STANDARDS RESEARCH

Exploring Circular Strategies to Extend the Life of Existing Buildings

Retrofit Versus Demolition and New Construction

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Authors

Zahra Teshnizi, Senior Advisor, Mantle Developments

Mandi Wesley, Advisor, Mantle Developments

Javaria Ahmad, Advisor, Mantle Developments

Kathleen Kauth, Chief Operating Officer, Mantle Developments

Alanna Komisar, Senior Advisor, Mantle Developments

Ryan Zizzo, Founder and Chief Executive Officer, Mantle Developments

Project Advisory Panel

Alexandra Thompson, National Research Council

Christian Cianfrone, Ellis Don

Eli Miller, Hullmark

Hannah Teicher, Pacific Institute for Climate Solutions

Hazel Sutton, JLL Canada

Helen Goodland, Scius Advisory Inc.

Jani Loots, BOMA Canada

Jean-Martin Lessard, Natural Resources Canada

Paul Shorthouse, Circular Economy Leadership Canada

Adriana Shu Yin, CSA Group (Project Manager)

Ivica Karas, CSA Group

Jennifer Teague, CSA Group

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List of Abbreviations

AA	All air (system)
AHU	Air handling units
BIM	Building information modelling
CAGBC	Canada Green Building Council
CMU	Concrete masonry unit
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DCV	Demand control ventilation
EPD	Environmental Product Declaration
EPS	Expanded polystyrene insulation
ERV	Energy recovery ventilators
GHG	Greenhouse gas
GHGi	Greenhouse gas intensity
GSHP	Ground source heat pump
GWP	Global warming potential
HVAC	Heating, ventilation, and air conditioning
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
MEP	Mechanical, electrical and plumbing
PCR	Product category rule
PH	Passive House (standard)
PSI	Pounds per square inch
PV	Photovoltaic (solar panels)
TI	Tenant improvement
VAV	Variable air volume
VIP	Vacuum insulated panel
wbLCA	Whole building life cycle assessment
XPS	Extruded polystyrene insulation

Executive Summary

Overview

The building sector contributes significantly to greenhouse gas (GHG) emissions. Reducing GHG emissions (also referred to as carbon emissions) from this sector is critical for Canada to achieve its climate targets.

In recent years, many real estate and asset management organizations have been setting near- and net-zero-carbon ambitions. However, many will be challenged to meet these targets without significant decarbonization of their existing buildings.

For many commercial buildings, there will need to be a decision between demolishing and rebuilding them, versus performing deep carbon retrofits. However, there is a lack of research comparing the full whole-life impact of these two options. Most assessments only focus on achieving energy efficiency and making links to potential operational carbon reductions.

Whole-life carbon emission assessments, on the other hand, consider both the operational and embodied carbon emissions of building projects. Embodied carbon emissions include emissions resulting from the manufacturing, transportation, installation, maintenance, and disposal of building materials.

This study aims to inform the commercial real estate (CRE) sector about the whole-life carbon impacts of extending building life – a key circular economy practice. Building on a more extensive review of the opportunities to apply circular strategies to commercial office buildings [1], this study also examines gaps in the research, data access and standardization, guidelines, standards, and tools that could help inform decisions about whether to demolish and rebuild, or retrofit, new commercial office buildings.

Review of Literature

A literature review of existing research, standards, guidelines and building life-cycle assessment (LCA) case studies was conducted. The LCA case studies reviewed found that the two options – retrofitting versus building new – resulted in comparable post-construction annual operational emissions.

However, retrofitting resulted in significantly less upfront embodied carbon emissions compared to building new. Retrofits had lower overall whole-life carbon than new construction in all but one case (that one case assumed a much shorter lifetime). Retrofits had a relatively short "carbon payback" period of three to five years for the upfront embodied carbon emissions investment associated with the retrofit, which was offset by annual operational emissions savings.

The review of LCA and circularity standards and guidelines found a lack of consistency on the aspects of LCA that could inform the decision between retrofitting versus rebuilding. The European standard EN 15804, *Sustainability of construction works – Environmental product declarations,* and its international counterpart, ISO 21930:2017, provide inconsistent guidance. EN 15804 requires the inclusion of end-of-life impacts or impacts beyond its life (stages C and D in LCA), whereas ISO 21930 does not include this requirement. Standards and guidelines for whole-building LCA (wbLCA) do not provide specific directions on the assumptions for an element's lifetime or impacts from stages C and D when product- or project-specific data is missing. Finally, current building circularity standards and guidelines do not provide any direction on assessing their whole-life carbon impacts.

Canadian LCA Case Study

An LCA case study was conducted to include six buildings across three major Canadian cities – Toronto, Edmonton, and Vancouver – with two types of office buildings each – mid-rise and high-rise.

The LCA results showed that, in all scenarios, the decision to retrofit resulted in significantly lower whole-life emissions than the demolition and new construction option. These reductions were most significant when embodied carbon emissions constituted a larger portion of a project's whole-life emissions. This was the case in higher-performance buildings in regions with a lower-carbon electricity grid, making the case for retrofit strongest in regions with green electricity, such as British Columbia, Quebec, Manitoba, PEI, Newfoundland, and Ontario.

It was found that a retrofit of these buildings led to a 26% to 70% lower whole-life carbon emissions than demolition and new construction by 2030, and 11% to 58% lower emissions by 2050. These reductions were mainly achieved by reusing the existing concrete structure when retrofitting.

In a sensitivity analysis, the retrofit option still showed lower whole-life carbon emissions even when compared to a modelled new mass-timber structure. However, the whole-life carbon emissions of the retrofit and new mass-timber building were similar when carbon stored in the wood of the timber structure was considered.

This finding was consistent with results from the literature review, suggesting that retrofit will likely outperform new buildings on life-cycle emissions, unless the new building is an ultra-low-carbon design. Even then, when considering near-term and long-term climate targets (2030 and 2050), retrofit could still outperform these low-carbon options. If a new building is preferred, projects should consider mass timber or other low-embodied-carbon materials and propose end-of-life scenarios that would reuse the wood without releasing its carbon back into the atmosphere.

Several limitations and assumptions are inherent in wbLCA and in this study. Nevertheless, results show that retrofitting office buildings and preserving the embodied carbon emissions in a structure[1] can help achieve Canada's climate targets and net-zero goals.

More LCA case studies would help to expand the findings of this research to other regions and types of buildings. Further, more standards and guidance on modelling carbon emissions from the later stages of product and building lifetimes is required and would help the commercial real estate industry make carbon-informed decisions about retrofit versus demolition and new construction.

Below are the main takeaways from this study:

1. Deep green retrofits achieve the same post-construction level of annual operating carbon emissions as demolition and new construction. Deep green retrofits also result in lower whole-life carbon emissions due to the savings from not rebuilding the structural system.
2. The case for retrofits is strongest in regions with green electricity, such as British Columbia, Quebec, Manitoba, and Ontario.
3. If new construction is required, it is beneficial to limit embodied carbon emissions by focusing on low-embodied-carbon materials, including low-carbon concrete and steel, and bio-based materials such as wood. Accounting for biogenic[2] carbon storage in biomass materials can also support the case for building new timber buildings, since it can lead to similar whole-life carbon as retrofits. More analysis for calculating biogenic carbon is required.
4. Additional guidance and data are needed to link circularity and reuse principles to embodied carbon emissions and LCA benefits.

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[1] In the form of columns, beams, slabs, shear walls, elevator cores and stairwells

[2] A term applied to materials, processes or activities of living or once-living organisms

"For a new high-performance building built in regions with a clean electricity grid, embodied carbon emissions are expected to contribute more than 80% of the building's total carbon emissions over a 28-year period (2022 to 2050)"

1 Introduction

1.1 Carbon Emissions in Buildings

The building sector is a significant contributor to GHG emissions (also referred to as carbon emissions). According to the Canada Green Building Council (CAGBC), the operation of buildings is responsible for 17% of Canada's total carbon emissions.

"Embodied" carbon emissions are those from the manufacturing, transportation, installation, maintenance and disposal of building materials. If embodied carbon emissions are added to the "operational" carbon emissions, the total contribution of the building sector to Canada's total carbon emissions increases from 17% to 30% [2].

Canada's population is estimated to increase by about 25% between 2018 and 2049, and the demand for new buildings is expected to rise [3]. However, new buildings represent a significant source of embodied carbon emissions. For a new high-performance building built in regions with a clean electricity grid,[3] embodied carbon emissions are expected to contribute more than 80% of the building's total carbon emissions over a 28-year period (2022 to 2050) [4].

The federal government has set an interim carbon emissions reduction target of 40% to 45% below 2005 levels by 2030, and a long-term target of net-zero emissions by 2050 [5]. In recent years, many leading real estate and asset management organizations have also been setting near- and net-zero-carbon ambitions. These targets cannot be met without significant decarbonization of their existing buildings. For many of these buildings, a choice will need to be made between a deep carbon retrofit versus demolition and new construction.

A deep carbon retrofit aims to minimize carbon emissions by improving operational performance that reduces energy demand, replacing mechanical systems with zero- or low-carbon alternatives, and producing on-site renewable energy [6].

Retrofitting existing buildings can also be one of the most effective ways to reduce embodied carbon emissions, as it minimizes the introduction of new materials and their related carbon emissions [7]. Most studies examining the carbon benefits of retrofits have only focused on operational energy efficiency – in some cases the resulting annual carbon savings.

Only a small body of literature investigates the overall carbon benefits of retrofit throughout the whole building's life, including both operational and embodied carbon. Even then, the comparison has often been with keeping the building as is, rather than tearing it down and building a new one [8]. Few have provided quantitative evidence for the overall carbon advantage of retrofit compared to demolition and new construction.

[3] British Columbia, Quebec, Manitoba, PEI, Newfoundland, and Ontario

1.2 Circular Economy in the Built Environment

Extending a building's life is an important circular economy practice, which offers an alternative to the current "take-make-use-dispose" linear economy. Benefits of circular economy practices include preserving natural ecosystems and green infrastructure, reducing resource and raw material use, reducing waste and GHG emissions, and improving supply chain resilience, investment, and employment opportunities [9].

In the built environment, circularity practices include the following:

- Durable materials and products
- Design-for-disassembly
- Design-for-flexibility
- Modular construction,
- Building life extension through retrofit
- Salvaging and reusing building products and materials at the end of building life

Recent years have seen an increased focus on circularity practices in Canadian construction policy and practice. Although these efforts have been successful, they have mainly focused on waste diversion. More effort is needed earlier in the building life cycle to promote and maximize the impact of circular strategies [9]. Despite the potential climate and circular economy benefits of deep retrofit and reuse of existing buildings, these practices have yet to become common practice in Canada [10].

1.3 Purpose

This study explores the whole-life carbon-emission impacts of building retrofit versus demolition and building new. It also identifies gaps in guidelines, standards and tools that might support carbon-informed decisions between retrofitting versus demolition and building new, to minimize whole-life emissions most effectively.

This report is focused on commercial real estate (CRE), particularly office buildings. Commercial buildings constitute a significant portion of existing buildings in Canada, at 25.5% of total floor space[4], with 10% of total floor space as office floor area [11]. CREs are well suited for retrofits because larger building projects typically have more resources, so their project teams have greater capacity to be early adopters of innovation beyond best practices. Others in the industry, such as residential developers, can benefit from the learnings from CRE projects.

2 Methods

A literature review of existing case studies, standards and guidelines was conducted to assess the carbon-emission benefits of retrofit and its trade-offs throughout a building's lifetime, compared to demolition and new construction, with a focus on commercial buildings. This review builds on a more extensive examination of opportunities to apply circular strategies to commercial office buildings [1]. A life-cycle assessment (LCA) case study was then conducted to compare the life-cycle carbon emissions between retrofit and demolition and new construction (rebuild) for two common office building archetypes from three geographical locations in Canada.

2.1 Literature Review

Although extensive content has been written on LCA and on the circular economy in the built environment, this study focused on the research gap at the intersection of these two topics. The review of the existing literature included LCA case studies, and relevant standards and guidelines on LCAs, of retrofit buildings:

- **Case studies:** Recent studies that included quantitative assessments of the whole-life carbon-emission benefits of retrofits using an LCA approach were reviewed, with a focus on office buildings.
- **Standards and guidelines:** Current Canadian, American, European, and other international standards and guidelines on circularity practices, LCA and embodied carbon assessment were reviewed.

[4] 758 million m^2 of floor space out of a total of 2,962 million m^2 of building floor area

The resources reviewed were limited to those written in English. Given the rapid advancement and adoption of LCA practices, especially in North America, the review focused on resources published in the last five years. However, references from the past 10 years were also considered if they were still relevant. The resources were identified through online research and communication with building industry experts and life-cycle assessment experts in Canada.

A more in-depth review of circular practices for extending the lives of existing office buildings can be found in the CSA report titled *Opportunities to Apply Circular Strategies to Existing Office Buildings* [1].

2.1.1 Case Studies

Several case studies assessing the carbon emissions of buildings using the LCA methodology were identified. This review targeted studies assessing the whole-life carbon-emission impacts of retrofitting large commercial buildings, especially those that included both operational and embodied carbon emissions and compared the results with demolition and new construction.

The initial scan was for Canadian case studies, but at the time this review was conducted, none of the publicly available LCA case studies of Canadian buildings focused on commercial building retrofits. Therefore, the scope was expanded internationally.

The sources reviewed to identify relevant case studies included peer-reviewed journals and publicly available reports and articles from academic institutions, governments,[5] reputable industry associations, non-profit organizations, and industry practitioners such as engineers, architects, and sustainability consultants.

Fourteen case studies were identified that assessed the life-cycle environmental benefits of circular practices such as retrofit, waste management and reuse of building components (See Table A-1 in Appendix A). Eight of these studies focused on buildings larger than single-family houses and used LCA to assess the carbon impacts of retrofit. Among these, only two European studies compared the operational and embodied carbon emissions of retrofitting commercial buildings to the status quo or new construction.

The LCA methodologies within each case study were also assessed. Criteria included the selected reference buildings, retrofit and rebuild scenarios, LCA scope, modelling tools used and other assumptions. Through this, best practices, and challenges of conducting LCA of retrofit projects were identified. This informed the methods of the LCA comparison of this study.

2.1.2 Standards and Guidelines

Standards and guidelines on circularity practices, LCAs and embodied-carbon assessments for the building industry were reviewed. The goal was to provide insights into the availability of resources designed to support the sector's use of a whole-life carbon-emissions approach. Assessing whole-life carbon impacts of buildings could help inform decisions between retrofitting existing buildings versus replacing them with new ones.

A search for standards or guidelines directly addressing a whole-life carbon emissions assessment in circularity practices in buildings yielded no results. However, Canadian, US, European, and international standards and guidelines were explored for content relevant to circularity practices. Notable information in 17 references was identified: 13 were Canadian, European, and international LCA and embodied carbon standards. Four standards referred to circularity practices as part of their guidelines. The review explored the overall intent of the standard and identified the gaps where more development is needed.

2.2 Life Cycle Assessment (LCA) Case Study

The second component of this study was to conduct a whole-life carbon-emissions assessment of retrofits compared with demolition and new construction, using typical Canadian office buildings as an example.

5 Federal, provincial/territorial, and municipal

LCA is the most widely accepted approach used to assess and analyze the environmental impact of products or processes throughout their entire life cycle. The LCA-based impacts of a product or material is summarized in a document known as an Environmental Product Declaration (EPD), and the LCA of a whole building is known as a whole-building LCA (wbLCA). Each should follow established standards and guidelines, as introduced in Sections 3.2.1 and 3.2.2.

Global warming potential (GWP) is one of the environmental impact categories typically assessed though an LCA. GWP compares the climate change impacts of various GHGs, measuring how much energy a tonne of each GHG can trap in the atmosphere compared to carbon dioxide (CO_2), typically over a period of 100 years [12]. In LCA results, GWP refers to the total emissions estimate of different GHGs calculated using GWP conversion factors and presented as CO_2 equivalents (CO_2e). Therefore, the focus of this study was on GWP results – both in the literature review and the LCA case study.

wbLCAs typically focus on GWP, including for the following life-cycle stages and modules (see Figure 1).

- Stage A: Product and construction process
  - A1 Raw material and supply
  - A2 Transport
  - A3 Manufacturing
  - A4 Transport
  - A5 Construction – the installation process
- Stage B: Use
  - B1 Use
  - B2 Maintenance
  - B3 Repair
  - B4 Replacement
  - B5 Retrofit
  - B6 Operational energy use
  - B7 Operational water use
- Stage C: End-of-life
  - C1 Deconstruction/demolition
  - C2 Transport
  - C3 Waste processing
  - C4 Disposal
- Stage D: Benefits and loads beyond the system boundary.
  - D1 Recycling
  - D2 Reuse
  - D3 Energy recovery
  - D4 Exported energy

The LCAs conducted in this study followed the National Research Council of Canada (NRC) National Guidelines for Whole-building Life Cycle Assessment [13], which follow the European Standard EN 15978 [14], which is the most widely accepted standard for wbLCA.

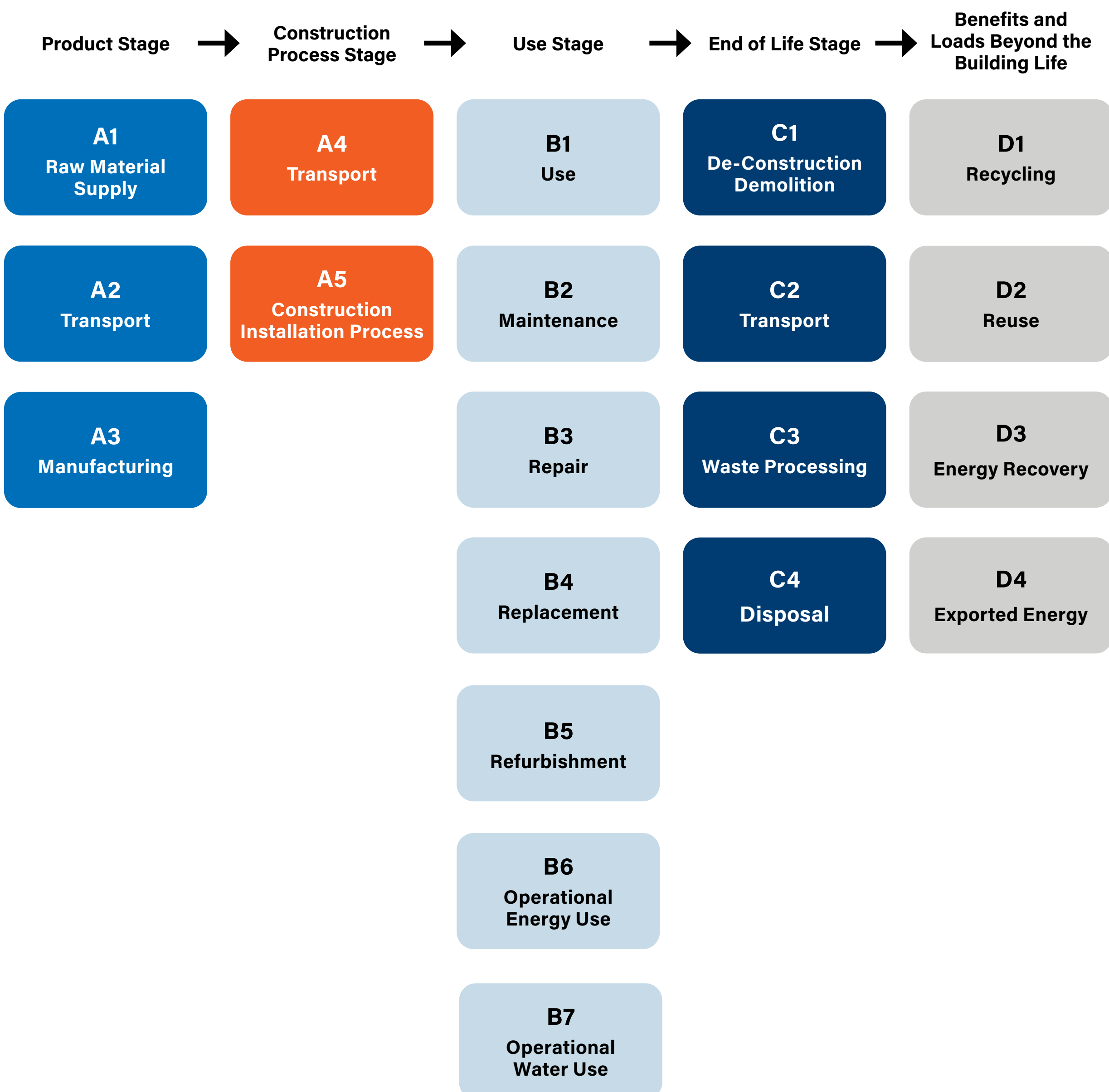
The following sequence was applied:

1. Specifying the purpose of assessment
2. Specifying the object of assessment
3. Defining the building life-cycle scenarios
4. Quantifying of the building and its life-cycle
5. Selecting environmental data and calculating the environmental indicators
6. Reporting and communication
7. Verification.

Third-party review is optional for wbLCA and was not conducted in this study. However, in-house quality control was performed.

The results from the literature review informed the approach and assumptions of the LCA for retrofit and rebuild scenarios, the LCA scope, modelling tools used and other assumptions. These approaches and assumptions are described in the following sub-sections. The limitations of this study are discussed in Section 5.

Figure 1: Life cycle stages in a whole-building life cycle assessment, per EN 15978 and ISO 21930. Adapted from NRC National Guidelines for Whole-building Life Cycle Assessment [13] with permission from the National Research Council of Canada.



2.2.1 Purpose of Assessment

The objectives for these assessments were to:

- Assess the whole-life carbon-emission benefits of deep carbon retrofits and compare it to demolition and new construction
- Evaluate the impact of building type and geographical location on the significance of the whole-life carbon-emission benefits of retrofits
- Assess the availability and gaps in data, tools, standards, and guidelines to conduct standardized whole-life carbon-emission assessments of retrofit projects and rebuild projects.

Two office building archetypes in three Canadian cities were analyzed. The building archetypes, mid-rise and high-rise offices, were chosen to represent Canada's most common existing commercial buildings in Canada [1]. Edmonton, Toronto, and Vancouver were selected as the three locations to represent various climate zones and electricity grids in major Canadian cities.

2.2.2 Reference Buildings

Material types and quantities, known as a "bill of materials," are among the key data required to conduct a wbLCA. A bill of materials can be generated from a building information model (BIM)[6] tool, such as Revit, through take-offs from the project drawings, or from a building cost estimate. Obtaining a bill of materials can be time-consuming and was not in the scope of this study.

Instead, data from LCAs previously conducted by the authors on two relevant office buildings in Toronto were used as the basis for the LCA models of this study, with some additional quality controls applied. These two reference buildings provided the basis of our analysis and were modified for the various other cases examined.

Data from comparable buildings in Vancouver and Edmonton were not available to conduct LCAs. Therefore, the reference buildings were modified to assume they were built in Vancouver and Edmonton. These modifications included changes to the exterior wall, roof assembly and insulation, where applicable.

The key characteristics of the reference buildings are presented in Table 1 for the mid-rise office buildings and Table 2 for the high-rise office buildings. Where material quantity data on the reference buildings were not available, input from industry experts, in-house knowledge, the project advisory panel, estimates from the LCA tool and external guidance documents were used.

Tables B-1 and B-2 in Appendix B list the assumptions and the sources used to address data gaps from the reference buildings, as well as for the modifications to adjust the reference buildings to the Vancouver and Edmonton contexts.

2.2.3 Demolition and New Construction Scenarios

In the demolition and new construction scenarios, the reference buildings were assumed to be demolished and replaced with the exact same building. In other words, the new building constructed in each city is assumed to have the same materials and systems as the building that was demolished.

A sensitivity analysis was conducted on the mid-rise office building in Toronto to assess how replacing the existing building with a low-carbon new construction would impact the embodied carbon emissions results. It was assumed that the new building was built with a mass-timber structure and wood-stud interior partitions.

2.2.4 Retrofit Scenarios

The reference buildings were modified using a deep carbon retrofit scenario, where the envelope, mechanical, electrical, and plumbing (MEP), and interior, non-load-bearing elements and finishes were replaced like-for-like. The rest of the building elements remained as is.

A high-level sensitivity analysis was conducted on the mid-rise office building in Toronto to assess the impact of implementing additional element- and material-level circularity practices in the retrofit scenario.

[6] Building information model (BIM) is a three-dimensional digital model that contains data on the physical and functional characteristics of a building [13].

Table 1: Mid-rise office reference building used for the LCA case study.

Project information	
Location	Toronto, Ontario
Year built	Under construction (estimated completion: 2024)
Number of above-grade floors	6
Number of below-grade floors	2
Gross floor area above grade (m^2)	12,256
Gross floor area, below grade (m^2)	5,919
Project data sources	▪ Architecture drawing set dated January 2022 ▪ Mechanical drawing set dated July 2022 ▪ Structural quantity takeoffs dated January to September 2021

Operational emissions		**Reference No.**
Greenhouse Gas intensity (GHGi)[7] (kg $CO_2e/m^2/yr$)	15 (GHGi target in the Toronto Green Standard Version 4, Tier 1)	[16]
Annual electricity energy demand (kWh/m^2)	88.4	[17]
Annual natural gas energy demand (kWh/m^2)	38.3	[17]
Ontario grid intensity	Varies annually	[18]

Building design		**Reference No.**
Structure	▪ Footings, subgrade walls, floors, columns and beams: Reinforced concrete ▪ Interior load-bearing interior walls: Reinforced concrete, steel-framed and reinforced concrete masonry unit (CMU)[8]	Reference building data sources
	▪ Stair and elevator shaft construction: Reinforced concrete	[19]
Roof	▪ Roof structure: Reinforced concrete slab ▪ Roof assembly: Two-ply hot rubber waterproofing membrane, protection board, R30 XPS insulation, filter fabric or drainage panel, various finishes	Reference building data sources
Envelope	▪ Exterior walls: Double-glazed aluminum framed curtain wall with 100 mm of semi-rigid mineral fibre insulation at frames ▪ Exterior doors: Steel and revolving glass doors	Reference building data sources
Interior partition walls ***Non-load bearing***	▪ Steel frame with mineral wool insulation, gypsum wallboard and paint finish	[19]
Ceilings	▪ Acoustic suspended ceiling ▪ Gypsum wallboard	Reference building data sources
Floor finishes	▪ Carpet ▪ Tiles ▪ Concrete floor finish	Reference building data sources

[7] Greenhouse gas intensity (GHGi) is the measure of GHG emissions from the total energy consumption of a building for its operations, per metre of building floor area per year [6].

[8] Concrete masonry unit (CMU) is a standard rectangular, pre-cast concrete block used in masonry construction.It is also known as a "concrete block" or "cinder block" [15].

Building design		Reference No.
Mechanical equipment	▪ Natural gas boiler, 879 kW ▪ Domestic hot water natural gas boiler, 85 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation, 50,000 m3/h ▪ Liquid chiller, 619 kW	Reference building data sources
Refrigerant	▪ R-134a, 110 kg	Advisory panel recommendation
Ventilation system	▪ Default ventilation system for office buildings9	[20]
Electrical system	▪ Default electricity distribution system, cabling and the central system for a ll building types9	[20]
Plumbing system	▪ Sewage water drainage piping network for office buildings[10]	[20]
Other	▪ All concrete mixes: Ontario industry average concrete, general use cement, baseline mix per strength class – Canadian industry average EPD[11] ▪ CMU: Concrete masonry unit, normal weight, general use limestone cement, East Region – Canadian industry average EPD ▪ Concrete transportation distance from manufacturing to the construction site: 50 km	[20] Reference building data sources

Table 2: High-rise office reference building used for the LCA case study.

Project information	
Location	Toronto, Ontario
Year built	1984
Number of above-grade floors	28
Number of below-grade floors	3
Gross floor area above grade (m²)	63,000
Gross floor area, below grade (m²)	14,423
Project data sources	▪ Architectural drawing set dated 1981–1983 ▪ Structural drawing set dated 1981–1983 ▪ Curtain wall drawing set dated 1982

9 Estimated per unit of gross floor area.
10 Estimated per unit of gross internal floor area.
11 The Environmental Product Declaration (EPD) quantifies environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function.

Operational emissions		Reference No.
GHGi (kg $CO_2e/m^2/yr$)	15 (GHGi target in the Toronto Green Standard Version 4, Tier 1)	[16]
Annual electricity energy demand (kWh/m²)	88.4	[17]
Annual natural gas energy demand (kWh/m²)	38.3	[17]
Ontario grid intensity	Varies annually	[18]

Building design		Reference No.
Structure	▪ Footings, subgrade walls, shear walls, floors, stairs, columns and beams: Reinforced concrete	Project data sources
	▪ Elevator shaft construction: Reinforced concrete	[19]
Roof	▪ Roof structure: Reinforced concrete slab	Reference building data sources
	▪ Roof assembly: Metal deck, vapour barrier, 152 mm polyiso insulation, roof board, SBS roofing membrane	[10]
Envelope	▪ Exterior wall: Double-glazed aluminum frame curtain wall with stainless steel panel and 102 mm mineral-wool insulation at spandrel	Reference building data sources
	▪ Exterior doors: Steel and revolving glass doors	[19]
Interior partition walls ***Non-load bearing***	▪ Steel frame with mineral wool insulation, gypsum wallboard and paint finish	[19]
Ceilings	▪ Reflected ceiling tile ▪ Gypsum wallboard	Reference building data sources
Floor finishes	▪ Carpet ▪ Tiles ▪ Concrete floor finish	Reference building data sources
Mechanical equipment	▪ Natural gas boiler, 3,958 kW ▪ Domestic hot water natural gas boiler, 380 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation, four units x 50,000 m3/h ▪ Liquid chiller, 2,800 kW	Scaled from mid-rise reference building (Table 1)
Refrigerant	▪ R-134a, 495 kg	Advisory panel recommendation
Ventilation system	▪ Default ventilation system for office buildings[12]	[20]
Electrical and plumbing systems	▪ Default electricity distribution system, cabling and the central system for all building types[12]	[20]
Plumbing system	▪ Sewage water drainage piping network for office buildings[12]	[20]
Other	▪ All concrete mixes: Ontario industry average concrete, general use cement, baseline mix per strength class – Canadian industry average EPD[13] ▪ Concrete transportation distance from manufacturing to the construction site: 50 km	[20] Reference building data sources

[12] Estimated per unit of gross internal floor area.
[13] The Environmental Product Declaration (EPD) quantifies environmental information on the life cycle of the product to enable comparisons between products fulfilling the same function.

Since quantitative data from actual retrofit projects were not available, the following hypothetical scenarios were assumed:

- Salvaging and reusing materials and products: 30% of aluminum channels and 30% of the glazing in the curtain wall of the existing building were assumed to be salvaged and reused.
- Using materials and products with high recycled content: The following materials were replaced with high-recycled-content alternatives using available EPDs in the LCA tool:
  - Interior gypsum board: 90% recycled content
  - Commercial carpet: 100% recycled nylon and partially recycled backing
  - Extruded polystyrene (XPS) insulation in the roof: 68% recycled content (increased from 30%).
- Reduced material use: Reduced material quantity of the ventilation, electricity and heat distribution systems by 20%.

The materials and systems on which these strategies were implemented were chosen based on the significance of their contribution to embodied carbon emissions, the feasibility of modifying the systems, and data availability in the LCA tool. The sensitivity analyses were conducted after the initial LCA of the retrofit and new construction scenarios. This way, the contributions of different materials on embodied carbon emissions could be identified from the LCA results.

2.2.5 LCA Scope

The following represents the scope of the LCA models.

Building Elements: It was assumed that the following elements were replaced like-for-like in their entirety.

- **Demolition and new construction**: Foundation, horizontal and vertical structures, stairs, elevator shaft, envelope, exterior doors & windows, heating ventilation, and air conditioning (HVAC) systems and refrigerant, electrical distribution system, sewage piping network, interior walls, and interior finishes.
- **Retrofit:** Envelope, exterior doors and windows, HVAC systems and refrigerant, electrical distribution system, sewage piping network, interior non-load bearing walls, interior finishes. The structural elements were considered to last the entire life of the retrofitted building.

Building Lifetime[14]

- **Demolition and new construction:** The demolition and new construction were assumed to happen in 2022. The building was assumed to be operational at the beginning of 2023 and demolished at the beginning of 2083.
- **Retrofit:** The removal and replacement of elements were assumed to happen in 2022. The building was assumed to be operational at the beginning of 2023 and demolished at the beginning of 2083.

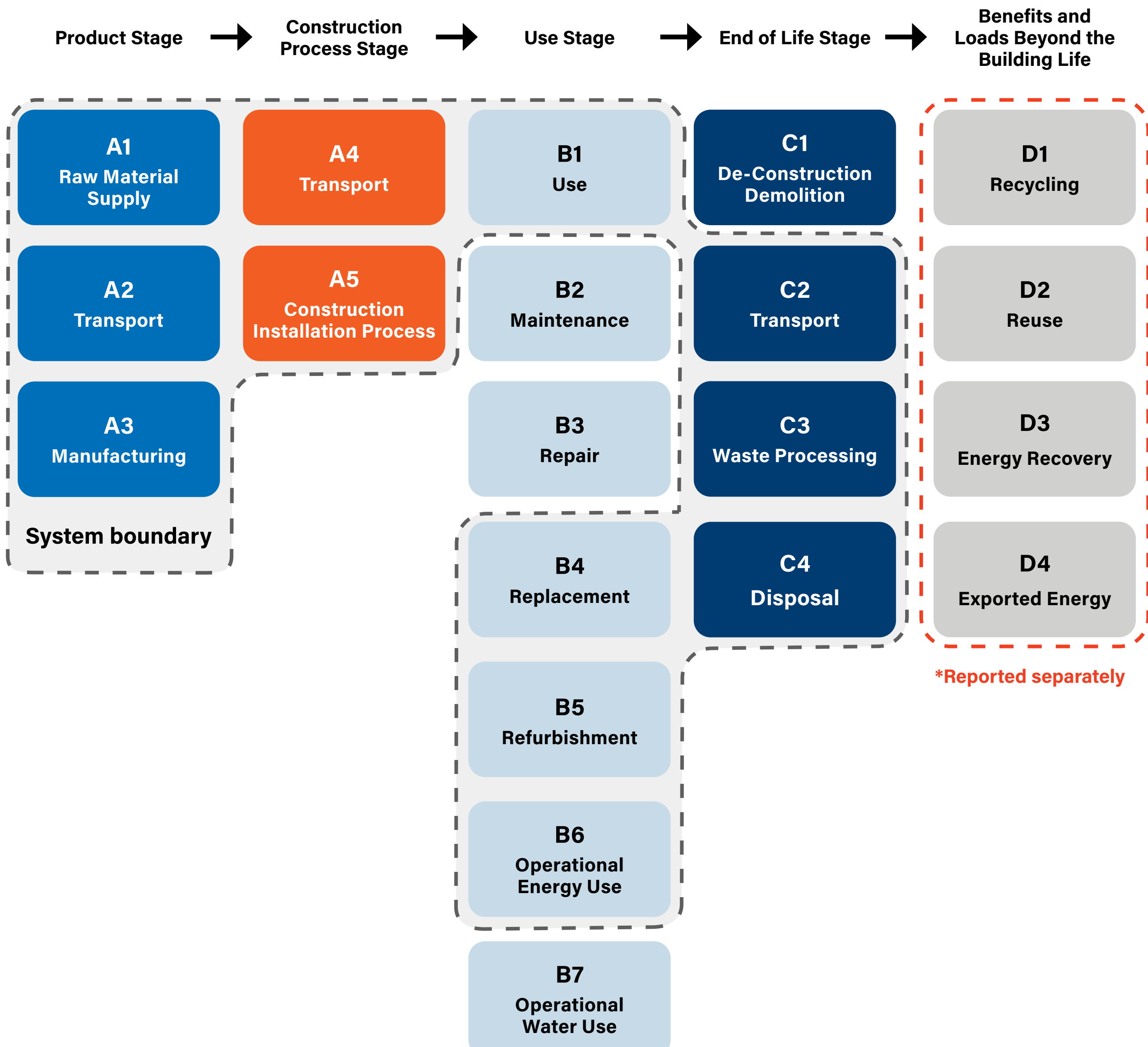
Life-cycle Stages: Product (A1-A3), construction (A4-A5), use (B1), replacement and retrofit (B4-B5), operational energy use (B6) and end-of-life (C2-C4).[15] Benefits and load beyond the building life cycle (D) are reported separately. See Figure 2 for the life-cycle stages included in the LCA study.

- **Demolition and new construction:** Emissions from the demolition of the existing building were included and assumed to be the same as emissions at the end of the new building's life (C2-C4). In other words, C2-C4 emissions were calculated and assumed to be the same at the point of demolition (referred to as 'upfront') and at the end of the building's life (referred to as 'end-of-life').
- **Retrofit:** Emissions from the removal of elements that were to be replaced were included and were assumed to be the same as at the end of the retrofitted building's life, as reported as C2-C4 (upfront). Emissions from the demolition of the retrofitted building at the end of life were included and were assumed to be the same as the total end-of-life emissions for the demolition and new construction building. These emissions were reported as C2-C4 (end-of-life).

[14] This lifetime is in line with the LCA case studies reviewed in Section 3.1, the requirements in the Canadian green building certifications, and the CAGBC Zero Carbon Building Standard [48].

[15] C1 is not included in the system boundary because this module has no material impacts or there is a lack of data based on the selected materials in One Click LCA. This should be further investigated in future studies.

Figure 2: Life cycle stages included in the LCA study, known as the system boundary, per EN 15978 and ISO 21930. Adapted from NRC National guidelines for whole-building life cycle assessment [13] with permission from the National Research Council of Canada.



"The carbon-emissions modelling in this study focused on the embodied carbon emissions from building materials and mechanical equipment, and was accomplished using the One Click LCA tool"

2.2.6 LCA Modelling

The carbon-emissions modelling in this study focused on the embodied carbon emissions from building materials and mechanical equipment, and was accomplished using the One Click LCA tool [20]. One Click LCA is a web-based software tool designed explicitly for LCA of buildings and building assemblies. The tool's database includes One Click LCA generic data, and industry average and product-specific EPDs, complemented with regional and international LCA data calibrated to match each study's regional context [21]. One Click LCA is compatible with international and regional LCA standards, including EN 15978.

Canadian industry average EPDs or One Click LCA generic data were mainly used. Regional EPDs were used for each city where available. For example, the British Columbia industry average EPD for concrete was selected for the Vancouver LCAs. Similarly, Alberta and Ontario industry average EPDs for concrete were selected for the Edmonton and Toronto LCAs, respectively.

Unless otherwise specified, all default values and assumptions from One Click LCA were used for the following:

- Typical environmental impacts of provincial electricity grids
- Material waste factors[16]
- Transportation mode and distances, which varies by material type and region
- Product or material service life
- Product or material retrofit, replacement, and maintenance requirements
- Product or material end-of-life and beyond scenarios (recyclability, reuse, etc.)

Carbon Designer 3D is an add-on to One Click LCA that can be used when the quantity of building material is unavailable. This add-on is most suitable for early design stages, when knowledge of material quantities and types is limited. It estimates building material quantities with basic building information, such as location and structural system [19]. Carbon Designer 3D was used in this study to estimate material quantities of the elements for which quantities were not available from the previous LCAs on the reference buildings. These elements included stair and elevator shafts, interior non-load-bearing partitions, finishes and exterior doors.

Carbon Designer 3D was also used to estimate material quantities for the mass-timber new construction sensitivity analysis. Section 4.1.3 shows the key inputs to Carbon Designer 3D for estimating material quantities of the mass-timber structure alternative used in the sensitivity analysis. The mass-timber alternative is assumed to have the same building gross floor area,

[16] Additional material beyond the mass in the final project that is 'wasted' through the transportation and construction process, such as cut-offs.

height, width and length as the Toronto mid-rise reference building. The approximate contributions of the structural elements and materials, such as concrete and mass-timber columns, were based on features from actual mass-timber office buildings in Vancouver and Toronto. Information on these buildings was available online or from past Mantle Developments projects. Exterior walls, interior finishes and MEP systems were assumed to be the same as the mid-rise Toronto reference building. The interior, non-load-bearing walls were considered to have wood studs instead of steel studs in the reference building.

For operational carbon emissions, the buildings were assumed to meet the minimum requirements specified by each city's relevant building code or bylaw (See Table B-1 and Table B-2 in Appendix B). Annual grid decarbonization projections for each province were incorporated in the annual operational carbon emissions [18]. This study assumes the same operational carbon emissions for retrofit and new construction scenarios. This assumption is made based on the findings from a 2022 study by CAGBC that found that high-performance requirements for new construction can be achieved in existing buildings through deep carbon retrofit, including electrical, enclosure and mechanical upgrades [6].

Estimates for mechanical system-related emissions were gathered from previous project data, input from the advisory committee and relevant reports [22]. Representative data was then selected in One Click LCA. Carbon emissions from the mechanical systems were reported in three major categories: refrigerant leakage, operational emissions and embodied carbon emissions. This breakdown helped identify the significance of impact for each category.

The refrigerants were selected based on consensus from the advisory panel on what is considered "typical," as well as recommendations from a report by Integral Group [22], and validated by existing product specifications. Refrigerant impacts are labelled as life-cycle stage B1 impacts.

The mechanical system type and sizes for the mid-rise and high-rise office buildings were taken from the mechanical drawings for a mid-rise Toronto reference building. Units were selected from the reference building mechanical drawings and used directly in the model. For the high-rise office building, the same mechanical system configuration as the mid-rise was selected and then re-sized based on gross floor area. Edmonton was allocated the same configuration as Toronto. The heating and cooling systems for Vancouver were selected based on the gross floor area and guidance from a report by the Integral Group [22].

3 Literature Review

3.1 Case Studies

Eight LCA case studies for larger buildings[17] were found that compared retrofitting buildings with demolition and new construction, or the status quo, i.e., continuing to use the building as is without upgrades. Only two case studies focused on commercial buildings, and both included operational and embodied carbon emissions in their scopes. Summaries of the case studies are provided in the following sections, and Appendix A provides further details including the associated LCA methods and results.

3.1.1 Low-rise Office Building Energy Retrofit vs. Status Quo, Norway

3.1.1.1 Study Overview

This case study used LCA to evaluate embodied and operational emissions of a typical office building in Norway under different building retrofit scenarios, comparing it with the status quo [23]. The reference building was modelled as a three-storey office, representing the archetype for most existing office buildings in Norway from the 1980s. The building characteristics and energy performance were assumed to meet the minimum requirements of the Norwegian building regulations from the same period.

[17] Larger than single family homes

Four retrofit scenarios were considered, assessing all the combinations of two operational energy and two HVAC system upgrades. For operational energy, one scenario assumed upgrading to Passive House (PH) Standard. While the other assumed a below-PH, energy- and cost-efficient upgrade. For the HVAC system upgrades, one scenario replaced it with the same system as the existing one, but with waterborne heating. The other replaced it with a system that combined airborne heating and cooling with air conditioning.

3.1.1.2 Study Findings

All four retrofit scenarios significantly reduced whole-life carbon emissions, ranging from a 68% to 73% decrease. Additional insights from this case study include:

- Operational energy use (B6) represented the most significant contributor to whole-life carbon emissions of existing buildings before retrofit (77%), followed by embodied carbon emissions from the product stage (A1-A3) (16%).
- Replacing HVAC systems constituted a considerable portion of embodied carbon emissions of the existing building (~13%), as the lifespans of these elements are shorter than the building's life and are often replaced during the building's life.
- Deep retrofitting to the level of high-performance building standards, such as Passive House, significantly reduced operational carbon emissions.
- New materials used in the retrofits, for example, for the envelope and HVAC systems, resulted in upfront embodied carbon emissions (12% to 19%). These increased emissions can be considered an "investment" that is offset by significant operational carbon emission savings over the building life (69% to 73%), with a relatively short emissions payback period of four to five years.

3.1.2 Low-rise Office Building Energy Retrofit vs. Rebuild, Belgium

3.1.2.1 Study Overview

This case study used an LCA tool developed by the authors to compare the energy and carbon impacts of low-energy retrofitting with complete demolition and reconstruction of an existing building. Data was used from an actual retrofit of a two-storey office in Brussels, Belgium, built in 1934. In the retrofit, the facade was maintained, but the windows were replaced, and insulation was added to the internal skin. The real-life retrofit was compared with a modelled demolition and new construction scenario assumed to have the same size, envelope thermal performance and HVAC system as the retrofit.

3.1.2.2 Study Findings

The retrofit scenario showed 57% lower embodied carbon emissions in comparison to complete demolition and new construction. Additional insights from this study include:

- Space heating represented the highest whole-life carbon emissions (1.9 and 0.7 times higher than the embodied carbon emissions in retrofit and rebuild scenarios, respectively).
- The operational emissions after retrofit were comparable with the operational emissions of new construction, which were achieved by improving the energy efficiency of the building through the addition of insulation, prevention of thermal bridging, replacement of windows with energy-efficient windows, and the addition of heat recovery ventilation.
- Retrofitting reduced embodied carbon emissions by about half. In retrofit, most of the building is kept intact and reused, so emissions from upfront demolition, new material use and construction are limited.
- In both scenarios, the product stage (A1-A3) was the most significant contributor to embodied carbon emissions, followed by construction (A5). In the rebuild scenario, demolishing the existing building was the next most significant contributor. Since most of the building was kept intact in the retrofit project, the demolition represented a much smaller percentage of the embodied carbon emissions.

3.1.3 Findings from Other Case Studies

Six other LCA case studies provided informative insights on building retrofits larger than single-family houses. Further details on these case studies are presented in Appendix A.

3.1.3.1 Deep Retrofitting Reduces Life-Cycle Carbon Emissions

Asdrubal *et al.* [24] used an LCA method to evaluate the energy use and carbon payback of a school retrofit in Italy during the building's 50-year lifetime. The study compared three retrofit scenarios, with the existing building as the baseline. The retrofit scenarios were identified based on a combination of economic, environmental and energy impacts.

The results showed that the retrofit scenario that was the most cost efficient, where the building used only 70 kWh/m^2, had an energy and environmental payback period of 3.2 years. The study concluded that retrofitting can be an effective solution to convert existing buildings to near-zero-energy buildings.[18]

Piccardo *et al.* [25] analyzed the whole-life carbon emissions of a residential building retrofitted to the level of Passive House standard energy performance. The study considered various scenarios with alternative materials for elements such as insulation, façade and windows. The results showed that making thoughtful building material choices could result in a maximum 68% reduction of the net CO_2e in the retrofit compared to the building reference case.

Ferreira *et al.* [26] assessed what type of retrofit would be environmentally and economically beneficial compared to new construction. They used a literature review of LCA studies and conducted a case study that compared a seismically reinforced historical building retrofit with a hypothetical demolition and new construction. The significant use of carbon-intensive structural steel for seismic stability in the historical building added to the embodied carbon emissions of the building. However, the study showed that structural retrofit extended the life of the historic building and lowered the whole-life carbon emissions impact by 13% compared to the demolition and new construction scenario.

As part of the United Nations Capital Master Plan, the carbon benefits of renovating the United Nations Headquarters, built in the 1950s in New York City, were assessed for two scenarios – deep retrofit or demolition and new construction [27]. In all six connected buildings of the United Nations complex, structural elements, solid exterior walls, roofs and interior core walls were assumed to be maintained in the retrofit scenario. The results showed that the initial embodied carbon emissions for demolition and new construction would have taken 35 to 70 years to recover, compared to the retrofit. The study used energy modelling and assumed 65% operational carbon reduction through the improved efficiency in the retrofit scenario. The new building scenario assumed 70% or 75% operational carbon reduction compared to the status quo.

3.1.3.2 MEP and Interior Systems Have Significant Embodied Carbon Impacts

A study by Rodriguez *et al.* [28] looked at the embodied carbon-emission impacts of mechanical, electrical and plumbing (MEP) systems and tenant improvements (TI) in commercial office buildings in Washington and Oregon in the U.S. Pacific Northwest. The study focused on the relative significance of the embodied carbon emissions of MEP systems and TI, which are often replaced in retrofit projects, compared to the core and shell, over an assumed 60-year lifetime of the buildings.

The study incorporated actual TI data from five projects and created 16 hypothetical MEP models for the analysis. HVAC systems evaluated included air handling units (AHUs)[19], variable air volume (VAV)[20] units, parallel fan terminals, water source heat pumps, variable refrigerant flow units, energy recovery ventilators (ERV)[21] and dedicated outdoor air systems.

The results showed that the initial embodied carbon emissions of MEP and TI components were relatively small – about 30% of the total for the buildings.

[18] Near-zero-energy buildings (NZEB) are buildings that require an extremely low amount of energy, and whose energy is sourced (or a large portion is sourced) from renewable energy produced on-site or nearby [67].

[19] Air handling unit (AHU) is an accessible box unit that houses ventilation equipment for air conditioning, air purifying, and exchanging indoor and outdoor air in a building [68].

[20] Variable air volume (VAV) is a system that increases the energy efficiency of an HVAC system by optimizing the amount and temperature of airflow [68].

[21] Energy recovery ventilator (ERV) is a heat exchanger combined with a ventilation system that regulates temperature and moisture between the indoor and outdoor air exchange [69].

However, with recurring maintenance and replacement of the equipment over the life of the building, their impacts increase, becoming comparable to the core and shell systems.

These findings demonstrated the importance of including MEP and TI components in LCAs, which are optional in most regulations, standards and certifications, and are therefore often excluded. The study suggested that high-impact components should be reused or recycled to reduce the negative impacts of MEP and TI. High-impact MEP components included AHUs and other large and heavy units, galvanized sheet metal for ductwork, light fixtures, and cast-iron piping for wastewater and ventilation. High-impact TI components included furniture, ceiling panel suspension systems, carpet, doors, glazing and acoustic panels.

3.1.3.3 Despite Shorter Building Lifetime, Retrofit has Lower or Similar Carbon Emissions as New Construction

Palacios-Munoz *et al.* [29] compared the retrofit of an eight-storey 1950s residential building in Zaragoza, Spain, to demolition and new construction. The study assumed two operational performance levels for retrofit and new construction – standard and Passive House. It compared the results for three approaches to determining building lifetime:

1. Default of 100 years for both scenarios
2. A durability-based approach of estimating lifespan using degradation models of the concrete structure
   - 210 years for the new building
   - 34 years for the retrofit scenario
3. Statistical data
   - 80 years for the new building
   - 30 years for the retrofit scenario

The total whole-life carbon emissions were divided by the building's lifetime to get the annual whole-life carbon emissions for each scenario, measured in kg CO_2 e/m^2/year.

The study found that renovating to Passive House-level performance was one of the best alternatives, regardless of the lifetime assumed. In the default lifetime scenario of 100 years, the Passive House retrofit yielded the lowest annual whole-life carbon emissions (~33 kg CO_2 e/m^2/year), and the standard retrofit the second lowest (~36 kg kg CO_2 e/m^2/year).

However, assuming the same lifespan for retrofit and new construction buildings overestimates the whole-life carbon-emission benefits of retrofitting. When applying the durability lifespan approach (see 2. above), the Passive House new building produced the lowest emissions (~35 kg CO_2 e/m^2/year) and the Passive House retrofit the second lowest emissions (~36 kg CO_2 e/m^2/year).

The statistical lifespan approach (see 3. above) showed that most buildings are demolished before their natural end of life. Using the statistical data lifespan scenario, the Passive House retrofit yielded the lowest emissions (~ 36 kg CO_2 e/m^2/year). Meanwhile, the standard retrofit and Passive House new building showed similar performances (~39 kg CO_2 e/m^2/year).

The results above indicate the value of retrofitting existing buildings, especially given that the majority of embodied carbon emissions of new construction buildings are realized upfront. The authors concluded that extending the lifetime of new buildings using flexible and durable design is crucial to achieving climate targets.

3.1.4 Case Study Findings & Key Take-aways

- **Deep retrofit and new buildings had comparable operational carbon emissions.**
  The operational performance of retrofit and new buildings was similar when both were built to comply with the same energy and emissions standards. In the cases of deep energy and carbon retrofits, where high-performance standards such as Passive House are followed, operational carbon emissions were significantly reduced from the existing building, but comparable to levels for new construction.
- **Deep retrofit significantly reduced building whole-life carbon emissions, regardless of the building lifetime.**

"The operational performance of retrofit and new buildings was similar when both were built to comply with the same energy and emissions standards."

All the studies reviewed suggested that deep energy and carbon retrofits have significantly lower overall whole-life carbon emissions than demolition and new construction. This reduction results from comparable operational, but considerably lower embodied, carbon emissions. Maintaining and reusing major elements, such as the structure, considerably reduces the embodied carbon emissions of retrofits compared to new construction.

- **Despite shorter building lifetimes, deep retrofits had similar or lower whole-life carbon emissions than building new.**

  Except for one, all the studies assumed the same lifetime for retrofit and new buildings. One study looked at alternative scenarios for retrofit and new building lifetimes, including those based on structural durability and statistical data [29]. Even when the lifetime was based on statistical data, renovating to high-performance building standards had lower whole-life carbon emissions than high-performance new construction. When the lifetime was based on structural durability, the whole-life carbon emissions of a deep energy retrofit[22] and high-performance new construction were similar.

  Deep retrofit had significantly lower upfront emissions. In terms of contribution to hitting near-term climate targets (less than 10 and 30 years [5]), deep retrofitting almost always outperforms new buildings, even if the retrofitted buildings will not last as long as the new buildings.

- **Deep retrofit had a short payback period for the upfront embodied carbon emissions.**

  While deep retrofit resulted in upfront embodied carbon emissions from the addition of new materials compared to leaving the building as is, they act as an investment to reduce the operational emissions. This investment carried a three- to five-year payback in the reviewed case studies.

- **Mechanical and interior elements are significant contributors to retrofit embodied carbon emissions.**

  Replacing HVAC and tenant improvements were key contributors to the embodied carbon emissions of office retrofits, as their lifespans are typically shorter than the building's life and are often replaced multiple times. Low-carbon material choices for these elements could maximize the whole-life carbon emission benefits of the retrofit. Currently, most regulations, standards and certifications do not require including these elements in the scope of wbLCA. This can result in a missed opportunity to understand and reduce emissions from these elements.

[22] A deep energy retrofit is the process of changing, replacing, and adding components to a building to significantly educe its energy consumption, thereby reducing the building's operational carbon [70].

- **Few LCA case studies of retrofit versus new construction are available.**

  Eight LCA case studies of retrofitting buildings larger than single-family houses were reviewed. They varied in scope, with some comparing retrofit against demolition and new construction, and some against the status quo. Only two focused on commercial buildings. All eight studies relied fully or partially on modelling and hypothetical assumptions, rather than data from actual retrofit projects. In those involving a comparison against a new build, they all assumed the new building alternative to have the same size, shape and function as the existing building. Much more research is required in this space.

3.2 Standards and Guidelines

The study found no international or Canadian standards or guidelines specifically addressing LCA or carbon assessment of circularity practices in buildings. However, standards and guidelines for LCA and circularity practices, in general, were found and contained content relevant to the topic. The LCA standards and guidelines were reviewed to determine whether they consider the carbon-emission impacts of circularity practices specifically for buildings. In addition, the standards for circularity practices were reviewed to identify any guidance on assessing the embodied carbon-emission impacts and benefits of these practices.

The standards and guidelines reviewed through this search can be organized into three categories:

1. Building material and product LCA standards
2. Whole-building LCA standards and guidelines
3. Construction circularity standards and elines.

3.2.1 Building Material and Product LCA Standards

Building material and product LCA standards are based on ISO 14025:2006, *Environmental labels and declarations — Type III environmental declarations — Principles and procedures,* a general standard by the International Organization for Standardization (ISO) for environmental product declarations (EPDs) [30].

EPDs disclose the life-cycle environmental performance of products or materials and enable comparisons with products that fulfill a similar function. Type III EPDs, the most thorough type of EPD, cover a product developed by one or more manufacturers, and are reviewed and verified by a third-party.

ISO 14025 defines a Product Category Rule (PCR) as a set of specific rules, requirements, and guidelines for developing EPDs for one or more product categories, such as concrete or glass. PCRs help ensure consistency and comparability of product alternatives by providing direction on an approach and methodology, such as system boundaries, functional units, and end-of-life stages.

The following standards by ISO and the European Committee for Standardization (CEN) are the main PCR standards for building products referred to internationally and in Canada.

- ISO 21930:2017, *Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.* This standard is currently under review [31] and complements ISO 14025 by providing principles, specifications and requirements to develop EPDs for construction products and services. The standard helps ensure uniformity in EPD methodology, and enables consistent assessment and comparison between products in design and construction.
  - The current version of ISO 21930 was reaffirmed in 2023 and only requires the product stage of the life cycle (A1-A3) be included in the EPD. This means that the environmental impacts at the end of product life (C1-C4) and the benefits and loads beyond its end-of-life (D1-D4) are not included.
- EN 15804:2019, *Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products* [32] is a European standard that provides similar guidance and framework as ISO 21930 for creating EPDs for construction products. ISO 21930:2017 aligns with the 2013 version of EN 15804+A1. However, an update (EN 15804+A2) was released in 2019 that is more stringent and deviates from ISO 21930:2017. EN 15804+A2 became mandatory in Europe in July 2022 [33] and includes the following updates.

- All products must include the end-of-life (stages C1-C4) and benefits and loads beyond the end-of-life (stages D1-D4). A newly added appendix provides detailed guidelines for calculating the benefits and loads beyond these defined stages as boundaries.
- Mandatory inclusion of the end-of-life stages creates more product-specific data and puts more emphasis on circularity practices.
- The biogenic carbon in the products and packaging needs to be included in EPDs, unless it is less than 5% of the product and packaging mass. Notably, negative carbon values are used when the biogenic materials are procured from sustainably managed forests and sources. This carbon storage is released in stage C3, which must be included if the product's end-of-life treatment is incineration.

3.2.2 Whole-Building LCA Standards and Guidelines

Life-cycle approaches play an essential role in assessing and setting requirements for building performance. The following international and European (ISO and CEN) standards, and a guideline from the NRC, provide frameworks for evaluating, comparing, benchmarking and improving the environmental performance of building construction, including their carbon emissions:

- ISO 21931-1:2022, *Sustainability in buildings and civil engineering works – Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment – Part 1: Buildings* [34] provides a general framework for the environmental, social and economic performance assessment of buildings. It identifies and describes issues to be considered in the development and use of assessment methods for the environmental, social and economic impacts of new or existing buildings throughout their life cycle.
- EN 15978:2011, *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method* [14] specifies the calculation rules to assess the environmental performance of new and existing buildings using an LCA methodology. Unlike ISO 21931-1, which covers environmental, social and economic impacts, this European standard is limited to the environmental effects. Other impact areas are covered in different standards. The standard defines system boundaries, data required for the calculations, the process of life-cycle inventory (LCI), indicators of environmental performance, and the presentation and reporting of results. The standard covers all LCA stages and requires using data from EPDs that are compliant with EN 15804.
  - Since this standard refers to EN 15804 [32], emissions for stage C and D are based on data available in the EPDs that follow the EN 15804 standard.
- NRC's 2022 National guidelines for whole-building life cycle assessment [13] provides comprehensive instruction for life-cycle assessments applied to buildings. The goal is to harmonize the practice of wbLCA across different studies, and assist in interpreting and complying with relevant standards. The two key standards these guidelines follow are EN 15978:2011 and ISO 21930:2017, recognizing that EN 15978 is the most advanced document on wbLCA.
  - It is important to note that at the time the NRC guidelines were developed, ISO 21931-1 had not been updated from the 2010 version.
  - NRC guidelines refer to ISO 21930:2017 rather than EN15804, as EPD practices in North America typically follow ISO 21930, which does not mandate including stage C and D.

3.2.3 Circularity Standards and Guidelines

The following Canadian and European standards and guidelines provide frameworks and requirements for implementing circularity practices, primarily for buildings and building elements. These standards address implementing an LCA lens to designing for durability, adaptability, disassembly and deconstructing buildings at the end of their life. While the building-specific standards and guidelines address the environmental benefits of the practices covered, they do not provide specific directions on using LCA to assess the environmental benefits, such as embodied carbon emissions reduction.

- CAN/CSA S478:19, *Durability in buildings* [34] sets minimum requirements for designers to create durable buildings. It includes durability requirements for the design of a new building, or repair or retrofit of an existing building and building elements. It also provides a framework to specify the design service life and the predicted service life of a building or a building element, and requirements for maintenance and degradation assessment. This standard is published as a National Standard of Canada and is referenced in the National Building Code of Canada. The scope of this standard excludes MEP.

  - This standard does not provide guidance on how to use LCA to assess the environmental and carbon benefits of extending the life of buildings.

- CSA Z782-06, *Guideline for design for disassembly and adaptability in buildings* [36] provides a framework for reducing the negative environmental impact of building construction and waste through design for disassembly and adaptability (DfD/A). It can be used for new construction or retrofits to develop disassembly- and adaptability-conscious details, and to adopt strategies for a building's overall structure or parts. DfD/A principles contribute to embodied carbon-emission reductions by extending the life of the building, thus reducing the need to construct new buildings and maximizing the potential for waste diversion.
  - The guideline reviews quantifiable metrics for each DfD/A principle, but these metrics do not include links to embodied-carbon emissions, LCA or carbon emissions.
- CSA Z783:12 (R2021), *Deconstruction of buildings and their related parts* [37] provides minimum requirements for efficient deconstruction methods and processes for directing salvaged materials for re-use. It improves the capacity of the industry to reduce waste and carbon emissions by preserving natural resources and reducing the use of new materials.
  - This standard does not cover guidance or requirements regarding links to embodied carbon emissions, or using LCA to assess the carbon impacts of building deconstruction.
- CEN/TC 350/SC 1, *Circular economy in the construction sector* [38] looks to help transition standardization to the built environment for principals, guidelines, processes and tools for circular economy practices. It applies to products, materials and components of new and existing building and civil engineering construction projects. This standard takes into account CEN/TC 350 [39] and other standards that address the circular economy, such as ISO/TC 323 [40] and CEN-CLC/JTC 10 [41]
  - This standard does not cover guidance or requirements regarding links to embodied carbon emissions, or using LCA to assess the carbon impacts of these circularity practices.
- CEN/TR 16816:2015, *End use performance of wood products – Utilization and improvement of existing methods to estimate service life* [42] is a technical report that emphasizes the need to test predictions to provide a realistic measure of wood product service life. It adds that service life predictions should be a part of the design and construction process, applicable to both new and existing buildings and construction projects. This technical report consolidates the discussions with CEN/TC38/WG28 Performance Classification to date.
  - This report can inform assumptions on the lifetime of wood products in wbLCA when product-specific data is missing.
  - It could also be updated with biogenic carbon guidance from EN15804:2019

3.2.4 Discussion of Standards Gaps

- **Unlike EN 15804, the current version of ISO 21930 used in North America does not provide specific guidance nor mandate the inclusion of stages C and D.**

  More standardized product- and project-specific data encompassing end-of-life, as well as benefits and loads beyond the building life cycle, need to be developed. ISO 21930 sets the standard for generating construction product and material EPDs in North America. The current standard version, reaffirmed in 2023, mandates the inclusion of the product stage (stages A1-A3) only. The 2019 version of the equivalent European standard, EN 15804+A2, mandates the inclusion of, and provides more specific guidance for, assessing the impacts at the end of a building or product lifetime (stage C), as well as the benefits and loads beyond their lifespan (stage D). It would be valuable to dive deeper into the variations between the two standards and assess how similar approaches could be adopted in Canada.

"Current building circularity standards and guidelines do not provide direction for assessing their environmental impacts"

- **wbLCA standards and guidelines do not provide directions on assumptions for stages B, C and D when product- or project-specific data is missing.**

  wbLCA standards require using data from either EPDs or the specific project. However, data on stages B, C and D are often unavailable. wbLCA standards and guidelines should provide more consistent direction on assumptions for these life-cycle stages, given the lack of available data.

- **Building circularity standards and guidelines do not provide direction on assessing whole-life carbon-emission benefits.**

  Current building circularity standards and guidelines do not provide direction for assessing their environmental impacts. Guidance for the following would be helpful in a wbLCA model:

  - Assumptions for building element lifetimes, replacement frequency, and lifetime extension resulting from implementing design for durability, adaptation and disassembly.
  - Assumptions for end-of-life scenarios and waste diversion rates in stages C and D, as the result of building deconstruction and demolition.

4 LCA Case Study

The case study conducted for this report compared whole-life carbon emissions (both operational and embodied) of retrofit versus demolition and new construction for mid-rise and high-rise office buildings in three cities across Canada – Toronto, Vancouver and Edmonton.

4.1 Results and Discussion

4.1.1 Whole-life Carbon Emissions

Figure 3, Figure 4 and Figure 5 show the cumulative whole-life carbon emissions from retrofit versus demolition and new construction for the mid-rise offices in Toronto, Vancouver and Edmonton. These graphs break down emissions by embodied, refrigerant and operational emissions. Figure 6, Figure 7, and Figure 8 show the same information for the high-rise offices.

Tables C-1 to C-3 in Appendix C show the percentage contribution of embodied, operational, and refrigerant emissions to the total emissions of retrofit and demolition/new construction for the mid-rise offices. The years specified represent the beginning and end of the building life (2022 and 2083), as well as 2030 and 2050, which are Canada's interim and long-term climate target years [5]. Tables C-4 to C-6 show the same information for high-rise buildings.

As shown in Figure 3 to Figure 8, deep carbon retrofits of existing buildings can result in significantly less whole-life carbon emissions than demolition/new construction in both mid-rise and high-rise buildings in all three cities. These results demonstrate that deep carbon retrofitting of existing buildings can be an effective measure to achieve Canada's climate targets.

For instance, by 2030, retrofit of the mid-rise office compared to rebuild can result in 70% lower whole-life carbon emissions in Vancouver, 57% in Toronto and

45% in Edmonton (see Tables C-1 to C-3). By 2050, the retrofit of the mid-rise office building is estimated to have 58% lower emissions in Vancouver, 41% in Toronto and 23% in Edmonton.

Tables C-4 to C-6 show the same comparisons for the high-rise office. By 2030, the retrofit of the high-rise office lowered emissions by 44% in Vancouver, 37% in Toronto and 26% in Edmonton. By 2050, the retrofit of the high-rise office lowered emissions by 32% in Vancouver, 22% in Toronto and 11% in Edmonton.

The emissions reduction benefits of retrofit are more significant when operational and refrigerant emissions are relatively small. This is the case in high-performance buildings in regions with a cleaner electricity grid, such as British Columbia and Ontario. As such, the case study show a 70% emissions reduction in the Vancouver mid-rise compared to a 45% reduction in the Edmonton mid-rise by 2030.

Further, the reduction of whole-life carbon emissions of retrofit compared to demolition and new construction is most significant at the beginning of the building's life. This is because the majority of embodied carbon emissions occur upfront and are released before the buildings are in use. Over the lifetime of the building, the operational and refrigerant emissions represent a larger portion of the whole-life carbon emissions, growing at a faster rate than the embodied carbon emissions. Nevertheless, by 2050, the carbon emissions reductions resulting from retrofit are still considerable.

The results of this case study showed greater emission reductions from retrofitting the mid-rise than from retrofitting the high-rise office buildings. This was partially because the mid-rise office buildings in this study had higher overall embodied carbon intensity than the high-rise office buildings. However, this difference in embodied carbon intensity may not be the case in all projects, depending on the site conditions, design, and material choices.

The results show that the contribution of refrigerant emissions to the overall emissions were relatively insignificant in Edmonton and Toronto's buildings, at less than 5% until the end of building life. Refrigerant impacts were more significant in the Vancouver model. For the mid-rise office, refrigerants contributed 19% of the emissions in the retrofit and 11% in the demolition and new construction scenarios. For the high-rise office, refrigerant emissions were 16% in the retrofit and 12% in the demolition and new construction scenarios, respectively.

The higher refrigerant emissions for the Vancouver offices were a result of the mechanical systems assumed and the higher carbon-intensive refrigerant used. The Vancouver office buildings assumed a heat pump for heating and cooling, which uses refrigerant type R-410A. The Toronto and Edmonton models assumed a natural gas boiler and central chiller combination using refrigerant type R-134a. The R-410A refrigerant operates at a higher pressure[23] and therefore the system requires a larger volume than the R-134a refrigerant.[24] In addition, the upfront carbon intensity (A1-A3) for R-410A is higher than R-134a.[25]

4.1.2 Embodied Carbon Emissions

A 2022 CAGBC study showed that a building that has had a deep carbon retrofit can have comparable operational carbon emissions to an equivalent new building [6]. As such, this case study assumed identical operational and refrigerant emissions in both the retrofit and rebuild scenarios. This allowed the changes in life-cycle carbon emissions of the two scenarios to be limited to variations in embodied carbon emissions.

The Vancouver models had the lowest emissions and Edmonton had the highest. The embodied carbon emissions of the mid-rise office in Vancouver were 22% lower than in Edmonton for the demolition and new construction scenario, and 24% lower for the retrofit scenario. The embodied carbon emissions of the high-rise office in Vancouver were 12% lower than in Edmonton for the demolition and new construction scenario, and 4% lower for the retrofit scenario.

[23] R-410A operates at 400 pound-force per square inch (PSI), minimum [71].

[24] R-134a operates at 22-57 PSI, minimum [72].

[25] The A1-A3 global warming potential (GWP) impacts in One Click LCA of R-410A and R-134a are 2,088 kg CO_2e/kg and 1,430 kg CO_2e/kg, respectively.

Figure 3: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Toronto, mid-rise office

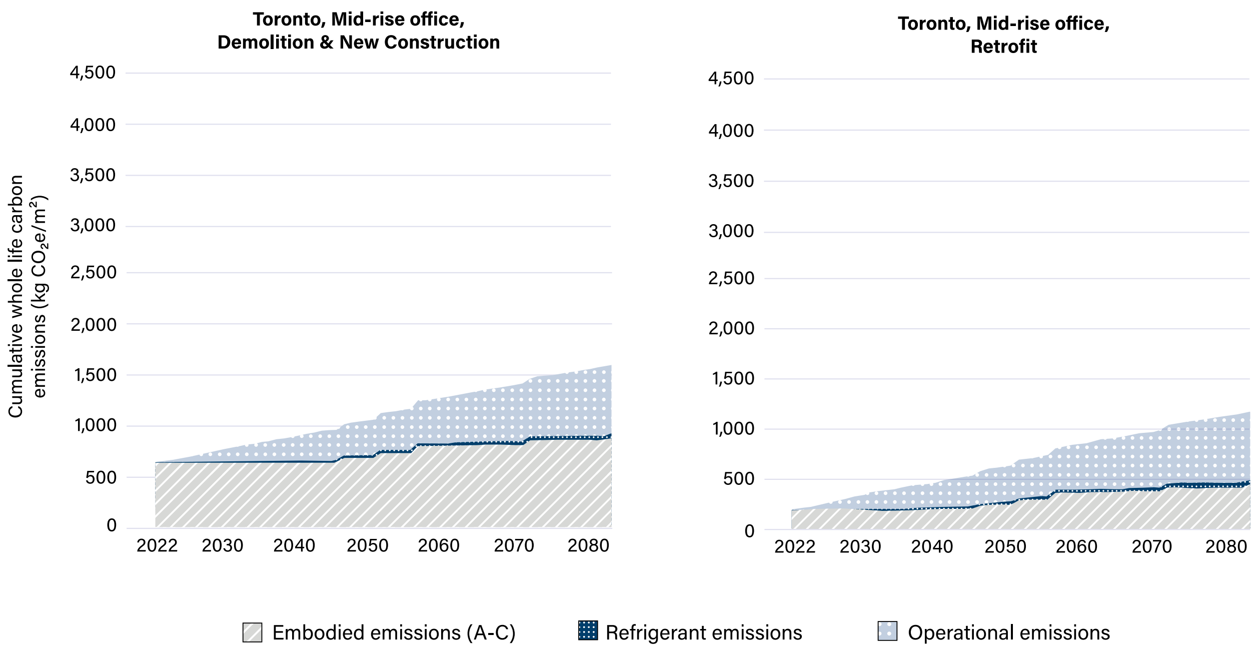


Figure 4: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Vancouver, mid-rise office

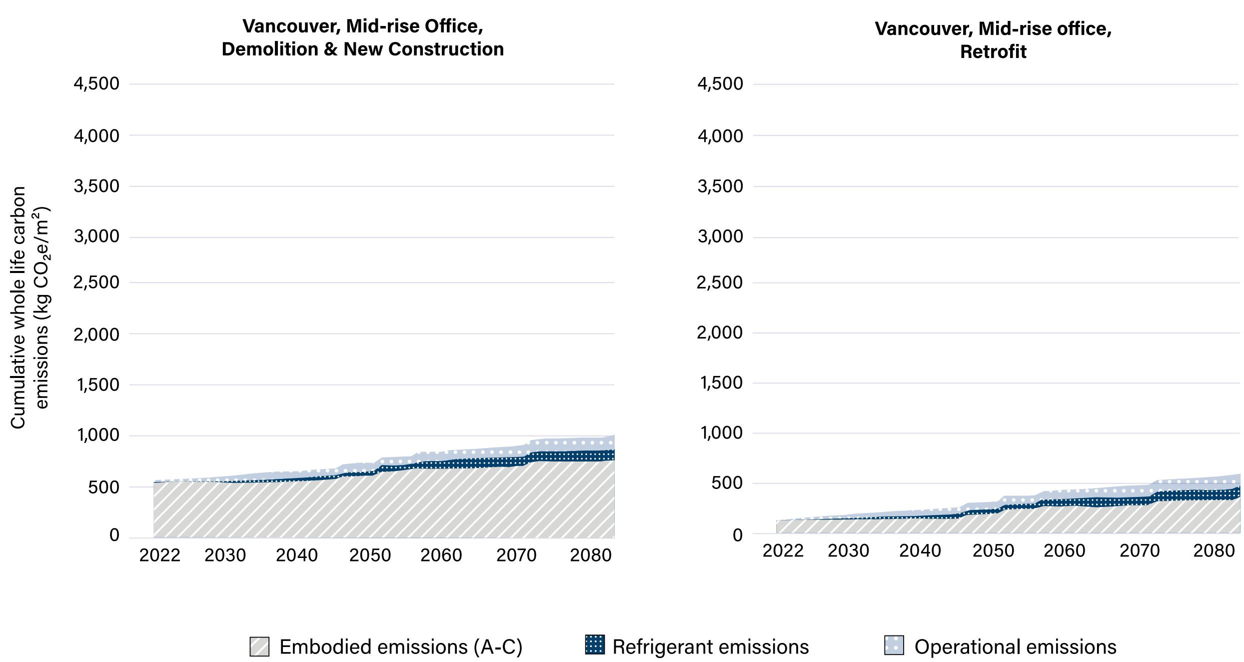


Figure 5: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Edmonton, mid-rise office

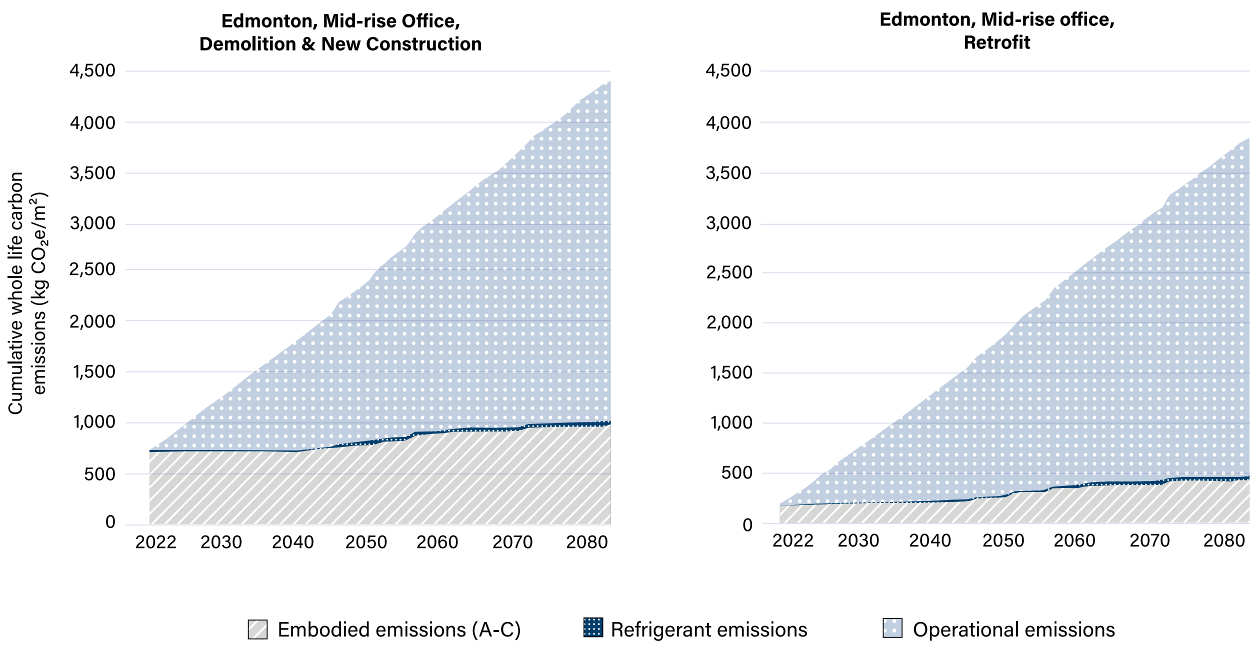


Figure 6: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Toronto, high-rise office

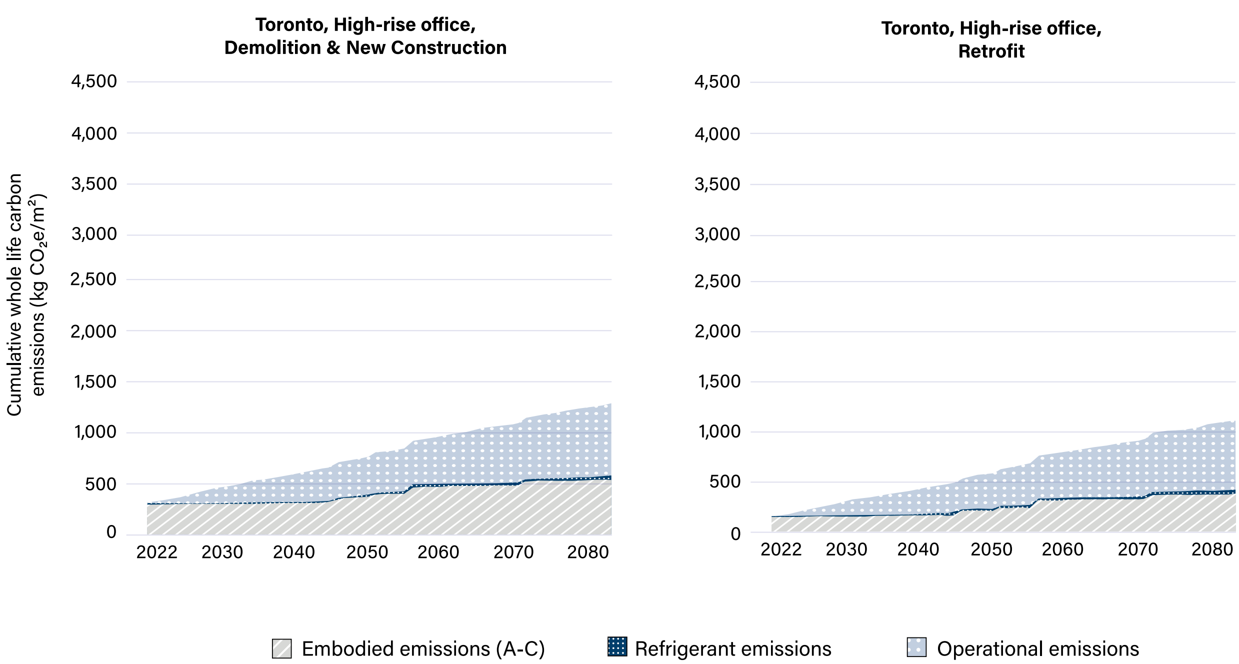


Figure 7: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Vancouver, high-rise office

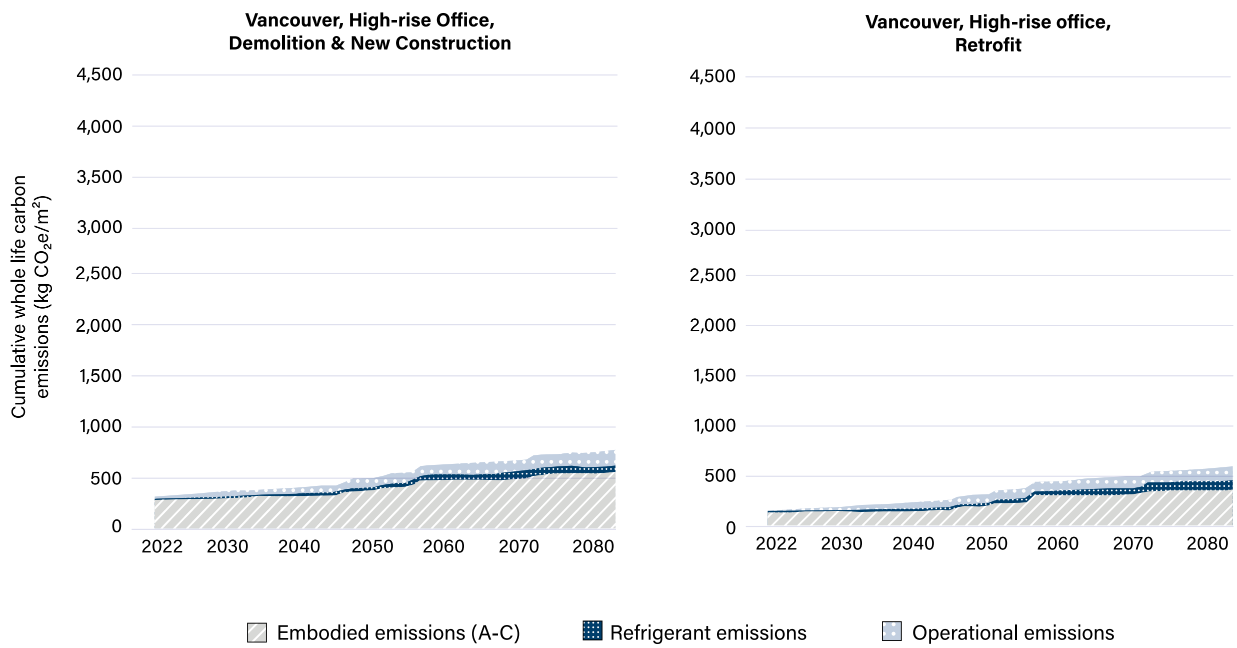
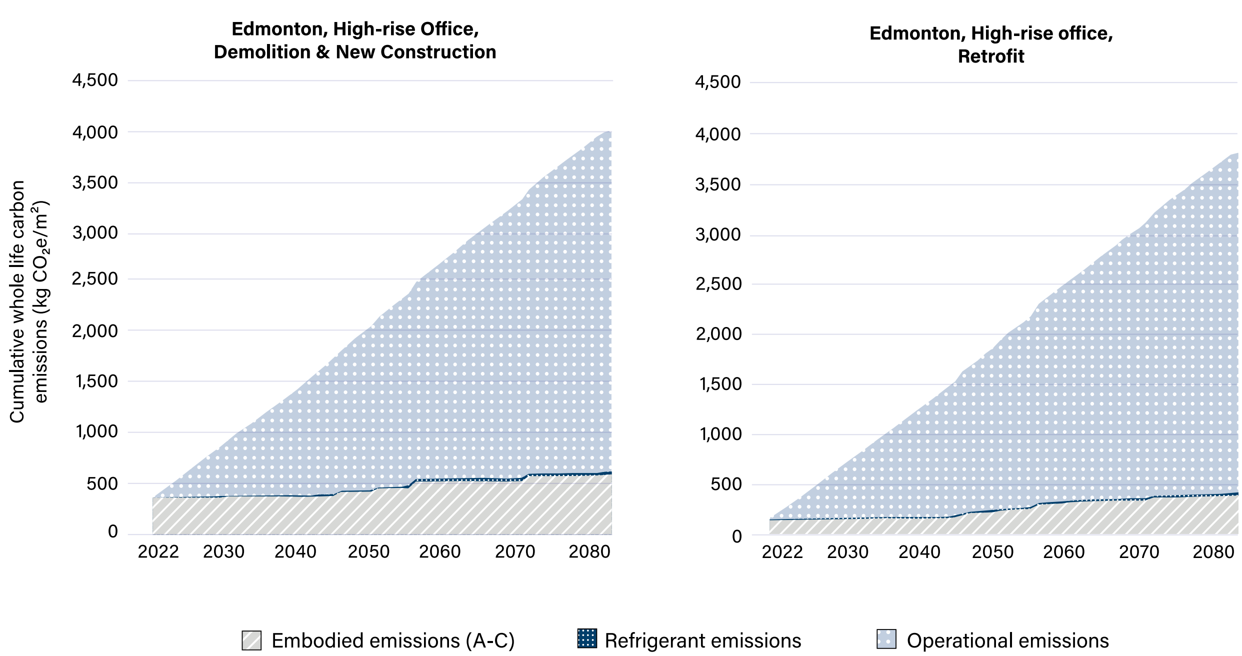


Figure 8: Cumulative whole-life carbon emissions of demolition & new construction vs. retrofit in Edmonton, high-rise office.



The most significant difference between the Vancouver and Edmonton offices were the embodied carbon emissions associated with the concrete mixes for floor construction and exterior wall assembly for the mid-rise office buildings. The product stage A1-A3 embodied carbon emissions for the provincial industry average concrete EPD selected for floor slab construction is 32% higher for Alberta than British Columbia. While the Edmonton mid-rise office exterior curtain wall assembly was adapted from the Toronto reference building, the Vancouver mid-rise exterior wall was based on actual mid-rise office building data received from Perkins + Will [43]. See Appendix B for the full assembly description. The embodied carbon emissions of the glass fiber reinforced concrete cladding wall assembly and double-glazed windows modelled for Vancouver was 74 kg CO_2e/m^2, which is a 47% reduction from the Edmonton exterior curtain wall assembly of 138 kg CO_2e/m^2.

The carbon intensity of British Columbia's electricity grid is also significantly lower than Alberta's. This contributed to lower embodied carbon emissions for all LCAs, as generic material data selected in One Click LCA was localized to the provincial electricity grid, which has manufacturing impacts.

Despite these variations, embodied carbon emissions distribution across life-cycle stages, building elements and material types were similar across the three cities. As such, only results generated for Toronto are presented. Figure 9 and Figure 10 show the embodied carbon emissions breakdown by life- cycle stage for mid-rise and high-rise office buildings, respectively. Figure 11 and Figure 12 show the embodied carbon emissions breakdown by building element and material for mid-rise and high-rise office buildings, respectively.

There was a significant reduction in the overall embodied carbon emissions[26] in the retrofit scenario compared to demolition and new construction. The reduction for the mid-rise office building in Toronto was 49% (Figure 9) and 31% for the high-rise office building (Figure 10).

The benefits and loads beyond the system boundary (life-cycle stage D) are shown separately in Figure 9 and Figure 10. Stage D represents the emissions and benefits from material and energy recovered at the end of the building's life.[27] These emissions are equivalent at the end of a 60-year building life for both retrofit and demolition and new construction. Small but negligible differences in upfront module D emissions were found for both the mid-rise and high-rise offices. This was due to the variations in Stage D impacts of the materials that are not demolished and replaced in the retrofit scenario, for example, the structure.

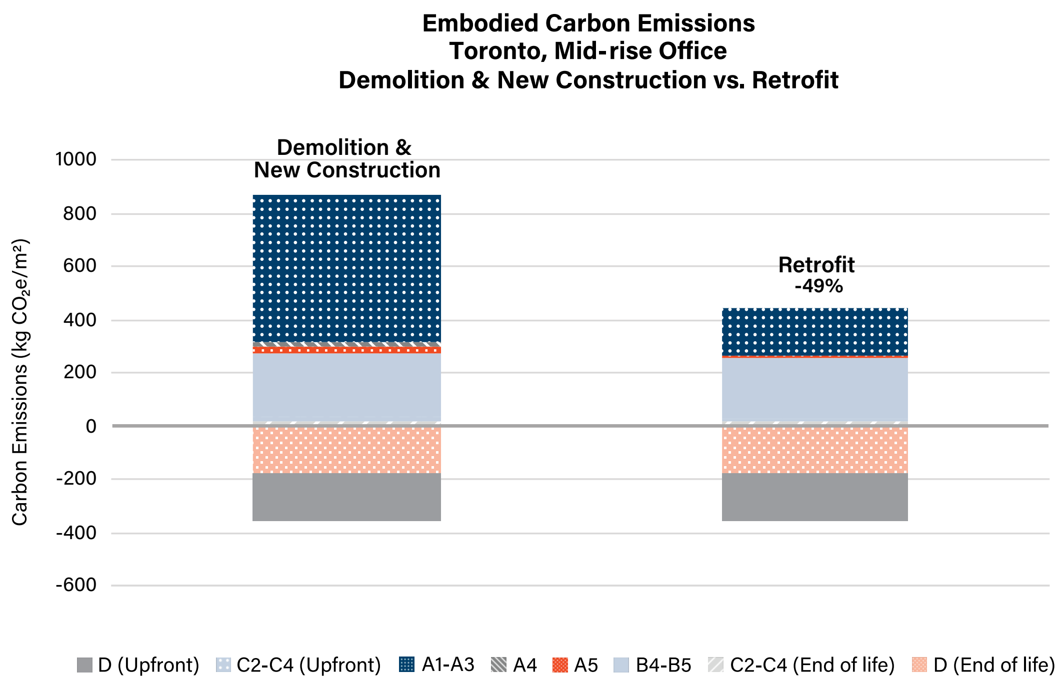
The most significant embodied carbon emissions reduction was found in the product stage (A1-A3). Figure 11 and Figure 12 show that this reduction was mainly because of the emissions avoided by reusing the concrete foundations and structure, rather than demolishing and using new materials to build a new building.

The mechanical systems constituted a significant portion of the embodied carbon emissions. For the mid-rise office building, the mechanical systems represented 15% of total embodied carbon emissions in the demolition and new construction scenario and 30% in the retrofit scenario (Figure 11). For the high-rise office building, the mechanical systems represented 24% of total embodied carbon emissions in the demolition and new construction scenario and 34% in the retrofit scenario (Figure 12). The embodied carbon emissions of mechanical systems were significant because they have high quantities of metal, with assumed lifespans of 22 to 25 years [20], which means they are expected to be replaced twice during the 60-year life of the building.

[26] Excluding the benefits and loads beyond the system boundary (life-cycle stage D)

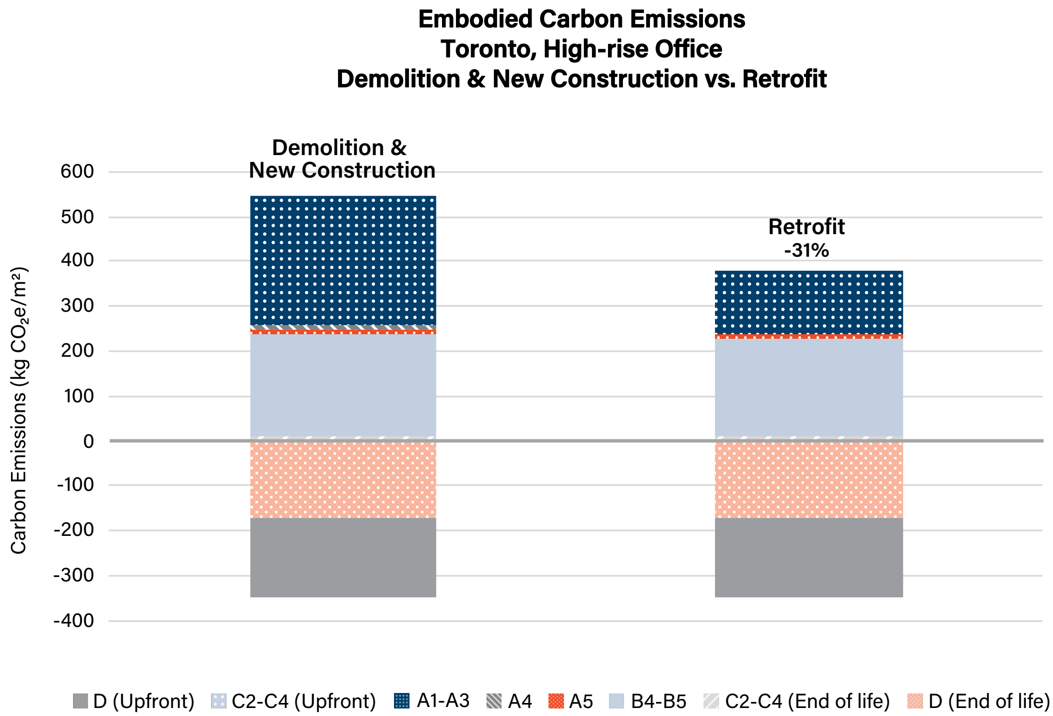
[27] This study used the default assumptions used in the One Click LCA tool for the Stage D impacts. These assumptions are generic and not based on regional waste diversion practices. Examples of the key assumptions from the tool include recycling concrete to use as aggregate; partial recycling of steel, aluminum, glass, and gypsum; incinerating plastics, membranes and carpet; landfilling or incinerating insulation; and recycling 90% of metal in the MEP systems.

Figure 9: Embodied carbon emissions by life-cycle stages of demolition & new construction vs. retrofit, Toronto, mid-rise office building



	Demolition & New Construction	Retrofit
A1-A3	559	177
A4	19	2
A5	26	8
B4-B5	232	232
C2-C4 (Upfront)	20	5
C2-C4 (End of life)	20	20
D (Upfront)	-178	-179
D (End of life)	-178	-178

Figure 10: Embodied carbon emissions by life-cycle stages of demolition & new construction vs. retrofit, Toronto, high-rise office building



	Demolition & New Construction	Retrofit
A1-A3	290	143
A4	9	1
A5	13	6
B4-B5	217	217
C2-C4 (Upfront)	10	3
C2-C4 (End of life)	10	10
D (Upfront)	-173	-172
D (End of life)	-173	-173

Figure 11: Embodied carbon emissions by building elements and material types, demolition & new construction (D & NC) vs. retrofit, Toronto, mid-rise office building. Total emissions for D & NC = 875 kg CO2e/m2 Total emissions for Retrofit = 444 kg CO2e/m2

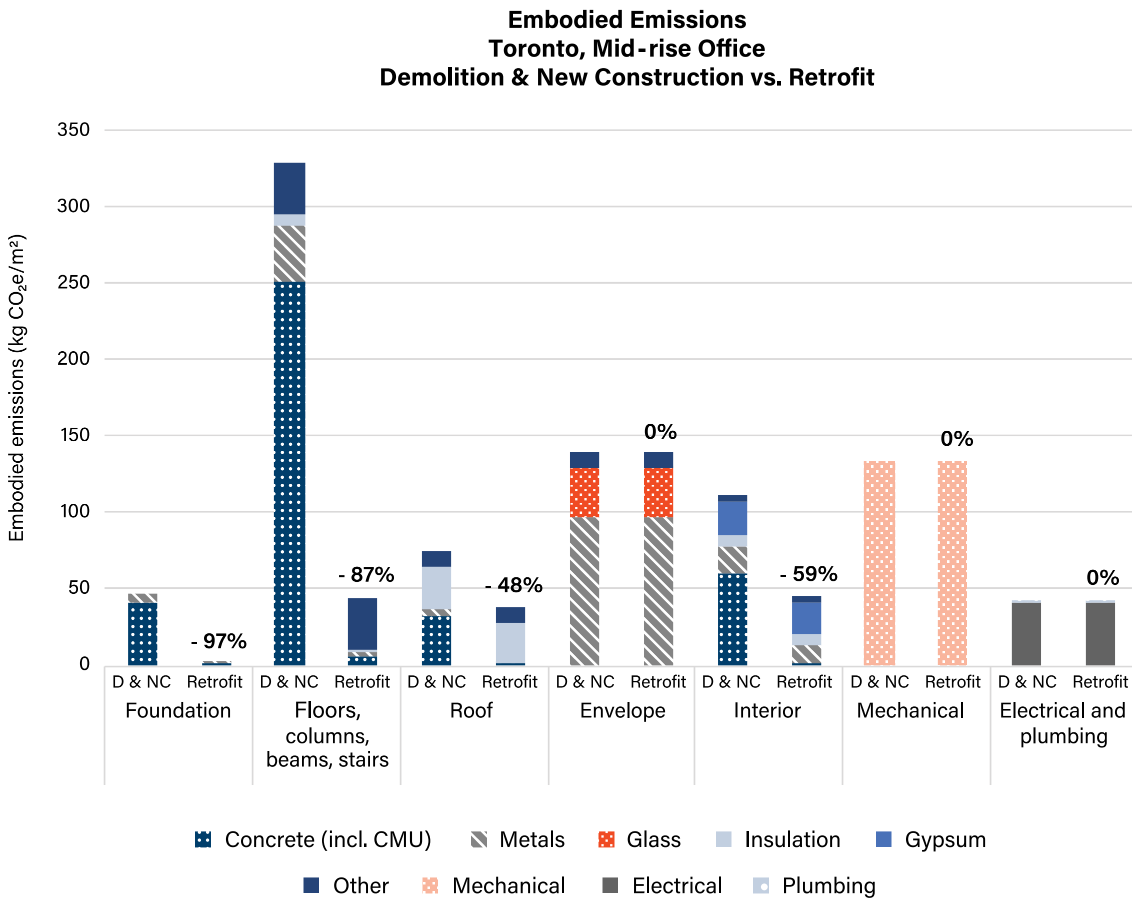
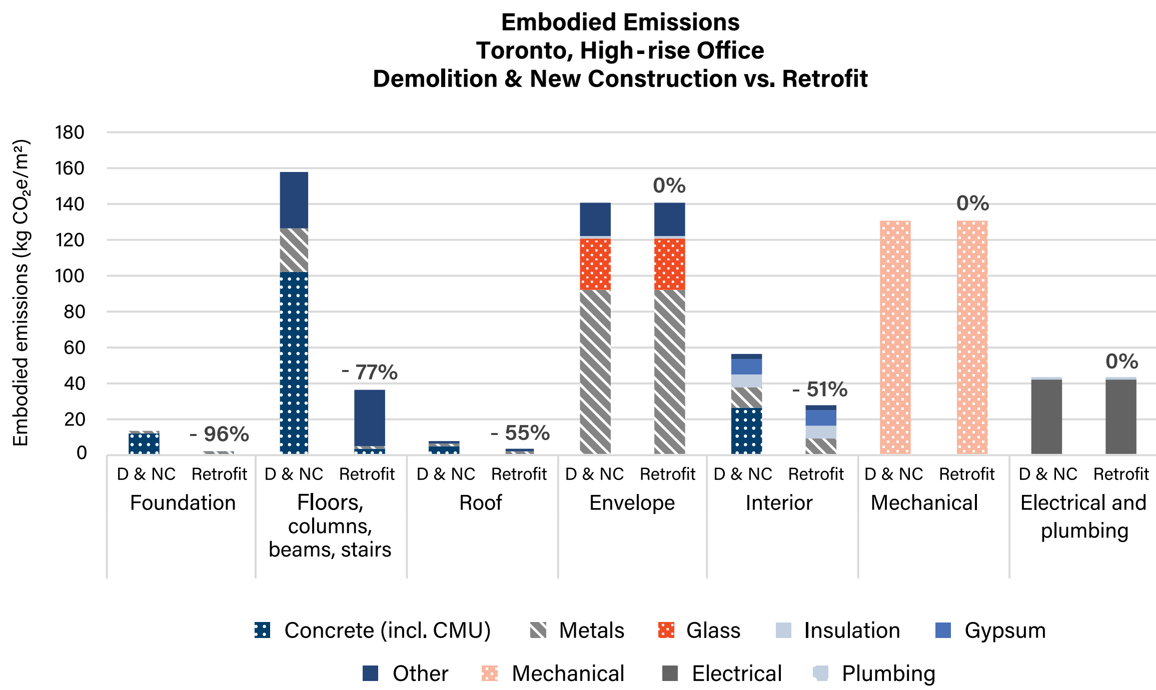


Figure 12: Embodied carbon emissions by building elements and material types, demolition & new construction (D & NC) vs. retrofit, Toronto, high-rise office building. Total emissions for D & NC = 548 kg CO_2e/m^2. Total emissions for Retrofit = 381 kg CO_2e/m^2.



4.1.3 Sensitivity Analysis

4.1.3.1 Wood Elements in the New Building Scenario

Two sensitivity analyses were conducted on the Toronto mid-rise office building. The first analysis assumed a new building with a mass-timber structure and wood-stud interior partitions. This analysis aimed to assess the embodied carbon emissions reduction of retrofit compared to a low-embodied-carbon new-building alternative.

The demolition and new construction mass-timber office building produced 31% lower embodied carbon emissions, compared to the demolition and new construction reference building with a concrete structure and steel studs (Figure 13). Overall, the retrofit scenario had the lowest embodied carbon emissions among all scenarios and, notably, a 26% reduction from the demolition and new construction mass-timber scenario. This demonstrates retrofit can be favourable, even compared to a new building with a mass-timber structure.

The biogenic carbon stored in wood elements were also calculated using One Click LCA[28]. Biogenic carbon is the carbon sequestered in organic matter and released at the end of its life due to decomposition or combustion [44]. The NRC National Guidelines for Whole-building Life Cycle Assessment advises that biogenic carbon be included in stage A of wbLCA reporting. However, the release of biogenic carbon at

[28] One Click LCA calculates biogenic carbon using two methods. The first method uses the biogenic carbon value provided in the building material EPD. The second method is used when the biogenic carbon of the building material is not provided by the data source and is, instead, estimated in One Click LCA in alignment with EN 16449:2014 [44].

the end of building life should also be accounted for in stage C [13]. Since the One Click LCA tool does not account for the release of biogenic carbon, it is not included in the embodied carbon emissions reported in this study. It is instead shown separately in Figure 13.

Product-stage embodied carbon, known as upfront embodied carbon (A1-A5), was 44% lower in the retrofit than in the mass-timber new construction. However, when biogenic carbon was subtracted from the life-cycle modules A1-A5 in the mass-timber new build, retrofit upfront embodied carbon emissions were only 0.7% lower. This means if biogenic carbon impacts are accounted for in a mass-timber structure, the whole-life carbon emissions of retrofit and rebuilding can be comparable. Further analysis using different methods of calculating biogenic carbon is warranted. given there is currently no consensus on the method for calculating biogenic carbon.

4.1.3.2 Element-level Circularity Measures in the Retrofit Scenario

The second sensitivity analysis looked at the potential benefits of embodied-carbon-emission reductions implementing element- and material-level circularity strategies, alongside retrofit.

Figure 14 shows the cascading embodied carbon-emission reductions from the three strategies implemented. These included:

- Partial salvaging and reuse of envelope components (30% of aluminium frame and glazing)
- Using higher-recycled-content materials (interior gypsum board, XPS insulation in the roof assembly, and carpet)
- Reducing MEP material use (20% reduction of electricity, heat and ventilation distribution systems)

Figure 13: Toronto mid-rise embodied carbon emissions, retrofit vs demolition & new construction with a mass-timber structure.

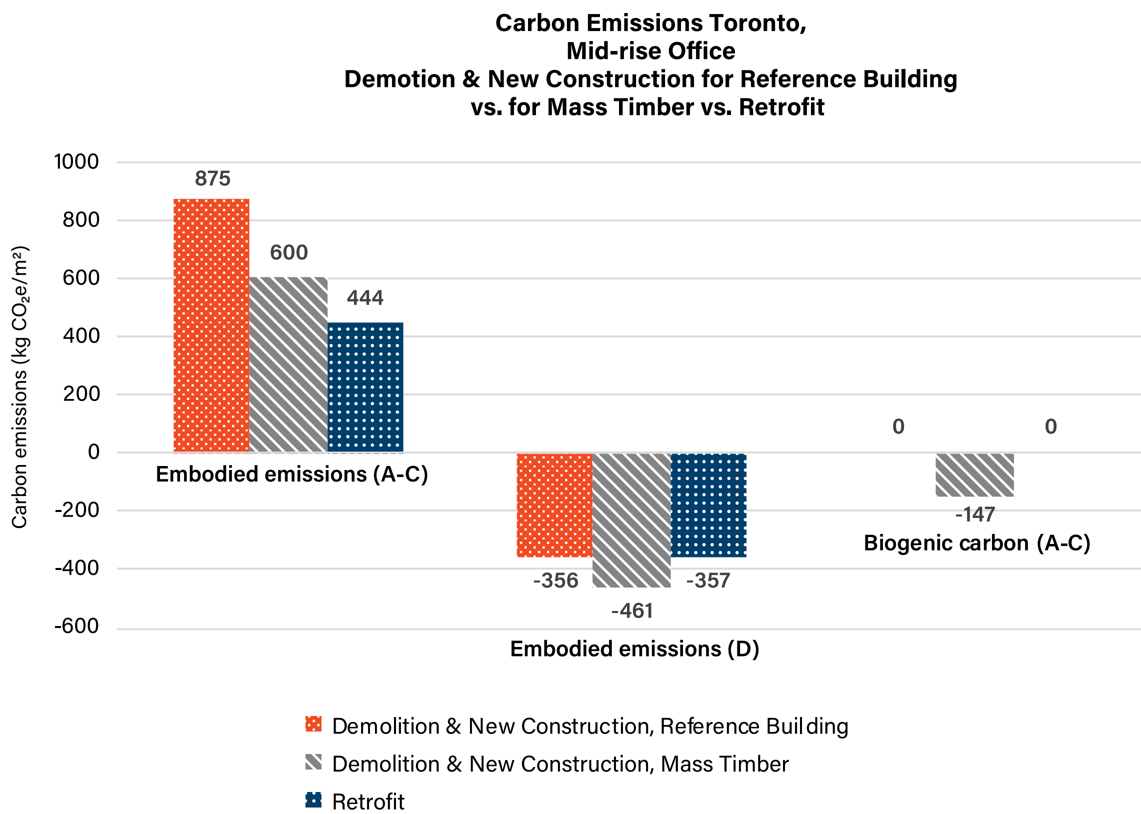
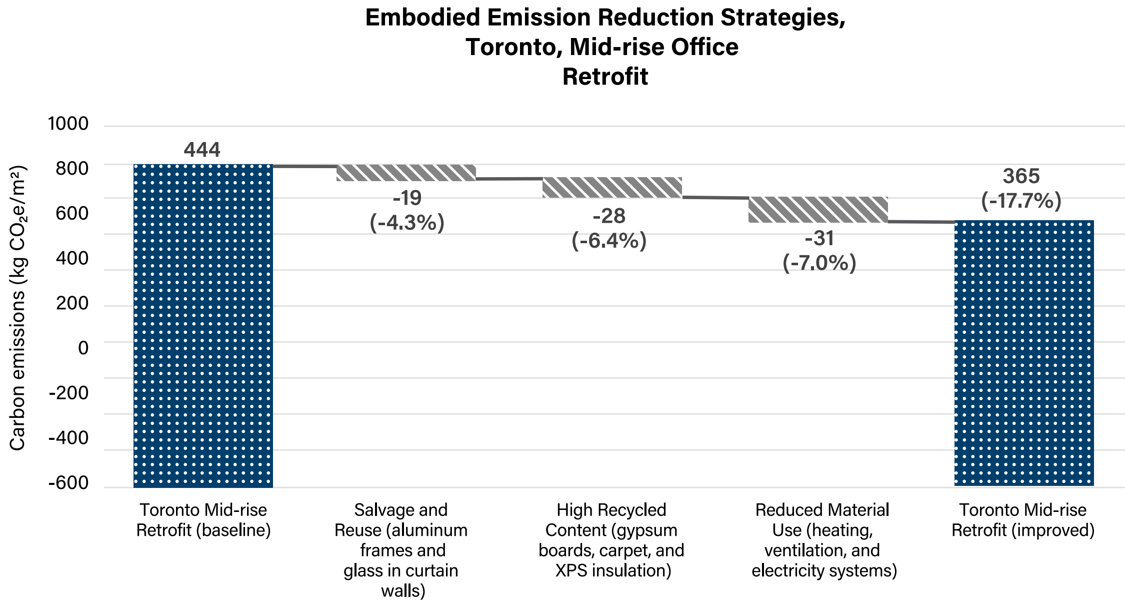


Figure 14: Opportunities for reducing embodied carbon emissions in a retrofit, Toronto, mid-rise office building



The assumptions for this analysis are discussed in Section 2.2.4. These strategies resulted in combined reduction of approximately 18% in embodied carbon emissions from the retrofit scenario.

4.2 Limitations

Several limitations and assumptions in scope, methods, data sources and LCA tools are noted for this case study, and should be considered when interpreting the results.

4.2.1 Data from Reference Buildings

Data from comparable reference buildings in the three cities of focus were unavailable. Therefore, reference buildings in Toronto were modified to model reference buildings in Vancouver and Edmonton. Efforts were made to make these modifications representative of present-day buildings in each city using various data sources. The results could have differed significantly if complete data from actual building projects in Vancouver and Edmonton were used. This modelling approach has the benefit of a mostly consistent building design between geographical regions, with only minimal changes where required.

The mid-rise reference building in Toronto is currently under construction, whereas the high-rise office was built in the 1980s. As such, the design and material selection in the two buildings correspond to standard practices and data sources from different times. Environmental factors, such as the soil condition and depth influencing the foundation also likely affected material quantities and types used for each building. Moreover, due to this study's time and resource limits, new bill-of-materials could not be generated from the reference buildings.[29] Therefore, material quantity data from previously conducted LCAs were used.

The LCAs used for the Toronto mid-rise and high-rise office buildings were conducted at different times (2022 and 2018, respectively) and each reference

[29] The bill of materials for the Toronto mid-rise reference building was compiled from structural takeoffs completed by the project team and manual in-house quantity takeoffs from the project drawings. Manual quantity takeoffs from the hand-drawn project drawings were used to compile the bill of materials for the Toronto high-rise reference building.

building LCA had a distinct goal and purpose. While the best available data sources for each project were used, some EPDs and other life-cycle inventory data within the LCA tool have expired since the time of the assessment or no longer apply [45]. As a result, the building materials selected for this case study may vary from the materials selected for the existing reference building LCAs. Therefore, the results of this study should not be used to compare emissions between the mid-rise and high-rise offices. Despite these limitations, the results are reliable for this study's purpose of assessing the relative carbon reduction of retrofit versus rebuild for each archetype.

High-level assumptions were made where building data was out of scope for the original building LCAs and therefore unavailable for the Toronto reference buildings. These assumptions were made based on in-house or external data resources, including the One Click LCA Carbon Designer 3D tool. For instance, material type and quantity data on MEP systems, refrigerants, interior partitions and finishings were not included in the previous LCAs used as the basis of this study. Similarly, this study did not have access to actual energy modelling data from the reference buildings. It instead assumed both retrofit and new buildings met the minimum performance requirements for new buildings in each city to estimate operational carbon emissions.

The two sensitivity analyses also required several assumptions. These included the feasibility and the extent to which existing elements can be salvaged and reused, and the material use reduction potential, both of which are not based on data from actual case studies. For the mass-timber new building alternative, the Carbon Designer 3D tool was used to estimate material quantities of the structural elements.

4.2.2 LCA Data and Tools

This study heavily relied on the assumptions and data availability in the One Click LCA tool. When regional and product-specific data is unavailable, the tool may exclude some impacts or rely on generic data and assumptions. For instance, the tool uses generic data for the end-of-life stage (stage C) and impacts beyond the building life (stage D), and does not have data on demolition and deconstruction emissions (Module C1).

An alternative tool that could have been used for this study is the Carbon Avoided: Retrofit Estimator (CARE) tool. The recently released CARE tool is a free, web-based carbon calculator that compares the embodied, operational and avoided carbon impacts of retrofitting versus building new [46]. The tool was not used because CARE currently only has data for the United States. In addition, the tool is best suited for early-stage building design.

4.2.3 Retrofit and Rebuilding Scenarios

Since data from actual retrofit and rebuilding of office buildings was unavailable, a like-for-like replacement of buildings and building elements was assumed for the two scenarios. In reality, it is unlikely that a new building would be identical to the demolished one. Similarly, the replaced elements in a retrofitted building would most likely not be the same as those in the existing building. This is because the needs, requirements and common practices have changed since many existing buildings were built.

Additionally, replacing different systems and elements is unlikely to happen all at once in real-world retrofits. Instead, replacing each system is typically aligned with the building-specific infrastructure and equipment renewal cycles [6].

Moreover, in some retrofit case studies, there have been additions or removals of floor space or changes in building function to respond to the changing needs of the users.

This study assumed the same 60-year lifetime for retrofit and new building scenarios. Yet in reality, the lifetime of a retrofitted building may be shorter than a new building [29]. Nevertheless, since building structures are typically expected to last more than 100 years [6], many retrofitted buildings will likely survive past 2050, supporting the case that retrofitting existing buildings can be key in achieving Canada's climate targets, and leading to less whole-life emissions than demolition and rebuild.

5 Key Takeaways and Recommendations

Deep retrofits can significantly reduce whole-life carbon emissions.

This report's literature review and case study show that deep carbon retrofits of CRE buildings can significantly reduce whole-life carbon emissions[30] compared to demolition and new construction. Deep retrofits can contribute to achieving Canada's climate targets and should be favoured over demolition and new construction.

The case for retrofits is strongest in regions with green electricity, such as British Columbia, Quebec, Manitoba and Ontario. If new construction is required, focusing on low-embodied-carbon materials, including low-carbon concrete and steel, and bio-based materials such as wood, can be beneficial in limiting embodied carbon emissions. Accounting for biogenic carbon storage in biomass materials can also support the case for building new timber buildings, since it can lead to a similar whole-life carbon to retrofits. However, more analysis for calculating biogenic carbon is required.

Advancement in wbLCA practices and data would enable regional and project-specific carbon assessment of retrofits.

While attention to the significance of embodied carbon emissions in the building industry is growing, using wbLCA in decision-making processes is yet to become common practice, especially in North America. As more databases and guidelines become available, wbLCA tools can better reflect regional and project-specific circularity practices. This study identified the following key gaps and actions required.

- **More LCAs case studies are needed.**

  The literature review identified a shortage of LCA case studies of retrofit projects and their comparison with rebuilding. All the identified studies relied fully or partially on modelling and hypothetical assumptions, rather than data from actual retrofit projects.

  More LCA case studies on other reference buildings are required to confidently expand the findings of this case study to other regions and building archetypes. Additionally, more LCAs of actual rebuild and retrofit projects can provide a more nuanced and realistic understanding of the carbon benefits of retrofits. For instance, this study used high-level assumptions and an early design stage LCA tool to estimate the impacts of a mass-timber new building alternative, rather than an actual mass-timber building.

  Asset owners and real estate companies with large building portfolios may be best able to access the internal data required for such studies. Internal data is essential because:

  - Demolition and new construction may not happen at the same time and by the same project teams.
  - Access to demolition data is more challenging, since there are currently no requirements for including demolition as part of new building LCAs.
  - Retrofit projects may occur at multiple stages.
  - Finding comparable demolition and new build versus retrofit projects in multiple cities can be difficult.

- **More standardized and product-specific data on stages B, C and D are needed.**

  More standardized product-specific EPDs need to be developed, encompassing an element's durability, impacts at the end of building and product lifetimes, and the benefits and loads beyond their lifespan (stages B, C and D). Requiring reporting stages C and D in EPDs can help bring consistency and attention to the embodied carbon benefits of circularity practices. Developing a standard method and requiring assessing and reporting of product and system lifetime should also be prioritized instead of using industry average data.

  ISO 21930:17 is the current standard for generating building product EPDs in North America. This version only mandates the inclusion of the product stage (stages A1-A3). The updated version of the equivalent European standard, EN 15804+A2:2019, provides more specific guidance and mandates the

[30] Includes both operational and embodied

inclusion of stages C and D. It would be valuable to dive deeper into the variations between the two standards and determine how similar approaches can be adopted in Canada.

- **More data on the lifetime of retrofitted buildings are needed.**

  Currently, wbLCA models use the same lifetime for new and retrofitted buildings. However, this likely overestimates the lifetime of retrofitted buildings. Similar to Palacios-Munoz *et al.* [29], regional statistical data on building lifetimes can be used to inform the retrofitted building lifetime assumptions in wbLCA guidelines.

- **With the lack of product- and project-specific data, more guidance for stage B, C and D assumptions in wbLCA is needed.**

  With the lack of product- and project-specific data regarding stages B, C and D, wbLCA practitioners use their best judgment or default assumptions in wbLCA tools, which are based on the best available industry data. Default values in wbLCA tools can be regional or international. As such, these values can vary widely between assessments or can be lacking entirely.

  To adequately estimate and reflect circularity practice benefits, more regional guidance and, ideally, proxy data for stages B, C and D in wbLCAs is required. Regional databases and proxies on element lifetimes, end-of-life scenarios and waste diversion practices should be developed. The growing embodied-carbon-emissions reporting requirements in policies and regulations should consider requiring the use of these regional databases for wbLCA assumptions if product- and project-specific data is missing.

- **wbLCAs should include interior and MEP elements.**

  HVAC and interior elements are currently excluded in most LCA studies. However, these elements represent a significant portion of embodied carbon emissions from retrofits. This is because these elements have a shorter life span than the building, and are often replaced multiple times during the building's life. Including these components in future LCAs and using low-carbon versions of these materials and systems are critical to realizing the carbon-emission reduction benefits of retrofits. The NRC National Guidelines for Whole-building Life Cycle Assessment requires these elements be included in the wbLCA scope. Building certifications, policies and regulations, such as the City of Vancouver Embodied Carbon Guidelines [47] and CAGBC Zero Carbon Building™ (ZCB) standards [48], are encouraged to include these elements in the mandatory wbLCA scope.

6 Conclusions

This study assessed the potential climate change benefits of circularity practices in construction, with a focus on extending the life of buildings through retrofit as one of the key strategies. The whole-life carbon emissions of retrofit versus demolition and new construction were compared through a literature review of the existing case studies, standards and guidelines, and an LCA case study of selected office buildings in Canadian cities.

The LCA case study featured mid-rise and high-rise office buildings in Toronto, Vancouver and Edmonton. Both scenarios were modelled using existing Toronto mid-rise and high-rise office buildings as reference buildings. The results showed that deep carbon retrofit of existing office buildings could significantly reduce whole-life carbon emissions, compared to demolishing and rebuilding. This finding is in line with findings from the case studies identified through the literature review.

Retrofit led to 35% to 70% lower whole-life carbon emissions than demolition and new construction by 2030, and approximately 10% to 60% lower by 2050, depending on the office archetype and location. These reductions were mainly achieved through the avoidance of upfront embodied carbon emissions, as retrofits maintain the existing structure. The reductions were more significant when the retrofit achieved a similar operational energy performance as the new buildings. This occurred in regions with a cleaner electricity grid and lower operational carbon intensity (GHGi) requirements, such British Columbia, Quebec, Manitoba, Ontario, Newfoundland and PEI.

The embodied-carbon assessment in this study included the structural, envelope, interior partitions, finishes and MEP systems. The results showed mechanical systems could represent a significant portion of the total embodied carbon emissions in retrofit projects. For example, in the mid-rise and high-rise offices in Toronto, mechanical systems represented about 30% of the embodied carbon emissions. This is largely because of the high quantities of metal in mechanical systems, and the regular replacement cycles of them during a building's life. Reducing embodied carbon emissions of mechanical systems should be prioritized to further decrease the embodied carbon emissions associated with retrofits.

The study showed that implementing element and material-level circularity practices, such as salvaging and reusing elements, using high-recycled-content materials and reducing the quantity of material used can all further reduce the embodied carbon emissions of retrofit buildings. A hypothetical implementation of these measures reduced the embodied carbon emissions of the case study mid-rise office building in Toronto by about 18%.

The retrofit scenario still showed lower embodied carbon emissions than a modelled new building with a mass-timber structure and wood-stud partitions (about 25% less in the mid-rise office building in Toronto). However, if the biogenic carbon is accounted for, the upfront embodied carbon benefits of retrofit compared to the mass-timber new building are comparable. Further analysis using other methods of calculating biogenic carbon is needed, as there is no consensus on the method for calculating biogenic carbon in mass-timber structures.

This study assumed identical lifetimes for elements in retrofit and new buildings. While this assumption can result in overestimating the whole-life carbon benefits of retrofit, it did not impact the upfront reduction from retrofit. Since many buildings will survive until 2050, deep carbon retrofits of existing buildings can contribute to achieving Canada's 2030 and 2050 climate targets.

7 Summary of Recommendations

- More LCA case studies need to be conducted to confidently expand the findings of this research to other regions and types of buildings. For example, asset owners and real estate companies with large building portfolios and access to internal data could conduct case studies on actual demolition and rebuild projects.
- More standardized and product-specific data on element lifetimes, and the impacts at the end of the element's lifetime and beyond its life (stages C and D), should be developed. The current version of ISO 21930:2017 does not provide specific guidance nor mandate the inclusion of stages C and D in EPDs.
- More data on retrofitted building lifetimes are needed. Regional, statistical data on how long a building's life can be extended after a deep retrofit can be used to inform wbLCA guidelines and assumptions for retrofitted building lifespans. A more representative period of time would allow for a better understanding of the impacts of retrofitting compared to rebuilding.
- Given the lack of product and project-specific data, more guidance and proxy data for stages B, C and D assumptions in wbLCA are needed. Regional databases on building element, system and material lifetimes, replacement frequency, end-of-life scenarios and waste diversion practices need to be developed. The growing embodied carbon emissions reporting requirements should include these regional databases for the wbLCA assumptions, if product- and project-specific data is missing.
- wbLCAs should include interiors, MEP elements and refrigerants. Building certifications, policies and regulations are encouraged to require the inclusion of these elements in wbLCA, since they can all have significant whole-life carbon impacts, yet are often excluded or ignored.

References

[1] H. Goodland and K. Walsh, “Opportunities to Apply Circular Strategies to Existing Office Buildings,” Canadian Standards Association, Toronto, ON, Canada, 2023. Available: https://www.csagroup.org/article/research/opportunities-to-apply-circular-strategies-to-existing-office-buildings/

[2] Canada Green Building Council, “Building climate solutions: A proven path to lower carbon emissions.” https://www.cagbc.org/why-green-building/building-climate-solutions/ (accessed Nov. 01, 2022).

[3] Canada Green Building Council, “Making the case for building to zero carbon | Appendix,” 2019. Accessed: Mar. 14, 2023. [Online]. Available: https://www.cagbc.org/wp-content/uploads/2022/06/Making_the_Case_for_Building_to_Zero_Carbon_2019_Appendix_EN-2.pdf

[4] Canada Green Building Council, “Embodied Carbon: A Primer for Buildings in Canada,” 2021. Accessed: Mar. 14, 2023. [Online]. Available: https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

[5] Environment and Climate Change Canada, “Net-Zero Emissions by 2050.” https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html (accessed Feb. 07, 2023).

[6] Canada Green Building Council, “Decarbonizing Canada’s Large Buildings: A Path Forward,” 2022. Accessed: Mar. 14, 2023. [Online]. Available: https://www.cagbc.org/wp-content/uploads/2022/04/Decarbonizing-Canadas-Large-Buildings-Report-w.-Appendices-Final-Revised-Copy_with-formtting_2022-04-25.pdf

[7] One Click LCA, “City Policy Framework for Dramatically Reducing Embodied Carbon,” 2020. Accessed: Sep. 17, 2022. [Online]. Available: https://www.embodiedcarbonpolicies.com/

[8] A. F. Marique and B. Rossi, “Cradle-to-grave life-cycle assessment within the built environment: Comparison between the refurbishment and the complete reconstruction of an office building in Belgium,” *J Environ Manage*, vol. 224, pp. 396–405, Oct. 2018, doi: 10.1016/J.JENVMAN.2018.02.055

[9] The Delphi Group in partnership with Scius Advisory, “Circular economy & the built environment sector in Canada,” May 2021. Accessed: Mar. 14, 2023. [Online]. Available: https://delphi.ca/wp-content/uploads/2021/04/Circularity-in-Canadas-Built-Environment-Final-Report-April-14-2021.pdf

[10] D. Calder, “The Case for Deep Retrofits: Improved business case evaluation and financing options for deep retrofits in multi-unit residential building,” The Atmospheric Fund, 2020.

[11] Natural Resources Canada, “Comprehensive Energy Use Database.” https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm (accessed Feb. 05, 2023).

[12] Environment and Climate Change Canada, “Global warming potentials,” 2023. https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/quantification-guidance/global-warming-potentials.html (accessed Mar. 16, 2023).

[13] M. Bowick, J. O'Connor, J. Salazar, J. Meil, and R. Cooney, "National guidelines for whole-building life cycle assessment," 2022. Accessed: Sep. 18, 2022. [Online]. Available: https://doi.org/10.4224/40002740

[14] *Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method,* EN 15978:2011, The European Committee for Standardisation, 2011. Accessed: Sep. 13, 2022. [Online]. Available: https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

[15] National Concrete Masonry Association, "What is the difference between a 'cinder block' and a 'concrete block'?" https://ncma.org/resource/faq-20-14/ (accessed Mar. 13, 2023).

[16] City of Toronto, "Buildings Energy, Emissions & Resilience." https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/toronto-green-standard/toronto-green-standard-version-4/mid-to-high-rise-residential-non-residential-version-4/buildings-energy-emissions-resilience/ (accessed Feb. 06, 2023).

[17] L. King, B. Purcell and N. Lysenko, "City of Toronto: Zero Emissions Buildings Framework," prepared for the City Planning Division, City of Toronto," 2017. Available: https://www.toronto.ca/wp-content/uploads/2017/11/9875-Zero-Emissions-Buildings-Framework-Report.pdf

[18] Environment and Climate Change Canada Data, "Canada's Greenhouse Gas Emissions Projections." https://data-donnees.ec.gc.ca/data/substances/monitor/canada-s-greenhouse-gas-emissions-projections/Current-Projections-Actuelles/Energy-Energie/Grid-O&G-Intensities-Intensites-Reseau-Delectricite-P&G/?lang=en (accessed Feb. 6, 2023).

[19] One Click LCA software, "Carbon Designer 3D." https://www.oneclicklca.com/carbon-designer-3d/ (accessed Feb. 06, 2023).

[20] One Click LCA, https://www.oneclicklca.com/ (accessed Nov. 5, 2022).

[21] Carbon Leadership Forum, "Tools for Measuring Embodied Carbon." https://carbonleadershipforum.org/tools-for-measuring-embodied-carbon/ (accessed Feb. 06, 2023).

[22] V. Mikler, "Greenhouse Gas Emissions of Refrigerants in Residential Heat Pump Based Mechanical Systems: Summary Report," 2021, Accessed: Feb. 6, 2023. [Online]. Available: https://vancouver.ca/files/cov/refrigerant-impact-ghgi-study.pdf

[23] M. Rabani, H. B. Madessa, M. Ljungström, L. Aamodt, S. Løvvold, and N. Nord, "Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian office building," *Build Environ,* vol. 204, Oct. 2021, doi: 10.1016/j.buildenv.2021.108159

[24] F. Asdrubali, I. Ballarini, V. Corrado, L. Evangelisti, G. Grazieschi, and C. Guattari, "Energy and environmental payback times for an NZEB retrofit," *Build Environ,* vol. 147, pp. 461–472, Jan. 2019, doi: 10.1016/j.buildenv.2018.10.047

[25] C. Piccardo, A. Dodoo, and L. Gustavsson, "Retrofitting a building to passive house level: A life cycle carbon balance," *Energy Build,* vol. 223, p. 110135, Sep. 2020, doi: 10.1016/j.enbuild.2020.110135

[26] J. Ferreira, M. Duarte Pinheiro, and J. De Brito, "Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction – A Portuguese benchmarking," *Journal of Building Engineering,* vol. 3, pp. 114–126, Jul. 2015, doi: 10.1016/j.jobe.2015.07.001.

[27] Vidaris and Syska Hennessy Group, "Assessing the Carbon-Saving Value of Retrofitting versus Demolition and New Construction at the United Nations Headquarters," 2016. Accessed: Mar. 16, 2023. [Online]. Available: http://www.vidaris.com/uploads/files/assessing-the-carbon-saving-value-of-retrofitting-versus-demolition-and-new-construction-at-the-united-nations-headquarters-199.pdf

[28] B. X. Rodriguez, M. Huang, H. W. Lee, K. Simonen, and J. Ditto, "Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation," *Energy Build,* vol. 226, p. 110324, Nov. 2020, doi: 10.1016/J.ENBUILD.2020.110324.

[29] B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, and B. López-Mesa, "Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach," *Build Environ,* vol. 160, p. 106203, 2019, doi: 10.1016/j.buildenv.2019.106203.

[30] *Environmental labels and declarations – Type III environmental declarations – Principles and procedures,* ISO 14025:2006(en), International Organization for Standardization, 2006. https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en (accessed Sep. 12, 2022).

[31] *Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services,* ISO 21930:2017(en), International Organization for Standardization, 2017. https://www.iso.org/obp/ui/#iso:std:iso:21930:ed-2:v1:en (accessed Sep. 12, 2022).

[32] *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products,* EN 15804+A2, The Commonwealth Standards Network, 2019. Accessed: Sep. 13, 2022. [Online]. Available: https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/

[33] One Click LCA, "Getting ready for EN 15804+A2: what's changed and how to prepare for it.," 2022. https://www.oneclicklca.com/getting-ready-for-en-15804-a2-whats-changed-and-how-to-prepare-for-it/ (accessed Sep. 27, 2022).

[34] *Sustainability in buildings and civil engineering works – Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment – Part 1: Buildings,* ISO 21931-1:2022(en), International Organization for Standardization, 2022. https://www.iso.org/obp/ui/#iso:std:iso:21931:-1:ed-2:v1:en (accessed Sep. 13, 2022).

[35] *Durability in buildings,* CSA S478:19, Canadian Standards Association, Toronto, ON, Canada, 2019. Accessed: Sep. 27, 2022. [Online]. Available: https://www.csagroup.org/store/product/2700252/

[36] *Guideline for design for disassembly and adaptability in buildings,* CSA Z782-06, Canadian Standards Association, Toronto, ON, Canada, 2006. https://community.csagroup.org/docs/DOC-156154 (accessed Sep. 27, 2022).

[37] *Deconstruction of buildings and their related parts,* CSA Z783:12 (R2021), Canadian Standards Association, Toronto, ON, Canada, 2021. Accessed: Sep. 19, 2022. [Online]. Available: https://www.csagroup.org/store/product/2703337/

[38] *Circular economy in the construction sector,* CEN/TC 350/SC 1, European Committee for Standardization, 2020. https://standards.iteh.ai/catalog/tc/cen/51316ef3-3dea-4483-8aab-cd1a8033cd41/cen-tc-350-sc-1 (accessed Feb. 09, 2023).

[39] *Sustainability of construction works,* CEN/TC 350, European Committee for Standardization, https://standards.iteh.ai/catalog/tc/cen/415e8b38-9bf9-455f-b531-96d83acf019d/cen-tc-350 (accessed Feb. 09, 2023).

[40] *Circular economy,* ISO/TC 323, International Organization for Standardization, https://www.iso.org/committee/7203984.html (accessed Feb. 09, 2023).

[41] *Energy-related product – Material efficiency aspects for eco-design,* CEN/CLC/TC 10, European Committee for Standardization. https://standards.iteh.ai/catalog/tc/clc/3df6f15c-1bca-4cc1-a7c5-d81c21135924/cen-clc-tc-10 (accessed Feb. 09, 2023).

[42] *End use performance of wood products – Utilisation and improvement of existing test methods to estimate life,* CEN/TR 16816:2015, European Committee for Standardization. https://standards.iteh.ai/catalog/standards/cen/e45315f6-d38d-44b7-a7e5-61f51c1d9803/cen-tr-16816-2015 (accessed Feb. 09, 2023).

[43] Perkins + Will, "Mid-rise office building data for Vancouver." Vancouver, 2022.

[44] One Click LCA, "Biogenic Carbon – Help Centre." https://oneclicklca.zendesk.com/hc/en-us/articles/360015036640-Biogenic-Carbon (accessed Feb. 07, 2023).

[45] Mantle Developments, "Which insulation most effectively reduces whole-life carbon (embodied and operational)?" https://mantledev.com/insights/reduces-whole-life-carbon/ (accessed Feb. 07, 2023).

[46] CARE Tool, "CARE Tool | Carbon Avoided: Retrofit Estimator." https://caretool.org/ (accessed Feb. 07, 2023).

[47] City of Vancouver, "Report, Climate Emergency – Bylaw and Policy Updates Applicable to New Buildings," May 17, 2022.

[48] Canada Green Building Council, "Zero Carbon Building: Design Standard, Version 3," 2022.

[49] Norwegian Building Authority, "Building Acts and Regulations," Direktoratet for byggkvalitet, Norway, 2013. https://dibk.no/regelverk/Building-Regulations-in-English/ (accessed Nov. 05, 2022).

[50] M. Rabani, H. Bayera Madessa, O. Mohseni, and N. Nord, "Minimizing delivered energy and life cycle cost using graphical script: An office building retrofitting case," *Appl Energy,* vol. 268, Jun. 2020, doi: 10.1016/j.apenergy.2020.114929.

[51] *Criteria for passive houses and low-energy buildings – Non-residential buildings,* NS 3701:2012, Standards Norway, 2012. https://infostore.saiglobal.com/en-us/standards/ns-3701-2012-850159_saig_ns_ns_2024590/ (accessed Nov. 05, 2022).

[52] IDA Indoor Climate and Energy (IDA ICE) simulation tool, EQUA Simulation AB, Stockholm, Sweden. https://www.equa.se/en/ida-ice (accessed Feb. 10, 2023).

[53] R. Turconi, A. Boldrin, and T. Astrup, “Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations,” *Renewable and Sustainable Energy Reviews*, vol. 28, pp. 555–565, Dec. 2013, doi: 10.1016/J.RSER.2013.08.013.

[54] “NS 3031: Collection contains standards referred to in 2014.” https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=434722 (accessed Feb. 10, 2023).

[55] B. Rossi, A. F. Marique, M. Glaumann, and S. Reiter, “Life-cycle assessment of residential buildings in three different European locations, basic tool,” *Build Environ*, vol. 51, pp. 395–401, May 2012, doi: 10.1016/J.BUILDENV.2011.11.017.

[56] *Environmental management*, ISO 14000 family of standards, International Organization for Standardization. https://www.iso.org/iso-14001-environmental-management.html (accessed Nov. 30, 2022).

[57] CRTI-B: Technology and Innovation Resource Center for Building, “The Luxembourg construction portal.” http://www.crtib.lu/ (accessed Nov. 30, 2022).

[58] Institute of Environmental Sciences, “CML 2001,” *Leiden University*. https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/cml-2001/ (accessed Nov. 30, 2022).

[59] HQE-GBC Alliance, “INIES, the reference environmental and health database for building and RE2020,” INIES. https://www.inies.fr/ (accessed Nov. 30, 2022).

[60] University of Bath Sustainable Energy Research Team, “Bath Inventory of Carbon and Energy (ICE),” Greenhouse Gas Protocol. https://ghgprotocol.org/Third-Party-Databases/Bath-ICE (accessed Nov. 30, 2022).

[61] “Building for Environmental and Economic Sustainability (BEES Online), The National Institute of Standards and Technology (NIST), U.S. Commerce Department. https://ws680.nist.gov/bees/(A(nGbpA0U82QEkAAAAZGE3ODQ0NGUtMzQwYi00NzI4LTkwODMtYzMwYzE1MDUxOWVmNxW-fbOoYJ7Fj-SvTippTKf6te81))/default.aspx (accessed Nov. 30, 2022).

[62] Evoke Buildings Engineering and E3 Eco Group, “BC Energy Step Code Metrics Report Update,” 2022.

[63] Canada Green Building Council, “Making the Case for Building to Zero Carbon,” 2019. [Online]. Available: http://publications.gc.ca/collections/collection_2014/ec/En81-18-2014-eng.pdf

[64] C. Tomaras, D. Sudeyko, M. Grace, and P. Eng, “City of Edmonton Emissions Neutral Buildings: Final Report,” Integral Group, 2020. Accessed: Feb. 08, 2023. [Online]. Available: https://www.aeso.ca/assets/Uploads/AESO-2019-LTO-updated-10-17-19.pdf

[65] Carbon Leadership Forum, “Recommended guidelines for building component lifespans in whole building life cycle assessment,” 2018.

[66] L. J. Schoen, “Preventive Maintenance Guidebook: Best Practices to Maintain Efficient and Sustainable Buildings,” BOMA International, Accessed: Feb. 08, 2023. [Online]. Available: www.boma.org.

[67] R. Cohen, “Net Zero Buildings – what does this mean?” GRESB, 2017. https://www.gresb.com/nl-en/net-zero-buildings-%E2%80%93-what-does-this-mean/#_ednref2 (accessed Feb. 10, 2023).

[68] S. Seyam, "Types of HVAC Systems," in HVAC System, *InTechOpen,* 2018. doi: 10.5772/intechopen.78942.

[69] Natural Resources Canada, "Heat and energy recovery ventilators." https://natural-resources.canada.ca/energy-efficiency/products/cooling-and-ventilating-equipment-for-residential-use/heatenergy-recovery-ventilators/16197 (accessed Mar. 13, 2023).

[70] Natural Resources Canada, "Retrofitting." https://natural-resources.canada.ca/energy-efficiency/buildings/existing-buildings/retrofitting/20707 (accessed Mar. 18, 2023).

[71] F. Prah, "Refrigerant 410A," *Refrigeration Service Engineers Society.* Accessed: Mar. 19, 2023. [Online]. Available: https://www.escogroup.org/training/documents/410apm_lookinside.pdf

[72] D. Dunning, "Normal Running Pressures for R134A," *Sciencing,* 2018. https://sciencing.com/normal-running-pressures-r134a-8003413.html (accessed Mar. 19, 2023).

[73] European Commission, "Green Public Procurement (GPP): Life-cycle costing." https://ec.europa.eu/environment/gpp/lcc.htm (accessed Mar. 13, 2023).

[74] C. St-Onge, P. Mukhopadhyaya, G. Torok, and T. Moore, "Canadian Construction Materials Centre guidelines for the evaluation of vacuum insulated panels," 2018. Available: https://nrc-publications.canada.ca/eng/view/ft/?id=c84bb13a-1479-4a68-8c79-6c1525c9aa11

[75] L.P. Levesque, "What is the difference between monocrystalline and polycrystalline solar panels?" Quebec Solar. https://quebecsolar.ca/what-is-the-difference-between-monocrystalline-and-polycrystalline-solar-panels/ (accessed Mar. 13, 2023).

Appendix A – Literature Review – Case Studies Identified

A.1 List of Case Studies Identified

Table A-1: List of the relevant LCA case studies of retrofit projects identified in the literature

Title	Year	Author	Location	Building type	Building lifetime	Methodology	Results
Life cycle analysis of GHG emissions from the building retrofitting: The case of a Norwegian offi e building	2021	M. Rabani, H.B.Madessa, M.Ljungstrom, L.Aamodt, S.Løvvold, N.Nord	Norway	Office building	60 years	LCA analysis of two modelled builds mapped on a typical office building in Norway complying with TEK 87 Norwegian building regulation. The study compares a standard-compliant building to the high standards of Passive House.	Operational carbon is comparable between scenarios that comply with the same standards. The embodied carbon emissions differ depending on material use. Retaining any part of the structure preserves some of the embodied carbon.
Cradle-to-grave life-cycle assessment within the built environment: Comparison between the retrofit and the complete reconstruction of an offi e building in Belgium	2018	A.F. Marique, B. Rossi	Belgium	Office building		LCA is a great tool to analyze the retrofit and new construction of a building objectively. A tool updated for this study is used for an LCA of a public office building comparing a retrofit versus a demolition and rebuild.	The greatest impact of carbon is from the operational use phase, followed by new construction and demolition. Retrofits have lower environmental indicators compared to new construction.
Energy and environmental payback times for an NZEB retrofit	2019	F.Asdrubali, Ballarini, V.Corrado, L.Evangelisti, G.Grazieschi, C.Guattari	Italy	School building	50 years	Evaluated energy use and carbon payback time of retrofit scenarios. Applied the LCA method to calculate environmental impact of the building during its lifetime.	The carbon payback time for the cost-optimal case, in which the total building energy use is around $70kWh/m^2a$ year, is 3.2 years.
Mechanical, electrical, plumbing and tenant improvements over the building lifetime: Estimating material quantities and embodied carbon for climate change mitigation	2020	B.X. Rodriguez, M. Huang, H.W. Lee, K. Simonen, J. Ditto	Pacific Northwest, USA and Canada	Office buildings	60 years	This study aimed to establish a preliminary range of material quantities and embodied carbon impacts for mechanical, electrical and plumbing systems (MEP) and tenant improvements (TI) components, focusing on commercial office buildings. The study evaluated various HVAC systems such as air handing units(AHU),variable air volume(VAV), parallel fan terminals,water source heat pumps, variable refrigerant flow, energy recovery ventilators (ERV) and dedicated outdoor air systems.	The embodied carbon emission estimates ranged from 40 to 75 kg CO_2e/m^2 for MEP, and 45 to 135 kg CO_2e/m^2 for TI. However, with recurring instalments during a lifespan of 60 years, the impacts become comparable to known impacts of core and shell systems.
Retrofitting a building to passive house level: A life cycle carbon balance	2020	C. Piccardo, A. Dodoo, L. Gustavsson	Sweden	Residential building		This study analyzes the whole-life carbon emissions balance of a building retrofitted to passive house level, considering two alternative standards applicable in Sweden. This study considered various alternate materials in building elements like insulation, facades and windows, etc., and various electricity production sources like fossil fuels, wind and biomass.	They study observed that making thoughtful building material choices could result in a maximum 68% reduction of the net CO_2e in the retrofitted compared to the building reference case.

Title	Year	Author	Location	Building type	Building lifetime	Methodology	Results
Economic and environmental savings of structural building retrofits compared with demolition and reconstruction – A Portuguese benchmarking	2015	J. Ferreira, M. Duarte Pinheiro, J. de Brito	Portugal	Historic residential building		The study takes two approaches: 1) A literature review of LCA studies of retrofits and new builds, and 2) An LCA and LCC[31] study that compares a retrofitted seismically reinforced building to a hypothetical demolition and rebuilding, with the same design requirements using reinforced concrete and clay brick walls.	The results of the study show that a structural retrofit is the more environmentally beneficial option. However, the difference is not very much, mainly because of the use of structural steel for seismic structural strength. In financial terms, a demolition and rebuild makes more economic sense. The study concluded that an integrated decision-making process is best, and that the market needs to develop cost-effective solutions for retrofits that would save resources.
Assessing the carbon-saving value of retrofitting versus demolition and new construction at the United Nations headquarters	2016	Vidaris, Inc., Syska Hennessy Group	US	Commercial office building	70 years	This study used energy modelling software DOE-2.2 to estimate annual energy use of the building, and LCA software ATHENA Environmental Impact Estimator (v5.1) to estimate the embodied carbon emissions. The study reviewed the relationship between operational and embodied energy/carbon in terms of a simple ratio of how many years it would take the operational improvement to payback the embodied carbon. This is similar to other studies, but is an oversimplification. The second analysis is in terms of "avoided impact" of renovation versus new construction.	New construction would take 30 to 70 years of operational improvements to payback the embodied carbon emissions involved. The core building has a life of 50 to 100 years. The HVAC, glazing, lighting, IT and MEP typically have a life of 15 to 30 years, which presents an opportunity to improve the buildings' energy performance at the systems replacement point. The economic investment that would be needed to demolish and rebuild new can be redirected to extensive energy efficiency and renewable energy measures.
Sustainability assessment of retrofit versus new construction by means of LCA and durability-based estimations of building lifespans: A new approach	2019	B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, B. López-Mesa	Spain	Residential building		This study looks at retrofit versus demolition and new construction at two performance levels – the standard code and the low energy requirements of Passive House standard. Using the cohesive pattern of reinforced concrete, the study estimates the life of a building. Using those lifespans, the study runs LCA analysis according to the GWP indicator, based on 2007 IPCC v1.02 methodology, and using the Ecoinvent (v2.2) database on various lifespans to plot the performance of the building with embodied carbon emissions.	The results show that the best solution may differ depending on the year of analysis. At a 50-year lifespan, the retrofit scenarios fair better than new construction, while at 150 years, standard retrofit and passive new buildings have equivalent impact. A similar pattern is seen in the GWP over a lifespan of 200 years. A nearly constant GWP is reached after a long time that is not in line with the commonly used LCA building lifespan. It is noted in the study that the building does not perform at a consistent level throughout its lifetime. A new building will have a longer lifespan and better performance for longer than a retrofitted building that is already at its mid-life. The demolition of buildings is often not because they have reached the end of their life or are in structural disrepair or corrosion. However, this study illustrates the longevity and durability of reinforced concrete structures and its physical potential. Considering this long lifespan has potential environmental benefits.

[31] Life Cycle Costing (LCC) is an assessment of the total financial cost of an asset over its lifetime, including initial capital, maintenance, operating cost and end-of-life value [73].

Title	Year	Author	Location	Building type	Building lifetime	Methodology	Results
Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada	2021	T. Opher, M. Duhamel, I.D. Posen, D.K. Panesar, R. Brugmann, A. Roy, R. Zizzo, L. Sequeira, A. Anvari, H.L. MacLean	Canada	Heritage building	60 years	Conducted an LCA to assess the embodied carbon emissions of renovating an existing building using the One Click LCA tool	Installation of renewable energy systems contribute 31%, and the raised concrete floor contributes 26%, of the embodied carbon dioxide equivalent.
Life cycle assessment of an offi e building based on site-specific data	2019	P. Ylmen, D. Penaloza, K. Mjornell	Sweden	Office building	50 years	The goal of this study was to calculate the emissions for a whole office building and investigate the contribution in terms of environmental impact for different parts of the building, as well as the impact from different stages of the life cycle, specifically the HVAC systems. The data for this study was collected directly from the contractors.	Materials for installation have been a significant contributor to the building's carbon emissions. The results showed that 38 $kgCO_2e/m^2$ are emitted in production, and 100 $kgCO_2e/m^2$ are emitted in the operational phase.
A life cycle approach to optimizing carbon footprint and costs of a residential building	2017	S.K. Pal, A. Takano, K. Alanne, K. Siren	Finland	Residential building		This study proposes using an LCA optimization approach to find the carbon-cost solution that optimizes both operational and embodied carbon emissions.	The results showed that when optimized for carbon, the embodied carbon emissions were 39% of the whole-life carbon emissions. When the LCA was optimized for cost, the carbon emissions were 28% of the whole-life carbon emissions.
Integrated life cycle assessment and thermodynamic simulation of a public building's envelope renovation: Conventional vs. Passivhaus proposal	2018	J. Sierra-Pérez, B. Rodríguez-Soria, J. Boschmonart-Rives, X. Gabarrell	Spain	Educational building	2 years	The building is analyzed with two scenarios. The first is a conventional project for energy renovation, while the second is a low-energy building proposal (following the Passivhaus standard). This study analyzed the scenarios using an integrated life-cycle and thermal-dynamic simulation assessment to compare the post-renovation energy performance of the building.	The results from both scenarios were an increase in the embodied carbon emissions from the additional insulation. The energy renovation achieved high energy savings for both proposals – between 60% and 80%. The Passivhaus proposal is 30% better than the conventional one, considering the total lifespan of the building.
Life cycle assessment of an ambitious renovation of a Norwegian apartment building to NZEB standard	2018	B. Wrålsen, R. O'Born, C. Skaar	Norway	Residential building	30 years	Study of an apartment block from 1960s standards to nearly passive house standard with three different scenarios for the energy supply.	The results of this study show that despite the low carbon intensity of the Norwegian energy mix, there was a considerable environmental benefit to renovation. It is recommended that renovation of existing buildings continue as part of a successful climate mitigation strategy in Norway.
Life cycle assessment of UBC Biological Sciences Complex renewal project	2011	Athena Sustainable Materials Institute, Recollective Consulting	Canada	Educational building		The study considers two scenarios. The first scenario is the renovation of the existing building. The second scenario is a hypothetical one whereby the building is demolished and a new building is constructed. Each footprint is then examined through an LCA using the Athena Impact Estimator for Buildings.	The results favoured renovation of the existing building over building new. The avoided impacts were 60% on average over a building-new scenario, and 30% over an average existing academic UBC building. The renovation scenario outperformed new construction. This holds true for the existing structure with a low cradle to gate impact amongst the 30 UBC academic buildings, including the four buildings constructed to LEED standards.

A.2 LCA Methods of the Two Selected Case Studies

Table A-2: Case studies of whole-life carbon emission assessments of office building retrofits selected for an in-depth review

Report Section	Study Overview			Study Scope				Carbon emissions Modelling Tools		Results		
	Region	Year	Objective	Year	No. of Floors	Modelled or Actual[32]	Building Elements	Life Cycle Stages[33]	Building lifetime	Operational Energy	Whole-life Carbon Emissions Tool	Retrofit Whole-life Carbon Emissions
3.1.1	Norway	2021	Comparing whole-life carbon emissions of four deep energy retrofit scenarios with the status quo	1980s	3	SQ: Modelled R: Modelled N: Out of the study scope	Structure Roof Envelope Doors Windows Interior walls Finishing HVAC Elevator Photovoltaic (PV)[34] panels	A1-A5 B4-B6 C1-C4	60 years *(for both SQ and R)*	IDA-ICE[35]	One Click LCA	68% to 73% reduction in whole-life carbon emissions over various scenarios compared to the status quo
3.1.2	Brussels, Belgium	2018	Comparing retrofit to complete demolition and new construction	1934	Existing: 2 + 1 semi-underground Retrofitted: 3 + 1 semi-underground	SQ: Actual R: Actual N: Modelled	Structure Roof *(R: green roof)* Envelope Doors Windows Interior walls Finishing	N: A1-A5 R: B4 N & R: B6, C1, C4 *(includes workers' travel)*	50 years *(for both R & N)*	Tool developed by the authors	Tool developed by the authors	Retrofitting has 57% lower embodied carbon emissions and lower overall emission than demolition and new construction.

[32] SQ: Status quo, R: Retrofit, N: New building

[33] See Figure 1 for life-cycle stages that can be included in an LCA study.

[34] PV: Photovoltaic

[35] IDA Indoor Climate and Energy (IDA ICE) is a building performance simulation tool [45]

A.2.1 Low-rise Office Building Energy Retrofit, Norway

A.2.1.1 Purpose of Assessment

This case study involved a systematic study of a typical office building in Norway using LCA to evaluate embodied and operational emissions under different building retrofit scenarios [23]. While the comparison was limited in scope compared to this study (i.e., does not include demolition and new building comparisons), the results provide valuable insights into the largest contributors to carbon emission levels, including building operations, new materials and ventilation systems.

A.2.1.2 Reference Building

The reference building was modelled as a three-storey office, built in the 1980s, similar to most existing office buildings in Norway. The study assumed the building characteristics and energy performance met the minimum requirements of the 1987 Norwegian building regulation, TEK 87, representing the same time period as the modelled reference building [49]. The building was assumed to have a rectangular geometry with a total floor area of 2,940 m^2 and an internal volume of 9,062 m^3 [50].

Materials specified in the LCA model are listed in Table A-3. In the case of retrofit scenarios, only emissions from materials added to the existing buildings were considered.

Table A-3: Reference building's material specifications used for the LCA case study

Project information	
Location	Norway
Year built	Modelled after a building in 1987
Number of above-grade floors	3
Gross floor area above grade (m^2)	3,000
Project data sources	Model stimulated in One Click LCA tool
Lifespan of the building	60 years

Operational emissions	Reference No.
Building energy simulation model in a previous study	[50]

Building design		
Foundation	Ground foundation	Base plate, 0.3 m generic concrete, reinforcement steel, gravel products
	Frost insulation	Expanded polystyrene insulation (EPS) 80
Vertical structure & facade	Exterior wall structure and construction	Wooden stud work, mineral wool insulation with wind barrier, generic concrete for external wall, reinforcement steel
Envelope	Exterior wall cladding	Fibre cement board
Interior partition walls ***Non-load bearing***	Columns	Generic mixed concrete, reinforcement steel
Ceilings	Internal concrete wall with reinforcement and filler	Mortar wall, generic mixed concrete, reinforcement steel
Floor finishes	Timber-framed wall	13 mm plaster cast 100 mm structural steel profile stud Mineral wool insulation board
Mechanical equipment	Ventilation system	Generic constant air volume (CAV)[36] system
	Heating system	Generic radiator space heating (RSH) system
	Hot water	Generic electric boiler, 280 kW
Horizontal structure	Floor towards ground	EPS insulation, generic concrete, reinforcement steel, vapour barrier in plastic, mineral wool insulation
	Floor separator	Hollow core slab with mineral wool insulation, generic concrete, reinforced concrete, reinforced steel mineral wool insulation
	Floor paint	Epoxy floor painting
	Floor covering	Linoleum covering
	External roof	Compact concrete, EPS and mineral wool insulation boards, vapour barrier plastic
	Roof membrane	External roof Reinforced steel, double layer of asphalt roof membrane
HVAC and heating supply system		Constant air volume system for cooling and heating of ventilation air RSH radiator hydronic heating distribution system

[36] Constant air volume (CAV) is a system of delivering conditioned air in a building. This system is often seen in older, smaller buildings and is less common in newer buildings [68].

A.2.1.3 Demolition and New Construction Scenarios

This case study did not include any demolition and new construction scenarios. Instead, it compared four retrofit scenarios with the status quo (i.e., the building continues operations without retrofit).

A.2.1.4 Retrofit Scenario

The study considered four retrofit scenarios.

- **Scenario 1**
  - Operational energy upgrade: Norwegian Passive House (PH) Standard NS 3701 for non-residential buildings [51]
  - HVAC system: The same as the reference building, but with new waterborne radiators
- **Scenario 2**
  - Operational energy upgrade: The same as Scenario 1
  - HVAC systems: All air (AA)[37] system equipped with a demand control ventilation (DCV)[38] system
- **Scenario 3**
  - Operational energy upgrade: Optimized energy and life-cycle cost (LCC) performance scenario identified in a previous study by the same authors [50]. This scenario was more energy efficient than the reference building, but did not reach the PH requirements.
  - HVAC systems: The same as the reference building, but with new waterborne radiators.
- **Scenario 4**
  - Operational energy upgrade: The same as Scenario 3
  - HVAC systems: The same as Scenario 2

All four scenarios assumed that the façade, exterior windows and doors would be replaced, and insulation would be added to the ground floors, exterior walls and roofs. The first two scenarios had greater insulation thickness, meeting PH standard requirements, whereas the latter two did not meet PH and had less insulation.

For heating energy, four scenarios were considered: district heating, a ground source heat pump (GSHP), an electric boiler, and a combination of GSHP and an electric boiler (60% of heating supplied by GSHP).

A.2.1.5 LCA Scope

- Building elements: The case study disclosed the full material quantities of all elements in the reference building and retrofit scenarios, including the following:
  - Reference building: Foundation, horizontal and vertical structures, stairs, elevator shaft, envelope, exterior and internal door and windows, HVAC systems, interior walls, interior and exterior finishes
  - Retrofit scenarios: Only additional quantities for the retrofit were included. For building components involved in the retrofit, the entire element was assumed to be replaced.
- Building lifetime: 60 years (for both reference building and retrofitted building scenarios)
- Life-cycle stages:
  - Included life-cycle stages: Product (A1-A3), construction (A4-A5), use-replacement and retrofit (B4-B5), operational energy use (B6), and end-of-life (C1-C4)
    (See Figure 1 for naming the life-cycle stages of the LCA studies.)

[37] All air system is a sub-classification of an HVAC system. A central HVAC system may service one or more thermal zones. The medium used to provide the thermal energy classifies the system. A central HVAC system is classified as an all-air system, air-water system, all-water system, water source heat pump, and heating and cooling panels [68].

[38] DCV is a system that adjusts airflow based on occupancy in a space. It is appropriate for buildings with unpredictable occupancy [68].

A.2.1.6 LCA Modelling

The LCA for this study was done using the web-based One Click LCA tool [20], which enabled an LCA that aligns with the Norwegian standard NS 3720:2018, *Method for greenhouse gas calculations for buildings* [24]. The data points used within the tool were mainly Norwegian EPDs, specifically for Norway or Nordic countries. Where local data was unavailable, data from other countries were used.

Operational carbon emissions were also calculated in accordance with NS 3720. IDA ICE [52] was used to compute the energy use of the reference building and the four retrofit scenarios. The emissions factor for electricity was assumed to be 0.13 kg CO_2 e/kWh, the expected average over 60 years based on a Norwegian and European supply mix [53]. For district heating, a factor of 0.0138 CO_2 e/kWh was used based on public data from Norwegian district heating suppliers [54].

A.2.1.7 Results

The LCA analysis revealed that 77% of the life-cycle emissions were from building operational energy use (B6), demonstrating the benefits of improving the energy performance of an existing building. The product stage (A1-A3) represented the next highest emission source, and was responsible for 16% of the total emissions of the building in this study.

Structural floors had the highest embodied carbon emissions in the reference building at approximately 27%, followed by the HVAC at 24%, about half of which was from system replacements at the end of their lifetimes. The service lives of the ventilation system, the heating system and the electric boiler were estimated at 50, 30 and 22 years, respectively, and would eventually need to be replaced during the assumed 60-year life of the building.

Finished concrete had the highest emissions across all life-cycle stages, except for the replacement and retrofitting, where the ventilation systems had the highest impact.

In comparison to the reference building, the modelled retrofit scenarios did not show significant variations between each other. They showed an increase in embodied carbon emissions between 12% to 19% across the four scenarios. However, the operational emissions were estimated to be reduced by 69% to 73%, with a carbon payback period between four and five years, for all four scenarios.

The study also compared the impact of various insulation materials on the total carbon emissions of the retrofit scenarios, including glass wool, rock wool, EPS, XPS, polyurethane foam, cellulose and vacuum insulated panel (VIP)[39]. The results showed that VIP had the highest and glass wool had the lowest impact (23.4% lower than VIP), followed by cellulose (25.1% lower than VIP).

Of the four heating supply systems compared in the study, the district heating system had the lowest and electric boiler had the highest whole-life carbon emissions. However, these results can vary between different regions depending on the emission factors for the electricity grids and district heating systems. The district heating system also had the lowest embodied carbon emissions. However, the embodied carbon only included the emissions from installation of heating systems on the building site, and not the embodied carbon emissions from energy production and transportation to site.

[39] Vacuum insulated panel (VIP) is a highly insulated unit that is made of a microporous core material inside a multilayer foil envelope. The envelope is evacuated and sealed to create a vacuum inside the envelope [74].

The authors also examined the impact of using two types of photovoltaic (PV) panels for the electrical energy supply in Scenario 1, including both operational and embodied carbon emissions. The models assumed that the panels supplied all the building's electrical energy requirements. Monocrystalline[40] and polycrystalline[41] panels showed an overall 39% and 44% carbon emissions reduction, with about 6 and 12 years of carbon payback period, respectively.

A.2.2 Low-rise Office Building Energy Retrofit vs. Rebuilding, Belgium

A.2.2.1 Purpose of Assessment

This case study used an LCA tool developed by the authors to compare the energy and carbon impacts of complete demolition and reconstruction to low-energy retrofitting of an existing building. This case study used data from an actual office retrofit in Brussels, Belgium, and compared it with a modelled demolition and new construction scenario.

A.2.2.2 Reference Building

The reference building was an office building built in 1934. Before the retrofit, the building had two levels above grade and a semi-underground level with a heated floor area of 756 m^2.

Materials specified in the LCA model are listed in Table A-4. In the case of retrofit scenarios, only emissions from materials added to the existing buildings were considered.

Table A-4: Reference building's material specifications used for the LCA case study

Project information	
Location	Brussels, Belgium
Year built	1934
Number of above-grade floors	2
Number of below-grade floors	1 semi-underground
Heated surface area (m²)	756 m2
Project data sources	Architects A2M
Lifespan of the building	50 years

Operational emissions	Reference No.
Thermal insulation level K of the Belgian regulation	[50]

[40] Monocrystalline panels are photovoltaic panels made from a single crystal of silicon [75].

[41] Polycrystalline panels are photovoltaic panels made from several silicon fragments melted together [75].

Retrofit building design		
Existing building	Retained façade and envelope	
Insulation	Existing walls	10 cm of PUR[42]
	Level 2, new walls	10 cm of PUR
	New slab	8 cm of PUR
	New roof	20 cm of mineral wool
Structure	Stability	Steel beam and columns Metal rods to join façade
Windows	Replaced	Energy efficient triple-glazed
New building design		
Vertical structure and facade	Exterior wall structure and construction	190 mm concrete blocks Insulation 100 mm PUR Brick cladding 90 mm

A.2.2.3 Demolition and New Construction Scenario

For the new construction model, the same thermal comfort level, heated floor area, number of floors, building envelope thermal performance, and ventilation system as the retrofit were assumed. The new construction was assumed to be more airtight than the retrofit, with an air change rate of 0.5 per hour versus 0.7 in the retrofit.

A.2.2.4 Retrofit Scenario

The architectural aspects of the façade were maintained in the retrofitted building. A new floor, two service annexes – one on the ground floor and one on the roof – and a green roof were added. The new heated floor area became 1,012 m^2.

The energy efficiency of the building was drastically improved by:

- Adding polyurethane insulation to the internal skin of the envelope and the roof.
- Separating the floor slabs from the existing façade to prevent thermal bridging.
- Replacing windows with new energy-efficient triple-glazed windows.
- Adding a new ventilation system with heat recovery.

Steel beams and columns were added to hold the floor slabs. The façade was also connected to this steel structure with metal rods. The interior spaces were reorganized to suit the functionality of a modern office building.

A.2.2.5 LCA Scope

- Building elements: External walls, floors, roofs, internal partitions, doors and windows. In the retrofit LCA, only elements that were removed or added to the buildings were included.
- Building lifetime: 50 years, for both retrofit and new construction scenarios.
- Life-cycle stages: Product (A1-A3), construction (A4-A5; A5 is only for new construction), retrofit (B5, only for the retrofit scenarios), operational energy use (B6), and end-of-life (C1, C4). See Table A-5 for the activities included in each life cycle stage.

[42] A rigid insulation foam made of polyurethane

Table A-5: Activities included in each life cycle phase for the new construction and retrofit scenarios [7]

Life Cycle Phases	Activities
Product (A1-A3)	▪ Extraction of raw materials ▪ Transportation from the extraction site to the production plant ▪ Fabrication/transformation into construction products
Transportation (A4)	▪ Transportation to the construction site ▪ Transportation to the waste disposal site
Construction (A5)	▪ Home-to-work travel of workers ▪ Use of equipment ▪ Loss of 5% of the materials
Operational energy use (B6)	▪ Space and water heating ▪ Space cooling ▪ Lighting
Demolition (C1)	▪ Travel of workers from home to work and vice versa ▪ Use of equipment
Disposal (C4)	▪ Impacts related to the landfill of dumped materials

A.2.2.6 LCA Modelling

The LCA tool the authors developed for a previous study was used, with some updates to enable the comparison between retrofit versus demolition and new construction [55]. The initial tool followed the ISO 14000 series [56] and used the following data sources:

- Luxembourg Construction Portal: Building Technology and Innovation Resource Centre (CRTI-B) [57]
- Leiden University: Institute of Environmental Sciences (CML) 2001 [58][59]
- INIES France [59]
- University of Bath: Inventory of Carbon and Energy (ICE) database [60]
- Building for Environmental and Economic Sustainability (BEES) database [61]

The LCA tool sorted and summarized materials into four main categories – the finishing, the roof, the concrete structure and masonry, and the steel structure. For each of these four categories, the user could specify if and how the building would be demolished, replaced, or retrofitted, and the transport means and distances for both materials and workers. For operational carbon emissions, the Electricity Belgium mix, with a carbon intensity of 0.33 kg CO_2 e/kWh was used [55].

A.2.2.7 Results

This case study does not share the carbon emission values with the breakdown of the life-cycle stage, elements or material types. The study results are only presented in two graphs showing embodied energy impact (kWh/m^2) and embodied carbon emissions (kg CO_2 e/m^2), and a table comparing the percentage difference of embodied carbon between retrofit and rebuild scenarios, broken down by life-cycle stages.

Space heating was the main contributor to operational energy use (B6) and had the highest carbon emissions within the whole life cycle of retrofit and rebuild scenarios. Its values were 1.9 and 0.7 times higher than all embodied carbon emissions in retrofit and rebuild scenarios, respectively. However, since the thermal insulation, ventilation system and thermal comfort levels were assumed to be the same between the retrofit and rebuild scenarios, emissions from space heating were similar in the two scenarios.

Therefore, the variations between the whole-life carbon emissions of the two scenarios were due to the difference in the embodied carbon emissions. Retrofit showed 57% less embodied carbon than a complete demolition and new construction.

In both scenarios, product stage (A1-A3) was the most significant contributor to embodied carbon emissions, followed by construction (A5). In the rebuild scenario, demolishing the existing building was the next most significant contributor. In the retrofit project, since most of the building was kept intact, the demolition represented a much smaller percentage of the embodied carbon emissions.

Appendix B – LCA Case Study – Assumptions and Sources for the Data Gaps in the Models

Table B-1: Assumptions and sources for the data gaps in the mid-rise office LCA models, Vancouver

Operational emissions		Reference No.
Gas intensity (GHGi) (kg $CO_2e/m^2/yr$)	3	[47]
Natural gas emissions factor (kg CO_2e/kWh)	0.185	[62]
Electricity emissions factor (kg CO_2e/kWh)	0.011	[62]
British Columbia grid intensity	Varies annually	[18]

Building design		Reference No.
Structure	Same as Toronto reference building	Reference building data sources
Roof	▪ Roof structure: Same as Toronto reference building ▪ Roof assembly: Vapour retarder, 152 mm polyisocyanurate insulation, 51 mm mineral wool insulation, modified bituminous membrane, concrete paver finish	Reference building data sources [43]
Envelope	▪ Double-glazed windows ▪ Glass fiber reinforced concrete cladding, 127 mm mineral wool insulation, vapour self-adhered membrane, gypsum wall board, metal studs	[43]
	▪ Window to wall ratio: 40%	[63]
	▪ Exterior doors: Same as Toronto reference building	Reference building data sources
Interior partition walls ***Non-load bearing***	Same as Toronto reference building	Reference building data sources
Ceilings	Same as Toronto reference building	Reference building data sources
Floor finishes	Same as Toronto reference building	Reference building data sources
Mechanical equipment	▪ Ground source heat pump, 441 kW (in lieu of an air source heat pump option in One Click LCA) ▪ Domestic hot water electric boiler, 85 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation heat recovery, 50,000 m3/h	Reference building data sources

Building design		Reference No.
Refrigerant	▪ R-410A, 203 kg	Advisory panel recommendation
Ventilation system	Same as Toronto reference building	Reference building data sources
Electrical system	Same as Toronto reference building	Reference building data sources
Plumbing system	Same as Toronto reference building	Reference building data sources
Other	▪ All concrete mixes: British Columbia industry average concrete, general use cement, per strength class – Canadian industry average EPD ▪ CMU: Concrete masonry unit, normal weight, general use limestone cement, West Region – Canadian industry average EPD ▪ Concrete transportation distance (manufacturing to construction site): 50 km	[20] Reference building data sources

Table B-2: Assumptions and sources for the data gaps in the mid-rise office LCA models, Edmonton

Operational emissions		Reference No.
Annual electricity energy demand (kWh/m²)	99	[64]
Annual natural gas energy demand (kWh/m²)	196	[64]
Natural gas emissions factor (kg CO_2e/kWh)	0.18	[64]
Electricity emissions factor (kg CO_2e/kWh)	0.585	[64]
Alberta grid intensity	Varies annually	[18]

Building design		Reference No.
Structure	Same as Toronto reference building	Reference building data sources
Roof	▪ Roof structure: Same as Toronto reference building ▪ Roof assembly: Metal deck structure, roof board, vapour retarder, R40 board insulation, membrane underlayment, 2-ply bituminous membrane roofing	Reference building data sources [10]
Envelope	Same as Toronto reference building	Reference building data sources
Interior partition walls ***Non-load bearing***	Same as Toronto reference building	Reference building data sources
Ceilings	Same as Toronto reference building	Reference building data sources
Floor finishes	Same as Toronto reference building	Reference building data sources

Building design		Reference No.
Mechanical equipment	▪ Natural gas boiler, 1,055 kW ▪ Domestic hot water natural gas boiler, 85 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation heat recovery, 50,000 m3/h ▪ Liquid chiller, 400 kW	Reference building data sources
Refrigerant	▪ R-134a, 70 kg	Advisory panel recommendation
Ventilation system	Same as Toronto reference building	Reference building data sources
Electrical system	Same as Toronto reference building	Reference building data sources
Plumbing system	Same as Toronto reference building	Reference building data sources
Other	▪ All concrete mixes: Alberta industry average concrete, general use cement, per strength class – Canadian industry average EPD ▪ CMU: Concrete masonry unit, normal weight, general use limestone cement, West Region – Canadian industry average EPD ▪ Concrete transportation distance (manufacturing to construction site): 50 km	[20] Reference building data sources

Table B-3: Assumptions and sources for the data gaps in the high-rise office LCA models, Vancouver

Operational emissions		Reference No.
Gas intensity (GHGi) (kg $CO_2e/m^2/yr$)	3	[47]
Natural gas emissions factor (kg CO_2e/kWh)	0.185	[62]
Electricity emissions factor (kg CO_2e/kWh)	0.011	[62]
British Columbia grid intensity	Varies annually	[18]

Building design		Reference No.
Structure	Same as Toronto reference building	Reference building data sources
Roof	Same as Toronto reference building	Reference building data sources
Envelope	Same as Toronto reference building	Reference building data sources
Interior partition walls ***Non-load bearing***	Same as Toronto reference building	Reference building data sources
Ceilings	Same as Toronto reference building	Reference building data sources

Building design		Reference No.
Floor finishes	Same as Toronto reference building	Reference building data sources
Mechanical equipment	▪ Ground source heat pump, 2,268 kW (in lieu of an air source heat pump option in One Click LCA) ▪ Domestic how water electric boiler, 380 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation heat recovery, 4 units x 50,000 m3/h	Reference building data sources
Refrigerant	▪ R-410A, 865 kg	Advisory panel recommendation
Ventilation system	Same as Toronto reference building	Reference building data sources
Electrical system	Same as Toronto reference building	Reference building data sources
Plumbing system	Same as Toronto reference building	Reference building data sources
Other	▪ All concrete mixes: British Columbia industry average concrete, general use cement, per strength class – Canadian industry average EPD ▪ Concrete transportation distance (manufacturing to construction site): 50 km	[20] Reference building data sources

Table B-4: Assumptions and sources for the data gaps in the high-rise office LCA models, Edmonton

Operational emissions		Reference No.
Annual electricity energy demand (kWh/m²)	99	[64]
Annual natural gas energy demand (kWh/m²)	196	[64]
Natural gas emissions factor (kg CO_2e/kWh)	0.18	[64]
Electricity emissions factor (kg CO_2e/kWh)	0.585	[64]
Alberta grid intensity	Varies annually	[18]

Building design		Reference No.
Structure	Same as Toronto reference building 100 mm polyisocyanurate insulation added to slab on grade	Reference building data sources [10]
Roof	Same as Toronto reference building	Reference building data sources
Envelope	Same as Toronto reference building	Reference building data sources
Interior partition walls ***Non-load bearing***	Same as Toronto reference building	Reference building data sources

Building design		Reference No.
Ceilings	Same as Toronto reference building	Reference building data sources
Floor finishes	Same as Toronto reference building	Reference building data sources
Mechanical equipment	▪ Natural gas boiler, 4,748 kW ▪ Domestic hot water natural gas boiler, 380 kW ▪ Air handling unit, with heat recovery through indirect liquid circulation heat recovery, 4 units x 50,000 m3/h ▪ Liquid chiller, 1,800 kW	Reference building data sources
Refrigerant	▪ R-134a, 315 kg	Advisory panel recommendation
Ventilation system	Same as Toronto reference building	Reference building data sources
Electrical system	Same as Toronto reference building	Reference building data sources
Plumbing system	Same as Toronto reference building	Reference building data sources
Other	▪ All concrete mixes: Alberta industry average concrete, general use cement, per strength class – Canadian industry average EPD ▪ Concrete transportation distance (manufacturing to construction site): 50 km	[20] Reference building data sources

Table B-5: Service life assumed in mid-rise and high-rise for LCA models, all cities

Building element	Service life (One Click LCA service life assumed, unless noted below)	Reference No.
Exterior walls	35 years	[65]
Interior non-load bearing walls	▪ Gypsum: 30 years ▪ Insulation: 30 years ▪ Steel studs: 30 years ▪ Paint: 10 years	[65]
Roofing	▪ Bitumen: 30 years ▪ Boards/membranes/barriers: 30 years ▪ Concrete paving: 50 years	[65] [65] [66]
Floor and ceiling finishes	▪ Tiles (stone): 50 years ▪ Carpet: 5 years ▪ Concrete seal (epoxy coating): 10 years ▪ Acoustic/suspended ceiling (lay-in suspended ceiling): 25 years ▪ Gypsum wall board: 30 years	[66] [66] [66] [66] [66]
Exterior doors	30 years	[65]
Electricity installations	30 years	[65]

Table B-6: Key inputs in the One Click LCA Carbon Designer 3D tool for the mass-timber structure sensitivity analysis of the mid-rise office building in Toronto

Building element	
Reference building	Canada (ASHRAE 90.1, climate zones 5 & 6)
Gross floor area, including below-grade area (m2)	18,176
Reference study period (years)	60
Building type	Office building
Number of above ground floors	6
Number of underground heated floors	0
Number of underground unheated floors	2

Building structure	
Floor construction	▪ Levels P2, P1, L1, L2: Reinforced concrete ▪ Levels L3-L6: Cross-laminated timber
Structural columns ***Max column spacing, 9m***	▪ Levels P2, P1, L1: Reinforced concrete ▪ Levels L2-L6: Glulam
Structural beams ***Assuming CLT carries loads two-directionally for levels L2-L6***	▪ Levels P2, P2, L1: Reinforced concrete

Building geometry and quantities	
Building width (m)	52
Building length (m)	57
Building height (m)	26
Concrete slab floor area (m^2)	8,627
CLT floor area (m^2)	9,549
Concrete column length (m)	522
Glulam column length (m)	889
Concrete beam length (m)	2,289

Appendix C – LCA Case Study – Results

Table C-1: Whole-life: carbon emissions at the milestone climate target years for the mid-rise office building in Toronto

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	60%	40%	38%	444	1,181
	Operational	0%	38%	57%	59%	695	
	Refrigerant	0%	2%	3%	4%	42	
Demolition and New Construction	Embodied	100%	83%	65%	54%	875	1,612
	Operational	0%	16%	33%	43%	695	
	Refrigerant	0%	1%	2%	3%	42	
Retrofit vs. Demolition and New Construction		**-69%**	**-57%**	**-41%**	**-27%**		

Table C-2: Whole-life carbon emissions at the milestone climate target years for the mid-rise office building in Vancouver

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	72%	59%	58%	348	601
	Operational	0%	19%	24%	23%	139	
	Refrigerant	0%	8%	17%	19%	114	
Demolition and New Construction	Embodied	100%	92%	83%	76%	784	1,037
	Operational	0%	6%	10%	13%	139	
	Refrigerant	0%	2%	7%	11%	114	
Retrofit vs. Demolition and New Construction		**-76%**	**-70%**	**-58%**	**-42%**		

Table C-3: Whole-life emissions at the milestone climate target years for the mid-rise office building in Edmonton

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	31%	14%	12%	456	3,893
	Operational	0%	69%	85%	88%	3,410	
	Refrigerant	0%	1%	1%	1%	27	
Demolition and New Construction	Embodied	100%	62%	34%	23%	1,007	4,444
	Operational	0%	38%	66%	77%	3,410	
	Refrigerant	0%	0%	1%	1%	27	
Retrofit vs. Demolition and New Construction		**-73%**	**-45%**	**-23%**	**-12%**		

Table C-4: Whole-life emissions at the milestone climate target years for the high-rise office building in Toronto

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	55%	36%	34%	381	1,113
	Operational	0%	43%	61%	62%	695	
	Refrigerant	0%	2%	3%	3%	37	
Demolition and New Construction	Embodied	100%	72%	51%	43%	548	1,280
	Operational	0%	27%	47%	54%	695	
	Refrigerant	0%	1%	2%	3%	37	
Retrofit vs. Demolition and New Construction		**-52%**	**-37%**	**-22%**	**-13%**		

Table C-5: Whole-life emissions at the milestone climate target years for the high-rise office building in Vancouver

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	76%	63%	61%	373	607
	Operational	0%	18%	24%	23%	139	
	Refrigerant	0%	6%	13%	16%	95	
Demolition and New Construction	Embodied	100%	86%	75%	69%	531	764
	Operational	0%	10%	16%	18%	139	
	Refrigerant	0%	4%	9%	12%	95	
Retrofit vs. Demolition and New Construction		**-51%**	**-44%**	**-32%**	**-21%**		

Table C-6: Whole-life emissions at the milestone climate target years for the high-rise office building in Edmonton

Scenario	Emissions	2022 *(Beginning of life)*	2030	2050	2083 *(End of life)*	Total Emissions *(kg CO_2e/m^2)*	
Retrofit	Embodied	100%	26%	12%	10%	389	3,823
	Operational	0%	74%	87%	89%	3,410	
	Refrigerant	0%	1%	1%	1%	24	
Demolition and New Construction	Embodied	100%	45%	21%	15%	603	4,036
	Operational	0%	55%	78%	84%	3,410	
	Refrigerant	0%	0%	1%	1%	24	
Retrofit vs. Demolition and New Construction		**-58%**	**-26%**	**-11%**	**-5%**		

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.