 $kgCO_2e/kWh$)
    e. In all cases natural gas is 0.185 $kgCO_2e/kWh$
4. **Climate zone**, differences between Vancouver (climate zone 4), Kamloops (climate zone 5), and Prince George (climate zone 6). It should be noted that the Benchmark BC results are for the whole province and are the same for each climate zone.

The findings presented in Figure 1 and Tables 1 to 3 are based on:

- Maximum allowable EUIs and TEDIs for various levels of the BC Energy Step Code,
- Benchmark BC data for existing MURBs, and
- An approximate conversion of Passive House (PHI) metrics to Step Code methodologies.

In reviewing, note that the Benchmark BC existing buildings data is provincial-wide, is not broken down by location, and is provided as a relative reference. Also, more energy consumption might be expected to heat a building in a colder climate, such as Prince George, than a milder climate such as Vancouver if the same energy conservation measures are applied. However, more measures are typically required in colder climates to meet the energy efficiency requirements per the BC Energy Step Code. For example, Step 4 requires an EUI of 100 in climate zone 4, and 110 in climate zones 5 and 6. More measures are required in climate zone 6 to achieve the same level of energy performance as in zone 5.

All the results for 60 years of operation and are presented as a GHGI ($kgCO_2e/m^2$).

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[1]Operating Energy and GHG savings will be slightly less for building envelope energy conservation measures for a heat pump compared to electric resistance heating, but have not been directly considered for this study to show high level impact.

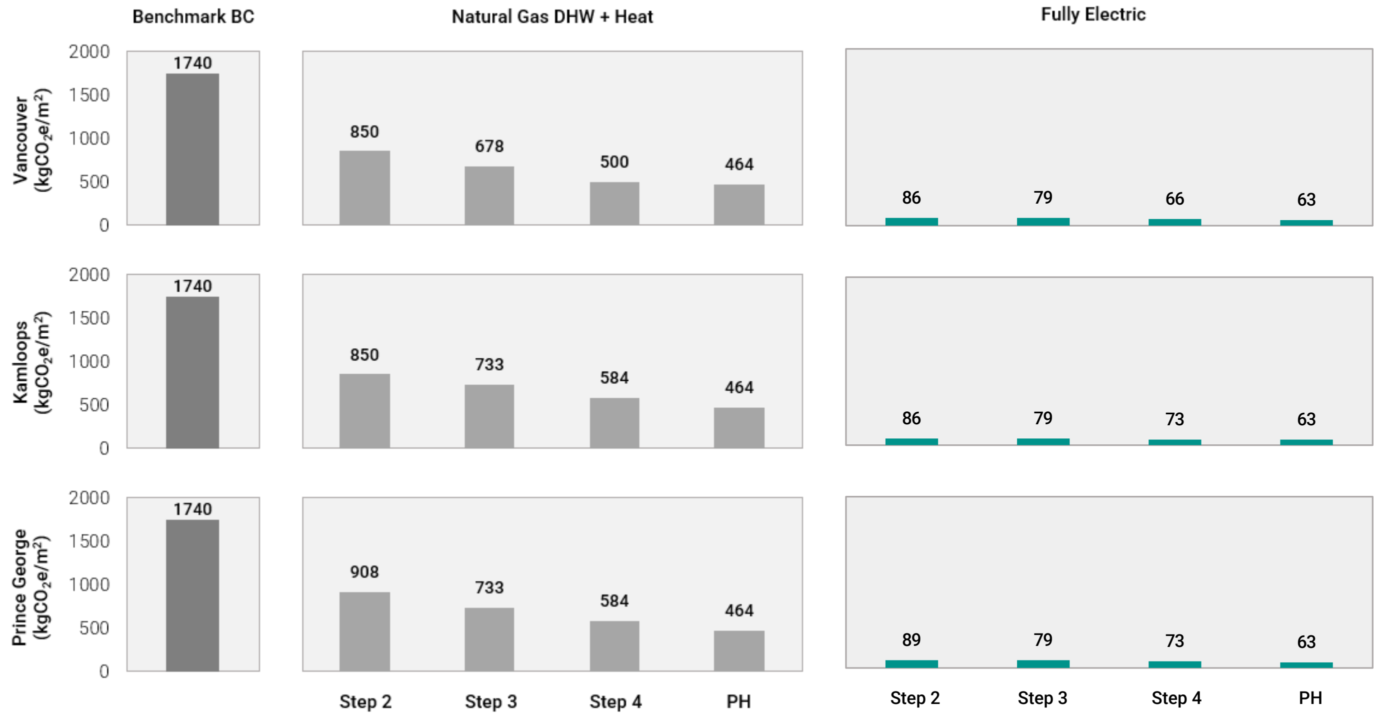


Figure 1: Relative Variation of Operational GHG emissions for Existing Buildings (Benchmark BC) Compared to Various Energy Conservation Targets for Natural Gas and Fully Electric Buildings

Non-baseload emissions are presented in the tables below but are not applied universally throughout this report. Non-baseload emissions are higher than emissions during overall annual operations. This is because non-baseload emissions are typically supplied by combustion-based sources that have higher emission factors and can be ramped up during peak times but are not required to meet base loads. When adding load to the grid, such as by electrifying buildings, the peak loads on the grid may be increased and therefore increase the non-baseload generation requirements. For B.C., these emission factors are still lower than a high-carbon grid, and therefore a high-carbon grid is presented to provide a higher emission bookend to the analysis.

Table 1. **Expected Variation in Operational Emissions (kg CO_2e/m^2) for Existing Buildings and Benchmarks for Energy Conservations Measures in Vancouver for 60 Years in Operation**

Benchmark	CoV EMG Emission Factors		BC 2020 Emission Factors		Non-Baseload BC Portfolio Manager		High-Carbon Grid Emission Factors	
	Natural[2] Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric
Existing buildings – Benchmark BC	1740	-	1920	-	-	-	-	-
Step 2	850	86	949	313	2240	3267	3164	5382
Step 3	678	79	788	289	2211	3016	3229	4968
Step 4	500	66	602	241	1929	2513	2879	4140
PHI	464	63	563	229	1848	2388	2768	3933

[2] Domestic hot water and heating by natural gas

Table 2. Expected Variation in Operational Emissions ($kgCO_2e/m^2$) for Existing Buildings and Benchmarks for Energy Conservations Measures in Kamloops for 60 Years in Operation

Benchmark	CoV EMG Emission Factors		BC 2020 Emission Factors		Non-Baseload BC Portfolio Manager		High-Carbon Grid Emission Factors	
	Natural Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric
Existing buildings – Benchmark BC	1740	-	1920	-	-	-	-	-
Step 2	850	86	949	313	2240	3267	3164	5382
Step 3	733	79	833	289	2137	3016	3069	4968
Step 4	584	73	690	265	2077	2765	3070	4554
PHI	464	63	563	229	1848	2388	2768	3933

Table 3. Expected Variation in Operational Emissions ($kgCO_2e/m^2$) for Existing Buildings and Benchmarks for Energy Conservations Measures in Prince George for 60 Years in Operation

Benchmark	CoV EMG Emission Factors		BC 2020 Emission Factors		Non-Baseload BC Portfolio Manager		High-Carbon Grid Emission Factors	
	Natural Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric	Natural Gas	Fully Electric
Existing buildings – Benchmark BC	1740	-	1920	-	-	-	-	-
Step 2	908	89	1007	325	2292	3393	3212	5589
Step 3	733	79	833	289	2137	3016	3069	4968
Step 4	584	73	690	265	2077	2765	3070	4554
PHI	464	63	563	229	1848	2388	2768	3933

Key insights from this comparison are:

1. Emission factor assumptions matter – there is a significant variation in emissions between the different assumptions for emission factors. However, in both the recent B.C. emission scenarios that were considered[3] emissions from the electric scenario were much lower than the natural gas use scenario.
2. Energy efficiency measures have a much bigger impact when using higher-carbon fuel.
3. There is approximately a 30% emission savings from a Step 2 to Passive house building for the same emission factors for a fully electric building. This is compared to a 70% emission savings for a building heated with natural gas.
4. Efficiency measures between a Step 2 building and Step 4 or Passive House building are targeting benefits other than solely reducing emissions, such as:
    a. reducing heating load,
    b. reducing peak demand,
    c. increasing resiliency, and
    d. increasing thermal comfort.

Similar general findings are presented for the archetype buildings below. Comparisons to embodied carbon emissions for specific energy conservations measures are provided in the following section.

[3] CoV EMGs, which are fairly well aligned with a number of recent years of data, and the BC worst-case 2022 factor

Building 1 – New Construction High-Rise MURB Operational Emissions

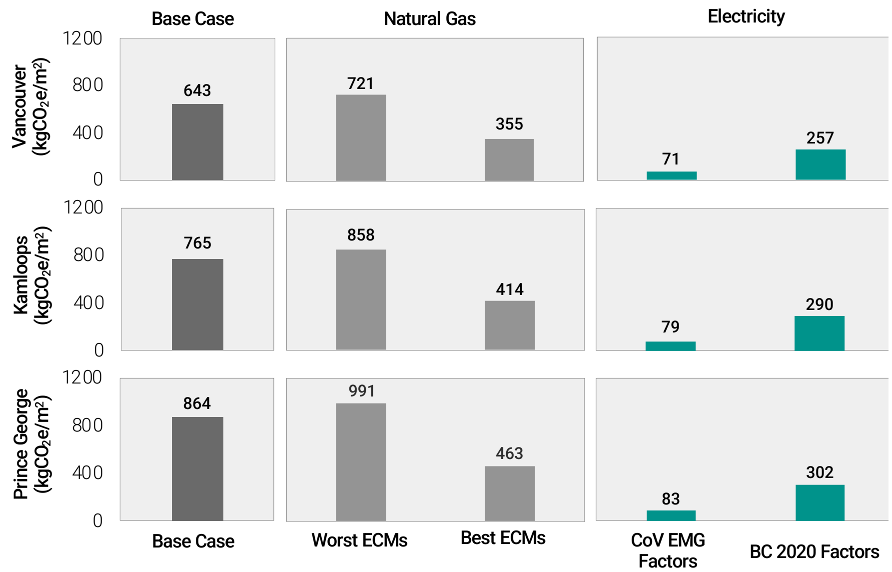


Table 4. Expected Variation in Operational Emissions for Building 1

Scenario	Vancouver		Kamloops		Prince George	
	Annual GHG Emissions ($kgCO_2e/m^2/yr$)	60 Year GHG Emissions ($kgCO_2e/m^2$)	Annual GHG Emissions ($kgCO_2e/m^2/yr$)	60 Year GHG Emissions ($kgCO_2e/m^2$)	Annual GHG Emissions ($kgCO_2e/m^2/yr$)	60 Year GHG Emissions ($kgCO_2e/m^2$)
Base Case	10.7	643	12.8	765	14.4	864
Worst ECMs, Natural Gas	12.0	721	14.3	858	16.5	991
Best ECMs, Natural Gas	5.9	355	6.9	414	7.7	463
Fully Electric, CoV EMG Factors	1.2	71	1.3	79	1.4	83
Fully Electric, B.C. 2020 Factors	4.3	257	4.8	290	5.0	302
Natural Gas, B.C. 2020 Factors	12.7	763	14.9	891	16.4	983
Fully Electric, High Carbon Grid	73.7	4423	83.1	4984	86.7	5201

The "best case" and "worst case" ECMs presented here assume a constant building shape and window to wall ratio. Window and wall thermal performance, heat recovery, and airtightness per the range of energy efficiency measures for this study are varied. The fully electric cases above use the base case ECMs, but with a fully electric heating and domestic hot water system. See chapter two for more information on the range of energy efficiency measures considered as part of this study.

Building 2 - New Construction Mid-Rise MURB Operational Emissions

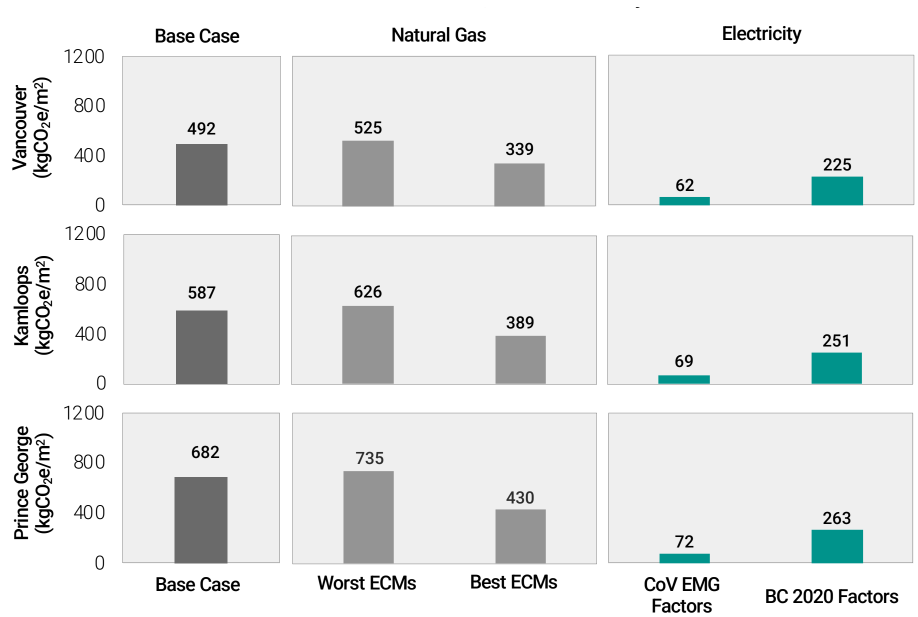


Table 5. **Expected Variation in Operational Emissions for Building 2**

Scenario	Vancouver		Kamloops		Prince George	
	Annual GHG Emissions ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)	**Annual GHG Emissions** ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)	**Annual GHG Emissions** ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)
Base Case	8.2	492	9.8	587	11.4	682
Worst ECMs, Natural Gas	8.8	525	10.4	626	12.3	735
Best ECMs, Natural Gas	5.7	339	6.5	389	7.2	430
Fully Electric, CoV EMG Factors	1.0	62	1.1	69	1.2	72
Fully Electric, B.C. 2020 Factors	3.7	225	4.2	251	4.4	263
Natural Gas, B.C. 2020 Factors	10.2	609	11.8	709	13.3	797
Fully Electric, High Carbon Grid	64.5	3871	71.9	4311	75.6	4534

Building 3 – Existing Building Retrofit High-Rise MURB Operational Emissions

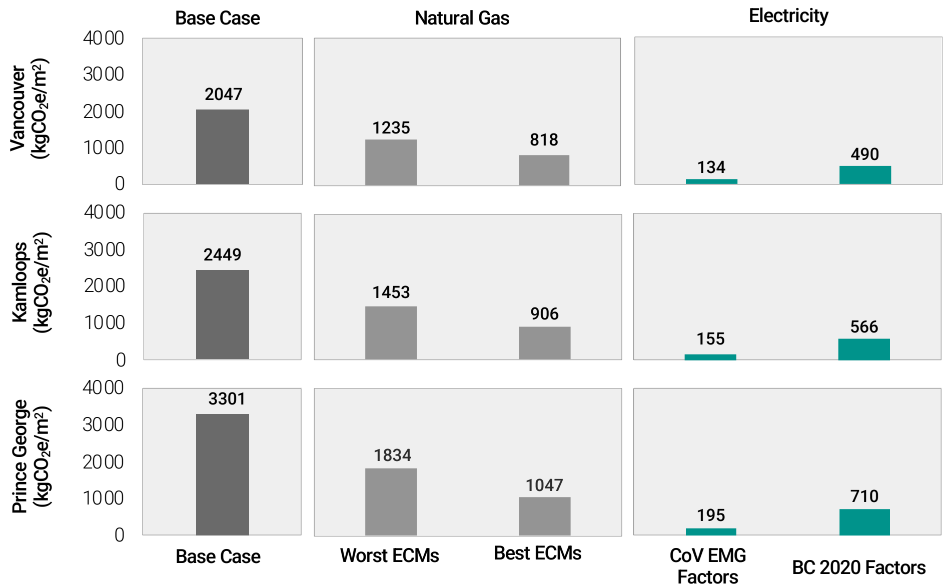


Table 6. **Expected Variation in Operational Emissions for Building 3**

Scenario	Vancouver		Kamloops		Prince George	
	Annual GHG Emissions ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)	**Annual GHG Emissions** ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)	**Annual GHG Emissions** ($kgCO_2e/m^2/yr$)	**60 Year GHG Emissions** ($kgCO_2e/m^2$)
Base Case	34.1	2047	40.8	2449	55.0	3301
Worst ECMs, Natural Gas	20.6	1235	24.2	1453	30.6	1834
Best ECMs, Natural Gas	13.6	818	15.1	906	17.4	1047
Fully Electric, CoV EMG Factors	2.2	134	2.6	155	3.2	195
Fully Electric, B.C. 2020 Factors	8.2	490	9.4	566	11.8	710
Natural Gas, B.C. 2020 Factors	35.8	2150	42.6	2557	56.8	3406
Fully Electric, High Carbon Grid	140.5	8430	162.4	9746	203.6	12217

In the case of an existing building retrofit, the “worst ECMs”, or minimal ECM, is an improvement over the existing base case without a retrofit. The relative difference is how much better the retrofit is in terms of:

- window performance (double versus triple glazing),
- wall effective R-value (R-5 versus R-35),
- airtightness (0.2 versus 0.08 $L/s/m^2$ at 5 Pa typical operating pressure),
- and heat recovery (60 versus 80%).

See chapter two for more information on the range of energy efficiency measures applied to the retrofit.

Embodied Carbon Emissions

This section presents the embodied carbon emissions for various building envelope energy conservation measures to:

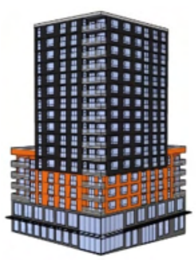
1. Establish benchmarks to how much embodied carbon (stages A to C) can be realistically minimized on projects through building envelope energy conservation measures.
2. Explore the impact of material choices versus system selection.
3. Explore the impact of thermal bridging mitigation for wall systems.
4. Explore the impact of detailed quantity take-offs versus only the clear field wall assembly for metal framed wall systems.
5. Compare expectations for the embodied carbon of the structure versus the building envelope.

Comparison of the embodied carbon emissions for various building envelope energy conservation measures is discussed in the following sections. Discussion on the impacts of other benefits and loads (stage D) is also covered to provide some additional context. This discussion includes end of life recycling, reuse, energy recovery, and carbon sequestration options.

Building 1 –New Construction High-Rise MURB Embodied Carbon Emissions

Building envelope embodied carbon emissions for building 1's residential levels, three to 17, are presented in Table 7.

Table 7. Building Envelope Embodied Carbon Emissions (kg CO_2e/m^2) for Building 1 Residential Levels 3 to 17[4]



Component	30% Glazing Ratio		40% Glazing Ratio		50% Glazing Ratio	
	Baseline	Maximum[5]	Baseline	Maximum	Baseline	Maximum
Windows	17	38	25	56	36	81
Doors	15	37	13	33	13	33
Walls	35	42	30	35	24	33
Roof	7	10	7	10	7	10
Total	**74**	**128**	**75**	**135**	**80**	**157**

The baseline scenario has fiberglass double glazed windows and doors, and split insulated steel-framed walls with four inches of exterior mineral wool insulation as illustrated in Figure 2. This is contrasted to the maximum evaluated embodied carbon scenario. The scenario examines a building envelope with thermally broken aluminum framed windows with triple glazing and ten inches of exterior mineral wool insulation.

The building envelope embodied carbon emissions for this broad range of ECMs is 74 to 157 kg CO_2e/m^2. The building envelope for the residential levels represents 22 to 38% of the total embodied

[4] The carbon emissions are for gross floor area (GFA) and mean GWP estimates.

[5] The maximum is the highest embodied carbon for the evaluated scenarios.

carbon (structure and building envelope) for the hybrid (concrete and mass timber) building structure that has 254 kg CO_2e/m^2 of embodied carbon.

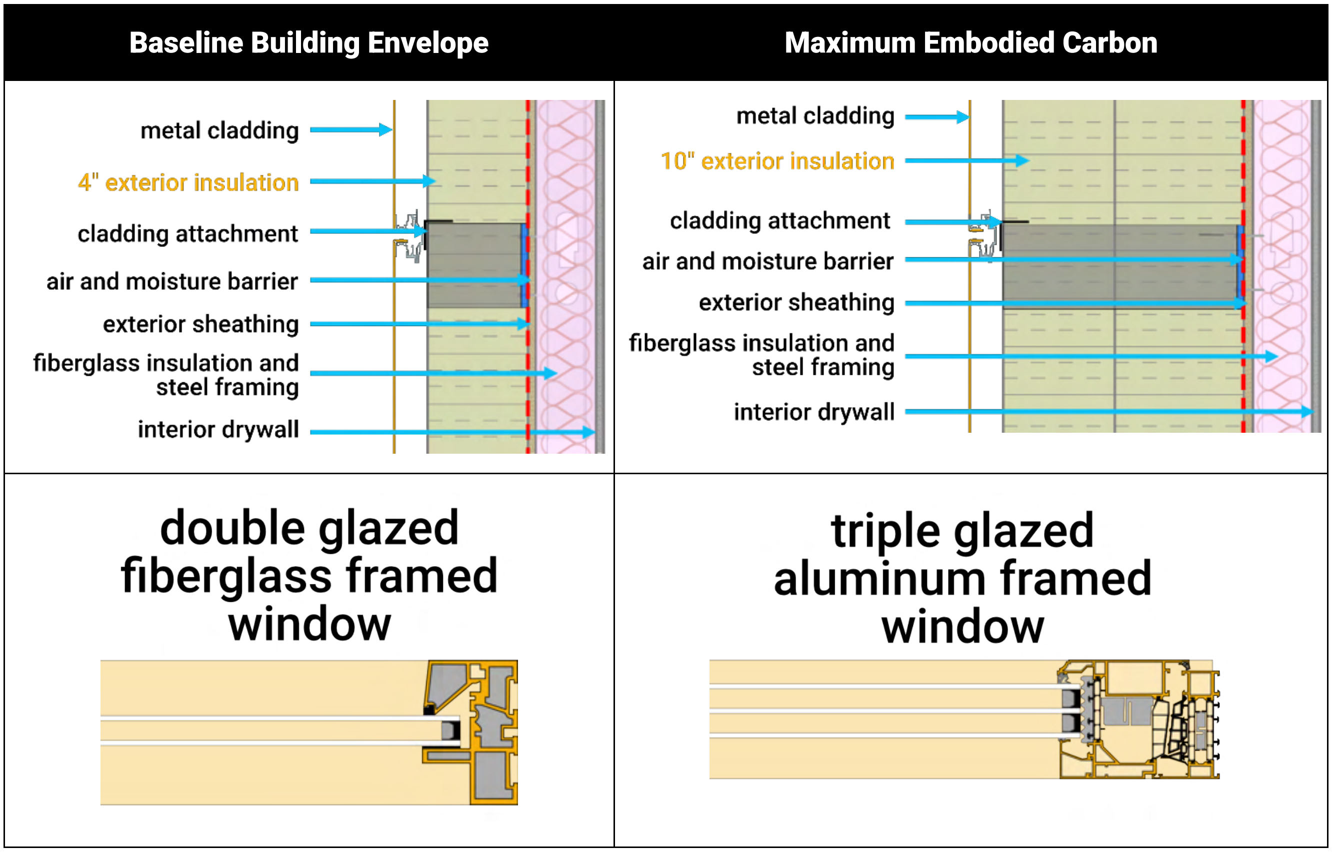


Figure 2: Baseline versus Maximum Building Envelope Embodied Carbon for Building 1 Comparison

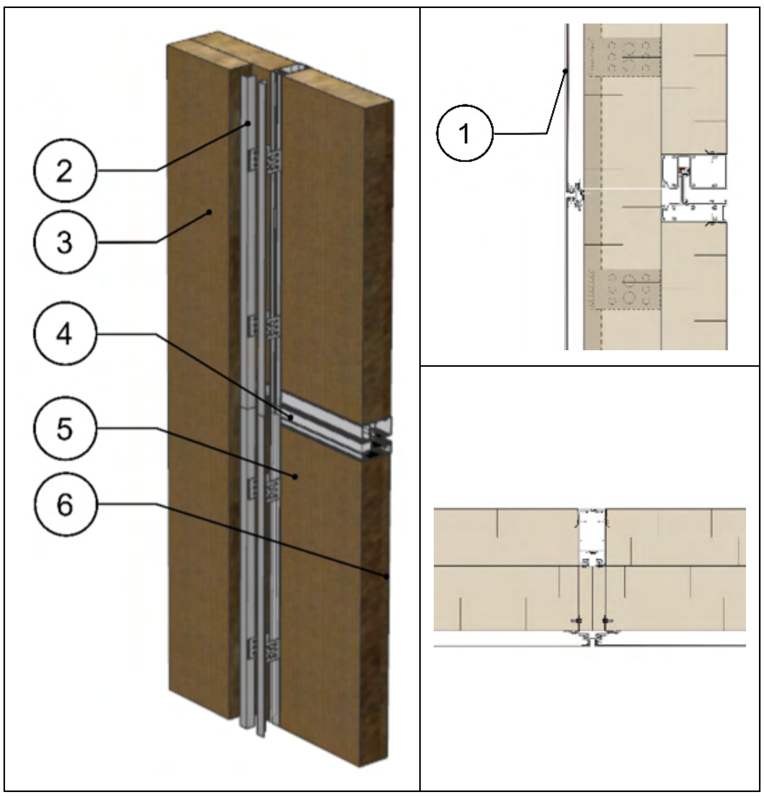
How much embodied carbon may be realistically minimized on projects through building envelope energy conservation measures can be outlined by:

- The difference between fiberglass double glazed windows and triple glazed premium aluminum framed windows and doors represents 83 to 85% (43 to 65 kg CO_2e/m^2) of the increase in embodied carbon for the evaluated ECMs.
- The top four contributors of embodied carbon for the walls and possible targets for mitigation, other than the specified ECM for reducing the quantity of materials, is outlined in in Table 8.
- Increasing the roof insulation from four inches to eight inches of XPS is only a 2.6 kg CO_2e/m^2 increase in emissions.
- The impact of clip orientation and layout to minimize the use of steel represents a one to two kg CO_2e/m^2 decrease in emissions.
- Increasing the roof insulation has the same order of magnitude as a more efficient layout of the clip system given the relative wall and roof area in relation to the total building floor area.

Table 8. Theoretical Reductions in Emissions (kg/CO_2e/m^2) for alternative material choices

Component	% Total Wall Emissions	Absolute Emissions ($kgCO_2e/m^2$)	Possible Mitigation, other than specified ECM	Theoretical Reduction in Emissions ($kgCO_2e/m^2$)
Cladding	10 to 35	3.2 to 14	Honeycomb aluminum panel (product specific EPD) to generic fiber cement board	10.8
Steel Framing	~20%	7.3	None for this type of wall for the evaluated facade	0
Exterior Insulation	8 to 16	2.7 to 6.7	None, except if there was a specific foam product with a low GWP that had the relevant fire testing	0.5 to 1.5
Cladding Attachment	7 to 12	2.7 to 4.9	Possible but lacks product specific EPDs to evaluate	N/A

An alternative facade system for high-rise construction was evaluated for a typical floor of the point tower and compared to the baseline split insulated steel-framed wall assembly as shown in Figure 3. This exterior insulated unitized curtain-wall system has potential high thermal performance and constructability advantages, but higher embodied carbon as shown in Table 9. The emissions presented in Table 9 includes the impact of the vision sections for the curtain-wall system and are compared to aluminum framed windows within the steel-framed wall for comparison.



1. Composite Metal Cladding
2. 16-gauge steel cladding attachment system with brackets and steel rail
3. 4 to 10 inches (102 to 254 mm) exterior mineral wool insulation
4. Aluminum curtain-wall framing
5. 5 inch (127 mm) mineral wool insulation in backpan
6. 20-gauge steel backpan
7. 20-gauge 1 5/8" X 1 5/8" (40 x 40 mm) steel-studs at 16" (406 mm)
8. 1/2" (13 mm) gypsum wall board

Figure 3: Alternative Evaluated Exterior Insulated Unitized Curtain-Wall System for High-Rise Construction

Table 9. **Increase in Emissions (kg/CO_2e/m^2) for Alternative Facade Systems**[6]

Wall System	Exterior Insulation	Emissions - 30% Glazing			Emissions - 50% Glazing		
		Using Clear Field Quantities	Using Detailed Quantity Take-off	Increase	Using Detailed Quantity Take-off	Emissions using Clear Field Quantities	Increase
Steel-framed walls with vertical clip system and aluminum framed windows	4″ (102 mm)	67	72	5	79	85	6
	6″ (152 mm)	70	75		81	87	
	8″ (203 mm)	73	77		83	89	
	10″ (254 mm)	76	80		86	91	
Exterior Insulated Unitized Curtain-Wall with clip system	4″ (102 mm)	124	223	99	138	193	54
	6″ (152 mm)	127	226		141	195	
	8″ (203 mm)	129	229		144	198	
	10″ (254 mm)	132	232		146	200	

This comparison highlights how an alternative façade system can increase the embodied carbon by two to three times for the same level of insulation. It also shows how much embodied carbon can be missed by not doing a detailed quantity take-off. A key insight is that as much as 99 kg eCO_2/m^2 is missed if the embodied carbon estimate is based on the clear field assembly for the exterior insulated curtain wall system compared to doing a detailed building specific quantity take-off.

The impact of the framing to accommodate the location of windows for the archetype buildings has a much bigger impact for the curtain-wall system with aluminum framing than for the steel-framed wall. The difference is greater than any of the potential reductions in embodied carbon for the building envelope presented above for the baseline wall system.

Building 2 - New Construction Mid-Rise MURB Embodied Carbon Emissions

Building envelope embodied carbon emissions for building 2's residential levels, two to five, with a 40% glazing ratio is presented in Table 10.

Table 10. **Building Envelope Embodied Carbon Emissions (kg CO_2e/m^2) for Residential Levels 2 to 5**

Scenario	Baseline	Max
Windows and Doors	13	33
Walls	7	10
Roof	23	23
Total	**61**	**110**

The baseline scenario has fiberglass double glazed windows and doors, and split insulated wood-framed walls with 4 inches of exterior mineral wool insulation. This is contrasted to the maximum embodied carbon for the building envelope with aluminum framed windows with triple glazing and 8 inches of exterior mineral wool insulation.

6 The facade includes the impact of the opaque walls and fenestration.

The building envelope embodied carbon emissions is 61 to 110 kg CO_2e/m^2. The building envelope for the residential levels represents 24 to 55% of the total embodied carbon for the structure that has 197 kg CO_2e/m^2 of embodied carbon.

Building 3 - Existing Building Retrofit High-Rise MURB Embodied Carbon Emissions

Building envelope embodied carbon emissions for building 3 with a 30% glazing ratio is presented in Table 11.

Table 11. Building Envelope Embodied Carbon Emissions ($kg\ CO_2e/m^2$)

Scenario	Baseline Retrofit	Max Retrofit
Windows and Doors	19	80
Walls	23	29
Roof	4	4
Total	**46**	**112**

The baseline retrofit scenario has fiberglass double glazed windows and doors, and exterior overclad with four inches of mineral wool insulation. This is contrasted to the maximum embodied carbon for the building envelope with aluminum framed windows with triple glazing and eight inches of exterior mineral wool insulation.

The cost effectiveness and level of energy and GHG savings possible through electrifying existing buildings vary by building and electrical capacity. Generally, some level of building envelope upgrade within the 46 to 112 kg CO_2e/m^2 range for building 2, as presented in Table 11, is required.

The structure plus the backup walls have approximately 234 kg CO_2e/m^2 of embodied carbon for building 3. This is embodied carbon that is already consumed and will not need to be replaced during a building retrofit. This is compared to the average embodied carbon for a high-rise building of 350 kg CO_2e/m^2 (Zera Solutions 2019). Hence, the order of magnitude of embodied carbon consumed for a new construction building compared to a retrofit is 3 to 7.5 times higher for a similar building archetype. Moreover, deep energy retrofits can significantly reduce the energy consumption and GHG emissions through electrification, which reduces the demand on the power grid and emissions.

The building structure is most of the 210 kg CO_2e/m^2 of embodied carbon for building 3 that can be retained during a retrofit. The drywall, fiberglass batt, sheathing, and steel framing is approximately 12 kg CO_2e/m^2 or 6% of the retained embodied carbon. This order magnitude of embodied carbon is good to keep in mind when making decisions to retain components, such as sheathing or insulation, that do not obviously need replacing due to moisture damage or durability concerns.

Overall Insights for Reducing Emissions

Comparison of the embodied carbon emissions for various building envelope energy conservation measures and insights for reducing emissions are discussed in the following sections.

Impact of Double versus Triple Glazing

Don't make durability and energy efficiency related decisions based on embodied carbon. Energy conservation measures evaluated in this study are always beneficial in a high carbon grid and worst case are slightly less than neutral for electrified buildings in a low carbon grid when there are energy savings. Nevertheless, there are opportunities to optimize by selecting a glazing system that has low GWP for the frames and low overall thermal transmittances.

Triple glazing may not pay off if there is not a strong case for energy savings and reducing peak demand. This will sometimes be the case for a fully electric building in a low carbon grid where the best-case energy conservation measures are employed for airtightness and heat recovery. Table 12 shows how the embodied carbon compares to the operational emissions for double versus triple glazing in Vancouver for building 1 residential windows at 40% glazing. The results for Kamloops and Prince George can be found in Appendix C.

From an embodied carbon perspective, the type of window frame has a much more significant impact than the impact of double versus triple glazing. For example, fiberglass windows have a much lower GWP than aluminum frames for currently available EPDs. However, the gap could be closed significantly through use of aluminum frames extruded from ingots smelted both in a low carbon grid and by using high secondary (recycled) material content.

Table 12. **Vancouver Operational versus Embodied Carbon Emissions for Glazing ECMs for Building 1 Residential Windows and 40% Glazing Scenarios**

		Operational Emissions						Embodied Carbon Increase to Tripe Glazing
Heating and DHW Fuel Source	Glazing	Energy Efficiency Measure	EUI	TEDI	GHGI ($kgCO_2e/m^2$)		GHGI Reduction	
			($ekWh/m^2/yr$)		Per year	60 Years	($kgCO_2e/m^2$)	($kgCO_2e/m^2$)
Natural Gas	Double	minimum	110	30	10.7	643	120	Estimates Low: 7 Mean: 9 High: 15
	Triple		99	20	8.7	523		
	Double	best case ECM	93	14	7.7	460	105	
	Triple		84	5	5.9	355		
Electrical	Double	minimum	107	30	1.2	71	7	
	Triple		96	20	1.1	64		
	Double	best case ECM	91	14	1.0	60	5	
	Triple		82	5	0.9	55		

Optimal Insulation Levels and Thermal Bridging

Does high levels of insulation beyond six inches payoff for embodied carbon? Yes, if thermal bridging is mitigated and there are energy savings. Not a lot of extra effort is needed to determine the optimal level of insulation when code compliance is determined by energy modeling. Simply apply enough insulation to reduce the thermal energy demand to meet TEDI targets for new construction and enable electrification for existing buildings.

If not moving the needle for energy savings, then the embodied carbon for thicker insulation will not be paid off by reduced operational emissions. Figure 4 shows the GHG emissions savings for building 1, a high-rise MURB, with increasing effective R-value of the opaque walls. This example has a baseline for the walls at R-10 effective, double glazing, and minimum energy conservation measures.

As can be seen, the TEDI does not improve much above R-25. The optimal zone, from an energy efficiency and GHG emission perspective, is between R-20 and R-25 effective.

The insulation thickness that is required to meet any wall effective R-value depends on the level of thermal bridging mitigation at the interfaces, or junctions, between components[7]. The higher the target for the overall effective R-value, the more critical that thermal mitigation is to minimize the insulation thickness and embodied carbon.

Table 13 and Figure 5 shows the increase in embodied carbon for the insulation levels required to meet an overall wall effective R-value from R-10 to R-35.

As this example shows, the embodied carbon of the extra insulation will always be paid off by the reduced emissions for gas fuel sources. However, there is an optimal zone for electric buildings that aligns with the energy savings. More importantly, the increase in embodied carbon will not be paid off with operational emission savings unless there is a high degree of thermal bridging mitigation within this optimal zone.

The thermal efficiency of the cladding attachment system also plays into how much insulation is required to meet overall Effective R-value targets. A system with large diminishing returns will require more insulation to meet higher targets.

For this example, a stainless-steel cladding attachment system, with high thermal efficiency, was utilized when more than five inches of exterior insulation was required to meet the effective R-value target.

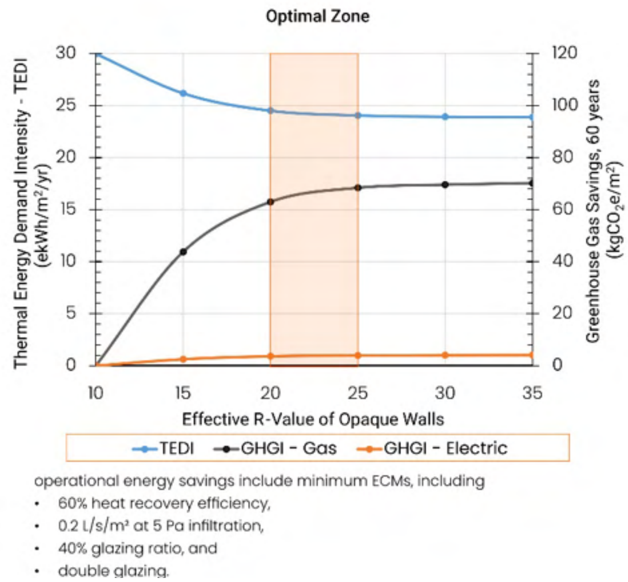


Figure 5: TEDI and GHGI Savings for Building 1 Highrise MURB in Vancouver with minimum energy conservation measures for varying levels of Opaque Wall Effective R-Value

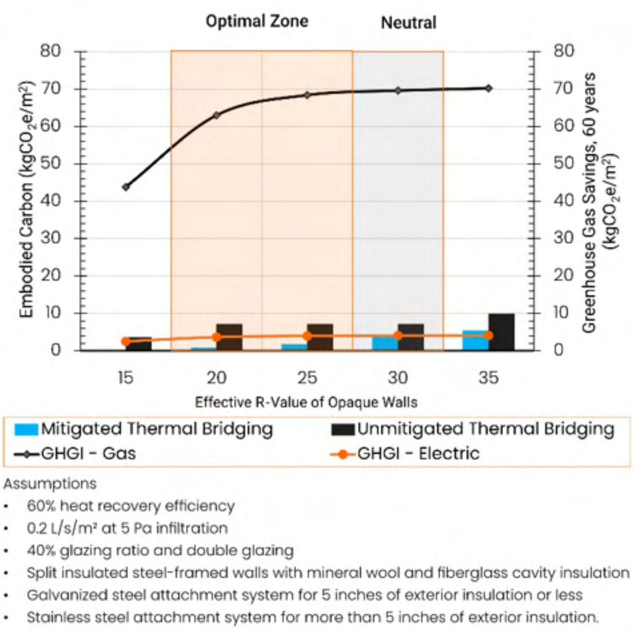


Figure 5: Operational emission savings versus embodied carbon for varying insulation thickness required to meet an overall effective R-value for the walls, depending on the level of thermal bridging mitigation.

The advantage of higher thermal efficiency cladding attachments is highlighted in this example. Exterior insulation, above about five inches, is where differences between systems are significant. Not surprising this breakpoint is also aligned with available systems that are stainless steel and can meet the higher targets with reasonable levels of insulation. Nevertheless, the results for a less

[7] Examples are the window-to-wall interface, roof-to-wall interface, and intermediate floors.

efficient system are more exaggerated than the presented scenarios and comparisons to less efficient systems are not needed to illustrate this insight.

Table 13. Vancouver Operational Emission Savings versus Embodied Carbon Increase for Varying Opaque Wall Effective R-Value and Thermal Bridging Mitigation

Overall R-Value of Opaque Walls	Operational GHG Savings, 60 Years ($kgCO_2e/m^2$)		Mitigated Thermal Bridging			Unmitigated Thermal Bridging		
	Gas	Electric	% Impact of Interface Details	Required Insulation Thickness	Increase in Embodied Carbon ($kgCO_2e/m^2$)	% Impact of Interface Details	Required Insulation Thickness	Increase in Embodied Carbon ($kgCO_2e/m^2$)
10	-	-	55%	4	-	60%	5	0.9
15	43.8	2.5	30%	4	0	60%	8	3.6
20	63.0	3.6	30%	5	0.9	60%	12	7.2
25	68.4	4.0	20%	6	1.8	50%	12	7.2
30	69.6	4.1	20%	8	3.6	40%	12	7.2
35	70.2	4.1	20%	10	5.4	40%	15	9.9

This example highlights how little is gained by going beyond R-30 effective for the walls in terms of energy savings and emissions reductions. Nevertheless, the intent of this example is not to state this is the case for every building and climate.

The key messages and insights are:

1. More insulation is likely always going to be paid off for buildings with gas heating.
2. The optimal insulation level is directly related to the energy savings regardless of the fuel source.
3. Thermal bridging mitigation and the thermal efficiency of exterior insulation impacts the overall embodied carbon much more than the differences in embodied carbon for the individual components or 1-to-2-inch difference insulation thickness.

Given these findings, targets for effective R-value of walls can be established on what is reasonable to meet energy efficiency targets without worrying too much about the embodied carbon for specific components. Opportunities to reduce embodied carbon can be done in parallel by making sure that the insulation is as effective as possible by mitigating thermal bridging and selecting thermally efficient cladding attachment systems. This parallel process aligns well for projects that require energy modeling, comprehensive thermal bridging calculations, and have teams with multi-disciplinary professionals.

Existing Building Retrofits versus New Construction

The biggest impact to reduce emissions is to electrify existing buildings in low carbon grids. Nevertheless, building envelope renewals should be considered to reduce loads, improve occupant comfort, and sometimes to avoid expensive electrical upgrades. Retrofitting existing buildings has less embodied carbon than for new construction because the structure is retained, which is a significant portion of the overall embodied carbon for new buildings.

Why not rebuild and increase capacity? A few reasons are:

- save carbon related to the structure, which makes up a significant proportion of the embodied carbon for a building,
- potentially make a bigger impact on more buildings,
- keep buildings in the affordable building stock without raising rent, and
- keep people housed during upgrades versus needing to find alternative affordable housing that might be in short supply.

Obviously, there are also benefits to densification and not every building should be upgraded when costs and other considerations are factored into the decision-making process. The answer to the question to rebuild versus retrofit is not binary and both need to happen in urban areas.

A few additional macrolevel considerations related to retrofitting existing MURBs are:

1. Retrofits that significantly reduce energy demand will not happen at scale in B.C. by relying on financing by energy savings because of climate and low energy costs.
2. Low energy costs are predicated on the existing energy grid infrastructure and demand. Maintaining affordable energy and supporting economic growth are objectives that factor into energy efficiency and GHG reduction policy. These considerations lead to demand side management, including energy efficiency and peak load reduction, as part of the policy and regulation supporting electrification. These policies reach across the building, transportation, and other industry sectors[8,9,10,11] even though there is a short-term capacity surplus in B.C.
3. Rents cannot be raised to finance affordable housing energy retrofits causing owners to rely on government funding for such upgrades.
4. Adding cooling and improving ventilation are often the necessary key measures to improve occupant safety and comfort in existing MURBs by addressing both overheating and exposure to wildfire smoke.
5. Building envelope retrofits enable significant gains in occupant comfort, energy savings, GHG savings, and may help avoid costly electrical upgrades when electrifying buildings.
6. There are planning synergies for undertaking building envelope and mechanical retrofits together when major renewals are required.

For these reasons, many MURBs in B.C. will get retrofitted in the short to medium term as a result of new regulation, incentives, funding, and the end of service life of major systems. However, there is currently a patchwork approach to assessing what measures or buildings should be targeted for MURB retrofits and funding. A path forward to effectively allocate funding, assess value based on performance, and target retrofits is to develop an existing building standard like the BC Energy Step Code. A standard for existing buildings might be tiered performance targets for absolute energy and GHG savings and provides prescriptive requirements for other requirements, such as cooling and improved indoor comfort.

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[8] BC Clean Energy Act

[9] BC Hydro and Power Authority 2021 Integrated Resource Plan – 2023 Update

[10] Climate 2050 Strategic Framework, 2019

[11] Energize Vancouver (website)

Focus on Reducing Material Quantities by Design

Many recent industry presentations have focused on insulation when discussing how to reduce the embodied carbon associated with the building envelope. This might be because insulation products have EPDs and are easy to talk about at a high level for audiences unfamiliar with embodied carbon. However, switching insulation for non-combustible buildings is not straightforward because of fire protection, structural, thermal, durability, constructability, and testing considerations. Even if swapping the type of insulation is possible, there may not be a clear payoff when the insulation is considered as part of a system that must meet all project performance requirements for a Part 3 building.

A better approach is to focus on minimizing material quantities and/or look at alternative systems that incorporate several material changes. Mitigating thermal bridging is clearly the obvious target for effectively reducing building envelope material quantities as outlined above.

An example of unlocking building envelope system synergies is a combination of:

1. Low GWP claddings,
2. Thermally and structurally efficient cladding systems that minimize insulation thickness,
3. Low GWP insulation(s),
4. Relevant testing to support use in non-combustible buildings, and
5. Mitigated thermal bridging at interfaces or junctions.

An example where an evaluation of systems, rather than components, can result in embodied carbon savings follows.

Wood-framed walls with screw through continuous insulation with strapping to attach cladding requires higher compressive strength insulation. For mineral wool applications, this means a higher density insulation is required and higher associated embodied carbon. In addition, thicker ¾" plywood is sometimes used for this type of wall system, so that fastening into the studs becomes less critical. The embodied carbon increases accordingly to accommodate the installation and structural redundancy.

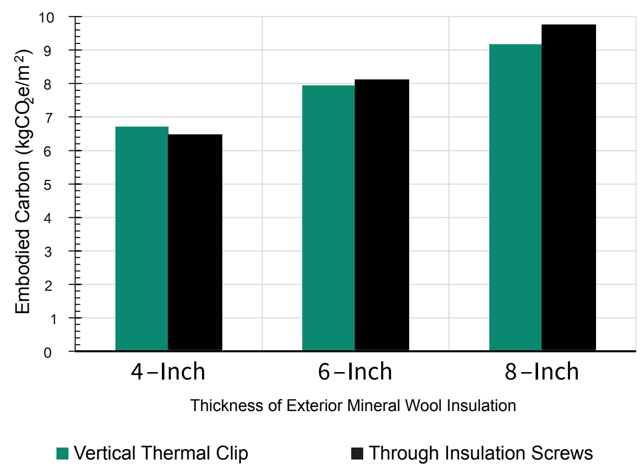

Figure 6: Building 2 Wood-Framed Wall Embodied Carbon for Two Methods of Cladding Attachment

Figure 6 compares two methods of cladding attachment for building 2. At four inches, the through insulation fasteners has less embodied carbon. But at six inches, the thermal clip system has less embodied carbon and the gap increases for thicker insulation levels. Coincidentally this is about the same breakpoint where long screws become very expensive, and cost effectiveness often tips in favour of thermal clip systems for wood-framed construction.

Prefabricated Systems

The prefabricated example included in this study is an aluminum system that has frequent spacing and higher end assumption for the GWP of the aluminum extrusions. This example is good to highlight the value of project specific quantity take-offs of the secondary structural components.

However, this example may overshadow the potential benefit of prefabricated systems to optimize waste reduction, use less materials, and advance the use of components with lower GWP (aluminum processed in B.C.).

Prefabricated systems are more likely to have an estimator involved that can get closer to the real material quantities used on a project than a design team can using standardized assumptions. This is important because more accurate estimates and control of materials can enable construction waste reduction.

For example, the size and layout of windows will more likely be optimized if:

- there was an incentive to demonstrate waste reductions compared to standard practice and/or,
- performance specifications are provided with absolute embodied carbon thresholds for the wall systems that are not based on clear field assembly assumptions.

Stage D impacts

The study calculations do not include end of life recycling, reuse, and energy recovery benefits, even though such benefits will be eventually realized in the future for some components. There is a great deal of uncertainty in quantifying these benefits far into the future. Further research of circular economy applications might reduce this uncertainty, but ultimately this study recognizes that they are too significant at the present time. Focusing on stage A to C impacts encourages designers to focus on ways to minimize material use.

The benefits of carbon storage or biogenic carbon for use of wood-based construction materials are also omitted from the study calculation. Moreover, the benefits of wood product are still demonstrated as good practice in the study given that:

1. Wood products have dramatically lower A1-A3 embodied carbon than competing concrete and metal solutions, regardless of carbon storage. Recognizing these differences is enough to encourage embodied carbon reductions by using wood.
2. There is significant variability in the net carbon emissions from different forestry practices and wood sources across North America.

At this point, industry considers all wood is good, but there is still work to be done to help industry to develop and specify, at scale, the use of wood products. Especially ones with the greatest carbon benefits on projects, such as the use of beetle kill wood.

Nevertheless, there is industry interest in demonstrating net zero embodied carbon and inevitably biogenic impacts are of interests to many projects seeking certifications and sustainability marketing. Hence, we recommend project teams and policy developers request greater granularity in biogenic impacts of the wood-based products beyond North American averages.

Omitting Stage D and biogenic benefit from calculations follows industry norms for compliance calculations in Canada which is understood to be based on similar reasoning.

Guidance and Further Development

There are key guidance takeaways from this study and many of these would benefit from further research and development.

1. Detailed take-offs are justified for framed wall systems for non-combustible construction to increase accuracy and consistency in embodied carbon calculations.

2. The material quantities for interface details for embodied carbon should be included in a database to ease the effort required for doing detailed calculations. Figure 7 illustrates how a detail at an intermediate floor slab can be quantified and included in a database with integrated calculated, such as ThermalEnvelope.ca. There are synergies to doing detailed take-offs for embodied carbon and thermal bridging calculations together.
3. Building envelopes should be evaluated for embodied carbon performance at the system level. Minimizing embodied carbon should be considered in parallel to other requirements, such as durability, thermal efficiency, fire protection, and cost. The building envelope embodied carbon can be a significant portion of the pie, but difficult to optimize by simple product substitutions. An example of an effective systems approach is to reduce thermal bridging in parallel with reducing insulation thickness.
4. More EPDs are needed, especially from local manufacturers. Differentiation between manufacturers plants and harvesting sources can assist designers in specifying optimal solutions and conducting accurate analysis.
5. Limited available EPDs, and alternative materials to consider, restrict the impact of doing LCA analysis on projects. Nevertheless, outcomes of requiring LCA analysis are encouraging industry to think about embodied carbon by going through the exercise, building capacity to do this work, and switching to wood when possible.
6. Some professionals are focused on the type of insulation, but overlook the impacts of glazing systems, cladding attachments, and cladding selections. Changing the type of insulation for non-combustible construction is not straightforward and has to be considered as part of system for the all the project requirements.
7. The belief that less site construction activity through use of prefabricated systems will achieve major embodied

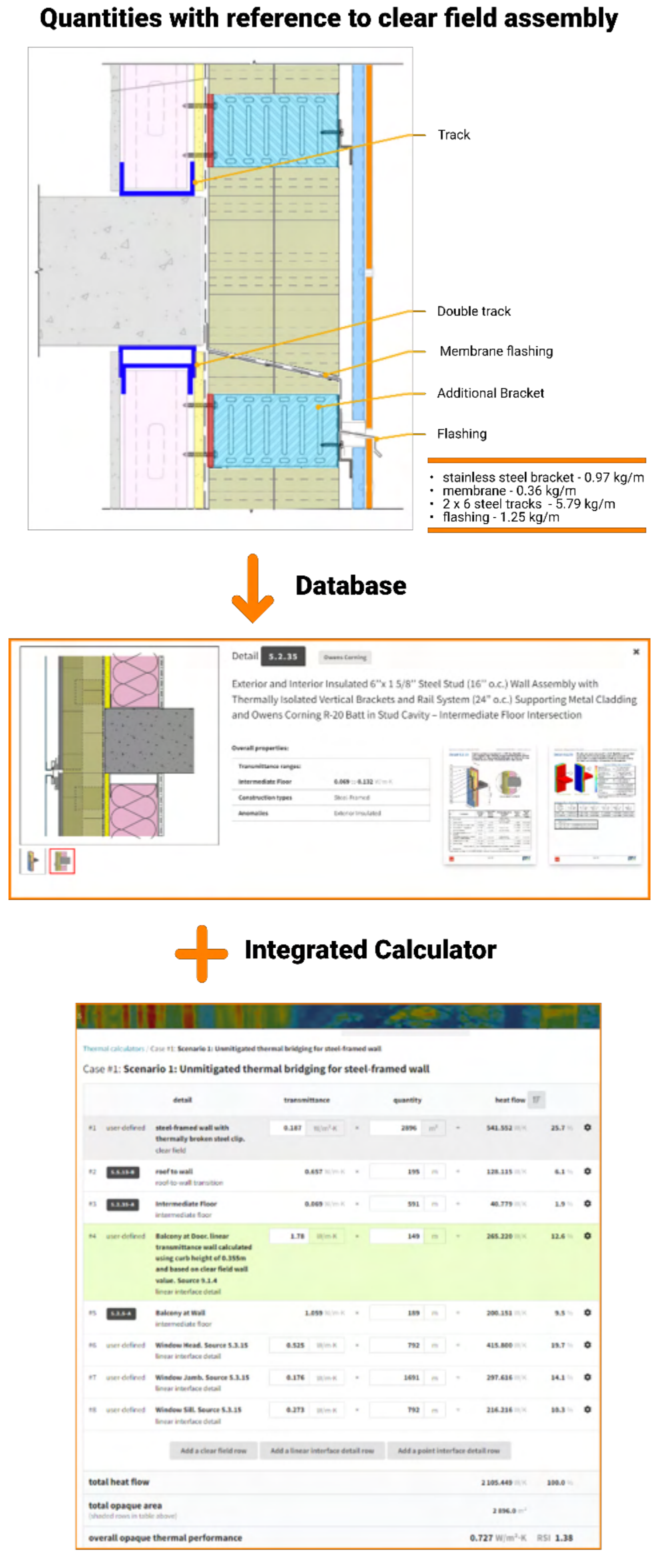

Figure 7: Tools where the extra materials at interface details are quantified in a database and integrated with a calculator will reduce the effort required to do detailed embodied carbon calculations.

carbon savings seems unlikely. Better to focus and develop systems that reduce the quantity of framing through use of low GWP materials and system optimizations.

8. The study suggests that there is less value in doing detailed embodied carbon calculations for wood-framed walls than compared to other types of construction. The embodied carbon is so low for wood-framed construction that there is not much of a penalty for overestimating framing using conservative framing factors. This is comparable to thermal bridging calculations, where detailed thermal simulations are not essential. Hand calculations using framing factors are sufficient because wood is somewhat insulating and lateral heat flow is not significant.
9. LCA analysis does not typically consider premature replacement of envelope components that are significant contributors to embodied carbon and can be avoided by selecting materials from a system perspective. Accordingly, durability requirements must always trump embodied carbon reductions (e.g. membrane or attachment selection).
10. From a practical perspective, absolute targets are better to encourage optimization of the building envelope because of the inherent difficulty of setting appropriate baselines for percent savings targets.
11. Percent savings baselines that do not require detailed calculations but meet performance requirements, without exaggeration, are difficult to produce and enforce. An example of a possible exaggeration is highlighted in the insight above that examines optimal insulation levels. A baseline with a less thermally efficient cladding attachment system and/or no thermal bridging mitigation will show a high level of subjective embodied carbon savings.

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Appendix A: Definition of Building Archetypes, Assemblies and Detailed Quantities

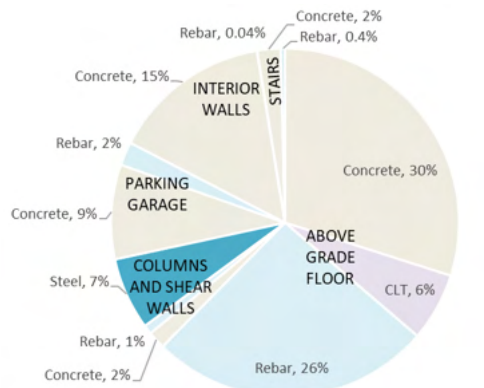
Archetype 1: 17-Storey Concrete Multi-Unit Residential Building

Overview

- 17-storey above grade and two level below grade parking
- Concrete structure for parking garage and two levels above grade
- Upper levels are mass timber floors with concrete topping, steel columns and concrete walls at the elevator and stairwell core
- Evaluated various non-combustible wall systems
- 1225 m² (13 185 ft²) footprint for parking garage and first 6-storeys
- 550 m² (5920 ft²) footprint for point tower
- 13 400 m² (144 230 ft²) GFA
- 0.5 vertical surface to floor VFAR (Typical)

Structural Quantities

% Embodied Carbon of the Structure



Breakdown by LCA Stage

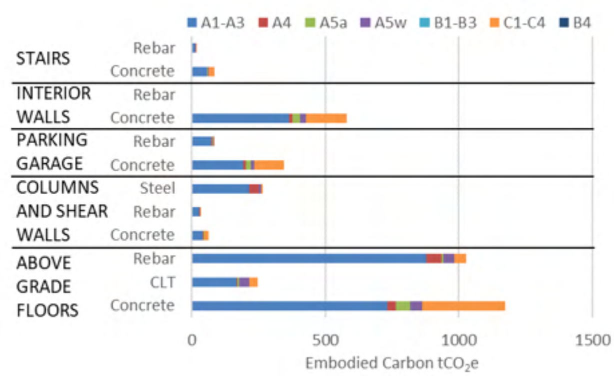


Table A1. Breakdown of CO_2 Emissions for 17-Storey MURB Structure with Mass Timber

Structural Component	Material	Quantity m³	Carbon Intensity kg eCO_2/m^3	Embodied Carbon kg eCO_2	% of Structure
Above-grade floors	Concrete	2,498	470	1,174,026	30%
	CLT	1,667	149	248,719	6%
	Rebar	132	7,771	1,025,811	26%
Columns and shear walls	Concrete	123	522	64,241	2%
	Rebar	4.3	7,771	33,417	1%
	Steel	16	16,451	263,218	7%
Parking garage and foundation	Concrete	876	393	344,246	9%
	Rebar	11	7,771	85,484	2%
Interior walls, roof slabs and beams	Concrete	1238	470	581,843	15%
	Rebar	0.2	7,771	1,554	0.04%
Precast Concrete	Concrete	162	522	84,611	2%
	Rebar	2	7,771	15,543	0.4%

Total 293 kg eCO_2/m^2

Insights

- The concrete in the building's structure contributes 57% of it embodied carbon. The rebar contributes to a further 30%.

Building Envelope Scenarios

The building envelope assemblies are based on the performance needed to meet BC Energy Step Code Step 3 and 4 for residential buildings and non-combustible construction. The following building envelope scenarios were evaluated for the vertical facade:

1. Window-to-wall (glazing) ratio: 30, 40, 50 %
2. Windows and Doors
   - IGU: double vs triple glazing
   - Window frame: aluminum, fiberglass, high performance aluminum
   - Window size and type: dependent on the glazing ratio and floor plan
3. Wall assemblies
   - Split insulated steel-framed walls
   - Exterior insulated unitized curtain-wall with clip system
4. Wall Insulation
   - Type: mineral wool
   - Thickness: 4 to 10 inches of exterior insulation
   - R-20 batt insulation for steel-framed walls and R-21 for curtain-wall in the back-pan
5. Balcony thermal mitigation
   - Cantilevered concrete
   - Steel balcony with thermal break

Details on the quantities and specific assembly components for each scenario follows.

Glass Scenarios

The impact of double versus triple glazing was explored for the following IGU scenarios.

Table A2. Glass Scenarios

IGU	Description
Double glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior
Triple glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm centre with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior

Window and Door Schedule

The size and type of the windows and doors vary for each glazing ratio scenario according to the suite layout and location of the demising walls. The suite layout constrains the location and type of window for higher glazing ratios for the archetype building because of the size of dwelling units and footprint. The objective of the varying window arrangement is to explore the relative quantity of extra framing required at the windows and how the extra framing scales with increasing glazing ratios.

The window size and type were selected based on:

1. Vertical oriented windows for smaller rooms and horizontal for larger rooms
2. Guidelines for maximum window module area (45 ft^2) and weight (240 lbs)
3. Maximum operable vent sizes of 30 in x 60 in for casement and 30 in x 48 in for awning

The window and door schedules for each scenario follows in Table A3 and A4.

Table A3. Window Schedule per Glazing Ratio Scenario

	30% Glazing Ratio	40% Glazing Ratio	50% Glazing Ratio
Window 1 (G1) Large horizontal with casement operable	102 in x 60 in (2.6 m x 1.5 m)	102 in x 78 in (2.6 m x 2.0 m)	102 in x 92 in (2.6 m x 2.3 m)
Window 2 (G2) Large vertical with awning operable	48 in x 72 in (1.2 m x 1.8 m)	48 in x 78 in (1.2 m x 2.0 m)	60 in x 92 in (1.5 m x 2.3 m)
Window 3 (G3) Wide vertical with awning operable		60 in x 48 in (1.5 m x 1.2 m)	60 in x 48 in (1.5 m x 1.2 m)
Window 4 (G4) Wide vertical with awning aperable		60 in x 78 in (1.5 m x 2.0 m)	

Table A4. Door Schedule per Glazing Ratio Scenario

	30% Glazing Ratio	40% Glazing Ratio	50% Glazing Ratio
Door 1 (D1) Sliding door	72 in x 84 in (1.8 m x 2.1 m)	72 in x 84 in (1.8 m x 2.1 m)	72 in x 92 in (1.8 m x 2.3 m)
Door 2 (D2) Swing door	36 in x 84 in (0.9 m x 2.1 m)	36 in x 84 in (0.9 m x 2.1 m)	60 in x 92 in (1.5 m x 2.3 m)
Door 3 (D3) Swing door with fixed lite and awning operable	72 in x 92 in (1.8 m x 2.3 m)	72 in x 92 in (1.8 m x 2.3 m)	102 in x 92 in (2.6 m x 2.3 m)

Figures A1 and A2 show the variation in window size and quantity for the south elevation and plan for levels 8 to 17.

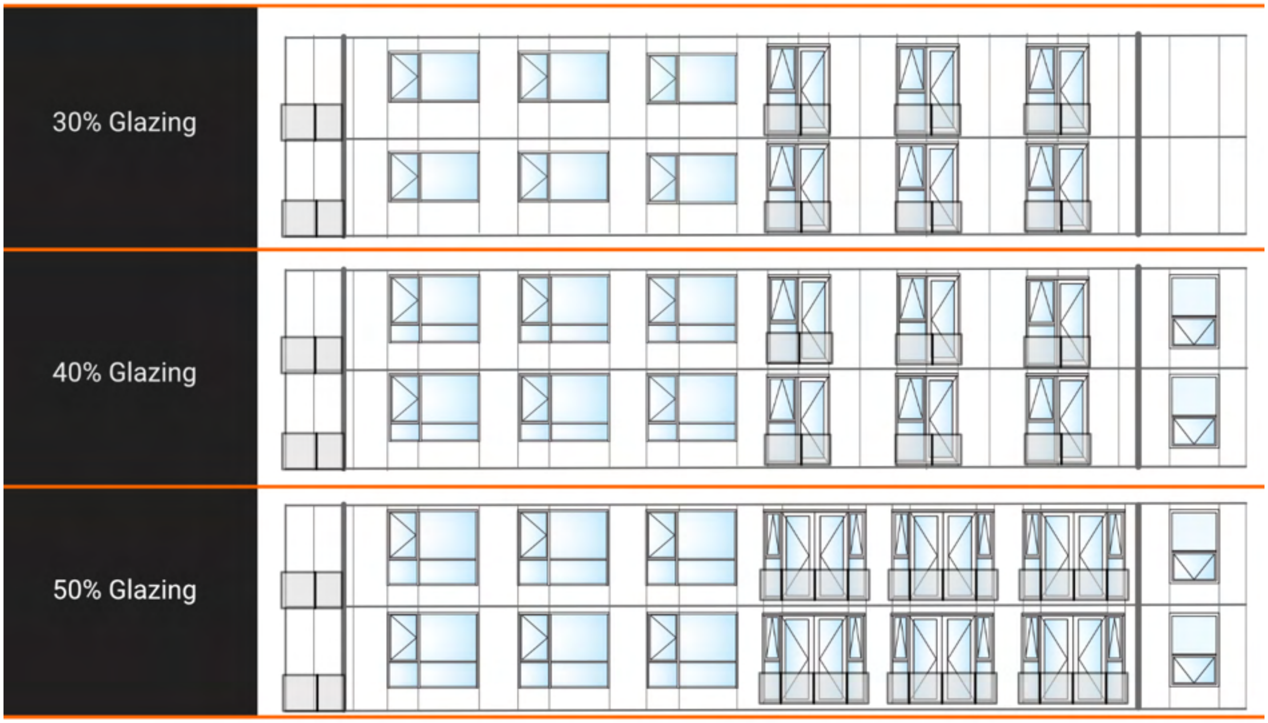


Figure A1. Variation of Window Size and Quantity for South Elevation (two levels shown)

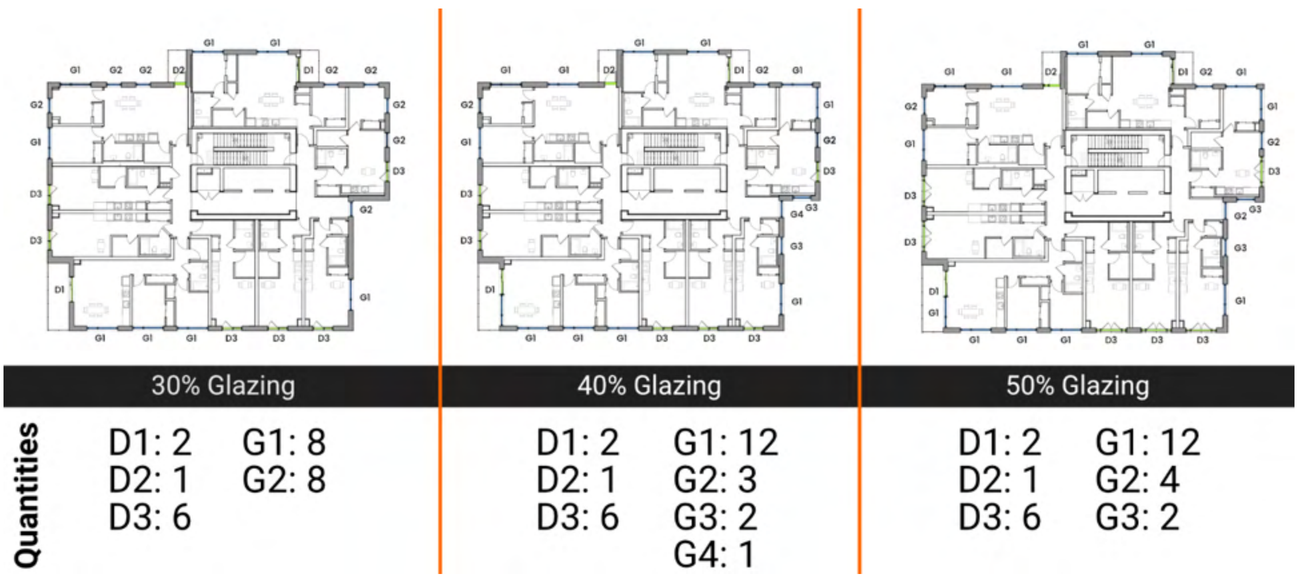


Figure A2. Variation of Window Size and Quantity for Plan of Levels 8 to 17

The mass of the glazing materials for each glazing scenario and window type is summarized in Table A5.

Table A5. **Total Weight (kg) of Residential Windows per Glazing Ratio (Levels 3 to 17)**

Component	Scenario	Glazing Ratio		
		30%(kg)	40%(kg)	50%(kg)
Glass	Double glazed	51,146	62,045	79,298
	Triple glazed	76,803	93,168	119,077
Frame	Aluminum – Unitized CW	2,534	2,646	3,042
	Aluminum – Premium, wide frame	19,531	22,095	27,627
	Fiberglass	16,997	18,856	23,424
Insulation	Aluminum – Unitized CW	167	183	227
	Aluminum – Premium, wide frame	167	183	227
	Fiberglass	167	183	227
Sealant	Aluminum – Unitized CW	239	271	330
	Aluminum – Premium wide frame	239	271	330
	Fiberglass	239	271	330

Exterior Wall Assemblies

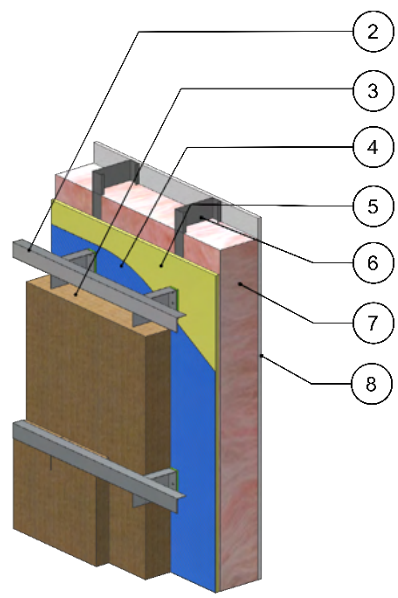
Scenarios for the building facade considered both wall systems where:

1. the secondary structural systems are supported within the primary concrete structure, and
2. for curtain-wall applications where the facade is hung outboard the concrete structure.

Where the primary building structure is part of the building envelope the concrete and steel are accounted for in the quantities for the structure.

Split Insulated Steel-Framed Walls

1. Cladding with rainscreen cavity
2. 16-gauge Stainless steel cladding attachment system with 18-guage galvanized steel rail and thermal isolator
3. 4 to 10 inches (102 to 254 mm) mineral wool insulation
4. Vapour permeable self-adhesive air and moisture barrier
5. 1/2″ (13 mm) fiberglass-mat gypsum exterior sheathing
6. 20-gauge 6 X 1 5/8″ (152 x 40 mm) steel-studs at 16″ (406 mm) o.c.
7. R-20 Fiberglass batt insulation
8. 1/2″ (13 mm) gypsum wall board with low vapour permeance primer



The split insulated steel-framed wall assemblies were evaluated for two cladding attachment scenarios as follows:

1. **Vertical**: the brackets spaced at 34″ o.c. vertically on every stud with vertical rails.
2. **Horizontal Staggard**: the brackets are spaced at 36″ o.c on every other stud with horizontal rails.

Tables A6 to A8 summarize the quantities for the steel framed wall that is utilized in the LCA analysis for the various glazing ratios.

Table A6. Steel-Framed Wall Quantities for LCA Analysis and 30% Glazing Ratio

Material	Component Description	Cladding Attachment Scenario	
		Vertical (kg)	Horizontal Staggered (kg)
Steel	Attachment for 4 in (102 mm)	8,166 kg	3,856 kg
	Attachment for 6 in (152 mm)	8,555 kg	4,051 kg
	Attachment for 8 in (203 mm)	8,977 kg	4,245 kg
	Attachment for 10 in (254 mm)	9,365 kg	4,407 kg
	Steel framing – clear wall	13,177 kg	
	Steel framing – at junctions	12,199 kg	
	Steel framing – at fenestration	5872 kg	
Mineral wool Insulation, 128 kg/m³ (8 lbs/ft³) density, R-4.2/inch	4 in (102 mm)	44,572 kg	
	6 in (152 mm)	66,783 kg	
	8 in (203 mm)	89,144 kg	
	10 in (254 mm)	111,355 kg	
Batt insulation	R-20, 6-inch batt	9,399 kg	
Cladding	Metal panel	3,241 m^2	
Membrane	Vapour permeable, polypropylene facer	3,586 m^2	
Gypsum	Exterior sheathing	3,005 m^2	
	Drywall	3,005 m^2	

Table A7. Steel-Framed Wall Quantities for LCA Analysis and 40% Glazing Ratio

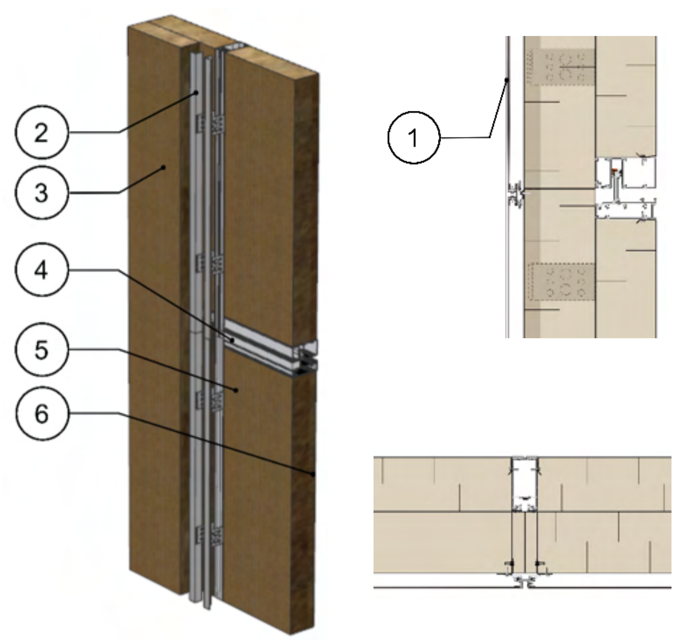
Material	Component Description	Cladding Attachment Scenario	
		Vertical	Horizontal Staggered
Steel	Attachment for 4 in (102 mm)	7,273 kg	3,434 kg
	Attachment for 6 in (152 mm)	7,619 kg	3,608 kg
	Attachment for 8 in (203 mm)	7,995 kg	3,781 kg
	Attachment for 10 in (254 mm)	8,341 kg	3,925 kg
	Steel framing – clear wall	12,489 kg	
	Steel framing – at junctions	17,599 kg	
	Steel framing – at fenestration	4,476 kg	
Mineral wool Insulation, 72 kg/m³ (4.5 lbs/ft³) density, R-4.2/inch	4 in (102 mm)	39,696 kg	
	6 in (152 mm)	59,477 kg	
	8 in (203 mm)	79,392 kg	
	10 in (254 mm)	99,173 kg	
Batt insulation	R-20, 6-inch batt	8,371 kg	
Cladding	Metal panel	2,886 m^2	
Membrane	Vapour permeable, polypropylene facer	3,480 m^2	
Gypsum	Exterior sheathing	2,651 m^2	
	Drywall	2,651 m^2	

Table A8. Steel-Framed Wall Quantities for LCA Analysis and 50% Glazing Ratio

Material	Component Description	Cladding Attachment Scenario	
		Vertical	Horizontal Staggered
Steel	Attachment for 4 in (102 mm)	6,063 kg	2,863 kg
	Attachment for 6 in (152 mm)	6,351 kg	3,007 kg
	Attachment for 8 in (203 mm)	6,664 kg	3,152 kg
	Attachment for 10 in (254 mm)	6,953 kg	3,272 kg
	Steel framing – clear wall	11,837 kg	
	Steel framing – at junctions	25,389 kg	
	Steel framing – at fenestration	3,412 kg	
Mineral wool Insulation, 72 kg/m³ (4.5 lbs/ft³) density, R-4.2/inch	4 in (102 mm)	33,089 kg	
	6 in (152 mm)	49,578 kg	
	8 in (203 mm)	66,178 kg	
	10 in (254 mm)	82,667 kg	
Batt insulation	R-20, 6-inch batt	6,978 kg	
Cladding	Metal panel	2,406 m^2	
Membrane	Vapour permeable, polypropylene facer	3,000 m^2	
Gypsum	Exterior sheathing	2,171 m^2	
	Drywall	2,171 m^2	

Exterior Insulated Unitized Curtain-wall with Clip System

1. Cladding with rainscreen cavity
2. 16-gauge steel cladding attachment system with brackets and steel rail
3. 4 to 10 inches (102 to 254 mm) exterior mineral wool insulation
4. Aluminum curtain-wall framing
5. 5 inch (127 mm) mineral wool insulation in backpan
6. 20-gauge steel backpan
7. 20-gauge 1 5/8" X 1 5/8" (40 x 40 mm) steel-studs at 16" (406 mm)
8. 1/2" (13 mm) gypsum wall board



The quantity of aluminum framing and steel clips depends on the module size that is dependent on the layout per glazing ratio scenario as illustrated in Figure A3.

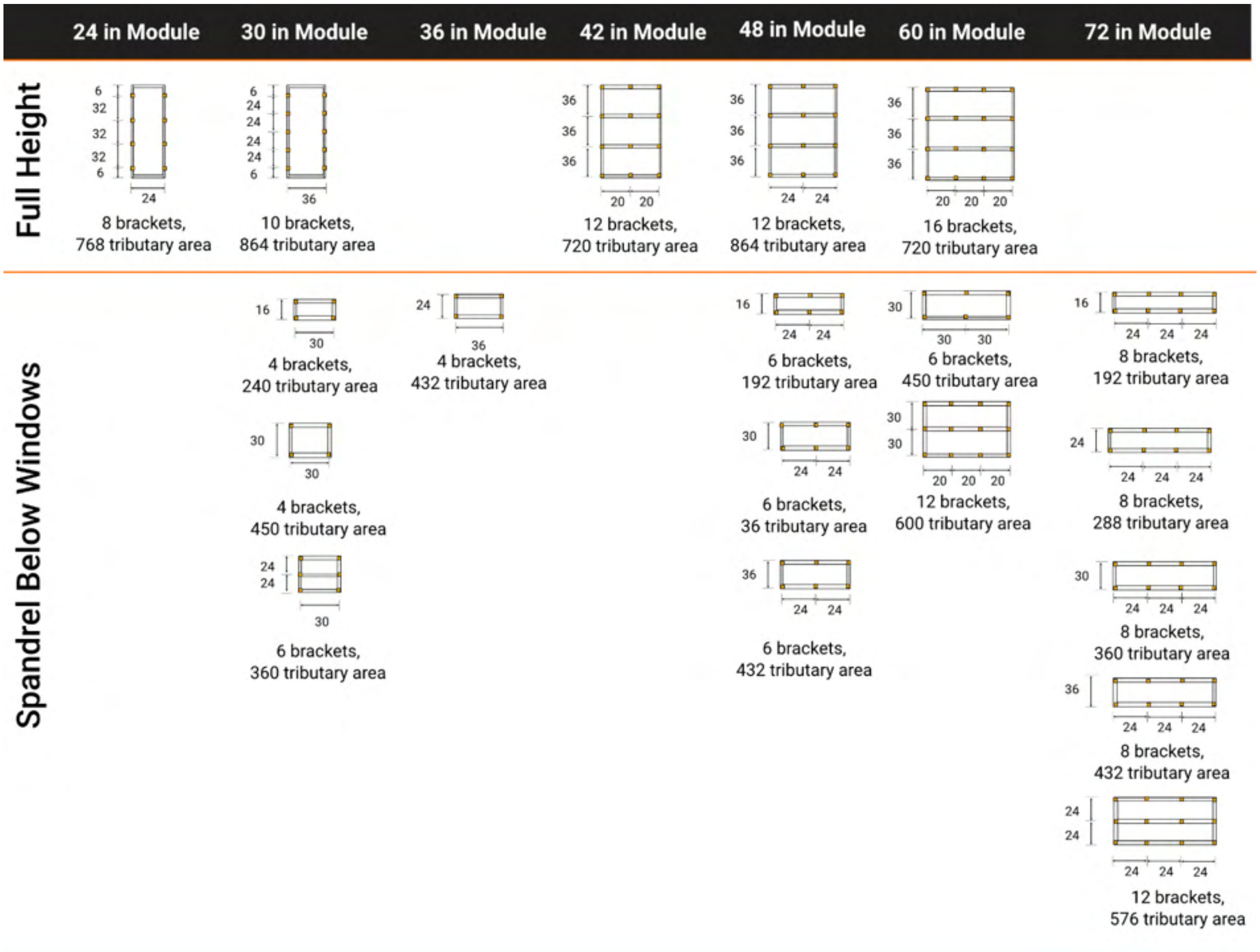


Figure A3. Variation of Steel Bracket Quantity per Curtain-wall Module Size

The exterior insulated curtain-wall assemblies were evaluated for only the upper floors of the point tower. The quantity of aluminum framing was determined using two methods:

1. **Clear wall:** common spacing of 48" o.c. (1.22 m) between vertical mullions and does not account for additional horizontal stack-joints and transoms at windows.
2. **Module specific:** overall quantity of framing for the module specific framing and accounting for additional framing at windows.

Tables A9 to A11 summarize the quantities for the exterior insulated curtain-wall assemblies, including the glass, that is utilized in the LCA analysis for the various glazing ratios.

Table A9. Exterior Insulated Curtain-wall Wall Quantities for LCA Analysis and 30% Glazing Ratio for Typical Floor of Point Tower (Levels 8 to 17)

Material	Component Description	Cladding Attachment Scenario	
		Vertical	Horizontal Staggered
Steel	Attachment for 4 in (102 mm)	8,166 kg	3,856 kg
	Attachment for 6 in (152 mm)	8,555 kg	4,051 kg
	Attachment for 8 in (203 mm)	8,977 kg	4,245 kg
	Attachment for 10 in (254 mm)	9,365 kg	4,407 kg
	Steel back-pan	8,739 kg	
	Steel framing for back-up wall	21,240 kg	
Aluminum	Framing – module framing	13,100 kg	
Mineral wool Insulation, 72 kg/m³ (4.5 lbs/ft³) density, R-4.2/inch	4 in (102 mm) + 5 inch (114 mm)	100,324 kg	
	6 in (152 mm) + 5 inch (114 mm)	122,535 kg	
	8 in (203 mm) + 5 inch (114 mm)	144,866 kg	
	10 in (254 mm) + 5 inch (114 mm)	167,107 kg	
Cladding	Metal panel	3,241 m^2	
Gypsum	Drywall	3,005 m^2	
Other	Sealant	8,100 ln.ft	

Table A10. Exterior Insulated Curtain-wall Wall Quantities for LCA Analysis and 40% Glazing Ratio

Material	Component Description	Cladding Attachment Scenario	
		Vertical	Horizontal Staggered
Steel	Attachment for 4 in (102 mm)	7,273 kg	3,434 kg
	Attachment for 6 in (152 mm)	7,619 kg	3,608 kg
	Attachment for 8 in (203 mm)	7,994 Kg	3,781 kg
	Attachment for 10 in (254 mm)	8,341 kg	3,925 kg
	Steel back-pan	7,556 kg	
	Steel framing for back-up wall	23,777 kg	
Aluminum	Framing – module framing	11,196 kg	
Mineral wool Insulation, 72 kg/m³ (4.5 lbs/ft³) density, R-4.2/inch	4 in (102 mm) + 5 inch (114 mm)	89,349 kg	
	6 in (152 mm) + 5 inch (114 mm)	109,130 kg	
	8 in (203 mm) + 5 inch (114 mm)	129,045 kg	
	10 in (254 mm) + 5 inch (114 mm)	148,826 kg	
Cladding	Metal panel	2,886 m^2	
Gypsum	Drywall	2,651 m^2	
Other	Sealant, gaskets, PVC	7,200 ln.ft	

Table A11. Exterior Insulated Curtain-wall Wall Quantities for LCA Analysis and 50% Glazing Ratio

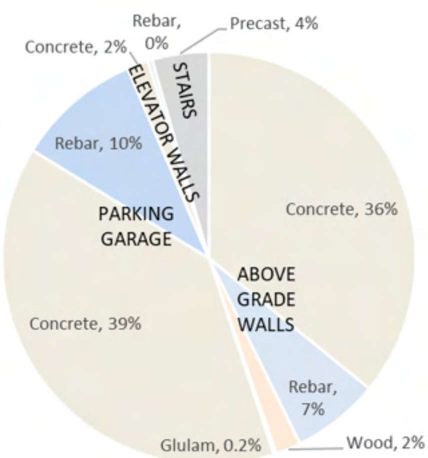
Material	Component Description	Cladding Attachment Scenario	
		Vertical	Horizontal Staggered
Steel	Attachment for 4 in (102 mm)	6,063 kg	2,863 kg
	Attachment for 6 in (152 mm)	6,351 kg	3,007 kg
	Attachment for 8 in (203 mm)	6,664 kg	3,152 kg
	Attachment for 10 in (254 mm)	6,953 kg	3,272 kg
	Steel back-pan	5,911 kg	
	Steel framing for back-up wall	27,106 kg	
Aluminum	Framing – module framing	8,699 kg	
Mineral wool Insulation, 72 kg/m^3 (4.5 lbs/ft^3) density, R-4.2/inch	4 in (102 mm) + 5 inch (114 mm)	74,478 kg	
	6 in (152 mm) + 5 inch (114 mm)	90,967 kg	
	8 in (203 mm) + 5 inch (114 mm)	107,567 kg	
	10 in (254 mm) + 5 inch (114 mm)	124,056 kg	
Cladding	Metal panel	2,406 m^2	
Gypsum	Drywall	2,171 m^2	
Other	Sealant, gaskets, PVC	6,000 ln.ft	

Overview

- Five storey above grade and two level below grade parking
- Poured-in-place concrete walls for first level
- Wood-frame for upper floors
- 1152 m² (12 800 ft²) footprint
- 5760 m² (64 000 ft²) GFA
- 2:1 aspect ratio
- 0.7 VFAR (complex)
- Expanded from BETB Guide V1 Wood-frame MURB Archetype (2014)

Structural Quantities

% Embodied Carbon of the Structure



Breakdown by LCA Stage

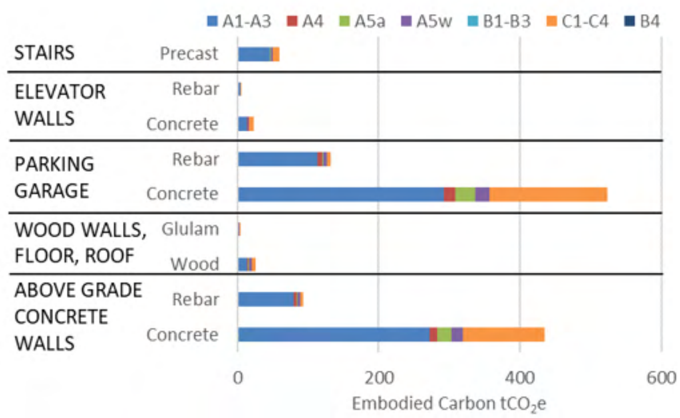


Table A12. Breakdown of CO_2 Emissions for Wood-Framed MURB Structure

Structural Component	Material	Quantity	GWP	Embodied Carbon	% of Structure
		m³	kg eCO₂/m³	kg eCO₂	
Above-grade concrete walls	Concrete	925	522	483,116	36%
	Rebar	12	7,771	92,478	7%
Wood-framed walls, roofs, and floors	Wood	313	85	26,605	2%
	Glulam	18	152	2,736	0.2%
Parking garage and foundation	Concrete	1331	393	523,049	39%
	Rebar	17	7,771	132,112	10%
Elevator walls	Concrete	48	470	22,559	2%
	Rebar	0.6	7,771	4,663	0%
Precast Concrete Stairs	Precast	74	804	59,512	4%
Total				234 kg eCO2/m²	

Insights

- The embodied carbon of the building's structure is dominated by concrete which is 81% of the emissions. Rebar contributes to most of the remaining emissions at 17% and the wood contributes very little at 2%.

Building Envelope Scenarios

The building envelope assemblies are based on the performance needed to meet BC Energy Step Code Step 3 and 4 for residential buildings. The following building envelope scenarios were evaluated for the vertical facade:

1. Window-to-wall (glazing) ratio: 40%
2. Windows and Doors
    - IGU: double vs triple glazing
    - Window frame: aluminum with thermal break, fiberglass, vinyl
3. Wall assemblies
    - Poured-in-place concrete walls for first level
    - Wood-frame for upper floors
4. Wall Insulation for wood-framed walls
    - Exterior Insulation Type: mineral wool
    - Thickness: 4 inch (102 mm) to 6 inch (152 mm) exterior insulation
    - Stud-Cavity Insulation: R-19 fiberglass batt or cellouse
5. Wall Insulation for concrete walls
    - Insulation: interior insulated XPS or EPS
    - Thickness: 3 inches (76 mm)
    - Stud-Cavity Insulation: none

Details on the quantities and specific assembly components for each scenario follows.

Glass Scenarios

The impact of double versus triple glazing was explored for the following IGU scenarios.

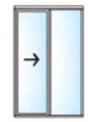
Table A13. Glass Scenarios

IGU	Description
Double glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior
Triple glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm centre with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior

Window and Door Schedule

The windows and door schedule for the wood-frame MURB with 40% glazing is outlined in Table A14.

Table A14. **Window and Door Schedule**

Large Window casement operable	**Small Window** awning operable	**Sliding Door**
		
72 in x 60 in (1.8 m x 1.5 m)	36 in x 48 in (0.9 m x 1.2 m)	60 in x 84 in (1.5 m x 2.1 m)

The mass of the glazing materials is summarized in Table A15 and A16.

Table A15. **Total Weight (kg) of Residential Windows per Glazing Ratio (Levels 2 to 5)**

Component	Component Description	Mass Kg
Glass	Double glazed	25,074
	Triple glazed	37,652
Frame	Aluminum	31,438
	Fiberglass	4,390
Insulation at perimeter and in frames	Aluminum	5
	Fiberglass	5
Other (gaskets, seals, thermal breaks)	Aluminum	1,469
	Fiberglass	1,469

Table A16. **Total Weight (kg) of Commercial Curtain-wall (Level 1)**

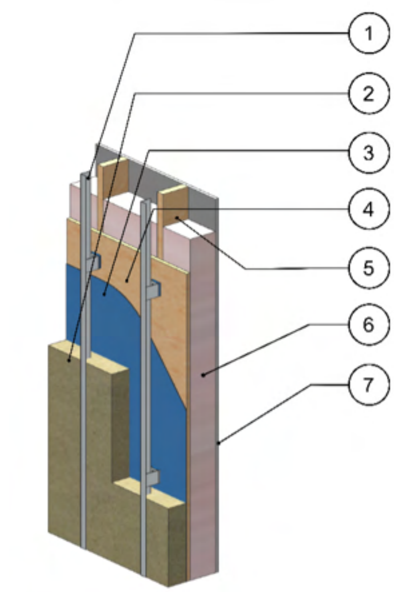
Component	Component Description	Mass Kg
Glass	Double glazed	10,030
Frame	Aluminum	12,575
Insulation	Aluminum	2
Other (gaskets, seals, thermal breaks)	Aluminum	588

Exterior Wall Assemblies

For the wood-framed MURB, wood-framed walls were considered for levels two to five and poured-in-place concrete walls for the first level.

Wood-Framed Walls

1. Cladding with rainscreen cavity and cladding attachment system (see below for description)
2. 4 to 6 inches (102 to 152 mm) mineral wool insulation
3. Vapour permeable self-adhesive air and moisture barrier
4. 1/2" (13 mm) or 3/4" (19 mm) plywood sheathing
5. 2x6 wood studs at 16" (406 mm) o.c.
6. R-19 Fiberglass batt insulation
7. 1/2" (13 mm) gypsum wall board with low vapour permeance primer



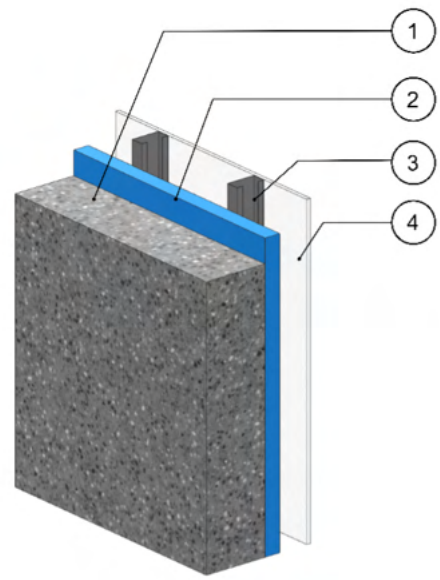
The wood-framed wall assembly was evaluated for two cladding attachment scenarios:

1. **Vertical clip system**: a 16-gauge stainless steel cladding attachment system with 18-gauge galvanized steel rail and thermal isolator. Brackets spaced at 36" (914 mm) o.c. This scenario includes ½" plywood sheathing and 72 kg/m³ (4.5 lbs/ft³) density mineral wool insulation.
2. **Through insulation fasteners**: #14 steel fasteners at 16"x 12" fastened through ¾" (19 mm) x 3" (76 mm) plywood wood strapping and insulation into the wood studs or sheathing. This scenario includes ¾" (19 mm) plywood sheathing and 128 kg/m3 (8 lbs/ft3) density mineral wool insulation.

Table A76 summarizes the quantities for the wood-framed wall that is utilized in the LCA analysis for the 5-storey mixed-use building.

Table A17. Wood-Framed Wall Quantities for LCA Analysis

Material	Component Description	Cladding Attachment Scenario	
		Clip System	Through Insulation Fasteners
Steel	Attachment for 4 in (102 mm)	972 kg	189 kg
	Attachment for 6 in (152 mm)	1,021 kg	284 kg
	Attachment for 8 in (203 mm)	1,070 Kg	379 kg
Wood	Plywood strapping	308 kg	308 kg
	Plywood sheathing 1/2" (13 mm) or 3/4" (19 mm) plywood	4,941 kg	7,514 kg
	Framing – clear field, 9% framing factor	13,121 kg	
Mineral wool Insulation, 72 kg/m³ (4.5 lbs/ft³) or 128 kg/m³ (8 lbs/ft³) density, R-4.2/inch	4 in (102 mm)	8,183 kg	10,603 kg
	6 in (152 mm)	12,274 kg	15,905 kg
	8 in (203 mm)	16,366 kg	21,206 kg
Batt insulation	R-19 batt	2,251 kg	
Cladding	Fiber cement	817 m²	
Membrane	Vapour permeable, polypropylene facer	817 m²	
Gypsum	Drywall	817 m²	



Concrete Walls

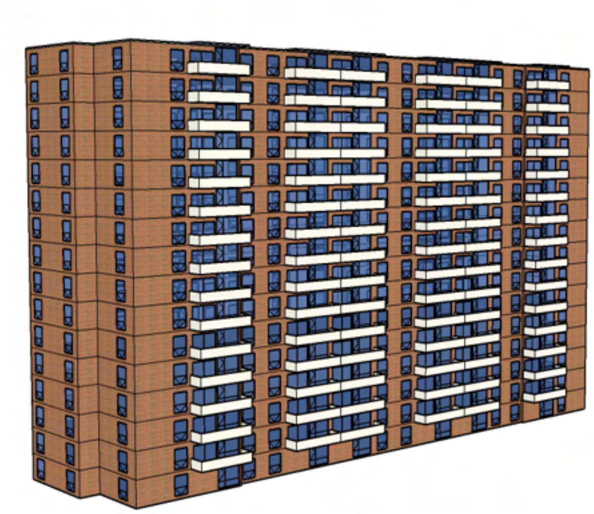
1. 8″ concrete wall or structural column
2. 3 inches (76 mm) XPS or Type 2 EPS Insulation with metalized polymer facer
3. 1 5/8″ x 1 5/8″ steel studs at 16″ (406 mm) o.c.
4. 1/2″ (13 mm) gypsum wall board

Table A18 summarizes the quantities for the concrete wall that is utilized in the LCA analysis for the five-storey mixed-use building.

Table A18. **Concrete Wall Quantities for LCA Analysis**

Material	Component Description	Insulation Scenario	
		XPS	EPS
Steel	Steel framing	1,475 kg	
	Fasteners through insulation	215 kg	
Concrete	CMU – Normal Weight	152 m3	
Rigid Insulation	4 in (102 mm)	2,075 kg	1,355 kg
Gypsum	Drywall	817 m^2	

Archetype 3: 16-Storey Existing Multi-Unit Residential Building

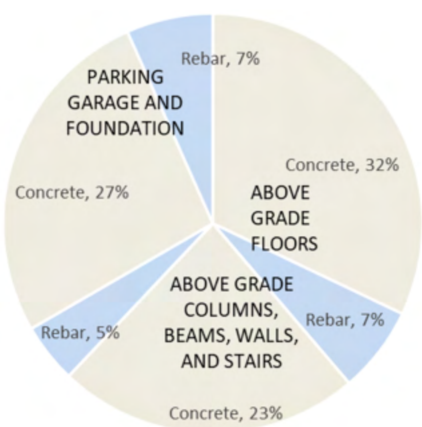


Overview

- 16-storey above grade and one storey below grade parking
- Concrete structure
- 1,250 m² (13,480 ft²) above-grade footprint
- 1250 m² (13 480 ft²) below-grade
- 20 000 m² (215 680 ft²) GFA
- 4:1 aspect ratio
- 0.45 VFAR (typical)
- Representative of apartment buildings from 1960s and 1970s.

Structural Quantities

% Embodied Carbon of the Structure



Breakdown by LCA Stage

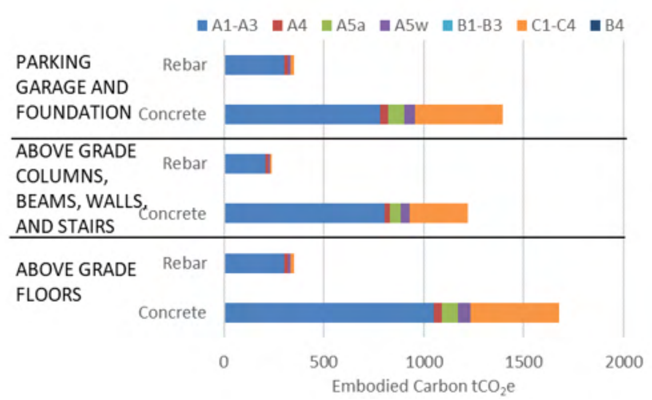


Table A19. Breakdown of CO_2 Emissions for Existing MURB Structure

Structural Component	Material	Quantity m³	GWP kg eCO_2/m^3	Embodied Carbon kg eCO_2	% of Structure
Above-grade floors	Concrete	3,575	470	1,680,201	32%
	Rebar	45	7,771	349,708	7%
Above-grade columns, beams, walls, and stairs	Concrete	2,337	522	1,220,587	23%
	Rebar	31	7,771	240,910	5%
Parking garage and foundation	Concrete	3,555	393	1,397,024	27%
	Rebar	45	7,771	349,708	7%
Total				262 kg eCO_2/m^2	

Insights

- The existing building's structure would have significant embodied carbon emissions if rebuilt. The analysis provides an estimate of those emissions if built with a similar design today.

Building Envelope Scenarios

The building envelope renewals are based on the performance needed to meet BC Energy Step Code Step 3 and 4 for residential buildings. The following building envelope scenarios were evaluated for the vertical facade:

1. Window-to-wall (glazing) ratio: 30%
2. Windows and Doors
    - IGU: double vs triple glazing
    - Window frame: aluminum, fiberglass, vinyl
3. Existing Wall Assemblies
    - 8-inch (203 mm) concrete with 3.5" studs inboard, R-12 batt and poly
    - 3.5-inch (89 mm) steel framed wall with stucco and building paper
4. Retrofit Wall Assemblies
    - Insulate and clad outboard existing walls
    - New sheathing at steel framed walls
    - EIFS and cladding options
5. Wall Insulation
    - Type: EPS or mineral wool
    - Thickness: 4 to 8 inches (102 to 203 mm) for mineral wool; 4-inch (102 mm) EPS for EIFS
6. Balcony scenarios
    - Cut-off existing balconies and do not replace
    - Cut-off existing balconies and replace with prefabricated bolt on balcony
    - Retain existing and provide good interface detailing

Details on the quantities and specific assembly components for each scenario follows.

Glass Scenarios

The impact of double versus triple glazing was explored for the following IGU scenarios.

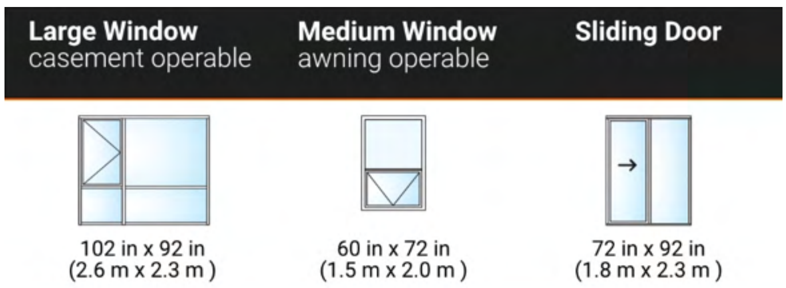
Table A20. Glass Scenarios

IGU	Description
Double glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior
Triple glazed	• 6 mm exterior with low E coating • 12 mm argon fill with warm edge spacer • 4 mm centre with low E coating • 12 mm argon fill with warm edge spacer • 4 mm interior

Window and Door Schedule

The windows and door schedule for the 16-Storey Existing MURB is outlined in Table A21.

Table A21. Window and Door Schedule



The mass of the glazing materials is summarized in Table A22.

Table A22. Total Weight (kg) of Windows and Doors

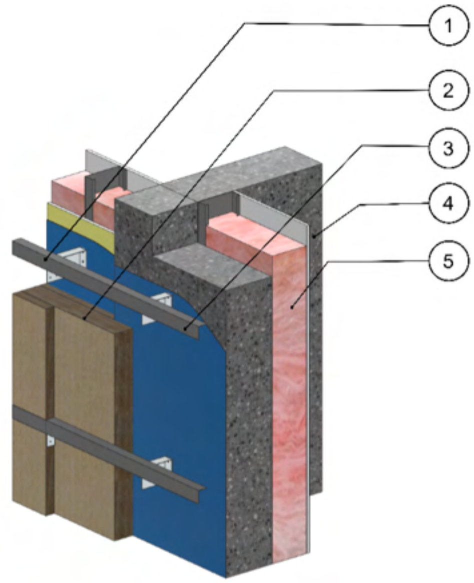
Component	Component Description	Mass
		Kg
Glass	Double glazed	50,665
	Triple glazed	76,080
Frame	Aluminum	50,379
	Fiberglass	20,127
Insulation at perimeter and in frames	Aluminum	12
	Fiberglass	12
Sealant	Aluminum	151
	Fiberglass	151
Polyamide Thermal Breaks	Aluminum	2,285
	Fiberglass	2,285

Exterior Wall Assemblies

The existing concrete and steel framed walls are exterior insulated with either an EIFS system or fibre cement cladding with mineral wool insulation.

Fiber Cement Cladding

1. Cladding with rainscreen cavity and cladding attachment system (see below for description)
2. 4 to 8 inches (102 to 203 mm) mineral wool insulation
3. Vapour permeable self-adhesive air and moisture barrier
4. New ½ inch (13 mm) gypsum sheathing at steel-frame walls
5. Existing substrate, steel framed wall or concrete



The fiber cement cladding walls is a 16-gauge stainless steel cladding attachment system with 18-gauge galvanized steel rail orientated in the horizontal direction. Brackets spaced at 36-inch (914 mm) o.c. vertically and 16" o.c horizontally.

Table A23 summarizes the quantities for fiber cement cladding wall assemblies that is utilized in the LCA analysis for the 16-storey existing residential building.

Table A23. Fiber Cement Cladding Wall Quantities for LCA Analysis

Material	Component Description	Quantity
Steel	Attachment for 4 in (102 mm)	15,489 kg
	Attachment for 6 in (152 mm)	16,227 kg
	Attachment for 8 in (203 mm)	17,026 kg
Mineral wool Insulation	4 in (102 mm)	84,490 kg
	6 in (152 mm)	126,735 kg
	8 in (203 mm)	168,979 kg
Cladding	Fiber cement	6,147 m^2
Membrane	Vapour permeable, polypropylene facer	6,147 m^2
Gypsum	Sheathing	6,147 m^2

EIFS Walls

1. EIFS base and finish coat with reinforcing mesh
2. 4-inch (102 mm) EPS insulation
3. Adhesive
4. Vapour permeable air and moisture barrier
5. Existing substrate, steel framed wall or concrete

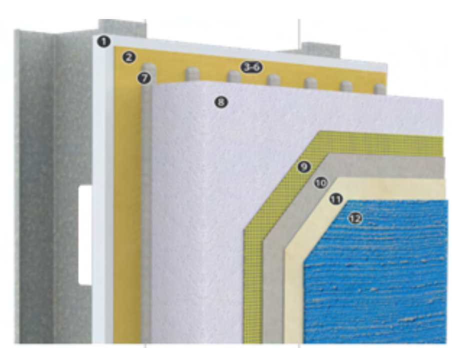


Table A24 summarizes the quantities for the EIFS wall assemblies that is utilized in the LCA analysis for the 16-storey existing residential building.

Table A24. **EIFS Wall Quantities for LCA Analysis**

Material	Component Description	Quantity
EIFS	Base and finish coat with mesh	6,147 m^2
Type 2 EPS	4 in (102 mm)	12,899 kg
Adhesive	Vertical notch for drainage	2,651 m^2
Membrane	Liquid applied polymer membrane	6,147 m^2
Gypsum	Sheathing	6,147 m^2
Other	Sealant, flashing	2,651 m^2

Appendix B: Assumptions for Embodied Carbon Emissions of Products and Materials

Embodied Carbon of Products and Materials

Appendix B presents embodied carbon data for products and materials that were used in the case study analysis in Chapters 2 and 3. Comparisons of data from different sources and products are presented and discussed to provide background on the study assumptions. This discussion also includes ways to improve practice and policy recommendations.

The subsections start with a table presenting reported A1 - A3 embodied carbon emissions and the assumed manufacturing locations for A4 transportation emissions. Remaining emissions from other life cycle stages are determined based on the methodology presented in Chapter 1.

The subsections start with major materials used for the structure and includes a table of data sources that are summarized in term of equivalent CO_2 emissions per mass of materials (kg eCO_2/kg):

- concrete,
- metals, and
- wood.

Then the following materials and products that make up the building envelope are presented and plotted in terms of equivalent CO_2 emissions per envelope areas (kg eCO_2/m^2):

- claddings,
- roofing,
- insulation,
- cladding attachments,
- air, moisture, vapour barriers,
- board sheathings and finishes,
- stud walls,
- roof decks, and
- fenestration.

In the case of insulation, the data is presented per envelope area and RSI (R-5.678) nominal thermal performance (kg eCO_2/m^2 RSI).

Concrete

Table B1. Concrete A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Density	A1-A3 emissions	A4 Location
Cast In Place (Concrete BC)	July 2022	2,400 kg/m³	151-422 kg CO_2e/m³	Local
Concrete Masonry Units (CCMPA)	Sep 2022	2,186 kg/m³	197-251 kg CO_2e/m³	Local
Structural precast concrete (CPCI)	Sept 2019	2,400 kg/m³	256 kg CO_2e/t	Local

Concrete structures tend to dominate embodied carbon emissions for new buildings. The VBBL guidelines requires the use of Concrete BC reported values for Cast-in-place (CIP) concrete in baseline models. The values have been converted to kg functional units and plotted in **Figure B1** for the following:

- compressive strength,
- supplementary cementitious material (SCM), and
- regular vs limestone cement (aka GUL).

Figure B1 plots compressive strengths provided in the VBBL guidelines as defaults as follows:

- Foundation, footing, slab on grade: 25 MPa.
- Exterior walls, interior walls, suspended floor and roof slabs and beams: 35 MPa.
- Stairs, columns, shear walls: 40 MPa.

The Concrete BC EPDs further put forth CIP baseline mixes with given SCM values of 20% for the default compressive strengths above. SCMs in these cases are slag or fly ash is added to the mix to reduce use of embodied carbon intensive Portland cement. Increasing SCMs to 35% decreases A1-A3 emissions by about 15%. The use of limestone concrete (with more limestone content to reduce Portland cement) results in a further 6 to 7% reduction.

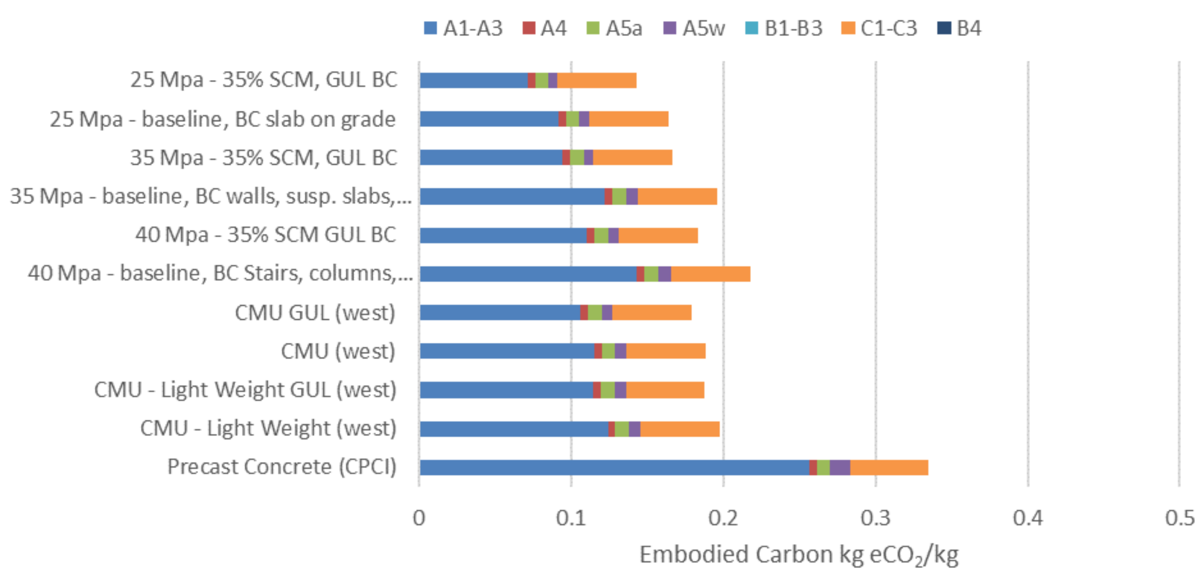


Figure B1: Embodied Carbon for Concrete

Figure B1 also includes normal and light weight concrete masonry units (CMUs) which are shown to have similar weight based embodied carbon as CIP concrete. Precast concrete is also shown to have much greater embodied carbon than CIP or CMUs. This is understood to be due to the embodied carbon of accessories, especially metal reinforcing.

Recommendations

Increasing SCM and use of limestone concrete should be considered within all projects for all concrete applications.

Metals

Table B2. Metal A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Density	A1-A3 Emissions	A4 Location
Rebar (CRSI)	Sep 2022	7,800 kg/m³	854 kg CO_2e/t	Local
Screws, Nuts and Bolts - Canadian Combined Mills (ASMI)	-	-	1,380 kg CO_2e/t	Regional
Hot Dip Galv Steel Section (AGA)	May 2021	7,800 kg/m³	1,710 kg CO_2e/t	North America
Cold Formed Steel Framing (SFIA)	May 2021	7,800 kg/m³	2,440 kg CO_2e/t	North America
Steel Deck (SDI)	Jan 2022	7,800 kg/m³	2,320 kg CO_2e/t	North America
Hot Dip Galv Steel Plate (AGA)	May 2021	7,800 kg/m³	2,230 kg CO_2e/t	North America
Stainless Steel (Outokumpu)	June 2019	7,900 kg/m³	3,390 kg CO_2e/t	North America
Aluminum extrusions, various (AEC)	Nov 2022	2,700 kg/m³	10,253-12,697 CO_2e/t	North America

Metals have more based embodied carbon per weight than most other construction materials. Amongst metals, aluminum has much higher embodied carbon than steel that is used in construction. However, avoiding use of metals based on embodied carbon per weight comparisons is overly simplistic. At the end of a building's life, many metals from buildings can be recycled. However, the D1 recycling benefit has not be included in our analysis as discussed in Chapter 1. Furthermore, metal weights vary significantly, and application specific analysis is warranted.

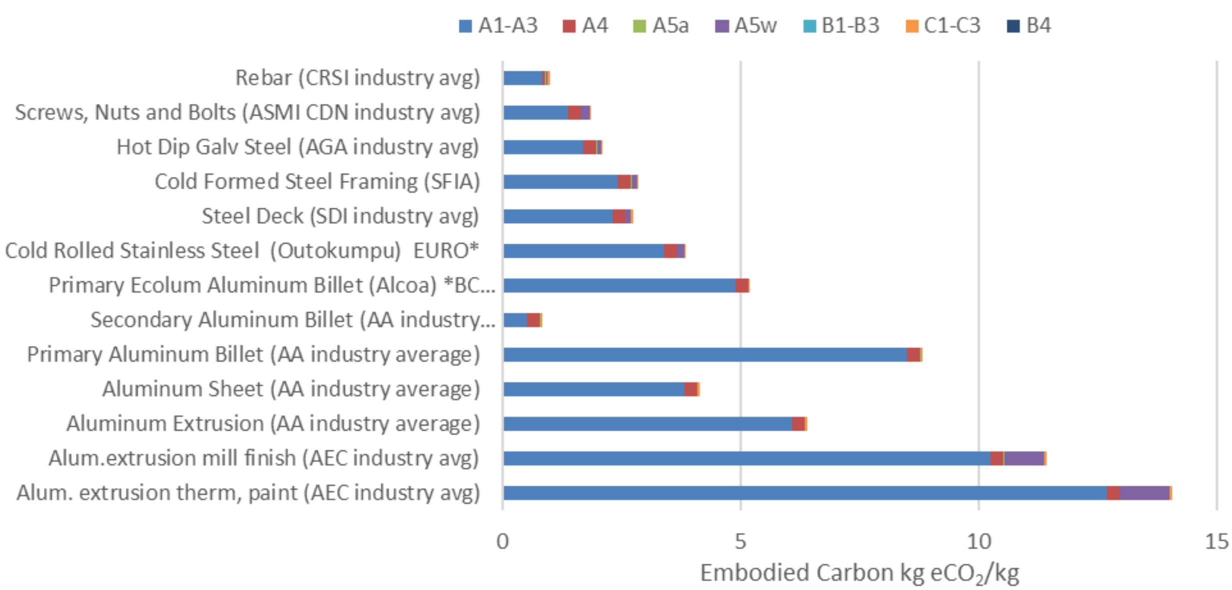


Figure B2: Embodied Carbon for Metals

There is potential for embodied carbon savings for electric arc manufactured steel in lieu of blast oxygen mill steel. This is especially true of electric arc mills from a low carbon intensity grid. Steel used in a structural capacity in the construction industry already tends to have very high recycled content.

Aluminum smelting on low carbon grids (like B.C. and Quebec) have relatively lower embodied carbon as illustrated by Ecolum primary billets vs the industry average billets in **Figure B2**.

Recycled aluminum has very low embodied carbon (see the secondary aluminum billet). Hence, use aluminum with as high a recycled content as technically feasible (e.g. retaining durability of coatings) and with virgin aluminum smelted in Quebec or B.C. to lower embodied carbon. Furthermore, processing aluminum into extrusions and sheet products also consumes considerable electricity (shown as 23% of A1-A3 emissions in AEC publication) and will benefit from manufacturing in low carbon grids like B.C.

Figure B2 shows that there is a significant difference in the reported A1-A3 emission for extrusions published by the Aluminum Association (AA) and the Aluminum Extruders Council (AEC). These industry averages are from the same program operator, UL Environment, using the same calculations (Product Category Rules - PCR) but may vary because they are based on different sets of manufacturers. Note that the VBBL guidelines call out use of an AEC EPD as an example and do not exclude the use of the AA EPD. Therefore, a design using aluminum extrusions may consider the AA EPD values to lower their reported embodied carbon intensity. A design using strategies to avoid use of aluminum extrusions, or using less carbon intensive extrusion, may consider the AEC EPD value to raise the claimed savings. This is not a practice we are advocating, but pointing out an example of how baselines can be gamed and where users might not be considering similar baselines when reporting savings.

Recommendation

Hence, care is needed when defining baselines in such situations of overlapping industry average EPDs for embodied carbon policies to ensure users are considering the same actual baselines.

Adding the end-of-life recycling benefit values for metals from their EPDs dramatically lowers their embodied carbon intensity. For instance, the AEC EPD presents recycling benefits that are more than two-thirds the A1-A3 emissions. A major uncertainty of capturing the benefit of material recyclability is to forecast the impact of recycling on future material production. This is illustrated by the earlier discussion of variances in the intensity of different production methods and locations. Hence, the end-of-life recycling benefit of metals use were not included in our analysis as discussed in Chapter 1.

Wood

Table B3. Wood A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Density	A1-A3 Emissions	Location
Softwood Lumber (ASMI BC)	Feb 2020	460 kg/m^3	46 kg CO2e/m3	Local
Glue Laminated Timber (ASMI BC)			137 kg CO2e/m3	
Softwood Plywood (ASMI BC)			219 kg CO2e/m3	
Cross Laminated Timber (ASMI BC)			124 kg CO2e/m3	

Wood products used in buildings have low embodied carbon per weight and tend to have lower weight than alternative materials for similar applications.

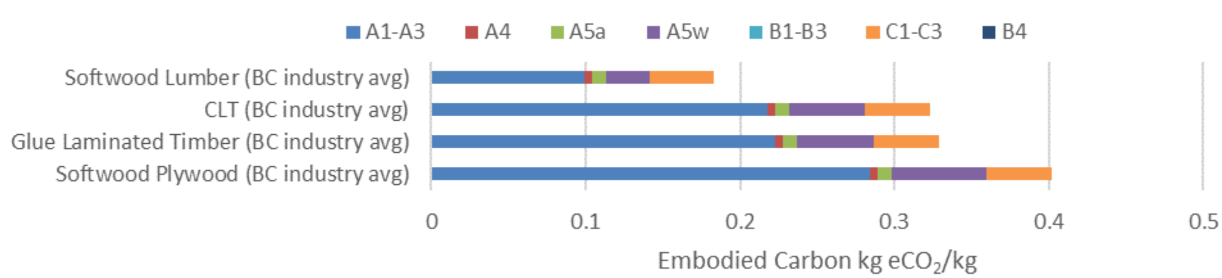


Figure B3: Carbon Intensity of Wood Products

The carbon storage or biogenic benefits of using wood products were not included in our analysis as discussed in Chapter 1.

Thermal Insulation

Table B4. Thermal Insulation A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Weight	A1-A3 Emissions	A4 Location
Fibreglass Batt (Owens Corning)	Sep-23	0.35 kg/m² RSI	0.66 kg eCO_2/m² RSI	Regional
Comfortbatt (Rockwool)	Jul-19	1.48 kg/m² RSI	1.31 kg eCO_2/m² RSI	Local
PUR Closed Cell (SPFA)	Oct-18	0.93 kg/m² RSI	3.47 kg eCO_2/m² RSI	North American
PIR Roofing, paper face (PIMA)	Nov-20	0.85 kg/m² RSI	2.11 kg eCO_2/m² RSI	North American
PIR Roofing, CGF (PIMA)	Nov-20	0.94 kg/m² RSI	2.95 kg eCO_2/m² RSI	North American
EPS Type 2 (EPS Industry Alliance)	Mar-23	0.63 kg/m² RSI	3.54 kg eCO_2/m² RSI	Local
Sopra-XPS (Soprema)	Dec-21	1.10 kg/m² RSI	1.80 kg eCO_2/m² RSI	North American
GreenGuard 25psi XPS (Kingspan)	Jul-21	0.91 kg/m² RSI	3.74 kg eCO_2/m² RSI	North American
GreenGuard 40psi XPS (Kingspan)	Jul-21	0.93 kg/m² RSI	3.77 kg eCO_2/m² RSI	North American
GreenGuard 60psi XPS (Kingspan)	Jul-21	1.16 kg/m² RSI	4.53 kg eCO_2/m² RSI	North American
Styrofoam ST-100 XPS (Dupont)	Jul-21	0.74 kg/m² RSI	3.51 kg eCO_2/m² RSI	North American
Foamular NGX(OwensCorning)	Jan-21	0.78 kg/m² RSI	6.93 kg eCO_2/m² RSI	North American
Canadian Average XPS	-	0.89 kg/m² RSI	4.00 kg eCO_2/m² RSI	North American
EPS Type 2 (EPS Industry Alliance)	Mar-23	0.63 kg/m² RSI	3.54 kg eCO_2/m² RSI	Local
Curtainrock80 (Rockwool)	Jul-19	3.6 kg/m² RSI	3.14 kg eCO_2/m² RSI	North American
Comfortboard80 (Rockwool)	Jul-19	4.6 kg/m² RSI	4.06 kg eCO_2/m² RSI	North American
Heavy Min Wool Board (NAIMA)	Mar-24	3.3 kg/m² RSI	6.82 kg eCO_2/m² RSI	North American

Low density insulations (e.g. batt insulations) have the lowest embodied carbon impacts. However, these materials need to be installed within cavities supported by other materials (studs, meshes, sheathing boards, etc.) and cannot be exposed to water or excessive water vapour diffusion.

VBBL guidelines direct users to consider an average of embodied carbon intensities from available EPDs for XPS. They refer to CLF's reporting but direct users to exclude products with HCF blowing agents, which are banned in Canada. We have calculated a Canadian Industry Average value as shown in Figure B4. We used the 40 psi XPS from GreenGuard in the average and excluded their reported values for their 25 psi and 60 psi products. None of the other manufacturers indicate what product was reported within their EPDs and we assume these are blended averages of their product lines. This current limitation in reporting makes it difficult for users to optimize the type of XPS used in their projects. Soprema appears to have optimized their products for embodied carbon which presents an optimization opportunity for specifiers within projects.

Rockwool mineral wool board products have similar embodied carbon as most XPS board products. The Rockwool products are significantly lower than the industry average for mineral wool. However, it should be noted that they incur significant A4 transportation impacts if the analysis considers many of the products are currently shipped from Ontario to B.C. projects.

Insulation used in conventional roofs is often replaced at least once through a building life span doubling their emissions as shown in the plot. The dramatic impact of B4 replacement highlights the importance of good roofing design, construction, and maintenance to limit embodied carbon emissions associated with premature deterioration and replacement.

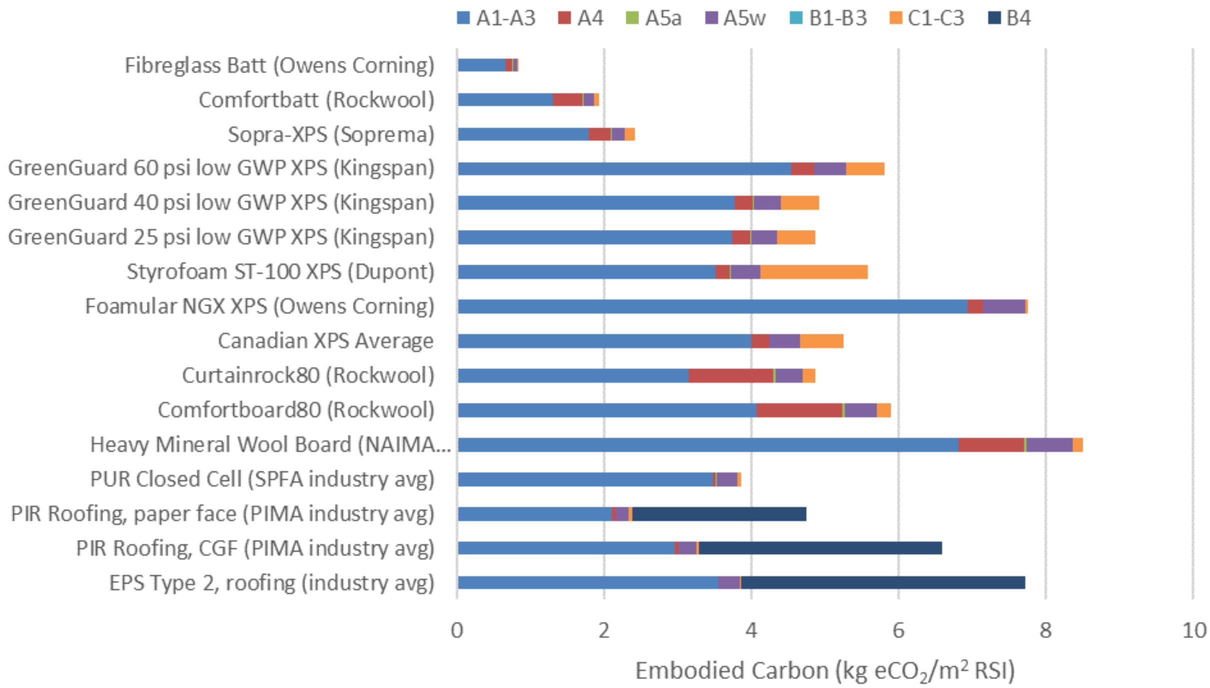


Figure B4: Embodied Carbon of Thermal Insulations

Recommendations

Project teams should seek optimal assembly strategies to use products with higher embodied carbon only where necessary for application and choose lowest carbon materials if practical. This includes using the lowest density as feasible for the application and system.

All materials providing thermal insulation in the building envelope assemblies should provide clear EPD directions on adjustment of A1-A3 impacts for different insulation thicknesses or when installed at different densities.

Wall Cladding

Table B5. Wall Cladding A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	EPD Date	Weight	A1-A3 Emissions	A4 Location
10 mm FCB (James Hardie)	May-23	13.65 kg/m²	7.56 kg eCO_2/m²	North American
10 mm FCB colour (Swiss Pearl)	May-23	17.50 kg/m²	12.80 kg eCO_2/m²	East Coast Port
6 mm, alum. honeycomb (Alucoil)	Oct-20	4.19 kg/m²	42.0 kg eCO_2/m²	East Coast Port
EIFS base, mesh, finish (Sto)	Dec-19	4.99-7.80 kg/m²	5.55-14.76 kg eCO_2/m²	North American

There is no published North American industry average EPD for fibre cement board. The James Hardie reveal panel is part of the case study analysis. This EPD includes coatings and repainting 3.33 times through a 50-year service life. It is a lighter weight product and involves significantly less A4 transportation emissions than importing European products (e.g. Swiss Pearl). However, there are other considerations to selecting products and denser products are often more durable. The fiber cement scenarios used the James Hardie panel data for a 60-year service life.

EIFS coating systems have lower embodied carbon impact than cladding systems but can be expected to require comparatively more maintenance during their service lives. The impacts vary by almost a factor of three based on finish coating and use of heavy meshes (shown as mesh+). The Sto finish coating EPDs used in this study consider a 10-year coating service life. It is very unlikely that EIFS coatings would be replaced at that frequency and more likely this reflects the warranty and recommended repainting period. The plot shows two replacements during the building life which may be coupled with insulation replacement (typically Type 1 EPS) and adhesive.

An imported honeycomb aluminum cladding was also considered in the study. It has very high A1-A3 emissions but low emissions for other life cycle stages due to its durability and light weight (for shipping).

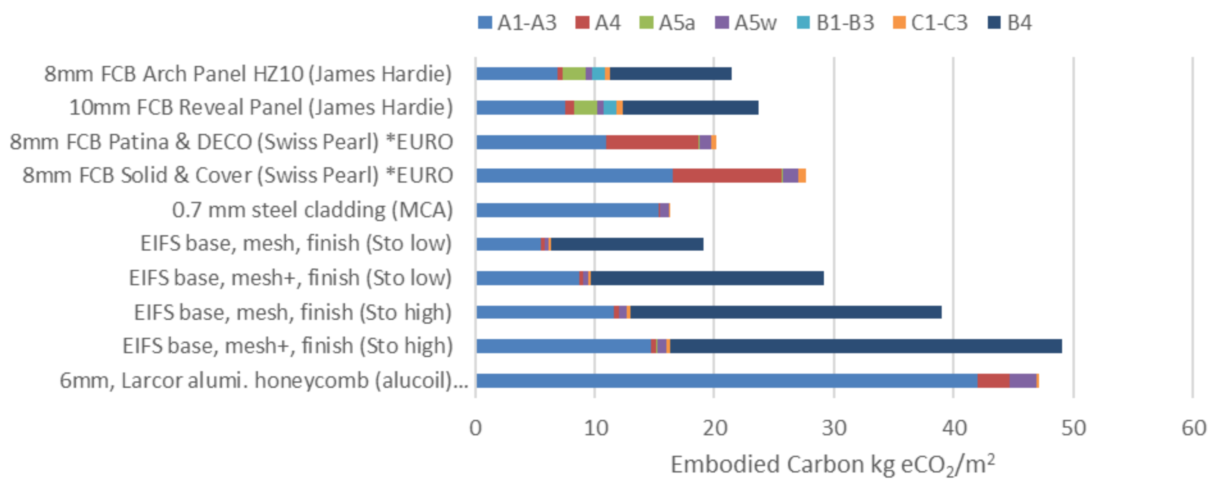


Figure B5: Wall Cladding Embodied Carbon

Membranes and Roofing

Table B6. Membrane and Roofing A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Weight	A1-A3 Emissions	Location
Dampproofing Membrane (Quartz)	Jan 2019	0.46 kg/m²	0.26 ekgCO₂/m²	North American
Foundation Waterproofing (Quartz)	Jan 2019	1.50 kg/m²	1.48 ekgCO₂/m²	North American
Drainage Board (estimate)		0.67 kg/m²	1.80 ekgCO₂/m²	North American
6 mil poly (LDPE at 0.15 mm)	2015	0.19 kg/m²	0.31 ekgCO₂/m²	North American
Sopraseal Stick 1100T (Soprema)	Jul 2023	0.98 kg/m²	1.95 ekgCO₂/m²	North American
Perm-A-Barrier (GCP)	Sep 2022	1.35 kg/m²	1.85 ekgCO₂/m²	North American
Miraply V (Carlisle)	Jun 2021	2.12 kg/m²	8.55 ekgCO₂/m²	North American
Barrithane VP (Carlisle)	Jun 2021	0.67 kg/m²	5.18 ekgCO₂/m²	North American
Gold Coat over plywood (Sto)	Dec 2019	3.08 kg/m²	5.35 ekgCO₂/m²	North American
Mirra Seal (Carlisle)	Jun 2021	2.07 kg/m²	8.37 ekgCO₂/m²	North American
Gold Coat over CMU (Sto)	Dec 2019	8.87 kg/m²	15.4 ekgCO₂/m²	North American
Self-Adhered 2-ply Mod Bit (ARMA)	Jul 2023	7.48 kg/m²	5.20 ekgCO₂/m²	Regional
Torch Applied 2-ply Mod Bit (ARMA)		9.62 kg/m²	5.89 ekgCO₂/m²	
Cold Applied 2-ply Mod Bit (ARMA)		12.31 kg/m²	5.81 ekgCO₂/m²	
Hot Mopped 2-ply Mod Bit (ARMA)		12.85 kg/m²	5.81 ekgCO₂/m²	

EPDs are not available for common foundation wall damp and waterproofing. We used the Quartz database and an estimate of drainage board embodied carbon impacts based on polypropylene siding. These membranes appear to have low embodied carbon.

Due to lack of wall membrane EPDs, wall membranes and roofing are lumped together in this subsection. There are currently a few published EPDs for peel and stick membranes and they are the most intensive products used in our analysis. A value for a European polyethylene vapour barrier was used in the study.

Sheet membranes generally have a total embodied carbon of less than 1 kg eCO2/m2. Fluid applied barriers range from 6 to over 20 kg eCO_2/m^2. Liquid applied membranes have a similar intensity to roofing membranes, except when installed at greater thicknesses which may be necessary when used in roof applications.

Recommendation

Consider using relative conservative assumptions for embodied carbon analysis, such as the Carlisle Miraply with an intensity of 10 kg eCO_2/m^2.

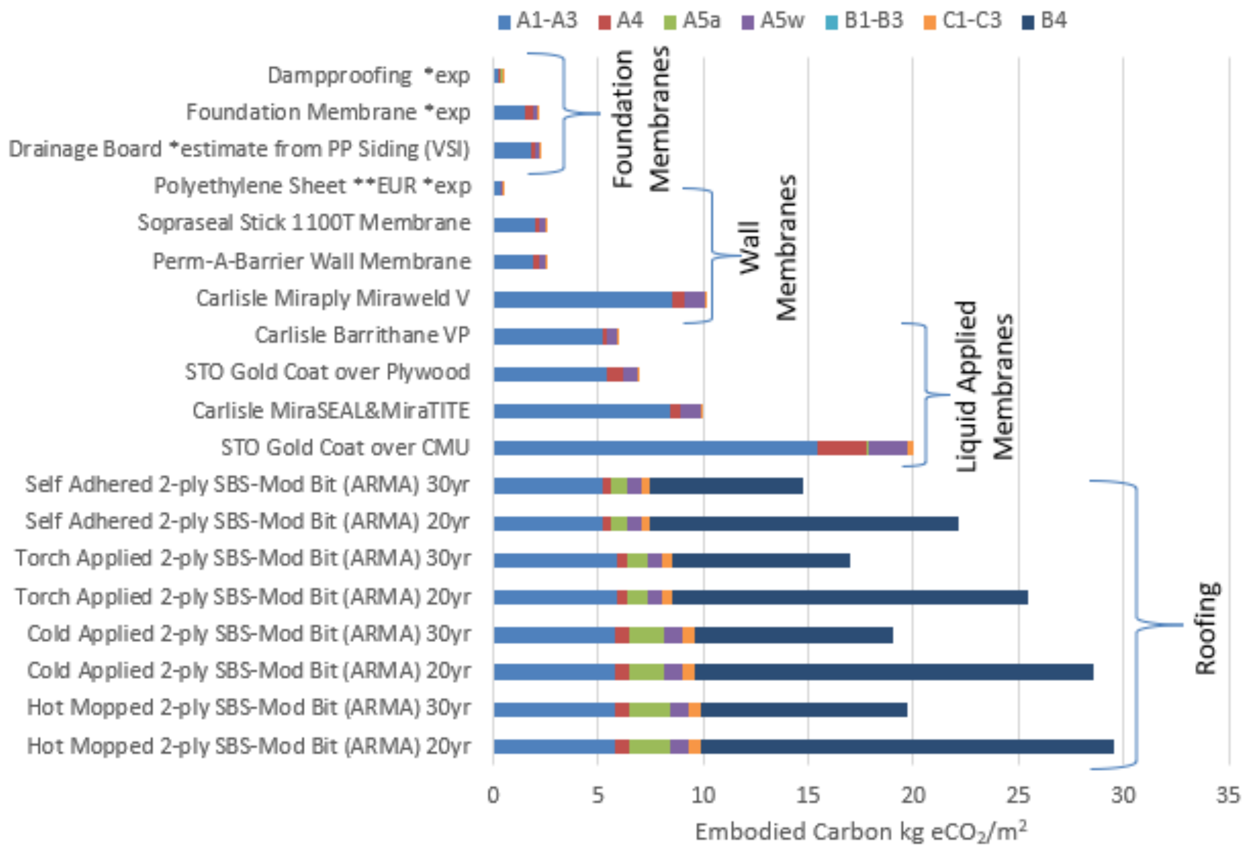


Figure B6: Wall and Roof Membranes Embodied Carbon

Installation of membranes that involve asphalt heating kettles have higher embodied carbon than torch-applied or heat-welded membranes. Nevertheless, BUR roofs using asphalt kettles is not currently a common practice in B.C., but hot fluid-applied rubberized asphalt membranes for products like Hydrotech monolithic membrane 6125 is common for inverted or protected membrane roofs. Moreover, the use of adhesives in cold-adhered systems still require heat-welding of seams and edges and the release of VOC emissions. These emissions contribute to the overall embodied carbon of the materials.

Recommendation

The installation methods should be accounted for when calculating the embodied carbon of the roofing membrane by using data for the applicable EPDs for specific product and application.

The transportation of materials can increase the overall embodied carbon by approximately 2-23% depending on the membrane type and location of the manufacturing facility.

Recommendation

Local materials should be sourced and used to minimize the impact of embodied carbon related to transportation from the manufacturing facility to the construction site.

Roofing membranes have a service life of between 15 to 30 years in B.C. when directly exposed to sun in conventional applications. As such, an exposed roofing membrane is assumed to be replaced between two to four times for a building with a 60-year lifespan. The whole-life embodied carbon of materials can be estimated based on the number of replacements required for different roof membrane types. The embodied carbon for each membrane type is significantly reduced over the lifecycle of a building when the service life of the roof membrane is increased from 20 years to 30 years. Protected membrane roofs, with durable membranes, are expected to last more than 30 years and there are examples of membranes lasting more than 50 years.

Recommendation and Insight

Durable roofing membranes will have a significant impact on the overall embodied carbon of a building due to the need to replace less often. This is especially true of protected membranes and durable membrane systems that are well detailed and installed.

Sheathings and Gypsum Board

Table B7. Sheathing and Gypsum Board A1-A3 Embodied Carbon Emissions and Assumed Manufacturing Location

Material (Owner of EPD)	Issued	Weight	A1-A3 Emissions	A4 Location
1/2" Softwood Plywood (BC)	Feb 2023	5.9 kg/m^2	1.67 kg eCO_2/m^2	Local
1/2" Wood Fibreboard (NAFA)	Jan 2020	3.0 kg/m^2	2.49 kg eCO_2/m^2	Local
1/2" Gypsum Board (ASMI)	Apr 2020	9.9 kg/m^2	2.23 kg eCO_2/m^2	Regional
5/8" Gypsum Board (GA)	Apr 2020	10.4 kg/m^2	2.98 kg eCO_2/m^2	Regional
1/2" Roofing Cover Board (PIMA)	Nov 2020	1.2 kg/m^2	4.82 kg eCO_2/m^2	Regional
1/2" Glass-Mat Gypsum Board (GA)	May 2021	10.2 kg/m^2	4.71 kg eCO_2/m^2	Regional
5/8" Glass-Mat Gypsum Board (GA)	May 2021	13.6 kg/m^2	5.42 kg eCO_2/m^2	Regional

Sheathings and gypsum board add similar embodied carbon to the building envelope as 1 RSI or about an inch of insulation. There is an embodied carbon range greater than 2x for difference products, however, their use is necessary as dictated by codes and by selection for durability. Project optimizations may be available when balancing options for increasing thickness vs the impact of reducing supporting elements (e.g. 16" o.c. vs 24" o.c. stud spacings).

Similar to insulation products, A4 transportation emissions can be significant for B.C. projects where the A4 emissions contribute to up to 15% of the product emissions for North American products and more for products imported from overseas.

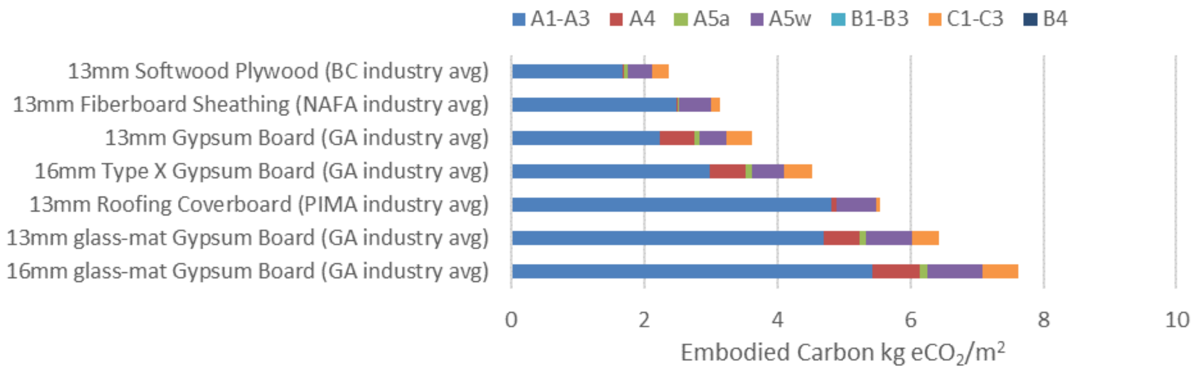


Figure B7: Embodied Carbon of Sheathing Materials

Glazing

Material (Owner of EPD)	Issued	Weight	A1-A3 Emissions	A4 Location
Float Glass (NGA)	Dec-19	7.5-15 kg/m^2	10.5-21.5 kg eCO_2/m^2	North American
Flat Glass (Cardinal)	May-20	7.5 kg/m^2	10.3 kg eCO_2/m^2	North American
Processed Glass (Cardinal)	May-20	7.5 kg/m^2	13.7-22.3 kg eCO_2/m^2	North American
Insulated Glazing Units (Cardinal)	May-20	15.6-23.9 kg/m^2	39.6-93.9 kg eCO_2/m^2	North American

The National Glass Association (NGA) has published North American industry average EPDs for float glass and is referenced by the VBBL embodied carbon guideline for the baseline calculation. The impacts of glass shown in Figure B8 are calculated from an assumed 2500 kg/m^3 glass density for common thicknesses. Unfortunately, they haven't published an industry average for insulated glazing units including the coatings and gas fill for comparison.

Cardinal Glass EPD values have been used in this study. Their various EPDs provide impacts for a helpful range of materials and IGU configurations as follows. Note Cardinal's glass is slightly lower than the NGA reported value.

- 33% increase in A1-A3 emission for adding low-e coating to glass
- 66% increase in A1-A3 emission for tempering
- Double pane IGUs have almost double the A1-A3 emission beyond that of their two panes of glass.
- Use of tempered glass in double pane IGUs have 37% more A1-A3 emissions that IGU without tempered glass.
- Triple pane adds 49% and 73% more A1-A3 emissions than double pane without and with tempered glass.

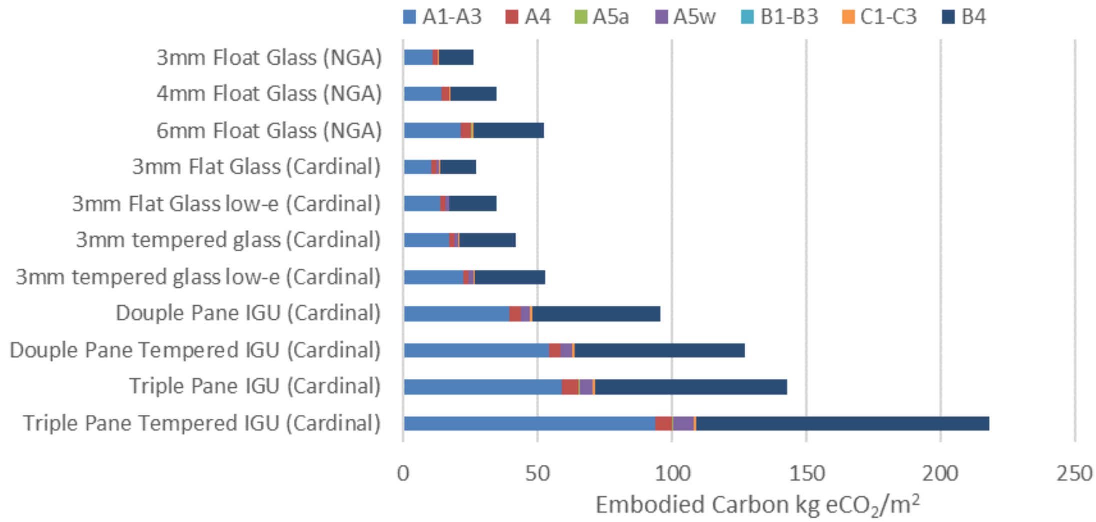


Figure B8: Embodied Carbon of Glazing Components and IGUs

A 30-year IGU service life has been assumed in this study, meaning that one replacement of the IGUs will occur throughout the building 60 year assumed lifecycle. This makes B4 emissions a significant contributor to the overall embodied carbon emissions of fenestration components. If fenestration components need to be replaced more often due to poor design, manufacturing, or installation, the embodied carbon emissions can increase significantly.

Recommendation and Insight

More product and application specific EPD data is needed to assess the full impact of design, manufacturing, and installation of glazing systems. This is needed to encourage low embodied carbon and durable systems that do not require frequent replacement. Nevertheless, when assessing embodied carbon, the applications that minimize replacement are the solutions that need to be targeted to have the greatest impact in practice.

Fenestration Materials

Material (Owner of EPD)	Issued	Density	A1-A3 Emissions	A4 Location
PVC, processed (VSI)	Jul 2022	1,300 kg/m3	1.74 kg CO_2e/kg	North America
Polypropylene, processed (VSI)	Jul 2022	1,300 kg/m3	2.70 kg CO_2e/kg	North America
IGU Silicone Sealant (Quartz)	Jan 2019	1,179 kg/m3	6.74 kg CO_2e/kg	North America
Polyamide 6 granules x 2 (Radici)	Sep 2020	1,350 kg/m3	10.12 kg CO_2e/kg	North America
Polyamide 66 granules x 2 (Radici)	Sep 2020	1,310 kg/m3	10.62 kg CO_2e/kg	North America
Fibreglass Mullion (ASMI Study)	Jun 2009	-	2.49 kg CO_2e/kg	North America
Aluminum extrusions, thermal (AEC)	Nov 2022	2,700 kg/m3	12.70 kg CO_2e/kg	North America

There are several EPDs published for standard size windows which are helpful for comparison between systems. However, the embodied carbon of windows varies with size due to the differences between IGU and frame relative impacts. An objective of this study was to assess such impacts and therefore used fenestration component embodied carbon impacts in our analysis.

The A1-A3 emissions were taken from EPD data of raw materials for IGUs, window framing components and whole assembled windows. To provide adequate analysis, the framing components and IGU data were combined to compare various window systems. Data was reviewed to determine whether framing or glazing components dominate the embodied carbon emissions of fenestration.

Insights

PVC and fiberglass framed fenestration had lower embodied carbon emissions than aluminum framed fenestration. However, aluminum framing still dominates the commercial fenestration market.

Aluminum store front and window wall systems have higher A1-A3 emissions than traditional curtain wall framing because the amount of aluminum framing required for the systems is significantly higher. **This indicates that the embodied carbon of fenestration is most affected by the framing components.** This is further reinforced by the embodied carbon values of the unitized curtain wall framing systems which have the highest A1-A3 emissions (with the exception of electrochromic glass).

A1-A3 emissions of fenestration components are significantly higher than individual opaque wall components. **Designers should be mindful of how much glazing is used on a project and should optimize the window-to-wall ratio to reduce embodied carbon emissions.**

Many manufacturers declare window system specific A1 - A3 emissions based on given dimensions. However, these dimensions are often different from other window manufacturers and North American Fenestration Standard (NAFS) standard sizes. Additionally, only one manufacturer separated the impact of framing from IGU components and all EPDs had product specific A1-A3 emissions. Manufacturers should aim to provide material results with multiplication factors to allow consultants to indicate relevant emissions when not using specific products.

The A4 emissions of glazing components do not contribute significantly to the overall embodied carbon emissions of the glazing system. However, locally manufactured fenestration systems can have lower total embodied carbon emissions than fenestration systems manufactured in Europe.

Although glass IGU waste on site is negligent, waste still occurs when site adjusting framing, applying sealants, or making replacements to framing components.

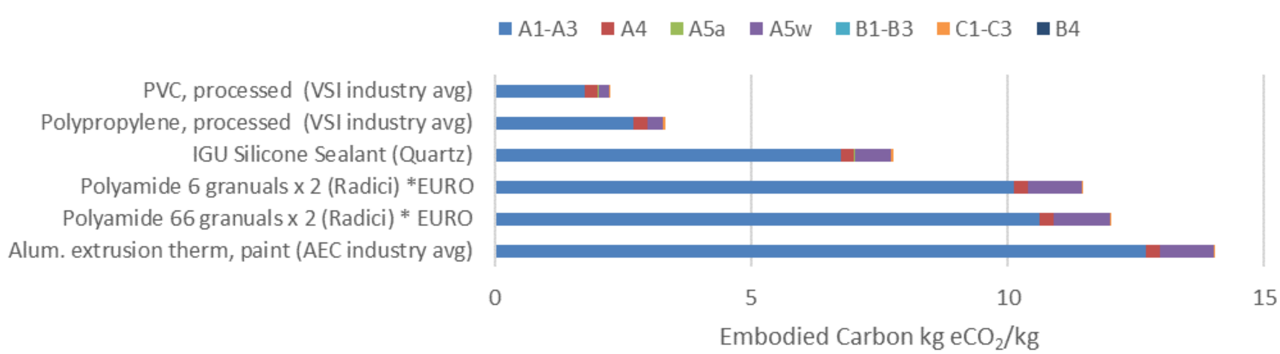


Figure B9: Embodied Carbon of Fenestration Components

Appendix C: Detailed Assumptions for Operational Emissions Calculations

Emission Factors

Table C1. Range of Published Emission Factors for BC and Alberta

Source	Electricity Emission Factor ($kgCO_2e$/ kWh)	Natural Gas Emission Factor ($kgCO_2e$/ ekWh)
City of Vancouver Energy Modelling Guidelines v2	0.011	0.185
BC Electricity emission intensity factors for grid-connected entities, for 2022 (Ministry of Environment and Climate Change Strategy)	0.0115	Not Published (use other sources)
B.C. Best Practices Methodology for Quantifying Greenhouse Gas Emissions (April 2021)	0.011	0.180
BC Electricity emission intensity factors for grid-connected entities, for 2020 (Ministry of Environment and Climate Change Strategy)	0.040	Not Published (other sources used)
Portfolio Manager Technical Reference - Greenhouse Gas Emissions (August 2021) – BC Indirect emissions	0.013	0.181
Portfolio Manager Technical Reference - Greenhouse Gas Emissions (August 2021) – BC Non-Baseload Factors for Avoided Emissions	0.419	0.181
Portfolio Manager Technical Reference - Greenhouse Gas Emissions (August 2021) - Alberta Indirect emissions	0.690	0.182
Portfolio Manager Technical Reference - Greenhouse Gas Emissions (August 2021) - Alberta Non-Baseload Factors for Avoided Emissions	0.465	0.182

Vancouver Operational vs Embodied Carbon Emissions

Table C2. Vancouver Operational versus Embodied Carbon Emissions for Triple Glazing ECMs (kg CO2 e/m^2) for the Residential Windows with 40% Glazing

Heating and DHW Fuel Source	Glazing	Energy Efficiency Measure	Operational Emissions: EUI (ekWh/m^2/yr)	TEDI (ekWh/m^2/yr)	GHGI ($kgCO_2e/m^2/yr$)	EUI Step (BC Step)	GHGI ($kgCO_2e/m^2$)	GHGI Reduction ($kgCO_2e/m^2$)	Embodied Carbon ($kgCO_2e/m^2$)
Natural Gas	Double	minimum	110	30	10.71	3	643	120	7 to 15
	Triple		99	20	8.71	3	523		
	Double	best case ECM	93	14	7.66	4	460	105	
	Triple		84	5	5.91	4	355		
Electrical	Double	minimum	107	30	1.18	3	71	7	
	Triple		96	20	1.06	3	64		
	Double	best case ECM	91	14	1.00	4	60	5	
	Triple		82	8	0.91	4	55		

Table C3. Vancouver Operating Energy Results

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m2/yr)	TEDI (ekWh/m2/yr)	GHGI (kgCO2e/m2/yr)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	5	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.86	36.8	12.01	3	2	2
0.5	Typical Double Glazed	5	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.86	36.8	12.01	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	109.71	29.98	10.71	3	3	3
0.5	Typical Double Glazed	10	80%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	103.4	23.9	9.55	3	3	3
0.5	Typical Double Glazed	10	60%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	104.07	24.37	9.64	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	105.5	27.56	10.24	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	112.67	32.36	11.17	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	115.66	34.73	11.63	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Elec. Resist.	CoV EMG	108.42	29.98	6.20	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	Provincial 2020	109.71	29.98	12.71	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	Non-Baseload BC Portfolio Mgr	109.71	29.98	32.54	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	High-Carbon Grid	109.71	29.98	46.73	3	3	3
0.5	Typical Double Glazed	15	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	105.71	26.18	9.98	3	3	3
0.5	Typical Double Glazed	20	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	103.91	24.51	9.66	3	3	3
0.5	Typical Double Glazed	25	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	103.4	24.06	9.57	3	3	3
0.5	Typical Double Glazed	30	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	103.25	23.93	9.55	3	3	3
0.5	Typical Double Glazed	35	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	102.54	23.23	9.41	3	3	3
0.5	Typical Double Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	93.38	14.06	7.66	4	4	4
0.5	Improved Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	107.79	28.28	10.38	3	3	3

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m2/yr)	TEDI (ekWh/m2/yr)	GHGI (kgCO2e/m2/yr)	EUI Step	TEDI Step	Step
0.5	Typical Triple Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	101.84	22.46	9.27	3	3	3
0.5	Improved Triple Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	98.72	19.55	8.71	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	99.49	20.48	8.89	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	97.92	18.56	8.53	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	97.15	17.56	8.34	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	83.87	4.93	5.91	4	4	4
0.7	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	125.11	44.08	13.41	2	2	2
0.9	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	140.9	58.5	16.18	0	0	0
0.5	Typical Double Glazed	5	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.63	36.8	1.25	3	2	2
0.5	Typical Double Glazed	5	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.63	36.8	1.25	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Natural Gas	CoV EMG	108.33	29.98	5.89	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	106.84	29.98	1.18	3	3	3
0.5	Typical Double Glazed	10	80%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	100.85	23.9	1.11	3	3	3
0.5	Typical Double Glazed	10	60%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	101.50	24.37	1.12	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	30%	Elec. Resist.	Elec. Resist.	CoV EMG	102.76	27.56	1.13	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	109.68	32.36	1.21	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	112.54	34.73	1.24	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	Provincial 2020	106.84	29.98	4.28	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	Non-Baseload BC Portfolio Mgr	106.84	29.98	44.76	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	High-Carbon Grid	106.84	29.98	73.72	3	3	3

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m2/yr)	TEDI (ekWh/m2/yr)	GHGI (kgCO2e/m2/yr)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	15	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	103.04	26.18	1.13	3	3	3
0.5	Typical Double Glazed	20	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	101.33	24.51	1.11	3	3	3
0.5	Typical Double Glazed	25	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	100.84	24.06	1.11	3	3	3
0.5	Typical Double Glazed	30	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	100.70	23.93	1.11	3	3	3
0.5	Typical Double Glazed	35	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	100.03	23.23	1.10	3	3	3
0.5	Typical Double Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	91.35	14.06	1.00	4	4	4
0.5	Improved Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	105.01	28.28	1.16	3	3	3
0.5	Typical Triple Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	99.37	22.46	1.09	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	0.4	Elec. Resist.	Elec. Resist.	CoV EMG	96.40	19.55	1.06	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	30%	Elec. Resist.	Elec. Resist.	CoV EMG	97.12	20.48	1.07	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	95.65	18.56	1.05	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	94.93	17.56	1.04	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	82.32	4.93	0.91	4	4	4
0.7	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	121.50	44.08	1.34	2	2	2
0.9	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	136.53	58.50	1.50	0	0	0

Kamloops Operational vs Embodied Carbon Emissions

Table C4. Kamloops Operational versus Embodied Carbon Emissions for Triple Glazing ECMs (kg CO2 e/m^2) **for the Residential Windows with 40% Glazing**

Heating and DHW Fuel Source	Glazing	Energy Efficiency Measure	Operational Emissions: EUI (ekWh/m^2/yr)	TEDI (ekWh/m^2/yr)	GHGI (kgCO_2e/m^2/yr)	EUI Step (BC Step)	GHGI (kgCO_2e/m^2)	GHGI Reduction (kgCO_2e/m^2)	Embodied Carbon (kgCO_2e/m^2)
Natural Gas	Double	minimum	123.79	40.29	12.75	2	765	136	7 to 15
	Triple		110.81	28.45	10.48	2	629		
	Double	best case ECM	103.69	20.69	9.00	4	540	126	
	Triple		91.35	9.77	6.90	4	414		
Electrical	Double	minimum	120.38	40.29	1.32	2	79	8	
	Triple		108.02	28.45	1.19	3	71		
	Double	best case ECM	102.38	20.69	1.13	4	68	8	
	Triple		91.04	9.77	1.00	4	60		

Table C5. Kamloops Operating Energy Results

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI (kgCO₂e/m²/yr)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	5	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	132.46	48.40	14.30	0	0	0
0.5	Typical Double Glazed	5	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	132.46	48.40	14.30	0	0	0
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	123.79	40.29	12.75	2	2	2
0.5	Typical Double Glazed	10	80%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.29	33.12	11.38	3	3	3
0.5	Typical Double Glazed	10	60%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.84	33.56	11.46	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Elec. Resist.	CoV EMG	122.50	40.29	8.24	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	120.19	37.55	12.22	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	127.36	42.99	13.27	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	130.94	45.68	13.80	0	0	0
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	Provincial 2020	123.79	40.29	14.85	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	Non-Baseload BC Portfolio Mgr	123.79	40.29	35.90	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	High-Carbon Grid	123.79	40.29	50.96	2	2	2
0.5	Typical Double Glazed	15	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	118.91	35.76	11.88	3	2	2
0.5	Typical Double Glazed	20	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.72	33.75	11.50	3	3	3
0.5	Typical Double Glazed	25	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	116.09	33.19	11.39	3	3	3
0.5	Typical Double Glazed	30	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	115.92	33.05	11.36	3	3	3
0.5	Typical Double Glazed	35	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	115.09	32.24	11.21	3	3	3
0.5	Typical Double Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	103.25	20.69	9.00	4	4	4

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI (kgCO₂e/m²/yr)	EUI Step	TEDI Step	Step
0.5	Improved Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	121.55	38.45	12.39	2	2	2
0.5	Typical Triple Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	114.57	31.80	11.12	3	3	3
0.5	Improved Triple Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	110.81	28.45	10.48	3	3	3
0.5	Improved Triple Glazed	10	60%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	111.60	29.49	10.68	3	3	3
0.5	Improved Triple Glazed	10	60%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	109.98	27.34	10.27	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	109.15	25.12	10.06	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	91.35	9.77	6.90	4	4	4
0.7	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	142.45	56.81	15.92	0	0	0
0.9	Typical Double Glazed	10	60%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	161.45	73.57	19.15	0	0	0
0.5	Typical Double Glazed	5	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	128.62	48.40	1.41	2	0	0
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Natural Gas	CoV EMG	121.92	40.29	6.21	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	120.38	40.29	1.32	2	2	2
0.5	Typical Double Glazed	10	80%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.26	33.12	1.25	3	3	3
0.5	Typical Double Glazed	10	60%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.78	33.56	1.25	3	3	3
0.5	Typical Double Glazed	10	60%	0.2	30%	Elec. Resist.	Elec. Resist.	CoV EMG	116.92	37.55	1.29	3	2	2
0.5	Typical Double Glazed	10	60%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	123.81	42.99	1.36	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	127.24	45.68	1.40	2	0	0
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	Provincial 2020	120.38	40.29	4.83	2	2	2
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	Non-Baseload BC Portfolio Mgr	120.38	40.29	50.43	2	2	2

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI (kgCO₂e/m²/yr)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	High-Carbon Grid	120.38	40.29	83.06	2	2	2
0.5	Typical Double Glazed	15	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	115.74	35.76	1.27	3	2	2
0.5	Typical Double Glazed	20	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.65	33.75	1.25	3	3	3
0.5	Typical Double Glazed	25	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	113.05	33.19	1.24	3	3	3
0.5	Typical Double Glazed	30	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	112.89	33.05	1.24	3	3	3
0.5	Typical Double Glazed	35	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	112.10	32.24	1.23	3	3	3
0.5	Typical Double Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	102.38	20.69	1.13	4	4	4
0.5	Improved Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	118.24	38.45	1.30	3	2	2
0.5	Typical Triple Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	111.61	31.80	1.23	3	3	3
0.5	Improved Triple Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	108.02	28.45	1.19	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	0.3	Elec. Resist.	Elec. Resist.	CoV EMG	108.76	29.49	1.20	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	107.25	27.34	1.18	4	3	3
0.5	Improved Triple Glazed	10	60%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	106.54	25.12	1.17	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	91.04	9.77	1.00	4	4	4
0.7	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	138.17	56.81	1.52	0	0	0
0.9	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	156.29	73.57	1.72	0	0	0
0.9	Typical Double Glazed	10	60%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	136.53	58.50	1.50	0	0	0

Prince George Operational vs Embodied Carbon Emissions

Table C6. Prince George Operational versus Embodied Carbon Emissions for Triple Glazing ECMs (kg CO2 e/m^2) **for the Residential Windows with 40% Glazing**

		Operational Emissions							Embodied Carbon
Heating and DHW Fuel Source	Glazing	Energy Efficiency Measure	EUI	TEDI	GHGI	EUI Step	GHGI	GHGI Reduction	
			(ekWh/m^2/yr)	(ekWh/m^2/yr)	($kgCO_2e/m^2$/yr)	BC Step	($kgCO_2e/m^2$)	($kgCO_2e/m^2$)	($kgCO_2e/m^2$)
Natural Gas	Double	minimum	129.48	48.83	14.40	2	864	187	7 to 15
	Triple		112.30	32.54	11.28	3	677		
	Double	best case ECM	109.12	29.34	10.67	4	640	177	
	Triple		93.09	13.93	7.72	4	463		
Electrical	Double	minimum	125.62	48.83	1.38	2	83	11	
	Triple		109.30	32.54	1.20	4	72		
	Double	best case ECM	107.87	29.34	1.19	4	71	11	
	Triple		91.07	13.93	1.00	4	60		

Table C7. Prince George Operating Energy Results

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI (kgCO₂e/m²/yr)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	5	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	141.19	59.92	16.52	0	0	0
0.5	Typical Double Glazed	5	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	141.19	59.92	16.52	0	0	0
0.5	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	129.48	48.83	14.40	2	2	2
0.5	Typical Double Glazed	10	80%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	124.42	43.99	13.47	2	2	2
0.5	Typical Double Glazed	10	70%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	123.46	43.02	13.29	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	124.87	44.71	13.61	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	134.05	52.87	15.17	2	0	0
0.5	Typical Double Glazed	10	70%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	138.63	56.88	15.94	0	0	0
0.5	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Elec. Resist.	CoV EMG	128.19	48.83	9.89	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	Provincial 2020	129.48	48.83	16.38	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	Non-Baseload BC Portfolio Mgr	129.48	48.83	36.18	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	High-Carbon Grid	129.48	48.83	50.35	2	2	2
0.5	Typical Double Glazed	15	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	122.93	42.66	13.22	2	2	2
0.5	Typical Double Glazed	20	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	120.01	39.94	12.70	2	2	2
0.5	Typical Double Glazed	25	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	119.21	39.23	12.56	3	2	2
0.5	Typical Double Glazed	30	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	119.02	39.08	12.53	3	2	2
0.5	Typical Double Glazed	35	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	117.92	38.02	12.33	3	2	2
0.5	Typical Double Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	109.12	29.34	10.67	4	3	3

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI (kgCO₂e/m²/yr)	EUI Step	TEDI Step	Step
0.5	Improved Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	126.69	46.26	13.91	2	2	2
0.5	Typical Triple Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	117.35	37.27	12.19	3	2	2
0.5	Improved Triple Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	112.30	32.54	11.28	3	3	3
0.5	Improved Triple Glazed	10	70%	0.2	30%	Natural Gas Hydronic	Natural Gas	CoV EMG	113.40	33.70	11.51	3	3	3
0.5	Improved Triple Glazed	10	70%	0.2	50%	Natural Gas Hydronic	Natural Gas	CoV EMG	111.14	31.28	11.04	3	3	3
0.5	Improved Triple Glazed	10	70%	0.2	60%	Natural Gas Hydronic	Natural Gas	CoV EMG	109.97	29.95	10.79	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	93.09	13.93	7.72	4	4	4
0.7	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	152.82	70.52	18.56	0	0	0
0.9	Typical Double Glazed	10	70%	0.2	40%	Natural Gas Hydronic	Natural Gas	CoV EMG	176.25	92.29	22.72	0	0	0
0.5	Typical Double Glazed	5	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	136.75	59.92	1.50	0	0	0
0.5	Typical Double Glazed	5	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	136.75	59.92	1.50	0	0	0
0.5	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Natural Gas	CoV EMG	121.92	40.29	6.21	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	125.62	48.83	1.38	2	2	2
0.5	Typical Double Glazed	10	80%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	120.81	43.99	1.33	2	2	2
0.5	Typical Double Glazed	10	70%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	119.90	43.02	1.32	3	2	2
0.5	Typical Double Glazed	10	70%	0.2	30%	Elec. Resist.	Elec. Resist.	CoV EMG	121.23	44.71	1.33	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	129.98	52.87	1.43	2	0	0
0.5	Typical Double Glazed	10	70%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	134.35	56.88	1.48	2	0	0
0.5	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	Provincial 2020	125.62	48.83	5.04	2	2	2

VFAR	Window system	Wall R (effective)	Heat Recovery	Airtightness	WWR	Mech System Type	DHW Fuel Source	Emission Factors	EUI (ekWh/m²/yr)	TEDI (ekWh/m²/yr)	GHGI ($kgCO_2e/m^2/yr$)	EUI Step	TEDI Step	Step
0.5	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	Non-Baseload BC Portfolio Mgr	125.62	48.83	52.62	2	2	2
0.5	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	High-Carbon Grid	125.62	48.83	86.68	2	2	2
0.5	Typical Double Glazed	15	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	119.39	42.66	1.31	3	2	2
0.5	Typical Double Glazed	20	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	116.62	39.94	1.28	3	2	2
0.5	Typical Double Glazed	25	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	115.85	39.23	1.27	3	2	2
0.5	Typical Double Glazed	30	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	115.67	39.08	1.27	3	2	2
0.5	Typical Double Glazed	35	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	114.63	38.02	1.26	3	2	2
0.5	Typical Double Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	107.87	29.34	1.19	4	3	3
0.5	Improved Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	122.96	46.26	1.35	2	2	2
0.5	Typical Triple Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	114.10	37.27	1.26	3	2	2
0.5	Improved Triple Glazed	10	70%	0.2	0.4	Elec. Resist.	Elec. Resist.	CoV EMG	109.30	32.54	1.20	4	3	3
0.5	Improved Triple Glazed	10	70%	0.2	30%	Elec. Resist.	Elec. Resist.	CoV EMG	110.34	33.70	1.21	3	3	3
0.5	Improved Triple Glazed	10	70%	0.2	50%	Elec. Resist.	Elec. Resist.	CoV EMG	108.20	31.28	1.19	4	3	3
0.5	Improved Triple Glazed	10	70%	0.2	60%	Elec. Resist.	Elec. Resist.	CoV EMG	107.10	29.95	1.18	4	3	3
0.5	Improved Triple Glazed	35	80%	0.08	40%	Elec. Resist.	Elec. Resist.	CoV EMG	91.07	13.93	1.00	4	4	4
0.7	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	147.82	70.52	1.63	0	0	0
0.9	Typical Double Glazed	10	70%	0.2	40%	Elec. Resist.	Elec. Resist.	CoV EMG	170.10	92.29	1.87	0	0	0

Building 1 Overall Thermal Transmittance Calculations

Table C8. Quantities for Commercial Levels 1 and 2

	30% Glazing				40% Glazing				50% Glazing			
Brick Veneer Assembly	449	m^2	4833	ft^2	435	m^2	4,682	ft^2	378	m^2	4,069	ft^2
Roof-to-wall	40	m	429	ft	40	m	429	ft	40	m	429	ft
Intermediate Floor	97	m	1044	ft	97	m	1,041	ft	97	m	1,044	ft
At-Grade	71	m	764	ft	71	m	759	ft	71	m	764	ft
Window Head	85	m	915	ft	143	m	1,538	ft	103	m	1,109	ft
Window Jamb	243	m	2616	ft	310	m	3,335	ft	291	m	3,132	ft
Window Sill	85	m	915	ft	143	m	1,538	ft	103	m	1,109	ft
Canopy	35				35				35			

Table C9. Quantities for Common Alley Levels 1 to 7

	30% Glazing				40% Glazing				50% Glazing			
Interior insulated concrete	160	m^2	1717	ft^2	160	m^2	1717	ft^2	160	m^2	1717	ft^2
Intermediate Floor	34	m	369	ft	34	m	369	ft	34	m	369	ft
Roof-to-wall	8	m	86	ft	8	m	86	ft	8	m	86	ft
At-Grade	34	m	365	ft	34	m	365	ft	34	m	365	ft

Table C10. Quantities for Residential Levels 3 to 17

	30% Glazing				40% Glazing				50% Glazing			
Split insulated steel-framed wall	3,286	m^2	35,370	ft^2	2,896	m^2	31,170	ft^2	2384	m^2	25,661	ft^2
Roof-to-wall	195	m	2095	ft	195	m	2,095	ft	195	m	2,095	ft
Intermediate Floor	591	m	6361	ft	591	m	6,362	ft	591	m	6,361	ft
Balcony at Door	149	m	1604	ft	149	m	1,604	ft	149	m	1,604	ft
Balcony at Wall	189	m	2034	ft	189	m	2,039	ft	189	m	2,034	ft
Window Head	682	m	7341	ft	792	m	8,525	ft	974	m	10,484	ft
Window Jamb	1,469	m	15,812	ft	1,691	m	18,203	ft	2176	m	23,422	ft
Window Sill	682	m	7341	ft	792	m	8,525	ft	974	m	10,484	ft
Balcony point connection	82				82				82			

Table C11. Glazing Quantities

	30% Glazing				40% Glazing				50% Glazing			
Commercial, Levels 1 and 2	345	m^2	3,714	ft^2	362	m^2	3,896	ft^2	416	m^2	4,478	ft^2
Residential, Levels 3 to 17	1,288	m^2	13,864	ft^2	1,678	m^2	18,061	ft^2	2189	m^2	23,562	ft^2
Total Glazing	1,633	m^2	17,577	ft^2	2,040	m^2	21,957	ft^2	2605	m^2	28,040	ft^2
Total Opaque	3,895	m^2	41,920	ft^2	3,490	m^2	37,569	ft^2	2922	m^2	31,447	ft^2
Ratio	30%				37%				47%			

Table C12. Thermal Transmittances for Commercial Levels 1 and 2

	Unmitigated					Mitigated					Mitigated + Insulation				
Brick Veneer Assembly	0.284	W/m^{2}K	0.050	BTU/ft^2·°F·hr	7.3.14	0.284	W/m^{2}K	0.050	BTU/ft^2·°F·hr	7.3.15	0.210	W/m^{2}K	0.037	BTU/ft^2·°F·hr	7.1.13
Roof-to-wall	0.502	W/m K	0.290	BTU/ft·°F·hr	5.5.11	0.209	W/m K	0.121	BTU/ft·°F·hr	7.5.12	0.189	W/m K	0.109	BTU/ft·°F·hr	5.5.24
Intermediate Floor	0.506	W/m K	0.293	BTU/ft·°F·hr	7.2.22	0.093	W/m K	0.054	BTU/ft·°F·hr	7.2.23	0.093	W/m K	0.054	BTU/ft·°F·hr	7.2.23
At-Grade	0.557	W/m K	0.322	BTU/ft·°F·hr	7.7.9	0.418	W/m K	0.242	BTU/ft·°F·hr	7.7.10	0.102	W/m K	0.059	BTU/ft·°F·hr	5.8.2
Window Head	0.626	W/m K	0.362	BTU/ft·°F·hr	7.3.14	0.026	W/m K	0.015	BTU/ft·°F·hr	7.3.15	0.026	W/m K	0.015	BTU/ft·°F·hr	7.3.15
Window Jamb	0.132	W/m K	0.076	BTU/ft·°F·hr	7.3.14	0.100	W/m K	0.058	BTU/ft·°F·hr	7.3.15	0.100	W/m K	0.058	BTU/ft·°F·hr	7.3.15
Window Sill	0.227	W/m K	0.131	BTU/ft·°F·hr	7.3.14	0.026	W/m K	0.015	BTU/ft·°F·hr	7.3.15	0.026	W/m K	0.015	BTU/ft·°F·hr	7.3.15
Canopy	0.480	W/m K	0.900	BTU/ft·°F·hr	5.7.6	0.116	W/m K	0.067	BTU/ft·°F·hr	2.4.1	0.116	W/m K	0.067	BTU/ft·°F·hr	2.4.1

Table C13. Thermal Transmittances for Common Alley Levels 1 to 7

	Unmitigated					Mitigated					Mitigated + Insulation				
Interior insulated concrete	0.370	W/m^{2}K	0.065	BTU/ft^2·°F·hr	7.1.14	0.370	W/m^{2}K	0.214	BTU/ft^2·°F·hr	7.1.14	0.370	W/m^{2}K	0.065	BTU/ft^2·°F·hr	7.1.14
Intermediate Floor	0.865	W/m K	0.500	BTU/ft·°F·hr	7.2.5	0.865	W/m K	0.500	BTU/ft·°F·hr	7.2.5	0.865	W/m K	0.500	BTU/ft·°F·hr	7.2.5
Roof-to-wall	0.777	W/m K	0.449	BTU/ft·°F·hr	7.5.3	0.777	W/m K	0.449	BTU/ft·°F·hr	7.5.3	0.777	W/m K	0.449	BTU/ft·°F·hr	7.5.3
At-Grade	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1

Table C14. Thermal Transmittances for Residential Levels 3 to 17

	Unmitigated					Mitigated					Mitigated + Insulation				
Split insulated steel-framed wall	0.187	W/m^{2}K	0.033	BTU/ft^2·°F·hr	5.1.147	0.187	W/m^{2}K	0.108	BTU/ft^2·°F·hr	5.1.147	0.144	W/m^{2}K	0.025	BTU/ft^2·°F·hr	5.1.147
Roof-to-wall	0.657	W/m K	0.380	BTU/ft·°F·hr	5.1.5.13	0.212	W/m K	0.123	BTU/ft·°F·hr	7.5.12	0.111	W/m K	0.192	BTU/ft·°F·hr	5.5.21
Intermediate Floor	0.069	W/m K	0.040	BTU/ft·°F·hr	5.2.35	0.069	W/m K	0.040	BTU/ft·°F·hr	5.5.17	0.015	W/m K	0.026	BTU/ft·°F·hr	5.2.14
Balcony at Door	1.780	W/m K	1.029	BTU/ft·°F·hr	9.1.4	0.325	W/m K	0.188	BTU/ft·°F·hr	9.1.15	0.170	W/m K	0.294	BTU/ft·°F·hr	9.1.151
Balcony at Wall	1.059	W/m K	0.612	BTU/ft·°F·hr	5.2.5	0.327	W/m K	0.189	BTU/ft·°F·hr	5.2.14	0.183	W/m K	0.317	BTU/ft·°F·hr	5.2.47
Window Head	0.525	W/m K	0.303	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.043	BTU/ft·°F·hr	5.3.24
Window Jamb	0.176	W/m K	0.102	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.043	BTU/ft·°F·hr	5.3.25
Window Sill	0.273	W/m K	0.158	BTU/ft·°F·hr	5.3.15	0.019	W/m K	0.011	BTU/ft·°F·hr	5.3.24	0.025	W/m K	0.043	BTU/ft·°F·hr	5.3.25
Balcony point connection	0.1	W/ K	0.058	BTU/ft·°F·hr	5.7.11, 2.4.1	0.1	W/ K	0.058	BTU/ft·°F·hr	5.7.11, 2.4.1	0.1	W/ K	0.173	BTU/ft·°F·hr	5.7.11, 2.4.1

Table C15. Heat Flow (W/K) for Quantities for Commercial Levels 1 and 2

	Unmitigated			Mitigated			Mitigated + Insulation		
	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing
Brick Veneer Assembly	127.5	123.5	107.4	127.5	123.5	107.4	94.3	91.4	79.4
Roof-to-wall	20.0	20.0	20.0	8.3	8.3	8.3	7.5	7.5	7.5
Intermediate Floor	49.1	48.9	49.1	9.0	9.0	9.0	9.0	9.0	9.0
At-Grade	39.5	39.3	39.5	29.7	29.5	29.7	7.2	7.2	7.2
Window Head	53.2	89.4	64.5	2.2	3.7	2.7	2.2	3.7	2.7
Window Jamb	32.1	40.9	38.4	24.3	31.0	29.1	24.3	31.0	29.1
Window Sill	19.3	32.4	23.4	2.2	3.7	2.7	2.2	3.7	2.7
Canopy	16.8	16.8	16.8	4.1	4.1	4.1	4.1	4.1	4.1
Total Heat Flow (W/K)	358	411	359	207	213	193	151	158	142
Area (m^2)	449	435	378	449	435	378	449	435	378
% Details	64%	70%	70%	38%	42%	44%	37%	42%	44%
Overall Effective R-Value	7.1	6.0	6.0	12.3	11.6	11.1	16.9	15.7	15.1

Table C16. Heat Flow (W/K) for Common Alley Levels 1 to 7

	Unmitigated			Mitigated			Mitigated + Insulation		
	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing
Interior insulated concrete	59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0	59.0
Intermediate Floor	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
Roof-to-wall	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
At-Grade	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Total Heat Flow (W/K)	118	118	118	118	118	118	118	118	118
Area (m^2)	160	160	160	160	160	160	160	160	160
% Details	50%	50%	50%	50%	50%	50%	50%	50%	50%
Overall Effective R-Value	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7

Table C17. Heat Flow (W/K) for Residential Levels 3 to 17

	Unmitigated			Mitigated			Mitigated + Insulation		
	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing	30% Glazing	40% Glazing	50% Glazing
Split insulated steel-framed wall	614.5	541.5	445.8	614.5	541.5	445.8	473.2	417.0	343.3
Roof-to-wall	127.9	127.9	127.9	41.3	41.3	41.3	21.6	21.6	21.6
Intermediate Floor	40.8	40.8	40.8	40.8	40.8	40.8	8.9	8.9	8.9
Balcony at Door	265.2	265.2	265.2	48.4	48.4	48.4	25.3	25.3	25.3
Balcony at Wall	200.2	200.6	200.2	61.8	61.9	61.8	34.6	34.7	34.6
Window Head	358.1	415.8	511.4	18.4	21.4	26.3	17.1	19.8	24.4
Window Jamb	258.5	297.6	383.0	39.7	45.7	58.8	36.7	42.3	54.4
Window Sill	186.2	216.2	265.9	13.0	15.0	18.5	17.1	19.8	24.4
Balcony point connection	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2	8.2
Total Heat Flow (W/K)	2059	2114	2248	886	824	750	643	598	545
Area (m^2)	3286	2896	2384	3286	2896	2384	3286	2896	2384
% Details	70%	74%	80%	31%	34%	41%	26%	30%	37%
Overall Effective R-Value	9.1	7.8	6.0	21.1	19.9	18.1	29.0	27.5	24.8

Building 2 Overall Thermal Transmittance Calculations

Table C18. Quantities for Commercial Level 1

Interior insulated concrete	140	m^2	1,507	ft^2
Wall at-grade	22	m	72	ft
Curtain-wall at-grade	64	m	210	ft
Door at-grade	8	m	28	ft
Window Head	64	m	210	ft
Window Jamb	154	m	505	ft

Table C19. Quantities for Residential Levels 2 to 5

Split insulated wood-framed	950	m^2	10,226	ft^2
Roof-to-wall	197	m	646	ft
Intermediate Floor	267	m	876	ft
Balcony at Door	73	m	240	ft
Balcony at Wall	170	m	558	ft
Door Head	73	m	240	ft
Door Jamb	195	m	640	ft
Window Head	212	m	696	ft
Window Jamb	434	m	1,424	ft
Window Sill	212	m	696	ft

Table C20. Glazing Quantities

Commercial, Level 1	234	m^2	2,519	ft^2
Residential, Levels 2 to 5	447	m^2	4811	ft^2
Total Glazing	681	m^2	7,330	ft^2
Total Opaque	1,090	m^2	11,733	ft^2
Ratio	38%			

Table C21. **Thermal Transmittances for Commercial Level 1**

	Unmitigated					Mitigated					Mitigated + Insulation				
Interior insulated concrete	0.320	W/m^{2}K	0.056	BTU/ft^2·°F·hr	7.1.14	0.320	W/m^{2}K	0.056	BTU/ft^2·°F·hr	7.1.14	0.210	W/m^{2}K	0.037	BTU/ft·°F·hr	7.1.22
Wall at-grade	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1	0.506	W/m K	0.292	BTU/ft·°F·hr	5.8.2	0.102	W/m K	0.059	BTU/ft·°F·hr	5.8.2
Curtain-wall at-grade	0.640	W/m K	0.370	BTU/ft·°F·hr	2.5.1	0.506	W/m K	0.292	BTU/ft·°F·hr	5.8.2	0.102	W/m K	0.059	BTU/ft·°F·hr	5.8.2
Door at-grade	0.640	W/m K	0.370	BTU/ft·°F·hr	2.5.1	0.506	W/m K	0.292	BTU/ft·°F·hr	5.8.2	0.102	W/m K	0.059	BTU/ft·°F·hr	5.8.2
Window Head	0.295	W/m K	0.171	BTU/ft·°F·hr	7.4.3	0.250	W/m K	0.145	BTU/ft·°F·hr	7.3.15	0.077	W/m K	0.045	BTU/ft·°F·hr	7.4.5
Window Jamb	0.295	W/m K	0.171	BTU/ft·°F·hr	7.4.3	0.101	W/m K	0.058	BTU/ft·°F·hr	7.3.15	0.077	W/m K	0.045	BTU/ft·°F·hr	7.4.5

Table C22. **Thermal Transmittances for Residential Levels 2 to 5**

	Unmitigated					Mitigated					Mitigated + Insulation				
Split insulated wood-framed*	0.167	W/m^{2}K	0.029	BTU/ft^2·°F·hr	8.1.31	0.167	W/m^{2}K	0.029	BTU/ft^2·°F·hr	8.1.31	0.136	W/m^{2}K	0.024	BTU/ft^2·°F·hr	8.1.31
Roof-to-wall	0.045	W/m K	0.026	BTU/ft·°F·hr	8.4.1	0.045	W/m K	0.026	BTU/ft·°F·hr	8.4.1	0.045	W/m K	0.078	BTU/ft·°F·hr	8.4.1 / 8.4.5
Intermediate Floor	0.077	W/m K	0.045	BTU/ft·°F·hr	8.2.1	0.021	W/m K	0.012	BTU/ft·°F·hr	8.3.7	0.021	W/m K	0.036	BTU/ft·°F·hr	8.3.7
Balcony at Door	0.115	W/m K	0.066	BTU/ft·°F·hr	8.2.3	0.115	W/m K	0.066	BTU/ft·°F·hr	8.2.3	0.115	W/m K	0.199	BTU/ft·°F·hr	8.2.3
Balcony at Wall	0.115	W/m K	0.066	BTU/ft·°F·hr	8.2.3	0.021	W/m K	0.012	BTU/ft·°F·hr	8.3.7	0.021	W/m K	0.036	BTU/ft·°F·hr	8.3.7
Door Head	0.049	W/m K	0.028	BTU/ft·°F·hr	8.3.2	0.041	W/m K	0.024	BTU/ft·°F·hr	8.3.7	0.041	W/m K	0.071	BTU/ft·°F·hr	8.3.7
Door Jamb	0.045	W/m K	0.026	BTU/ft·°F·hr	8.3.2	0.029	W/m K	0.017	BTU/ft·°F·hr	8.3.7	0.029	W/m K	0.050	BTU/ft·°F·hr	8.3.7
Window Head	0.049	W/m K	0.028	BTU/ft·°F·hr	8.3.2	0.041	W/m K	0.024	BTU/ft·°F·hr	8.3.7	0.041	W/m K	0.071	BTU/ft·°F·hr	8.3.7
Window Jamb	0.045	W/m K	0.026	BTU/ft·°F·hr	8.3.2	0.029	W/m K	0.017	BTU/ft·°F·hr	8.3.7	0.029	W/m K	0.050	BTU/ft·°F·hr	8.3.7
Window Sill	0.021	W/m K	0.012	BTU/ft·°F·hr	8.3.2	0.026	W/m K	0.015	BTU/ft·°F·hr	8.3.7	0.026	W/m K	0.045	BTU/ft·°F·hr	8.3.7

*Back-up wall adjusted for additional 10% framing to get to an overall 25% framing factor

Table C23. Heat Flow (W/K) for Quantities for Commercial Level 1

	Unmitigated	Mitigated	Mitigated + Insulation
Interior insulated concrete	44.8	44.8	29.4
Wall at-grade	14.8	11.1	2.2
Curtain-wall at-grade	41.0	32.4	6.5
Door at-grade	5.4	4.3	0.9
Window Head	18.9	16.0	4.9
Window Jamb	45.4	15.6	11.9
Total Heat Flow (W/K)	170	124	56
Area (m^2)	140	140	140
% Details	74%	64%	47%
Overall Effective R-Value	4.7	6.4	14.2

Table C24. Heat Flow (W/K) for Quantities for Residential Levels 2 to 5

	Unmitigated	Mitigated	Mitigated + Insulation
Split insulated wood-framed	159	159	129
Roof-to-wall	8.9	8.9	8.9
Intermediate Floor	20.6	5.6	5.6
Balcony at Door	8.4	8.4	8.4
Balcony at Wall	19.6	3.6	3.6
Door Head	3.6	3.0	3.0
Door Jamb	8.8	5.7	5.7
Window Head	10.4	8.7	8.7
Window Jamb	19.5	12.6	12.6
Window Sill	4.5	5.5	5.5
Total Heat Flow (W/K)	263	221	191
Area (m^2)	950	950	950
% Details	40%	28%	32%
Overall Effective R-Value	20.5	24.5	28.2

Building 3 Overall Thermal Transmittance Calculations

Table C25. Quantities for Residential Levels 1 to 16

Exterior Insulated Concrete	1,249	m2	13,444	ft2
Split Insulated Steel-Framed	4,154	m2	44,713	ft2
Roof-to-wall at concrete	28	m	92	ft
Roof-to-wall at steel framed	151	m	495	ft
At-grade at concrete	28	m	92	ft
At-grade at steel framed	151	m	495	ft
Intermediate Floor - concrete	390	m	1,280	ft
Intermediate Floor - steel framed	1,262	m	4,140	ft
Balcony at Door	260	m	853	ft
Balcony at Wall	594	m	1,949	ft
Door Head	260	m	853	ft
Door Jamb	664	m	2,178	ft
Window Head	969	m	3,179	ft
Window Jamb	2,048	m	6,719	ft
Window Sill	969	m	3,179	ft

Table C26. Glazing Quantities

Doors	607	m^2	6,535	ft^2
Large window at Balcony	1,090	m^2	11,731	ft^2
Medium windows	920	m^2	9,900	ft^2
Glazing	2,617	m^2	28,165	ft^2
Opaque	5,403	m^2	58,157	ft^2
Ratio	33%			

Table C27. Thermal Transmittances for Residential Levels 1 to 16

	Unmitigated					Mitigated					Mitigated + Insulation				
Exterior Insulated Concrete	0.232	W/m^{2}K	0.041	BTU/ft^2·°F·hr	7.1.27, 7.1.27	0.238	W/m^{2}K	0.042	BTU/ft^2·°F·hr	7.1.27, 7.1.27	0.144	W/m^{2}K	0.025	BTU/ft^2·°F·hr	7.1.27, 7.1.27
Split Insulated Steel-Framed	0.248	W/m^{2}K	0.044	BTU/ft^2·°F·hr	5.1.142	0.248	W/m^{2}K	0.044	BTU/ft^2·°F·hr	5.1.142	0.169	W/m^{2}K	0.019	BTU/ft^2·°F·hr	5.1.147
Roof-to-wall at concrete	0.436	W/m K	0.252	BTU/ft·°F·hr	7.5.1	0.253	W/m K	0.146	BTU/ft·°F·hr	7.5.2	0.110	W/m K	0.064	BTU/ft·°F·hr	5.5.20
Roof-to-wall at steel framed	0.657	W/m K	0.380	BTU/ft·°F·hr	5.5.13	0.323	W/m K	0.187	BTU/ft·°F·hr	5.5.4	0.111	W/m K	0.064	BTU/ft·°F·hr	5.5.21
At-grade at concrete	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1	0.468	W/m K	0.271	BTU/ft·°F·hr	5.8.2	0.010	W/m K	0.006	BTU/ft·°F·hr	7.7.8
At-grade at steel framed	0.674	W/m K	0.390	BTU/ft·°F·hr	7.7.1	0.506	W/m K	0.292	BTU/ft·°F·hr	5.8.3	0.010	W/m K	0.006	BTU/ft·°F·hr	7.7.8
Intermediate Floor – concrete	0.051	W/m K	0.029	BTU/ft·°F·hr	7.2.24	0.051	W/m K	0.029	BTU/ft·°F·hr	7.2.24	0.023	W/m K	0.013	BTU/ft·°F·hr	7.2.1
Intermediate Floor – steel framed	0.056	W/m K	0.032	BTU/ft·°F·hr	5.2.16	0.056	W/m K	0.032	BTU/ft·°F·hr	5.2.16	0.015	W/m K	0.009	BTU/ft·°F·hr	5.2.39
Balcony at Door	1.780	W/m K	1.029	BTU/ft·°F·hr	9.1.4	0.496	W/m K	0.287	BTU/ft·°F·hr	5.2.3	0.496	W/m K	0.287	BTU/ft·°F·hr	5.2.3
Balcony at Wall	1.059	W/m K	0.612	BTU/ft·°F·hr	5.2.5	0.496	W/m K	0.287	BTU/ft·°F·hr	5.2.3	0.496	W/m K	0.287	BTU/ft·°F·hr	5.2.3
Door Head	0.525	W/m K	0.303	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.014	BTU/ft·°F·hr	5.3.24
Door Jamb	0.176	W/m K	0.102	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.014	BTU/ft·°F·hr	5.3.25
Window Head	0.525	W/m K	0.303	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.014	BTU/ft·°F·hr	5.3.24
Window Jamb	0.176	W/m K	0.102	BTU/ft·°F·hr	5.3.15	0.027	W/m K	0.016	BTU/ft·°F·hr	5.3.25	0.025	W/m K	0.014	BTU/ft·°F·hr	5.3.25
Window Sill	0.273	W/m K	0.158	BTU/ft·°F·hr	5.3.15	0.019	W/m K	0.011	BTU/ft·°F·hr	5.3.24	0.025	W/m K	0.014	BTU/ft·°F·hr	5.3.25

Table C28. **Heat Flow (W/K) for Quantities for Residential Levels 1 to 16**

	Unmitigated	Mitigated	Mitigated + Insulation
Exterior Insulated Concrete	289.2	297.3	179.9
Split Insulated Steel-Framed	1,028.1	1,030.2	702.4
Roof-to-wall at concrete	12.2	7.1	3.1
Roof-to-wall at steel framed	99.2	48.8	16.8
At-grade at concrete	18.9	13.1	0.3
At-grade at steel framed	101.8	76.4	1.5
Intermediate Floor - concrete	19.9	19.9	9.0
Intermediate Floor - steel framed	70.7	70.7	18.9
Balcony at Door	462.8	129.0	129.0
Balcony at Wall	629.0	294.6	294.6
Door Head	1,36.5	7.0	6.5
Door Jamb	116.9	17.9	16.6
Window Head	508.7	26.2	24.2
Window Jamb	360.4	55.3	51.2
Window Sill	264.5	18.4	24.2
Total Heat Flow (W/K)	4,119	2112	1,478
Area (m^2)	5,403	5,403	5,403
% Details	68%	37%	40%
Overall Effective R-Value	7.4	14.5	20.8

Glossary of Terms and Abbreviations

Term	Description
At-Grade Interface Detail	An interface detail at the transition between the above-grade wall assembly intersections with either an at-grade floor slab or below grade assemblies.
Building Elevation	A view of a building seen from one side, a flat representation of one façade. Elevations drawings typically show views of the exterior of a building by orientation (North, East, South or West).
Building Envelope	The elements of a building that separate the conditioned space from unconditioned space of a building. This includes walls, roofs, windows and doors.
Clear Field Assembly	Wall, floor and roof assemblies of a building.
CO_2 e	Carbon dioxide equivalent
Corner Interface Detail	Where walls meet at a corner of the building. Interface details can have additional heat flow when compared to the clear field assembly because of additional framing and relations to geometry (increased exterior surface area).
CoV EMG v2	City of Vancouver Energy Modelling Guidelines version 2 (referenced in the BC Energy Step Code).
Curtain Wall	A non-load bearing building façade that sits outboard of the main building structure made up of metal framing, vision glass and spandrel sections. The curtain wall only carries its own dead-load and lateral loads (wind).
Dynamic Thermal Response	The time variant heat flows through the building envelope that result in delayed heat gain or loss depending on the amount of energy that is stored within the building envelope. The amount of energy that is stored within the building envelope at any given time is related to the mass of all the combined components of the building envelope (thermal mass).
Embodied Carbon Emissions	Greenhouse gas emissions arising from the manufacturing, transportation, maintenance, retrofitting and disposal of building materials.
EPD	Environmental product declaration that quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function.

Term	Description
EUI	Energy Use Intensity is how much energy the building uses on an annual basis, divided by the building floor area. Also referred to as TEUI, or total energy use intensity, is measured in $kWh/m^2/year$.
Fenestration	All areas (including the frames) in the building envelope that let in light, including windows, plastic panels, clerestories, skylights, doors that are more than one-half glass, and glass block walls.
Floor Slab	A concrete floor that partially or fully penetrates the building envelope at the exterior.
Floor Space Ratio	Ratio of gross floor area of a building to the area of land on which it is built.
GHGI	Greenhouse Gas Emissions Intensity, in $kgCO_2e/m^2/year$. Annual greenhouse gas emissions based on the annual energy use of the building, divided by the building floor area.
Glazing	See definition of fenestration. Examples of glazing are windows, window-wall, and curtain-wall.
Glazing Interface Detail	Linear thermal bridges that occur at the intersection of glazing and opaque assemblies.
GWP	Global warming potential
Insulating Glass Unit (IGU)	Double or triple glass panes separated by air or other gas filled space. The space between the glass panes is created by a physical spacer that is also adhered to the glass. Sealant is provided at the perimeter of the unit as a gas and moisture barrier.
Interface Details	Thermal bridging related to the details at the intersection of building envelope assemblies and/or structural components. Interface details interrupt the uniformity of a clear field assembly and the additional heat loss associated with interface details is accounted for by linear and point thermal transmittances.
Life Cycle Assessment (LCA)	Assessment of environmental impacts of buildings from extraction of raw materials to construction, operation, and demolition.
Linear Thermal Bridge	An interface detail that can be defined by a linear length along a plane of the building envelope.
MURB	Multi-unit residential building.

Term	Description
Linear Thermal Bridge	An interface detail that can be defined by a linear length along a plane of the building envelope.
MURB	Multi-unit residential building.
Opaque Assembly	All areas in the building envelope, except fenestration and building services openings such as vents and grilles.
Operational Carbon Emissions	Greenhouse gas emissions from the consumption of utilities (gas and electricity) that are needed for processes within the building and to heat, cool, and ventilate it for occupant comfort.
Plug Loads	Any system that draws electrical power through the building, but is not explicitly used to operate the building. This includes appliances, computers and other items that are dependent on the occupants use.
Poured-in-Place Concrete Wall	An architectural exposed concrete wall that is formed at the location of installation and is part of the building structural support.
Precast Concrete Wall	An architectural concrete cladding that is formed off site and shipped to the location of installation.
Roof-to-wall Interface	An interface detail that joins the walls to the roof, such as parapet
Setpoint Temperature	The desired operating temperature that a heating system works to maintain, ie: the interior space temperature set by a thermostat.
Shelf Angle	A structural support that transfers the dead load of brick veneer to the building structure at the floor slab.
Slab Bypass	A portion of window-wall that covers the floor slab edge to give the appearance of uninterrupted glazing across the entire façade of a building.
Spandrel Section	An opaque section of curtain wall or window wall with insulation between the system framing.
Stick Built Curtain Wall	A site installed and glazed curtain-wall system that is assembled by running long pieces of framing between floors vertically and between vertical members horizontally.
Structural Beam	A steel beam that penetrates through the building envelope to support an exterior element, such as a canopy.

Term	Description
Quantity Takeoff	A quantity measurement that determines the areas and lengths needed for U-value calculations. The quantities are determined using architectural drawings.
Thermal Break	A non-conductive material that interrupts a conductive heat flow path. For example, aluminum framing for glazing in cold climates typically utilizes a low conductivity material to join an exterior and interior portion of the metal framing.
Thermal Bridge	Part of the building envelope where otherwise uniform thermal resistance is changed by full or partial penetration of the thermal insulation by materials with lower thermal conductivities and/or when the interior and exterior areas of the envelope are different, such as what occurs at parapets and corners.
Thermal Performance	A broad term to describe performance indicators related to the heat transfer through an assembly. The performance indicators include thermal transmittances, effective R-values, and metrics to evaluate condensation resistance related to surface temperatures.
Total Energy Use	The amount of annual energy use of a building, including space heating/cooling, ventilation, lighting, plug loads, domestic hot water, pumps, fans etc.
Unitized Curtain Wall	A curtain-wall system that is assembled in modules that is glazed before arriving at site.
Vision Section	The section of curtain-wall or window-wall that contains transparent or translucent elements.
Window to Wall Ratio/ Glazing Ratio	The percentage of glazing to the wall area of a building.
Whole Building Energy Use	The amount of energy a building uses, typically on an annual basis. This includes, but is not limited to energy for space and ventilation heating and cooling, domestic hot water heating, lighting, miscellaneous electrical loads and auxiliary HVAC equipment such as pumps and fans.

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