City of Toronto

Net Zero Existing Buildings Strategy

Impact Modeling & Assessment Technical Appendix

Final Draft

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Purpose of the Technical Appendix

This technical appendix is a companion document to the City of Toronto's Net Zero Existing Buildings Strategy. It is organized around two main purposes:

1. ***Technical index to the main report****.* This document offers definitions for acronyms, technical terms and study-specific concepts and connects readers of the main report to additional material referenced in the report, particularly relating to Chapters 2 and 4.

For readers with this purpose, please use the section Technical Index as a guide to appropriate material.

2. ***Summary of overall impact analysis process***. The flow of the material past the Technical Index is used to summarize the analysis and assessment work conducted throughout the project. This material is organized in two pieces:
    - *FACILITY-SCALE* – ***Facility Archetype Identification & Package Analysis*** – Summary of facility-scale analysis work to identify zero carbon performance packages and quantify the impacts of those packages at the facility level.
    - *CITY-SCALE -* ***City-wide Impact Assessment*** – Summary of city-wide analysis work and results associated with the prototype recommended pathway to zero carbon illustrated in the report and used to set preliminary emissions reduction targets by major sector.

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Technical Index – Definitions and Links for Key Study Terms

This section includes a summary of key terms and definitions that have been used within the report. The definitions are organized chronologically instead of alphabetically to more effectively link to the report content.

REPORT SECTION 2.1 & 2.2 – CITY-SCALE GHG EMISSIONS AND BREAKDOWN Report pg. 9-16)

GHG EMISSIONS

Greenhouse Gas (GHG) Emission: Release of emissions from a process, typically expressed in equivalent Global Warming Potential to Carbon Dioxide (i.e. expressed in the gases CO_2 Equivalency). Within the report all emissions assume a 100-year average for the Global Warming Potential of GHGs.

***Scope 1 Emissions*:** GHG emissions from sources located within the site or city boundary (depending on where the boundary is drawn).

***Scope 2*:** GHG emissions occurring as a consequence of the use of grid-supplied electricity, heat, steam and/or cooling within the site/city boundary.

Scope 3: All other GHG emissions that occur outside the city boundary as a result of activities taking place within the city boundary. In this study, Scope 3 emissions were limited to the enclosure building material embodied carbon, operational refrigerant emissions from cooling equipment and upstream methane emissions.

Enclosure upgrades - Embodied Carbon: In this study Embodied Carbon is defined as the emissions associated with the material extraction and manufacturing of systems installed for enclosure (building envelope) upgrades only. See discussion in the *Facility-Scale* section for more insight.

Refrigerant leakage: Emissions associated with leakage of refrigerants from Heating, Ventilation, and Air-Conditioning (HVAC) equipment during building operations. Though this source can be considered a Scope 1 emission, it is not typically tracked well by operators or included in many GHG inventories.

Upstream emissions: The emissions associated with upstream energy use and direct methane emissions from natural gas extraction, production and transportation. These emissions are applied to be both the electricity and natural gas emission factors used for the study.

For further discussion on the data sources and analysis process for Scope 3 emissions see the *Facility-Scale* section.

CITY-SCALE GHG PERFORMANCE METRICS

Key metrics of performance for GHG reduction for *City-Scale* analysis were originally defined as part of the TransformTO quantification process, following the Global Report Initiative's recommendations for community inventories. The specific metrics explored in this study are:

***Study GHG emissions* reduction**: The overall savings in GHG emissions in a given year relative to a baseline year. The baseline year for the study is the 2016 TransformTO emissions.

City Targeted GHG emissions reduction: Similarly, emissions reductions relative to a 1990 baseline year are important to City of Toronto because they have set a 65% reduction target by 2030.

Accumulated Carbon / Carbon Budget: Instead of reporting the annual emissions vs. a target or baseline year, another more absolute measure of a given action is the reduction in total accumulated carbon over the study period. This metric is used implicitly in financial analysis (e.g. see LCC/tonne, as discussed below) but could be more explicitly used to assess the GHG implications of actions.

Note: This metric also motivates exploration of annual (or at least periodic) GHG emission factor changes associated with electricity, instead of using an average factor over the next 30 years. This is especially true in Ontario where emissions from electricity are scheduled to increase in the next 20 years during the refurbishment of nuclear plants. For more discussion on GHG factor changes, see the *City-Scale* section.

MAJOR BUILDING SECTOR GROUPINGS

There are four main groupings of buildings within the study, reflecting a variety of factors including size, building type and principal use and ownership model. Based on the clustering exercise outlined below, we have assigned all buildings in the available data set from 2016 to one cluster and each cluster to one of the four groupings above.

High-Rise / Large Institutional, Commercial & Industrial (High-rise ICI): Institutional, Commercial, Industrial (ICI) buildings are typically based on MPAC designations (see below) between 400 and 899. The typical building size of this sectoral group is around 100,000 ft² *or larger* and typically having more than one storey.

Low-Rise / Small Institutional, Commercial and Industrial (Low-rise ICI): All other ICI buildings fit into this category.

Multi-Unit Residential (MURB): Mostly MPAC designations 340, 341 for multi-unit residential buildings with sever or more units that are not row housing (i.e. typically fall under Part 3 of the building code).

Single Family Home / Dwelling (SFH or SFD): Most other residential occupancy types (within MPAC category 300).

For the exact detail on how facilities across Toronto have been assigned to each sector, see the *Facility-Scale* section discussion.

FACILITY-SCALE ENERGY & GHG INTENSITY PERFORMANCE METRICS

Report Figures 5, 6, and 7 show results for EUI, TEDI and GHGI comparing existing building sectoral results to their closest counterpart within the Toronto Green Standard (TGS) - Version 3. These metrics are defined as follows:

Thermal Energy Demand Intensity (TEDI): Annual energy load per unit area required to be delivered through the heating, ventilation and air-conditioning (HVAC) systems of a building in order to satisfy demands for ventilation air heating and zonal heating based on scheduled set-points and after accounting for all losses through the enclosure and all internal gains.

Passive Survivability (TEDI-related): This metric, borrowed from the City of Toronto's *Zero Emissions Framework* report connects the TEDI of a given facility to the amount of time a building remains habitable during a power outage when heating is no longer available.

***Cooling Energy Demand Intensity (CEDI or TEDI*-C):** Identical definition to TEDI, but reflecting energy load for cooling needs and cooling of ventilation air instead of heating.

Energy Use Intensity (EUI): All annual on-site energy used from all sources per unit area including on-site generation.

GHG Intensity (GHGI): *Annual* Scope 1 and 2 GHGs (associated with on-site building energy use) per unit area.

For more information, see the *Facility-Scale* section.

FACILITY CLUSTERING

For clarity on clustering process see the *Facility-Scale* section or follow the links below.

Archetype: A set of assumptions about form, operating procedure and building system features that can be considered representative of a given group of buildings within an actual building stock.

Cluster: Groups of buildings with similar characteristics. Clusters are based on multiple parameters – better suited to capture variations in building performance rather than only on building use or program type. For more information, see *Clustering (Typology Development)*.

Typology: Subgroup based on the underlying characteristics of properties within each group. The fuel and electricity energy use intensity of each typology, for example, would be based on the median energy use intensity values of all the properties contained in that typology group.

Focal / Focal Point Cluster: Clusters selected to be representative clusters for facility level energy analysis or for financial analysis. For more information, see *Clustering (Typology Development)*.

BUILDING ENERGY DATA SOURCES

EWRB: Ontario's Energy and Water Reporting and Benchmarking program. Under Reporting of Energy Consumption and Water Use regulation, large building owners need to report their building's energy and water use once a year to the Ministry of ENDM for buildings 100,000 square feet and larger.

EnerGuide: EnerGuide is the program developed by Natural Resources Canada to support energy efficiency in homes, products, etc. The EnerGuide rating process for residential homes produces a rich data set of modeled performance for existing residential buildings in Toronto and the data set is shared with the City. We have used this data set to characterize the energy use of Part 9 buildings.

MPAC: The Municipal Property Assessment Corporation supports municipalities to designate the classification of buildings mostly for the purpose of accurate taxation. The definition of MPAC numerical designations for properties can be found here. In some cases, MPAC-designated properties are aggregated into addresses (e.g. as with Condos) reflecting multiple properties within the same building.

BUILDING ENERGY BREAKDOWN

Fuel-specific Energy Use: Breaking a building's energy use down by the different sources of energy (e.g. electricity, natural gas, district heating, district cooling).

End-use Breakdown: Components of the energy use specific to different purposes (e.g. lighting, heating, cooling, equipment, domestic hot water, etc.)

BUILDING SYSTEM BREAKDOWN

User-driven energy: *Systems affected directly by space occupants (e.g. lighting, domestic hot water fixtures, equipment of various types).*

Enclosure: *System of walls, windows, doors, roof, floors, etc. - both above and below ground level – that separate the building's spaces from the outdoor environment.*

Heating, Ventilation and Air-conditioning (HVAC) – Delivery: *Air- and water-based systems (typically made up of coils, pumps, fans, ductwork and piping) used to connect the space/zonal needs for heating, cooling and ventilation with the energy-transforming systems of the Plant.*

HVAC Plant: *Systems used to transform the energy sources of the building (typically* *electricity and natural gas) into heating and cooling energy. Examples include hot water and domestic hot water (DHW) boilers, chillers, cooling towers, heat pumps, direct-expansion (DX) cooling units, refrigeration systems, etc.*

Electricity Generation: *Equipment used to generate electricity on site and either use it on site directly (behind the meter) or send it back to the electricity grid (grid-tied / grid-connected). For this study the most important type of electricity generation is that of Photovoltaic (PV) panels installed on roofs and over parking areas at the studied buildings/sites.*

For assumptions about how these system parameters varied across the cluster models see the *Facility-Scale* section.

NOTE: There are many industry-specific terms used to describe specific technologies and implementation strategies for building systems. We will endeavor to provide, if desired, a separate glossary of these terms for the final report.

REPORT SECTION 2.3.1 & 2.3.2 - SYSTEM- AND FACILITY-LEVEL ACTIONS (Report pg. 16-31)

BUILDING SYSTEM IMPROVEMENTS

Measures: A measure is an individual energy conservation, energy efficiency, fuel-switching, renewable generation, or embodied impact transformation that can be applied to a building in a specific way for each archetype / focal cluster.

Levels of Action: Categories of retrofit efforts towards achieving emission reductions used in this study:

Level 1 - Represents a minimum level of investment effort

Level 2 - Represents a level of improvement effort equivalent to typical new construction

Level 3 - Represents a “best in class” effort and the most aggressive investment in performance that can be made for a given system based on market-ready technology and know-how

For detailed descriptions of the levels of action within each system breakdown across the major sub-sectors, see the *Facility-Scale* section.

WHOLE FACILITY IMPROVEMENTS

Measure Packages (or just Packages): A package is a collection of measures that achieves a specific set of goals (e.g. a 50% GHG reduction target) in a specific way. For more information, see the *Key Individual Facility Metric Performance By Package and Major Category*. For this analysis, the packages are defined as:

Like-for-Similar (LFS) – Package aligning targeted measure-level improvements with systems and equipment that are expected to require replacement in a 30-year window of service life (e.g. windows & roof)

LFS + Easy Fuel Switch (LFS+FS-1) – Package starting with Like-for-Similar and adding 1 or 2 (max) measures/improvements (representing approximately Level 1 enclosure effort) as well as implementing a Level 1 fuel switch effort (fuel switch with natural gas support/backup)

LFS + Full Fuel Switch (LFS+FS-2) – Package starting with Like-for-Similar and adding 1 or 2 (max) measures/improvements (representing approximately Level 1 enclosure effort) as well as implementing a Level 2 fuel switch effort and DHW fuel switch.

Fuel Switch Ready (FSR) – Package with enclosure improvements and upgrades needed to ready the facility for future fuel switching as well as Level 2 HVAC delivery upgrades (including heat recovery)

Zero Carbon Ready (ZCR) – Package starting with Fuel Switch Ready and implementing Level 2 Fuel Switch (cold climate, minimal gas back up required) as well as including DHW fuel switch.

Max Site – Package of Level 3 enclosure upgrades, best HVAC upgrades and fuel switch with geo-exchange (including DHW fuel switch).

Full Fuel Switch Only (FS-2 only) – Level 2 Fuel Switch as well as DHW fuel switch with no enclosure or other load improvements

FACILITY-SCALE FINANCIAL PERFORMANCE METRICS

Example results for financial performance are included in Report Table 7 and Figure 15 of the report with additional results across all focal clusters and sectors provided in the Facility-Scale results. The financial metrics used at the facility scale are:

Incremental Capital Cost: The additional capital required to achieve the measures proposed energy reductions relative to the base case. For all of the results shown in this study at the facility-scale the base case is the LCS package.

Incremental Life-cycle Cost (ILCC): The net cost of a measure over its lifespan including upfront capital cost, operation and maintenance costs and residual (end-of-life value) as compared to base case. In our study Net Present Value (NPV) calculations are done with a 3% discount rate and residual value of capital is calculated using linear depreciation. The study period of all ILCC calculations is 25 years as this is a typically planning horizon for capital investment at a building scale.

ILCC/tonne: The incremental life-cycle cost to abate a tonne of carbon dioxide equivalent emissions. For building scale, this metric is most appropriate to measure packages. The denominator of this metric is the accumulated operational GHG emissions over the study period (i.e. excluding Scope 3).

REPORT SECTION 2.3.3, 2.4 and 4.1.1/4.1.2 – CITY LEVEL ANALYSIS (Report pg. 31-50 and 77-78)

***Pathway*:** A package or sequence of packages for a facility towards near zero emissions. Many facilities will not likely be able to achieve zero emissions operations in a single retrofit action and will therefore require multiple transformations to achieve near-zero emissions.

Emissions Reduction Scenario: A scenario is the roll-out/enaction of a suite of programs over time and its associated impacts. A scenario is not a prediction, but a possible future (or futures, with sensitivity analysis) based on the potential of the programs identified. It is also based on external factors and assumptions (e.g. grid decarbonization, climate change). Because of the uncertainty associated with scenario analysis, scenarios have multiple directions or *pathways* that can be considered that achieve the same (or similar) results. For more information, see the *City-Scale* section.

Business-as-planned: A scenario reflecting the use of LFS packages/levels of improvement across all sectors***.*** There was also a similar scenario as part of the TransformTO Report #2 that described the actions and policy as planned by the City prior to significant action initiated by TransformTO. An updated version of the TransformTO modeling exercise aligns with the BAP defined as part of this study.

Least Capital Net-Zero Ready: A low or virtually least-cost, net-zero scenario reflecting a constant pace of change across all buildings between 2022 and 2050.

Aggressive Net-Zero Ready: A net-zero scenario reflecting the level of acceleration and action needed to achieve a 60% chance of avoiding greater than 1.5°C of global warming, while maximizing investment in holistic upgrades.

Prototype/Recommended: A customized net-zero scenario developed by reflecting on the performance differences of the above three scenarios and via dialogue with the broader study team. The prototype recommended scenario is not an optimal scenario and will require further refinement as conditions change.

CITY-SCALE FINANCIAL & RESILIENCE PERFORMANCE METRICS

Report Section 2.4 is dedicated to summarizing city-scale performance in key decisions-making metrics. Several of those metrics are mimics of the Facility-scale Financial metrics. Those metrics are:

Total Cost of Ownership (TCO): The net cost incurred including upfront capital cost, operation and maintenance costs and residual (end-of-life value) over a set period. This metric is identical to Life-cycle Cost but without the time value of money analysis.

TCO/Tonne: The total cost of ownership to abate a tonne of carbon dioxide equivalent emissions. Similar to the facility-scale analysis, the TCO/Tonne in the study excludes Scope 3 emissions associated with the various packages implemented in the scenario.

Marginal Abatement Cost (MAC) Curves: Analysis of actions, reflecting a combination of carbon and life-cycle-cost implications. MAC Curves are a deconstructed version of the combined TCO/Tonne of a given emissions reduction scenario. In Report Figure 24 an example MAC Curve for the MURB sector is provided. For additional curves, see City-wide Results.

Overall Economic Activity (Construction Activity): This aggregated metric reflects the sum of all upgrade package capital costs expended during the period of 2016 to 2030 for a given reduction scenario. Energy-related cost, maintenance and renewal costs are excluded from this metric.

Direct, Retrofit-related Job-Hours: Assuming a simple labour fraction of 50% for enclosure upgrades, 30% HVAC and fuel switching upgrades and 20% for solar PV and an average labour rate of $110/hour we have estimated the number of construction-related job hours from the package-level analysis of measures for each scenario.

Direct, Full Time Jobs Created: The number of jobs created takes the number of Job-Hours and divides by 1,985 for number of full-time hours per year and then takes an average of this annual full-time jobs number over a 30-year study period (which was selected to align with the TransformTO planning horizon).

Grid resilience support / Grid stewardship: To accurately reflect grid resilience involves a grid-wide assessment of the impact of changes to the grid associated with energy conservation, electrification of heating systems, increases in distributed electricity generation and possible on-site battery storage systems. This level of effort was outside the scope of the study; however, a high-level proxy of grid impact was estimated from the change in heating and cooling peak loads estimated from the facility-scale modeling described in more detail in the *Facility-Scale* section. This proxy metric is used to give a high-level quantification of the potential grid implications / grid stewardship offered by the various scenarios. The units of this proxy metric are "Mega-Watts", but it does not reflect the actual estimated change in grid power demand within each of the heating and cooling seasons.

SECTORAL EMISSIONS REDUCTION TARGETS

Facility GHGI Emissions Reduction Targets*:* As discussed in Section 4.1.1 of the report and further detailed in the *City-Scale* section of this report, 5-year average facility-scale emissions reduction targets are calculated from the Recommended emissions reduction scenario results and estimates of the distribution of facility-scale GHGI performance for the major sectors. The process for calculating the targets assumes all non-compliant facilities reach, but do not exceed, the target by the end of the 5-year period.

1. FACILITY-SCALE - Archetype Identification & Zero Carbon Package Analysis

To evaluate the impact of existing building retrofits, there needed to be processes in place to reasonably estimate the underlying performance characteristics of the existing building stock. The challenge was how to use the limited set of information that is publicly available from the city of Toronto to estimate performance characteristics and subsequently model the impact of building retrofits.

The methodology used in this analysis is a four-step process that is designed for a planning-level analysis of existing building retrofits. Further details for each step is provided below and in the following sections.

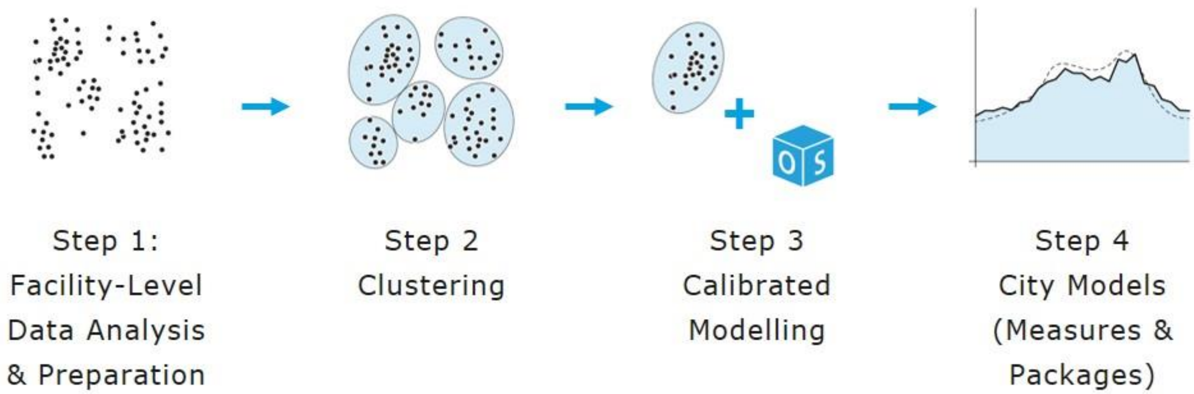


Figure 1: Planning-Level Analysis Process Overview

Facility-level Data Analysis & Preparation: Creating a linear regression model to estimate annual energy use for each building in the city based on known building attributes.

Clustering: Grouping facilities based on program type, fuel use, and electricity use to establish relevant building typologies.

Calibrated Modelling: Creating an energy model for each typology that is calibrated against the median energy use intensity of each or cluster.

Measure and Package Modelling: Using the calibrated energy models for each typology to model various retrofit interventions and bundling measures to represent various retrofit packages options.

1.1. Facility-Level Data Analysis & Preparation

1.1.1. Process, Data Sources and Assumptions

The first step was to create a linear regression model to estimate annual energy use for each building in the city. The regression model, which was used to create energy use estimates for each property, was based on common attributes across the MPAC, EWRB, EnerGuide, and MURBS datasets. Common attributes included: property type (program type), year of construction or major renovations, and building size (gross area). The regression model was used to generate estimates for fuel and electricity energy use intensity for each property in the MPAC dataset. To validate that the regression model created a reasonable prediction of energy use, the aggregate results (total fuel and electricity estimates) were compared against measured data from the city's greenhouse gas inventory. The model was within 10% of the measured data from the greenhouse gas inventory.

The regression model was developed using three datasets: EWRB data, which covers large ICI buildings, a MURBS database of approximately 130 MURB properties, and the EnerGuide rating system data, which covers single-family homes. One notable gap in these three datasets is small ICI buildings that are not adequately captured in the EWRB dataset. Roughly 95% of the buildings in the EWRB dataset were greater than 50,000 ft2. Though the effect of this will likely be to overestimate building energy use from the regression model, no adjustments were made to the regression model, as it was felt to be a conservative assumption.

Data Sources: EWRB data for multifamily (2018), commercial, industrial, and institutional properties; EnerGuide rating data for single family homes (2018); MURB audit data for mixed-use residential buildings (2008-2019); MPAC data for all properties (2016).

1.2.Clustering (Typology Development)

1.1.2. Process, Data Sources and Assumptions.

The goal of the clustering process was to identify groups of buildings that have similar performance characteristics. These groups form the basis of building typologies, which was used to evaluate the impact of energy efficiency retrofits in different building sectors. Groups were created from a k-means clustering process that used program type, fuel use, and electricity use as the clustering variables. Furthermore, the variables were standardized before using the k-means clustering algorithm. The variables were chosen to capture the most statistically significant differences in energy use across the building stock, with energy being the primary focus of this analysis. The number of groups was determined through a sensitivity analysis to find the optimal trade-off between modeling speed (more groups require more modeling time) and fidelity (fewer groups result in a wider margin-of-error). There is no significant benefit to having more groups or more typologies for the purposes of this analysis. The result of this process was 32 groups of buildings, with each group forming the basis of a distinct building typology.

Each building typology is based on the underlying characteristics of properties within each group. The fuel and electricity energy use intensity of each typology, for example, is based on the median energy use intensity values of all the properties contained in that typology group. For the most part, the groups are composed of similar property types (e.g. office, retail, etc.). However, in some instances there is a heterogenous mix of property types within the group, which simply means that those properties theoretically have similar performance characteristics and will respond similarly to various retrofit measures.

The typical approach to urban energy modeling relies on archetypal building definitions that take into account program, size, and vintage. The only difference in the approach in this study is the use of an additional two parameters – electricity and gas use – that can say more about how a building might respond to individual retrofits. By using energy use as a key parameter for archetypal definition, through a process of statistical clustering, the most significant differences in energy use can better capture across buildings in the city. While this process results in some definitional ambiguity with respect to individual clusters, or archetypes, it results in a much more robust set of results at the aggregate, urban scale.

Data Sources: MPAC data with fuel and electricity use intensity estimates for each property.

1.1.3. Calculated Data / Results

The following table outlines the results of the clustering analysis. The clusters were organized into four main sectors: Institutional & Large Commercial Buildings, Multi-Unit Residential Buildings, Single Family Homes and Small Commercial & Industrial Buildings. As well, for each cluster the number of buildings, total floor area and GHG emissions are shown. Of note is that six clusters account for almost half of the total annual emissions from Toronto's building stock. These represent key clusters within each building sector. Each cluster has a predominant program type and the breakdown of each cluster by percent floor area of each sub-sector within the cluster is also provided in the table below.

Each cluster was assigned a focal cluster for energy efficiency measures and for costs. (e.g. Cluster 6 was assigned to Cluster 10 energy efficiency measures and Cluster 22 costs) and these assignments are summarized in the table below.

Table 1: Clustering Analysis Summary

Sector	Cluster No.	Description – Predominant Program Type and Age	No. of Buildings	Total Area (m^2)	GHG Emissions (tCO_2e)	Cluster Assignments[1]	
						EE Measure Set	Cost Cluster
Institutional & Large Commercial Buildings	4	Education c. 1975	768	8,160,365	426,498	4/22	4
	16	Education c. 1960	362	4,937,845	252,132	4/22	4
	22	Large mixed-use developments, c.1980	100	7,892,828	494,693	4/22	22
	14	Large office buildings c. 1975	18	1,690,068	101,278	4/22	22
	6	Large properties, non-specific use, c.1965	19	1,026,393	53,154	4/22	22
Multi-Unit Residential Buildings	8	Multifamily housing, c. 1960	3,761	28,414,648	1,311,510	8/12	8
	12	Large multifamily properties, c. 1990	1,332	15,480,377	611,972	8/12	12
	15	Mid-size multifamily, higher performance, c. 2000	1,051	5,162,980	199,250	8/12	12
	20	Large multifamily properties, low performance, c. 1970	18	1,774,967	117,122	8/12	12
Single Family Homes	28	Single-family housing, low performance, c. 1960	88,949	10,229,962	430,924	28	28
	31	Single-family housing, better-performance, c. 1960	60,794	8,913,759	311,439	29	28
	23	Single-family housing, c. 1975	51,677	9,350,217	272,938	28	28

[1] Five sets of energy efficiency measures and nine costing models were defined for nine focal-point clusters. Remaining non-focal clusters were assigned a focal cluster to be used for measure and costing analysis (e.g. cluster 14 is defined by energy efficiency measure set for cluster 10 and costing for cluster 22).

Sector	Cluster No.	Description – Predominant Program Type and Age	No. of Buildings	Total Area (m^2)	GHG Emissions (tCO_2e)	Cluster Assignments[1]	
						EE Measure Set	Cost Cluster
Single Family Homes	30	Single-family housing, c. 1990	34,007	6,907,071	189,478	28	28
	32	Single-family housing, better performance, c. 2000	31,993	7,088,389	164,336	28	28
	24	New single-family housing, high performance, c. 2010	12,189	4,532,129	84,075	28	28
	29	Old single-family housing, low performance, c. 1920	60,176	8,142,153	410,198	29	29
	26	Single-family housing, c. 1945	46,816	5,984,849	253,962	29	29
	25	Old single-family housing, low performance, c. 1910	40,739	4,673,169	238,792	28	29
	27	Larger single-family housing, c. 1930	8,777	2,510,355	96,186	29	29
Small Commercial & Industrial Buildings	5	Retail c. 1980	1,683	7,884,831	353,936	10	5
	17	Mid-size retail, c. 1960	779	1,548,213	56,810	10	5
	7	Small retail c. 1950	643	1,012,047	32,619	10	5
	9	Small Retail c. 1990	890	469,468	12,762	10	5
	21	Small properties, non-specific use, c. 1970	3,359	4,417,690	194,199	10	10
	10	Mid size office, c. 1970	1,630	3,996,549	141,385	10	10
	19	Small mixed-use properties, c. 1940	8,560	2,774,253	130,858	4/22	10
	1	Mixed use hotel and office c. 1975	1,477	2,108,322	76,937	8/12	10
	2	Small commercial properties c. 1900	2,572	1,043,583	62,772	4/22	10
	11	Small mixed-use properties, c. 1920	888	1,409,494	36,188	4/22	10
	18	Small properties, non-specific use, c.	637	724,967	20,792	10	10

Sector	Cluster No.	Description – Predominant Program Type and Age	No. of Buildings	Total Area (m^2)	GHG Emissions (tCO_2e)	Cluster Assignments[1]	
						EE Measure Set	Cost Cluster
		2000					
	13	Manufacturing and warehousing c. 1980	7,028	13,252,156	506,762	10	13
	3	Manufacturing and warehousing c. 1960	2,445	4,111,970	146,289	10	13

Table 2: Cluster Summary Subsector % Breakdown

Building Sector	Cluster	Sub Sector % Floor Area								
		Education	Hotel	Manufacturing/ Warehouse	Mixed Use Property	Multifamily Housing	Office	Other[2]	Retail	Single Family Dwelling
Institutional & Large Commercial Buildings	4	**39.8%**	-	17.5%	-	-	19.5%	4.3%	18.8 %	-
	6	-	10.6%	-	-	-	-	**89.4 %**	-	-
	14	-	-	-	-	-	9.0%	**91.0 %**	-	-
	16	**82.0%**	-	-	-	-	9.0%	4.8%	4.1%	-
	22	**30.0%**	1.5%	23.0%	-	-	**29.2%**	3.2%	13.1 %	-
Multi-Unit Residential	8	-	-	-	0.1%	**99.9%**	-	-	-	-
	12	-	-	-	-	**100.0%**	-	-	-	-

[2] The term "Other" is defined by MPAC. "Other" includes building designations that do not fit in with the predominant program types otherwise identified and were clustered based on median energy use intensity such that they could be grouped together. While a predominant program type cannot be identified, this highlights the benefit of applying the clustering method over traditional archetyping as there are four distinct clusters that are primarily defined by "Other" that will theoretically have similar performance characteristics and will respond similarly to various retrofit measures.

Building Sector	Cluster	Sub Sector % Floor Area								
		Education	Hotel	Manufacturing/ Warehouse	Mixed Use Property	Multifamily Housing	Office	Other[2]	Retail	Single Family Dwelling
Buildings	15	-	-	-	3.6%	**96.4%**	-	-	-	-
	20	-	-	-	24.5%	**67.5%**	-	7.9%	-	-
Single Family Homes	23 to 32	-	-	-	-	-	-	-	-	100.0%
Small Commercial & Industrial Buildings	1	-	31.0%	0.3%	-	-	**48.3%**	20.4%	-	-
	2	-	-	-	**74.0%**	15.4%	-	10.6%	-	-
	3	-	-	**100.0%**	-	-	-	-	-	-
	5	-	-	**54.8%**	-	-	18.6%	-	26.5%	-
	7	69.2%	-	-	-	-	-	-	30.8%	-
	9	0.2%	10.1%	**58.0%**	-	-	15.5%	-	16.2%	-
	10	0.8%	-	-	-	-	**99.2%**	-	-	-
	11	**28.8%**	-	21.3%	-	-	-	**25.3%**	**24.6%**	-
	13	-	-	**80.0%**	-	-	20.0%	-	-	-
	17	8.0%	-	30.0%	-	-	-	10.5%	**51.4%**	-
	18	-	-	-	4.9%	-	-	**95.1%**	-	-
	19	-	-	-	**94.0%**	-	-	6.0%	-	-
	21	-	0.7%	-	-	-	2.5%	**96.8%**	-	-

Table 3: EUI Performance by Fuel Type

Building Sector	Cluster Number	Electric Energy (kWh/m²)	Fuel Energy (kWh/m²)	TEUI (kWh/m²)
Institutional & Large Commercial Buildings	4	284	201	485
	6	184	226	410
	14	219	270	489
	16	281	167	448
	22	322	268	590
Multi-Unit Residential Buildings	8	107	234	341
	12	93	215	308
	15	102	189	290
	20	152	336	488
Single Family Homes	23	47	169	216
	24	22	92	114
	25	59	261	320
	26	55	223	278
	27	38	203	241
	28	55	206	262
	29	56	243	299
	30	43	147	190
	31	51	190	241
	32	41	122	163
Small Commercial & Industrial Buildings	1	174	161	335
	2	121	229	349
	3	228	140	368
	5	254	178	433
	7	248	127	375
	9	183	120	303
	10	204	149	353
	11	226	97	323
	13	231	159	389
	17	253	151	404
	18	141	131	272
	19	130	226	356
	21	155	195	350

1.3.Calibrated Modeling

1.1.4. Process, Data Sources and Assumptions

Given the limited information for each typology (there was only information about the program type and energy use intensity), the goal of the calibrated modelling process was to create an energy model for each typology that reflects the performance characteristics of the underlying properties. The models were calibrated against the median energy use intensity of each group, or cluster. The calibrated modelling process relies on statistical surrogate models that help determine the input parameters of each energy model and was designed to take that limited set of information and predict the right set of input parameters for the energy model.

The general process involved using a machine learning model to identify the appropriate set of model input parameters for each typology. The process started by running EnergyPlus simulations for the full design space of possible solutions – roughly 10,000 simulations using energy plus that are designed to capture all possible combinations of input parameters. Half of these simulations are used to train the machine learning model, and half are used to test the model. For this process a random forest algorithm was deployed as the basis of the surrogate model. This process is described in detail in the following published papers:

- Shreshth Nagpal, Caitlin Mueller, Arfa Aijazi & Christoph F. Reinhart (2018): A methodology for auto-calibrating urban building energy models using surrogate modeling techniques, Journal of Building Performance Simulation, DOI: 10.1080/19401493.2018.1457722.
- Shreshth Nagpal, Jared Hanson & Christoph F. Reinhart (2019): A framework for using calibrated campus-wide building energy models for continuous planning and greenhouse gas emissions reduction tracking.

To develop a training set for the machine learning model, energy simulations were run using a randomized set of input parameters, representing the full set of possible solutions. The model then used the training data set to look for patterns in the data, which allowed identification of the most likely set of input parameters, or building attributes, for each typology. The input parameters identified through this process are listed below.

- Window to wall ratio (WWR)
- Window U value
- Window solar heat gain coefficient (SHGC)
- Wall R value
- Roof R value
- Occupant density
- Occupancy schedule
- Outside air flowrate (ACH)
- Equipment usage schedule
- Equipment power density
- Lighting usage schedule
- Lighting power density
- Heat recovery
- Economizer
- Cooling coefficient of performance (COP)

- Heating COP

The machine learning process then finds the combination of input parameters that yield the expected electricity and fuel energy use intensity for each cluster. The automated process yields ten least-error models (i.e. 320 models in total, 10 for each cluster), which are aggregated to better capture the extremes likely present in each cluster and therefore more accurately represent energy savings potential. The EnergyPlus simulation engine was used to generate the calibrated energy models, which were set as shoebox models with fixed width perimeter zones. The Toronto-City weather file was applied.

Table 4: Key data points in cluster analysis

Relevant Data Point	EWRB	EnerGuide
Year built	○	○
Occupancy	○	
Primary property type	○	○
GFA (ft2)	○	○
Electricity use (annual)	○	○
Fuel use (annual)	○	○
Total site energy (annual)	○	○
Heating energy (annual)		○
System descriptions		○
System efficiencies		○
Air tightness (ACH@50pa)		○
Envelope insulations values		○
EnerGuide rating		○

Energy use for all buildings in the city was provided by Enbridge and Toronto Hydro. These utility-scale data were only subdivided by broad type classification (e.g. MURBs, low-rise residential, commercial, industrial) and the electricity and gas classifications are not well-aligned. Archetypes which fit within the even broader, harmonized utility classifications were adjusted as a group to ensure that the energy use from the calibrated models matches the overall utility-scale data. The set of calibrated energy models by archetype and fuel, were spot-checked and refined based on other datasets available (i.e. SHEU/SCIEU, BPS, EWRB) and project team experience.

The model occasionally has trouble differentiating between model parameters that have similar thermodynamic implications. For some of the typologies composed of mixed-use residential buildings, for example, the model assumed a certain level of heat recovery, which could equally be explained by reduced ventilation airflow rates or a faulty ventilation air system. The best way to think about the model input parameters, as they relate to actual system performance, is an effective level of performance.

The systems are not modeled explicitly in EnergyPlus, but rather based on a simple abstraction using a coefficient of performance (COP) value. A COP of 1 or less represents a mixed-fuel system, while a COP of 1 or greater represents an all-electric system. If the COP is 1, the model determines whether the system should be mixed-fuel or all-electric depending on the relationship between fuel and electricity energy use intensity. The COP includes all fan and pumping energy associated with meeting the heating and cooling demand. Based on an initial review of the results, mixed-fuel systems for all typologies was decided to be used. Accommodations for the prevalence of electric resistance heating were made by attributing a portion of the thermal energy demand intensity to electricity in instances where the model was unable to clearly differentiate between mixed-fuel and all-electric systems.

Since domestic hot water is difficult to predict with the surrogate model, domestic hot water usage rates were manually assigned for each typology based on the project team's experience working on buildings with similar program distributions.

1.1.5. Calculated Data / Results

The model does not predict a single set of results, but rather a number of 'high-probability' input parameter combinations. Therefore, when representing the results of the calibration process, it's helpful to review the distribution of results for each parameter, rather than single, empirical values. The tables in this section show the first and third quartile results, which gives a sense of the range of results produced by the calibration routine. When there is a small difference between the first and third quartile values (or when they are the same) it generally indicates a high degree of confidence in the results. In cases where there is a larger difference, there is more uncertainty about the value. Note that these are all effective performance values used in planning-level energy models.

Table 5: Cluster Input Parameters Envelope - 1st and 3rd Quartile Values

Cluster	WWR		Window U value (W/m2-K)		Window SHGC		Wall R value (m2-K/W)		Roof R value (m2-K/W)	
	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3
1	0.4	0.6	3	5	0.5	0.5	1.67	1.67	2.50	2.50
2	0.6	0.6	3	3	0.4	0.4	0.40	0.40	0.83	0.83
3	0.6	0.6	5	5	0.4	0.5	3.33	3.33	2.50	2.50
4	0.4	0.6	1.875	3	0.4	0.5	1.67	0.40	0.83	0.83
5	0.45	0.6	5	5	0.5	0.5	0.93	0.40	0.83	0.83
6	0.4	0.6	3	5	0.4	0.5	0.93	0.40	2.50	2.50
7	0.4	0.6	5	5	0.4	0.5	1.67	1.67	4.00	2.50
8	0.4	0.6	1.5	1.5	0.5	0.5	1.67	0.49	0.83	0.83
9	0.4	0.6	3.5	5	0.4	0.4	0.40	0.40	0.83	0.83
10	0.6	0.6	5	5	0.4	0.4	1.67	0.40	2.50	2.50
11	0.45	0.6	5	5	0.4	0.5	0.93	0.40	0.83	0.83
12	0.25	0.6	3.5	5	0.5	0.5	1.67	0.40	1.67	0.83
13	0.45	0.6	3	3	0.325	0.4	0.93	0.40	2.50	2.50
14	0.45	0.6	3.5	5	0.425	0.5	0.93	0.40	0.83	0.83
15	0.6	0.6	3	3	0.5	0.5	3.33	1.90	5.00	2.50
16	0.6	0.6	5	5	0.4	0.4	0.40	0.40	2.50	2.50
17	0.4	0.6	1.5	3	0.5	0.5	0.40	0.40	2.50	1.00
18	0.4	0.6	5	5	0.5	0.5	0.40	0.40	0.83	0.83
19	0.4	0.6	1.5	1.5	0.5	0.5	0.40	0.40	0.83	0.83
20	0.4	0.4	1.5	3	0.4	0.4	3.33	3.33	2.50	2.50
21	0.4	0.6	1.875	5	0.425	0.5	1.67	0.40	0.83	0.83
22	0.2	0.4	3	3	0.325	0.4	2.67	1.67	0.83	0.83
23	0.4	0.4	5	5	0.5	0.5	1.67	1.67	0.83	0.83
24	0.4	0.4	5	5	0.5	0.5	1.67	0.40	2.50	2.50
25	0.4	0.6	3	4.5	0.4	0.4	1.67	1.67	0.83	0.83
26	0.2	0.4	5	5	0.5	0.5	1.67	1.67	2.50	2.50
27	0.2	0.4	5	5	0.5	0.5	1.67	1.67	4.00	2.50
28	0.4	0.6	1.5	1.5	0.5	0.5	1.67	1.67	2.50	2.50
29	0.4	0.4	1.875	3	0.5	0.5	1.67	1.67	0.83	0.83
30	0.2	0.2	5	5	0.5	0.5	1.67	1.67	0.83	0.83
31	0.4	0.4	1.875	5	0.5	0.5	1.67	1.67	2.50	2.50
32	0.2	0.6	5	5	0.5	0.5	1.67	1.67	2.50	2.50

Table 6: Cluster Input Parameters Occupancy, ACH, Schedule and Power Density - 1st and 3rd Quartile Values

Cluster	Occupant density (ppl/m2)		Occupancy schedule		ACH		Equipment usage schedule		Equipment power density (W/m2)		Lighting usage schedule		Lighting power density (W/m2)	
	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3
1	0.05	0.05	1	1.75	2	2	0	0	25	25	0	0	15	15
2	0.5	0.5	0	0	2	2	0	0	5	5	0	0	25	25
3	0.05	0.5	1	1	2	2	0	0	25	25	0	0	25	25
4	0.05	0.05	0	0	2	2	0	0	50	50	1	1	10	10
5	0.05	0.5	0	1	2	2	1	1	25	25	0	0	25	25
6	0.05	0.5	0	0	2	2	0	0	25	25	0	0	15	15
7	0.1625	0.5	1	1	2	2	1	1	25	25	0	1	25	25
8	0.01	0.05	0	0	2	2	0	0	5	5	1	1	25	25
9	0.5	0.5	1	1	2	2	0	0	25	25	0	0	15	15
10	0.05	0.05	2	2	2	2	0	0	25	25	1	1	25	25
11	0.5	0.5	1	1	2	2	0	0	25	25	0	0	25	25
12	0.05	0.5	0	1	2	2	0	1	5	5	0	0	15	15
13	0.02	0.05	0	1	2	2	0	0	25	25	0	0	25	25
14	0.5	0.5	1	1	2	2	0	0	25	25	0	1	25	25
15	0.02	0.05	1	2	2	2	0	0	5	5	1	1	25	25
16	0.05	0.05	0	0	2	2	0	0	50	50	1	1	10	10
17	0.5	0.5	1	1.75	2	2	1	1	25	25	0	1	25	25
18	0.05	0.3875	0.25	1	0.5	0.5	1	1	5	5	0	0	25	25
19	0.05	0.05	0	0	2	2	2	2	5	5	0	0	25	25
20	0.02	0.05	0	0	2	2	0	0	25	25	1	1	10	10
21	0.05	0.05	0	1	2	2	0	0	25	25	1	1	10	10
22	0.05	0.05	1	1.75	2	2	0	0	50	50	0	0.75	15	15
23	0.02	0.05	0.25	1	0.5	0.5	0	0	5	5	1	1	10	10
24	0.01	0.05	0	1	0.5	0.5	0	0	5	5	1	1	10	10
25	0.05	0.05	0.25	1	2	2	0	0	5	5	1	1	10	10
26	0.05	0.05	0	1	2	2	0	0	5	5	1	1	10	10
27	0.01	0.05	0	1	2	2	0	0	5	5	1	1	10	10
28	0.05	0.05	1	1	2	2	0	0	5	5	1	1	10	10
29	0.01	0.05	0	0	2	2	0	0	5	5	1	1	10	10
30	0.01	0.04	0	1	0.5	0.5	0	0	5	5	1	1	10	10
31	0.05	0.05	0.25	1	2	2	0	0	5	5	1	1	10	10
32	0.01	0.05	0	0	0.5	0.5	0	0	5	5	1	1	10	10

Table 7: Cluster Input Parameters HVAC - 1st and 3rd Quartile Values

Cluster	Heat recovery		Economizer		Cooling COP		Heating COP	
	Q1	Q3	Q1	Q3	Q1	Q3	Q1	Q3
1	30%	30%	1	1.75	6	6	1	1
2	30%	30%	0	0	2	2	1	1
3	30%	30%	0	1.75	2	3.5	1	1
4	0%	0%	1	2	4	6	1	1
5	30%	30%	0	0	2	2	0.7	1
6	30%	30%	0	0	2	4	0.7	0.7
7	30%	30%	0	1	2	2	1	1
8	30%	30%	0	0	4	4	1	1
9	60%	60%	1	1	2	3.5	0.7	0.7
10	30%	30%	0	0	4	4	1	1
11	60%	60%	0	0	2	2	0.7	0.7
12	38%	60%	0	1	2	2	0.7	0.925
13	30%	30%	0	0	2	2	1	1
14	0%	0%	1	1	2	4	1	1
15	30%	30%	0	0	4	4	1	1
16	0%	0%	1	1	4	4	1	1
17	30%	30%	0	0.75	2	2	0.7	0.7
18	30%	60%	0	0	2	2	0.7	0.7
19	30%	30%	0	0	4	6	1	1
20	0%	0%	1	1	4	5.5	0.7	0.7
21	30%	30%	1	1	4	6	1	1
22	0%	0%	0	0	2	2	0.7	0.7
23	30%	30%	1	2	6	6	0.7	0.7
24	30%	60%	1	1	6	6	1	1
25	30%	30%	2	2	4	4	1	1
26	30%	30%	2	2	6	6	1	1
27	30%	53%	2	2	6	6	0.775	1
28	30%	30%	2	2	4	6	1	1
29	30%	30%	2	2	4.5	6	1	1
30	60%	60%	1	1.75	6	6	0.7	0.7
31	60%	60%	1.25	2	4	6	0.7	0.7
32	30%	60%	1	1.75	6	6	0.7	0.7

1.4.Measures - Energy & Cost Analysis

1.1.6. Process, Data Sources and Assumptions

Once the input parameters were established, energy modelling was used to evaluate the impact of various retrofit packages to assess energy and GHG savings for both individual retrofit measures and packages of retrofit measures. The models were built in EnergyPlus, using simplified geometry and fixed-width perimeter zones. The output of the models was energy demand, which was converted to energy use by using a fuel and electricity coefficient of performance (COP) to represent various systems configurations.

The main challenge with modeling retrofits is parametrizing the results so that each retrofit measure can be evaluated individually or in combination with others. Furthermore, the planning-level energy models do not have complex system definitions, requiring a slightly different approach for modeling system upgrades.

The retrofits were classified into two categories: envelope measures and system measures.

- For the envelope measures, which included air-sealing, insulation, and window upgrades, EnergyPlus was used to explicitly model every unique measure combination. This resulted in a database of reference models that was used to analyze different combinations of envelope retrofit measures.
- For system measures, a new effective COP was calculated for each upgrade measure using 5 energy models with more complex system definitions. These “partner models” represent typical buildings within each of the major building sectors in Toronto (low-rise ICI, high-rise ICI, MURB, and two models for SFH). To calculate the COPs, the heating and cooling energy demand was compared to the amount of fuel and electricity used to meet that demand. Each typology had a corresponding partner model, with the assumption being most of the typologies within a given sector would have similar system configurations. The effective COP of the partner model and the energy demand of the typology reference model was used to derive the energy savings for each retrofit package.

Further details on the modelling process are below:

- Static Variables: There were no changes made for any of the baseline assumptions for window-wall-ratio, occupancy, scheduling, equipment power density, lighting power density, or ventilation air flowrates in the retrofit models.
- Envelope Retrofits: Envelope retrofits were modeled explicitly for each typology using EnergyPlus. In the model, the baseline envelope parameters (R value, U value, infiltration, etc.) were replaced with the target values for each retrofit measure. For any given property, it is difficult to predict the exact proportion of energy loss that results from poor insulation (conductive losses) or poor air sealing (convective losses). Therefore, our model may over- or underestimate the savings from measures that differentially impact insulation or air sealing, though combined measures (e.g. wall insulation, window-replacements, air sealing) will still produce accurate results.
- Low Flow Fixtures: Low flow fixtures energy savings were calculated by applying the flowrate savings, as a percentage, against the baseline domestic hot water energy use assumption.
- System Upgrades: For system upgrades, energy models with more complex system definitions were used to derive new COP values for fuel and electricity. As is the case with the baseline COP values, this includes all fan and pumping energy required to meet the heating and cooling demand. The “partner” energy models are based on typical buildings within each of the major building sector in Toronto.

- Fuel Switching: The same process used to model system upgrades was used for fuel switching. The main difference with fuel switching is that the heating electricity COP will increase while the heating fuel COP will decrease or become zero. As is the case with the COPs used for system upgrades, the COPs include all pump and fan energy needed to meet the heating and cooling demand.

Each cluster was assigned a partner model and a costing model. The cluster assignments can be seen in the cluster summary above.

Further details on the cost analysis process are below:

- Enclosure Capital Costs: Class D estimates for enclosure upgrades were prepared by A. W. Hooker and Associates from enclosure system descriptions developed by WSP for all costing focal cluster models.
- HVAC Capital Costs: Class D-minus estimates were derived by WSP from similar projects and working with local contractors. Special thanks to Peter Washer at HTS and Jim Bolger from Waterloo Energy Products.
- Life-cycle Service Lives: Based on study work from previous projects, WSP estimated service life for major system upgrades on average (i.e. an entire enclosure or HVAC system upgrade) instead of on an item-by-item basis (i.e. separating out fans from ductwork, etc.). Residual value estimates are based on linear depreciation.
- Incremental maintenance costs: Based on previous study experience, maintenance cost differences were assumed to be zero. Though this assumption penalizes some measures and benefits others, the average package studied includes a very similar set of equipment to the base case (i.e. LFS) package.
- Inflation was 2% and discount rate was 3%.
- Energy costs and escalation rates are included in the next section (i.e. *City-Scale*).

Further details on the embodied carbon and bio-based carbon storing analysis process are as follows:

- Chris Magwood (Endeavor Centre) performed detailed life-cycle cost analysis using a customized analysis process developed during his Master's Thesis and available for download here.
- Chris' process was reviewed for completeness and consistency with general LCA principles by one of WSP's North American experts in Building Life-cycle Assessment. The methodology was found to be in line with ISO 14040 protocols.
- The process employed by the work to quantify the amount of biogenic carbon storage was also reviewed by researchers at the University of Toronto. Overall, the U of T conclusions highlight the need for more research into biogenic carbon storage, suggesting the use of values below 1.0 may be more appropriate for some materials, especially Timber-based products. The following discussion addresses this observation in more detail.
- See the tables below for example material changes for the improved embodied carbon cases.

Future Recommendation – More nuanced accounting of biogenic carbon storage values

Methodologies for accounting for the value of biogenic carbon storage in building materials are in a phase of rapid development. Consensus is building that there are different accounting strategies for three kinds of biogenic carbon found in building materials:

1. Timber-based products
2. Purpose grown crops (i.e. cork and bamboo)
3. Agricultural residues and recycled fibers (i.e. cellulose insulation, straw)

Of these, timber is the most prevalent and also the most difficult to quantify. This uncertainty about the climate mitigation value of timber was addressed in this study by showing timber products at both zero-storage value and at a maximum storage value of 1kgC in timber = 1kgC removed from the atmosphere. This equation holds up well for residue and recycled fiber because the carbon contained in these materials was destined to return to the atmosphere quickly if not captured in a building material. Timber, however, has a long regrowth cycle and, if left unharvested, the tree would have continued to be a carbon sink.

New tools, such as the Biogenic Carbon Footprint Calculator for Harvested Wood Products from the World Wildlife Fund https://www.worldwildlife.org/projects/biogenic-carbon-footprint-calculator-for-harvested-wood-products are attempting to quantify the meaningful storage impact of timber products. In this tool, typical spruce/pine/fir (SPF) lumber is given a carbon storage value of 1kgC in a wood product = 0.495 kgCO2 sequestration. The development of these types of tools and methodologies will help to inform future versions of this kind of study.

Further details on the measures not studied selection process are as follows:

- Lighting & zonal plug/electrical equipment system upgrades: As discussed in the main report, lighting and plugged system improvements were not studied explicitly in the work following form two basic assumptions:
    1. Where applicable, most facilities have already or will likely undertaken these upgrades in the near future as part of normal retrofit actions, even without the motivation of GHG reduction.
    2. The benefit to electrical energy savings from lighting and plug loads is typically offset by an increase in required heating energy (and associated GHGs). When the heating system is electrified using heat pumps, this can result in a significant improvement, but when the heating is from typical gas-fired equipment, the impact is typically negative.

Future Recommendation – Further study of lighting upgrade benefits in ICI buildings
Recognizing the overall importance of electricity savings in ICI buildings, a separate review of the benefit of lighting upgrades in ICI buildings should be studied. It is possible that lighting upgrades can improve the cost-effectiveness and overall GHG performance of this sector in a similarly meaningful manner to enclosure and other upgrades when fuel switching is also planned for a site.

- BAS improvements and Re-Commissioning: Though discussed in the main report in detail, it is difficult to effectively ascribe savings associated with coordinated BAS, VFD and ReCx efforts though it is well understood that such efforts can be very successful at reducing electrical energy use and associated GHG emissions.

1.1.7. Calculated Data / Results

What follows are a series of matrices showing the nature of the upgrades analyzed for the major sectoral types. A total of 6 upgrade packages were analyzed, but the two SFH and two MURB packages are similar enough to be summarized together in one table.

Table 8: Single Family Homes - Major Category Measure Descriptions

SINGLE-FAMILY HOMES

	Baseline (typical EB)	Level 1 Improvement	Level 2 Improvement	Level 3 Improvement
Foundation	Typically no insulation	Partial cover foundation with insulation (inside or outside)	Cover full foundation ***code-level*** thickness	Cover full foundation ***maximum*** thickness
Walls	Typically little to no insulation (up to R4 equivalent)	Fill cavities without disrupting finishes, air-sealing ~ R-10	Replace interior **OR** exterior wall finish, new framing ~R-20	Replace interior **AND** exterior wall finish, new framing ~R-30
Roofs	Minimal insultation (up to R-8 equivalent)	Blow-in/insulate cavity ~R-20 to 40	Blow-in/insulate ***more + air sealing*** ~R-30 to 50	Blow-in/insulate ***most + best air sealing*** ~R-40 to 60
Windows	Mostly double glazed, air filled Wood & older vinyl frames	Best double glazed, argon Improved vinyl frames	Best ***triple glazed***, argon Improved vinyl frames	–
HVAC – Delivery	90% efficient furnace, constant Air-conditioner	95% efficient, variable-flow New A/C	–	–
HVAC – Plant (i.e. fuel-switching)	No fuel switch	95% efficient, variable-flow Switch New A/C to ASHP	No furnace ***Cold climate*** ASHP	No furnace ***GSHP***
DHW	10L/ min shower 2010s era typical washers	5L/ min shower Top 10% of Energy Star washers	5L/ min shower Top 10% of Energy Star Washers ***ASHP water heater***	–
PV	No PV	Fixed, best angle ~50% of Roof Area	–	–

Table 9: Single Family Homes – Package Measures

Cluster	Package	Enclosure				HVAC		DHW	PV
		Foundation	Walls	Roof	Window	Delivery	Plant		
28	LFS	F0	R2	W0	G1	SYS1	FS0	DHW1	-
	LFS+FS-1	F2	R1	W0	G1	SYS0	FS1	DHW1	-
	LFS+FS-2	F2	R1	W0	G1	SYS0	FS2	DHW2	-
	FS Ready	F1	R3	W2	G1	SYS1	FS0	DHW1	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW2	-
	ZC Ready + PV	F3	R4	W2	G1	SYS0	FS2	DHW2	PV
	ZC Ready – w/o PV	F3	R4	W2	G1	SYS0	FS2	DHW2	-
	Max Site + PV	F4	R4	W3	G2	SYS0	FS3	DHW2	PV
	Max Site – w/o PV	F4	R4	W3	G2	SYS0	FS3	DHW2	-
29	LFS	F0	R1	W0	G1	SYS1	FS0	DHW1	-
	LFS+FS-1	F0	R1	W0	G1	SYS0	FS1	DHW1	-
	LFS+FS-2	F0	R1	W0	G1	SYS0	FS2	DHW2	-
	FS Ready	F2	R2	W2	G1	SYS1	FS0	DHW1	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW2	-
	ZC Ready + PV	F2	R2	W2	G1	SYS0	FS2	DHW2	PV
	ZC Ready – w/o PV	F2	R2	W2	G1	SYS0	FS2	DHW2	-
	Max Site + PV	F3	R2	W3	G2	SYS0	FS3	DHW2	PV
	Max Site – w/o PV	F3	R2	W3	G2	SYS0	FS3	DHW2	-

Table 10: Single Family Homes – EC Options
The table below summarizes the differences in material selection between the baseline/typical, best-case and worst-case material selections.

Important Note: *The choices made were done so to support the analysis of possible variation in embodied emissions and do not reflect a recommendation for one product over another.* These material selections were made to show the possible range of embodied impact for products with similar expected performance and service life. WSP and Endeavor Centre are not suggesting that the specific product selections are the only, or even the right, material choice for all enclosure systems of the given type and we have not verified the service life or functionality of all products in the discussed application.

Cluster 28 / 29 Materials	Enclosure EC Materials		
Enclosure System	Typical	Lowest Embodied (Best Case)	Highest Embodied (Worst Case)
Foundation	Wood framing Fibreglass Drywall	Wood framing Dense packed Cellulose Wood siding/finish	Metal framing Mineral wool MgO board
Walls (interior refit)	Wood framing HFO Foam Drywall	Wood framing Cellulose Wood siding/finish	Wood framing HFC Foam Drywall
Walls (exterior over-/re-clad)	Mineral wool Stucco (1-1-6)	Wood fibreboard Lime/cord plaster	XPS foam Acrylic stucco
Roof (blown insulation type)	Fibreglass	Cellulose	Mineral wool

Table 11: MURBs - Major Category Measure Descriptions

MURBs

	Baseline (typical EB)	Level 1 Improvement	Level 2 Improvement	Level 3 Improvement
Walls	Typically little to no insulation (up to R5 equivalent)	Upgrade walls from the inside, avoiding condensation risk ~R-10	Reclad or over-clad building with additional insulation ~R-20	Reclad building with significant additional insulation ~R-30
Roofs	Minimal insultation (up to R-10 equivalent)	Maximum insulation without change to parapets ~R-15 to 20	Maximum feasible roof insulation, affecting parapets ~R-30 to 40	–
Windows	Mostly double glazed, air filled Wood & older vinyl frames	Best double glazed, argon Improved vinyl frames	Best ***triple glazed***, argon Improved vinyl frames	–
HVAC – Delivery	Perimeter radiation and window shakers or 2/4 pipe fan-coils Corridor pressurization	In-suite ERVs	Centralize, variable-flow ERV system	–
HVAC – Plant (i.e. fuel-switching)	Central boiler and chiller (where fan-coils)	Add balcony-mounted heat pumps or replace central chiller with heat pump	Distributed low-temp heat pumps or full central heat pump replacing boilers and chillers	Distributed or centralized ground-source heat pumps
DHW	10L/ min shower 2010s era typical washers	5L/ min shower Top 10% of Energy Star washers	5L/ min shower Top 10% of Energy Star Washers ***ASHP water heater***	–
PV	No PV	Fixed, best angle ~50% of Roof Area	–	–

Table 12: MURBs – Package Measures

Cluster	Package	Enclosure				HVAC		DHW	PV
		Foundation	Walls	Roof	Window	Delivery	Plant		
8	LFS	F0	R1	W0	G1	SYS0	FS0	DHW1	-
	LFS+FS-1	F0	R1	W0	G1	SYS0	FS1	DHW1	-
	LFS+FS-2	F0	R1	W0	G1	SYS0	FS2	DHW2	-
	FS Ready	F0	R2	W2	G1	SYS1	FS0	DHW1	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW2	-
	ZC Ready + PV	F0	R2	W4	G2	SYS1	FS2	DHW2	PV
	ZC Ready – w/o PV	F0	R2	W4	G2	SYS1	FS2	DHW2	-
	Max Site + PV	F0	R3	W4	G2	SYS2	FS3	DHW2	PV
	Max Site – w/o PV	F0	R3	W4	G2	SYS2	FS3	DHW2	-
12	LFS	F0	R1	W0	G1	SYS0	FS0	DHW1	-
	LFS+FS-1	F0	R1	W0	G1	SYS0	FS1	DHW1	-
	LFS+FS-2	F0	R1	W0	G1	SYS0	FS2	DHW2	-
	FS Ready	F0	R2	W2	G1	SYS1	FS0	DHW1	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW2	-
	ZC Ready + PV	F0	R2	W4	G2	SYS1	FS2	DHW2	PV
	ZC Ready – w/o PV	F0	R2	W4	G2	SYS1	FS2	DHW2	-
	Max Site + PV	F0	R2	W5	G2	SYS2	FS3	DHW2	PV
	Max Site – w/o PV	F0	R2	W5	G2	SYS2	FS3	DHW2	-

Table 13: MURBs – EC Options
The table below summarizes the differences in material selection between the baseline/typical, best-case and worst-case material selections.

Important Note: ***The choices made were done so to support the analysis of possible variation in embodied emissions and do not reflect a recommendation for one product over another.*** These material selections were made to show the possible range of embodied impact for products with similar expected performance and service life. WSP and Endeavor Centre are not suggesting that the specific product selections are the only, or even the right, material choice for all enclosure systems of the given type and we have not verified the service life or functionality of all products in the discussed application.

All other clusters, especially cluster 8 and 12 (MURBs)	Enclosure EC Materials		
Enclosure System	Typical	Lowest Embodied (Best Case)	Highest Embodied (Worst Case)
Walls (interior refit)	Mineral wool, metal studs Drywall	Wood fiberboard, wood studs Drywall	Medium density spray foam (HFO), metal studs Drywall
Walls (exterior over-/re-clad)	EIFS (EPS, typical)	EIFS (cork)	EIFS (XPS)
Roof (flat, re-/over-roof)	Polyisocyanurate TPO membrane	Wood Fiberboard TPO membrane	XPS EPDM membrane

Table 14: Small / Low-Rise ICI - Major Category Measure Descriptions

SMALL / LOW-RISE ICI

	Baseline (typical EB)	Level 1 Improvement	Level 2 Improvement	Level 3 Improvement
Walls	Minimal insulation (up to R5 equivalent)	New insulation in interior walls with air sealing ~R-10	Re-clad exterior walls+ additional insulation and sealing ~R-20	–
Roofs	Minimal insultation (up to R-10 continuous)	Maximum insulation without parapet modifications ~R-15 to 20	More extensive insulation including changes to parapets ~R-30 to 40	–
Windows	Mostly double glazed, air filled Aluminum frames	Best double glazed, argon Improved aluminum frames	Best ***triple glazed***, argon Best aluminum frames	–
HVAC – Delivery	Typical DX rooftop unit with 80% efficient furnace, constant speed fan	Improved RTUs including built-in heat recovery	Dedicated outdoor air system With best-in-class RTU or distributed system	–
HVAC – Plant (i.e. fuel-switching)	Sometimes central boiler to serve perimeter heating	Heat pump roof-top with gas-fired back-up or maintain perimeter heat	Cold climate ASHP system (e.g. VRF)	Ground Source Heat Pump System (e.g. VRF+GHX)
PV	No PV	Fixed, best angle ~50% of Roof Area	–	–

Table 15: Small / Low-Rise ICI – Package Measures

Cluster	Package	Enclosure				HVAC		DHW	PV
		Foundation	Walls	Roof	Window	Delivery	Plant		
5	LFS	F0	R1	W0	G1	SYS0	FS0	DHW0	-
	LFS+FS-1	F0	R1	W0	G1	SYS1	FS1	DHW0	-
	LFS+FS-2	F0	R1	W0	G1	SYS1	FS2	DHW0	-
	FS Ready	F0	R2	W1	G1	SYS2	FS0	DHW0	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS1	FS2	DHW0	-
	ZC Ready + PV	F0	R2	W1	G2	SYS2	FS2	DHW0	PV
	ZC Ready – w/o PV	F0	R2	W1	G2	SYS2	FS2	DHW0	-
	Max Site + PV	F0	R2	W3	G2	SYS2	FS3	DHW0	PV
	Max Site – w/o PV	F0	R2	W3	G2	SYS2	FS3	DHW0	-
10	LFS	F0	R1	W0	G1	SYS0	FS0	DHW0	-
	LFS+FS-1	F0	R1	W0	G1	SYS1	FS1	DHW0	-
	LFS+FS-2	F0	R1	W0	G1	SYS1	FS2	DHW0	-
	FS Ready	F0	R2	W1	G1	SYS2	FS0	DHW0	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS1	FS2	DHW0	-
	ZC Ready + PV	F0	R2	W1	G1	SYS2	FS2	DHW0	PV
	ZC Ready – w/o PV	F0	R2	W1	G1	SYS2	FS2	DHW0	-
	Max Site + PV	F0	R2	W3	G2	SYS2	FS3	DHW0	PV
	Max Site – w/o PV	F0	R2	W3	G2	SYS2	FS3	DHW0	-
13	LFS	F0	R1	W0	G1	SYS0	FS0	DHW0	-
	LFS+FS-1	F0	R1	W0	G1	SYS1	FS1	DHW0	-
	LFS+FS-2	F0	R1	W0	G1	SYS1	FS2	DHW0	-
	FS Ready	F0	R2	W1	G1	SYS2	FS0	DHW0	-

Cluster	Package	Enclosure				HVAC		DHW	PV
		Foundation	Walls	Roof	Window	Delivery	Plant		
	Full Fuel Switch Only	F0	R0	W0	G0	SYS1	FS2	DHW0	-
	ZC Ready + PV	F0	R2	W2	G1	SYS2	FS2	DHW0	PV
	ZC Ready – w/o PV	F0	R2	W2	G1	SYS2	FS2	DHW0	-
	Max Site + PV	F0	R2	W3	G2	SYS2	FS3	DHW0	PV
	Max Site – w/o PV	F0	R2	W3	G2	SYS2	FS3	DHW0	-

Table 16: Large / High-Rise ICI - Major Category Measure Descriptions

LARGE / HIGH-RISE ICI

	Baseline (typical EB)	Level 1 Improvement	Level 2 Improvement	Level 3 Improvement
Walls	Minimal insulation (up to R5 equivalent)	New insulation in interior walls with air sealing ~R-10	Reclad exterior walls + additional insulation and sealing ~R-20	–
Roofs	Minimal insultation (up to R-10 continuous)	Maximum insulation without parapets modification ~R-20	More extensive insulation, including changes to parapet ~R-30	–
Windows	Mostly double glazed, air filled Aluminum frames	Best double glazed, argon Improved aluminum frames	Best ***triple glazed***, argon Best aluminum frames	–
HVAC – Delivery	Variable air volume and dual duct with perimeter baseboards	Add variable-flow heat recovery ventilation system to existing system types	Dedicated outdoor air system with best-in-class replacement of heating/cooling delivery	–
HVAC – Plant (i.e. fuel-switching)	Central boiler and chiller no fuel switching	Heat recovery chiller system serves 20-40% of heat needs	Fuel central, cold climate ASHP system that minimizes need for natural gas back-up	Full, central ground source heat pump system
PV	No PV	Fixed, best angle ~50% of Roof Area	–	–

Table 17: Large/ High-Rise ICI – Package Measures

Cluster	Package	Enclosure				HVAC		DHW	PV
		Foundation	Walls	Roof	Window	Delivery	Plant		
4	LFS	F0	R1	W0	G1	SYS0	FS0	DHW0	-
	LFS+FS-1	F0	R1	W0	G1	SYS1	FS1	DHW0	-
	LFS+FS-2	F0	R1	W0	G1	SYS1	FS2	DHW0	-
	FS Ready	F0	R2	W2	G1	SYS2	FS0	DHW0	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW0	-
	ZC Ready + PV	F0	R2	W2	G2	SYS2	FS2	DHW0	PV
	ZC Ready – w/o PV	F0	R2	W2	G2	SYS2	FS2	DHW0	-
	Max Site + PV	F0	R2	W3	G2	SYS2	FS3	DHW0	PV
	Max Site – w/o PV	F0	R2	W3	G2	SYS2	FS3	DHW0	-
22	LFS	F0	R1	W0	G1	SYS0	FS0	DHW0	-
	LFS+FS-1	F0	R1	W0	G1	SYS1	FS1	DHW0	-
	LFS+FS-2	F0	R1	W0	G1	SYS1	FS2	DHW0	-
	FS Ready	F0	R2	W2	G1	SYS2	FS0	DHW0	-
	Full Fuel Switch Only	F0	R0	W0	G0	SYS0	FS2	DHW0	-
	ZC Ready + PV	F0	R2	W2	G2	SYS2	FS2	DHW0	PV
	ZC Ready – w/o PV	F0	R2	W2	G2	SYS2	FS2	DHW0	-
	Max Site + PV	F0	R2	W3	G2	SYS2	FS3	DHW0	PV
	Max Site – w/o PV	F0	R2	W3	G2	SYS2	FS3	DHW0	-

1.5. Packages – Energy & Cost Analysis

1.1.8. Process, Data Sources and Assumptions

Typologies were grouped by major building sector to show the impact of specific retrofit packages for low-rise ICI, high-rise ICI, MURBs, and SFHs. Results were aggregated for each typology to derive the total energy and greenhouse gas emissions savings for each retrofit package. The packages ranged from minimal interventions such as retrofitting with similar equipment to maximum onsite reductions.

The typology energy models are designed to capture the average performance of a group of buildings. They were designed specifically for planning level analyses and are most useful for estimating aggregate energy and GHG reductions. Given the inherent variability of the building stock, the typology models may not accurately represent any individual building in the city, although results were cross-referenced against 'typical' buildings within each major sector to ensure that reasonable conclusions could be drawn with respect to energy savings and project costs.

1.6. Facility-Scale Performance Results

1.1.9. Key Individual Facility Metric Performance By Package and Major Category

The emission reductions of each package are shown for each sector in the below figures. It should be noted that savings are based on 2016 emission factors and the two most aggressive packages (ZCR and Max Site) are shown both with the package alone and for the package with PV. Each figure also includes the reduction threshold to meet a 50% and 80% reduction in the sector relative to the 2016 baseline emissions. Generally, like-for-similar packages are not sufficient to meet the 50% reduction whereas the remainder of the packages generally meet the 50% threshold and only the more aggressive packages trend towards the 80% reduction threshold. Notable, the addition of PV to the more aggressive packages does not appreciably improve package performance as the greatest impact is seen in the Low-Rise/Small Commercial sector with a maximum incremental improvement of 4% followed closely by Single Family Homes with an incremental improvement of 3%.

Large/High-Rise ICI

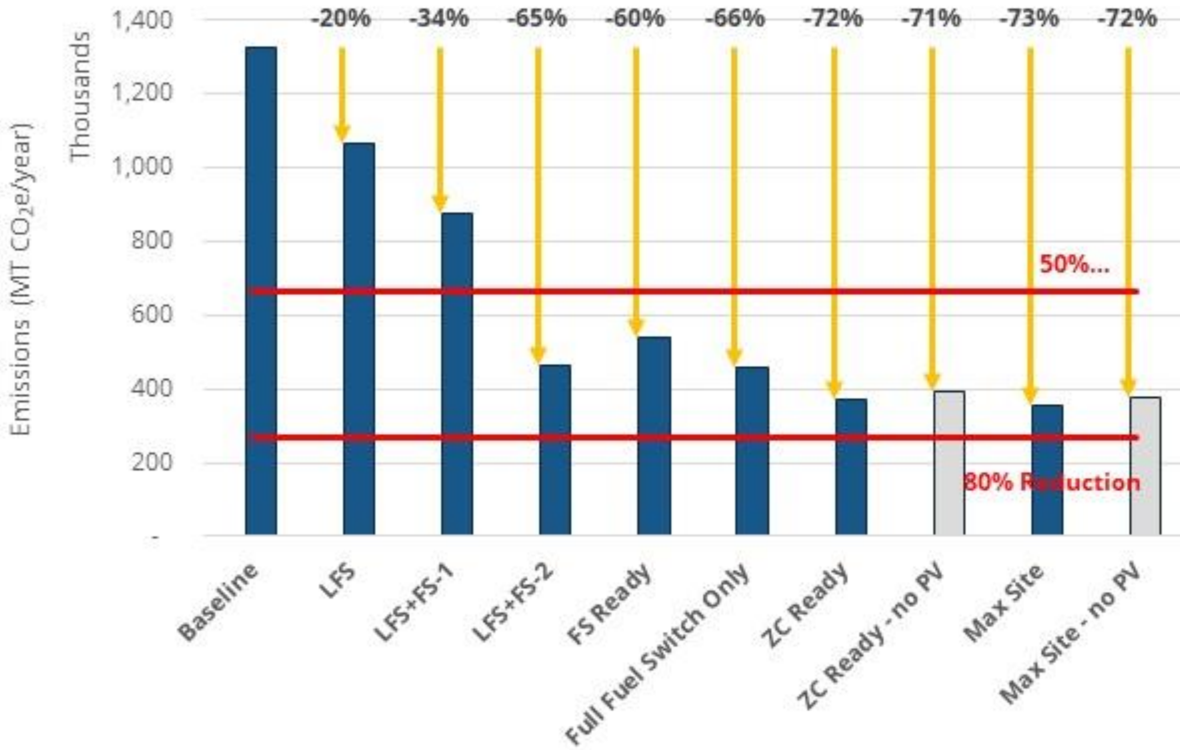


Figure 2: Large/High-Rise ICI emissions reductions by package

Small/Low-Rise ICI

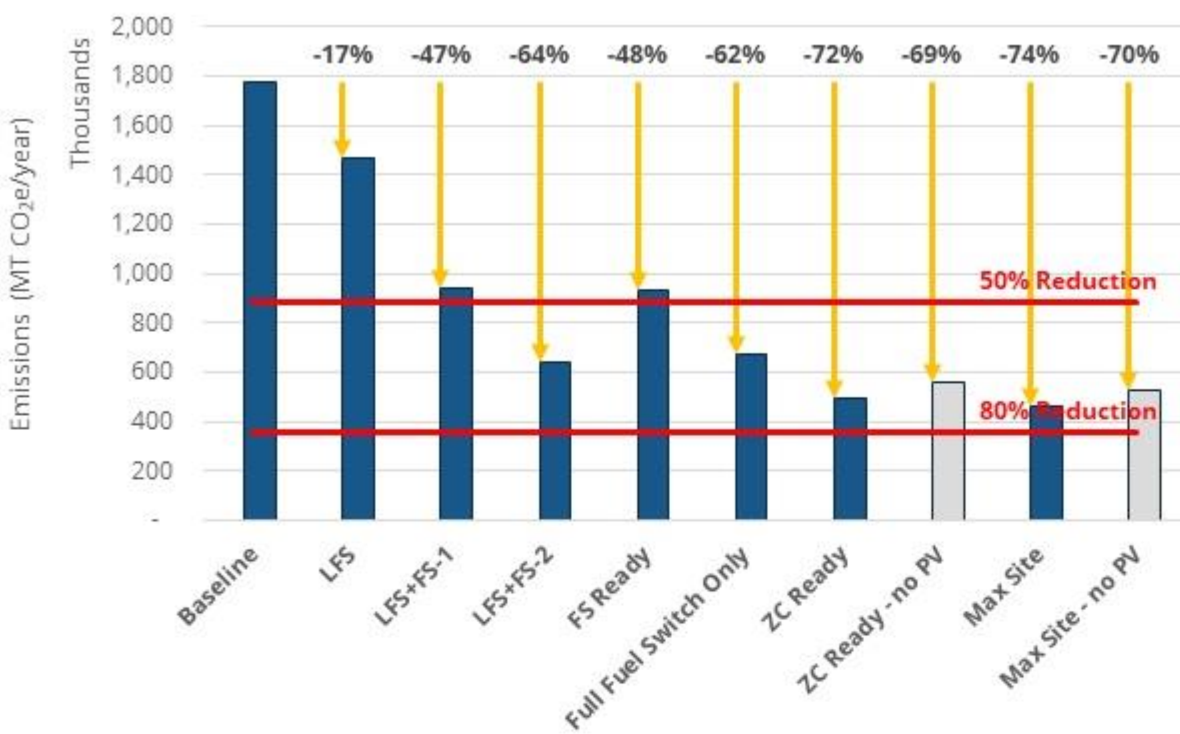


Figure 3: Small/Low-Rise ICI emissions reductions by package

MURBs

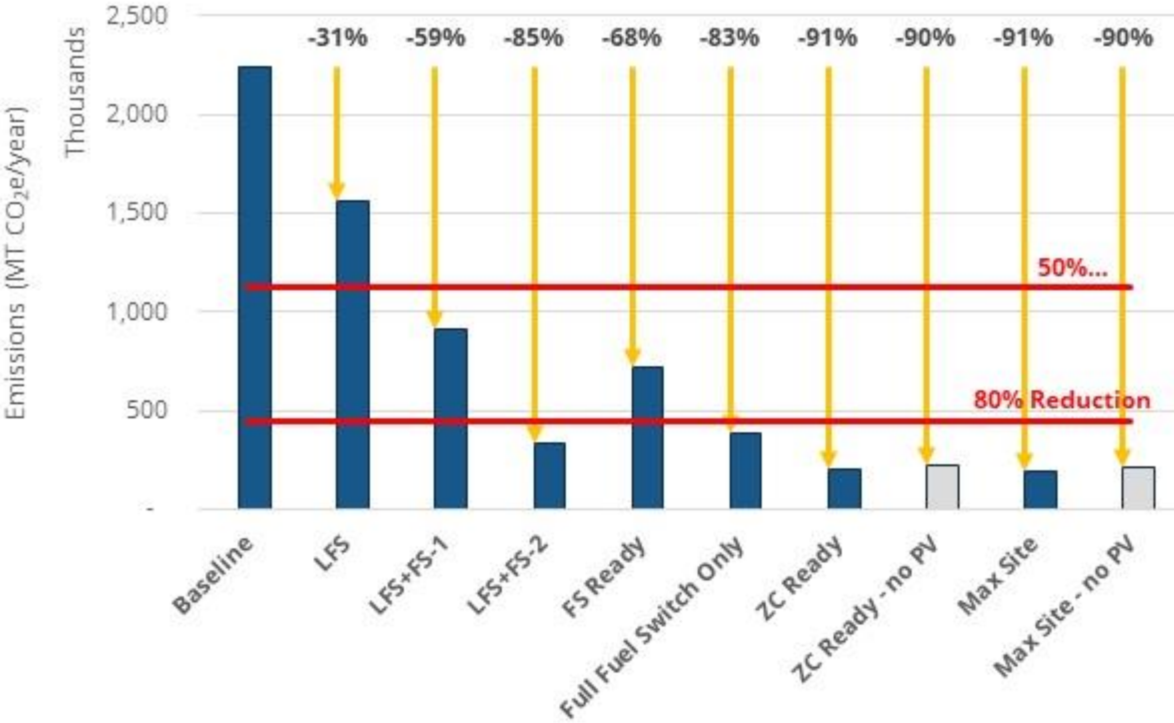


Figure 4: MURB emissions reductions by package

SFHs

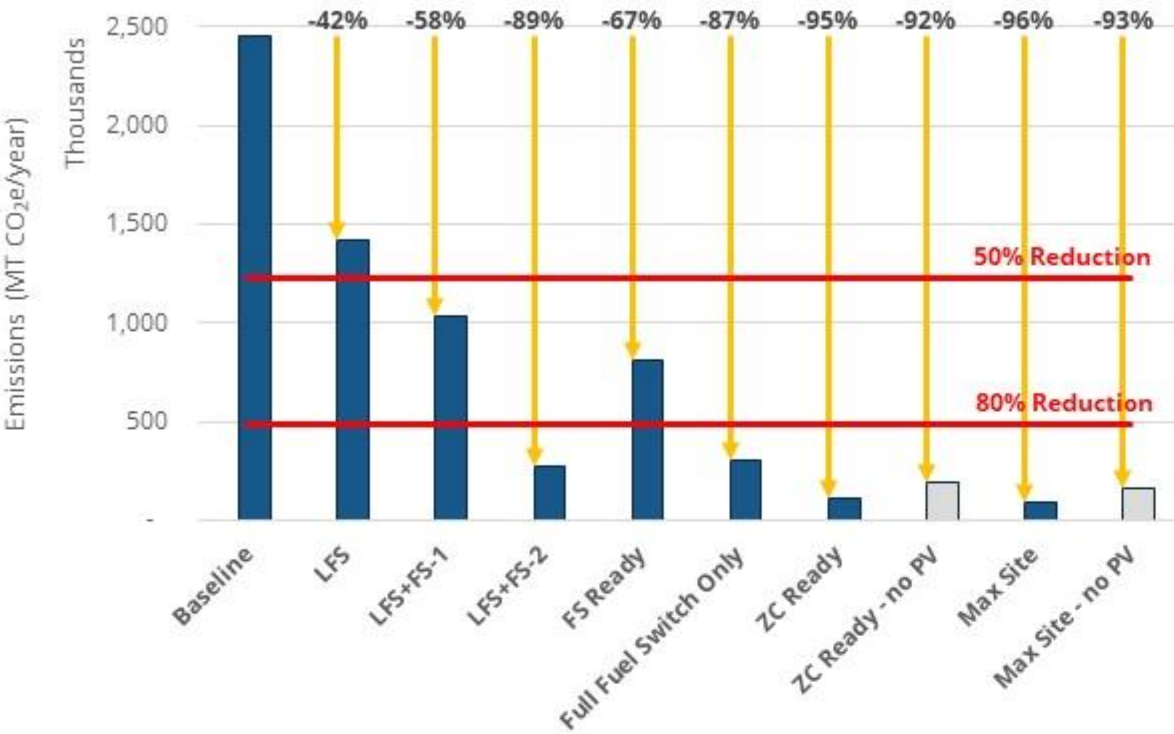


Figure 5 SFH emissions reductions by package

Focal Clusters Financial Results & Sensitivity Analysis

The tables below summarize the capital, life-cycle cost and incremental life-cycle cost per tonne of each of the packages of the focal costing clusters. Note that the incremental life-cycle cost per tonne are incremental to the like for similar (LFS) package. These metrics are presented on a per unit area basis.

Table 18 Large/High-Rise ICI SFH Focal Cluster Package Cost Results

Cluster	Package	Capital Cost ($/ft²)	Life-Cycle Cost ($/ft²)	ILLC/tonne ($/tonne)
4 Large ICI c. 1975	LFS	$108	$228	-
	LFS+FS-1	$147	$277	$9,645
	LFS+FS-2	$163	$302	$1,338
	FS Ready	$151	$264	$824
	Full Fuel Switch Only	$73	$215	-$245
	ZC Ready + PV	$183	$289	$963
	ZC Ready – w/o PV	$177	$294	$1,094
	Max Site + PV	$190	$291	$983
	Max Site – w/o PV	$183	$296	$1,112
22 Large ICI c. 1980	LFS	$68	$205	-
	LFS+FS-1	$108	$243	$1,300
	LFS+FS-2	$123	$270	$878
	FS Ready	$109	$228	$360
	Full Fuel Switch Only	$73	$221	$217
	ZC Ready + PV	$137	$260	$703
	ZC Ready – w/o PV	$136	$261	$711
	Max Site + PV	$155	$274	$864
	Max Site – w/o PV	$155	$274	$872

Table 19: Small/Low-Rise ICI SFH Focal Cluster Package Cost Results

Cluster	Package	Capital Cost ($/ft²)	Life-Cycle Cost ($/ft²)	ILLC/tonne ($/tonne)
5 Small ICI c. 1980	LFS	$108	$214	-
	LFS+FS-1	$122	$226	$396
	LFS+FS-2	$143	$243	$639
	FS Ready	$172	$260	$1,548
	Full Fuel Switch Only	$43	$155	-$1,362
	ZC Ready + PV	$210	$278	$1,287
	ZC Ready – w/o PV	$204	$283	$1,473
	Max Site + PV	$258	$316	$1,988
	Max Site – w/o PV	$252	$322	$2,210
10 Small ICI c. 1970	LFS	$64	$148	-
	LFS+FS-1	$70	$157	$349
	LFS+FS-2	$71	$153	$148
	FS Ready	$76	$151	$154
	Full Fuel Switch Only	$24	$118	-$895
	ZC Ready + PV	$86	$148	$4
	ZC Ready – w/o PV	$81	$152	$95
	Max Site + PV	$114	$170	$542
	Max Site – w/o PV	$110	$173	$655
13 Small ICI c. 1980	LFS	$158	$252	-
	LFS+FS-1	$165	$257	$152
	LFS+FS-2	$165	$252	$15
	FS Ready	$188	$261	$388
	Full Fuel Switch Only	$24	$123	-$2,820
	ZC Ready + PV	$227	$264	$241
	ZC Ready – w/o PV	$214	$274	$480
	Max Site + PV	$264	$294	$756
	Max Site – w/o PV	$250	$304	$1,043

Table 20: MURB SFH Focal Cluster Package Cost Results

Cluster	Package	Capital Cost ($/ft²)	Life-Cycle Cost ($/ft²)	ILLC/tonne ($/tonne)
8 MURB c. 1960	LFS	$46	$92	-
	LFS+FS-1	$60	$118	$929
	LFS+FS-2	$63	$118	$467
	FS Ready	$90	$125	$915
	Full Fuel Switch Only	$22	$96	$72
	ZC Ready + PV	$116	$144	$842
	ZC Ready – w/o PV	$118	$148	$928
	Max Site + PV	$90	$124	*under review*
	Max Site – w/o PV	$117	$144	$859
12 MURB c. 1990	LFS	$30	$78	-
	LFS+FS-1	$32	$89	$406
	LFS+FS-2	$37	$87	$172
	FS Ready	$48	$85	$210
	Full Fuel Switch Only	$17	$78	$8
	ZC Ready + PV	$66	$95	$294
	ZC Ready - w/o PV	$63	$96	$328
	Max Site + PV	$86	$116	$665
	Max Site - w/o PV	$85	$119	$728

Table 21: SFH Focal Cluster Package Cost Results

Cluster	Package	Capital Cost ($/ft²)	Life-Cycle Cost ($/ft²)	ILLC/tonne ($/tonne)
28 SF Home c. 1960	LFS	$23	$51	-
	LFS+FS-1	$38	$62	$609
	LFS+FS-2	$42	$67	$254
	FS Ready	$68	$74	$643
	Full Fuel Switch Only	$9	$47	-$69
	ZC Ready + PV	$82	$82	$532
	ZC Ready – w/o PV	$73	$80	$446
	Max Site + PV	$110	$100	$777
	Max Site – w/o PV	$109	$104	$796
29 SF Home c. 2000	LFS	$40	$69	-
	LFS+FS-1	$40	$70	$43
	LFS+FS-2	$41	$74	$83
	FS Ready	$130	$123	$1,447
	Full Fuel Switch Only	$9	$55	-$243
	ZC Ready + PV	$132	$125	$837
	ZC Ready – w/o PV	$130	$124	$859
	Max Site + PV	$155	$141	$1,053
	Max Site – w/o PV	$149	$139	$1,060

1.1.10. Package 25-year ILLC Sensitivity Analysis

A sensitivity analysis was performed on the sectoral ILCC/tonne results as shown below with the following sensitivity conditions:

1) Doubling the average cost of carbon up to $300 between 2020 and 2050 (in hatched blue)
2) Reducing the capital cost of measures by 50%, including the LFS baseline (in striped blue)

Notably insight from the sensitivity analysis included:

- Changing carbon costs brings the more aggressive packages below a $300/tonne threshold.
- Decreasing capital costs can produce life-cycle cost negative (i.e. cost saving) result for the aggressive Zero Carbon Ready and Max Site packages with solar PV.

High-Rise ICI

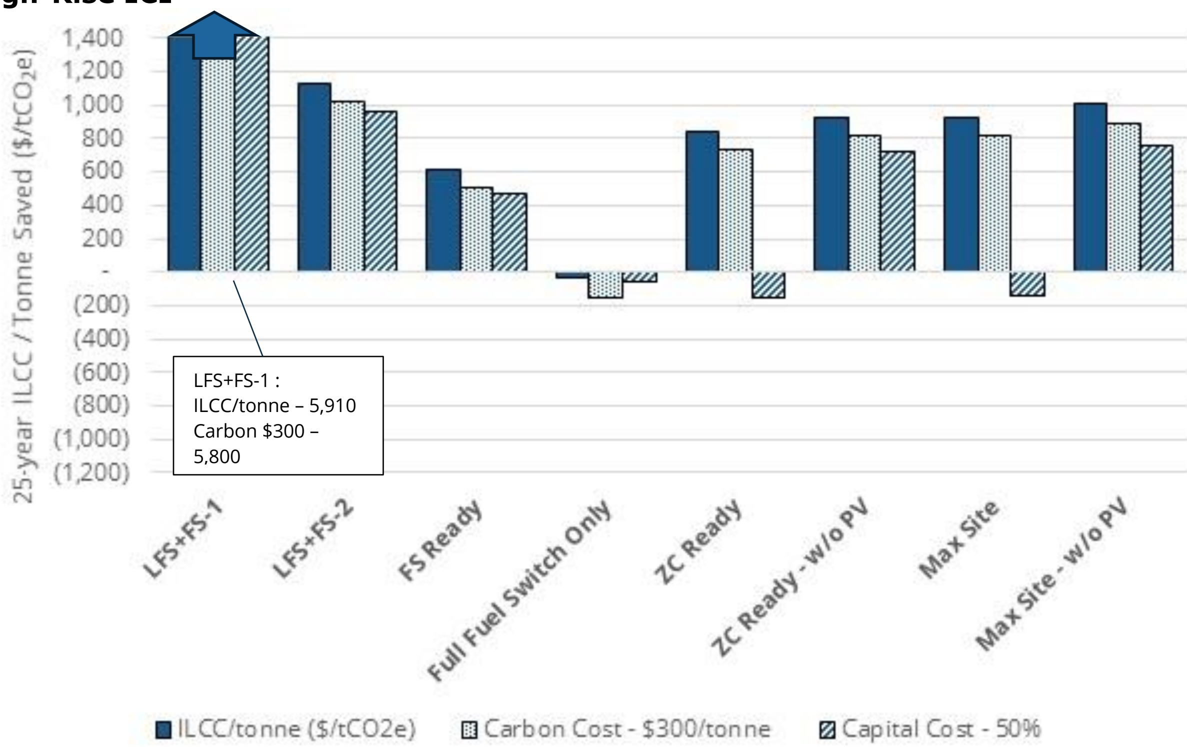


Figure 6: Large/High-Rise ICI Package 25-Year ILCC/Tonne Saved

Small/Low-Rise ICI

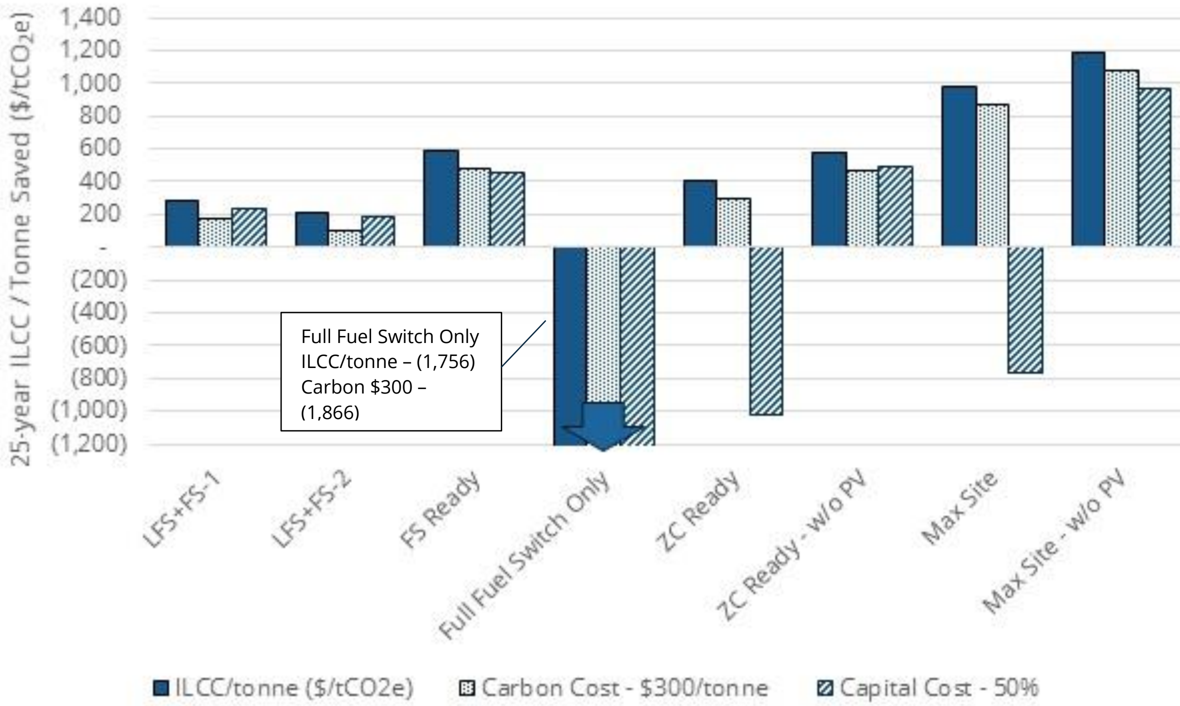


Figure 7: Small/Low-Rise ICI Package 25-Year ILCC/Tonne Saved

MURB

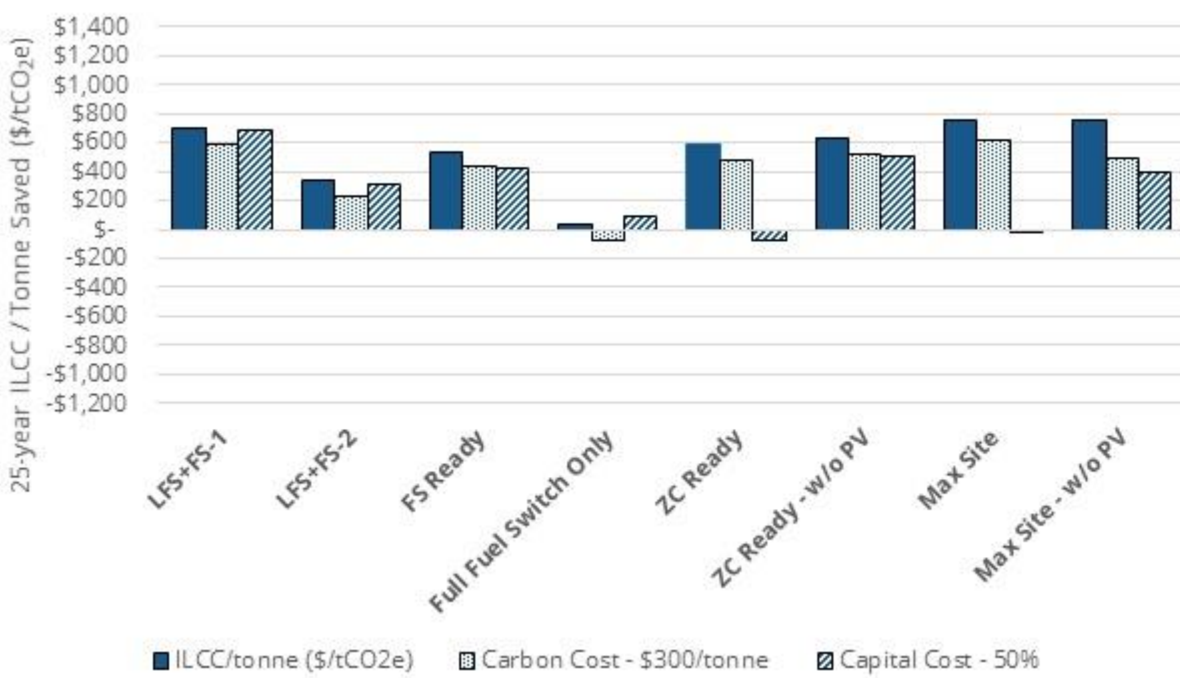


Figure 8: MURB Package 25-Year ILCC/Tonne Saved

SFH

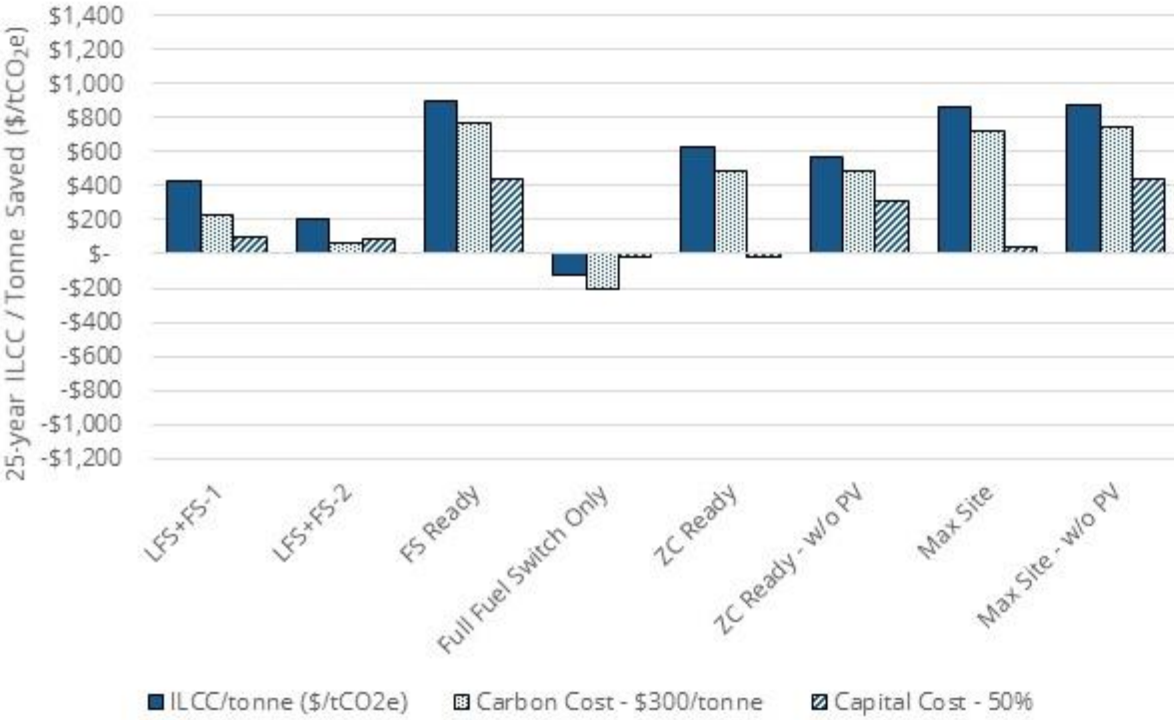


Figure 9: SFH Package 25-Year ILCC/Tonne Saved

1.1.11. MURB and SFH Comparative Results With/Without Embodied Impact Improvements.

Accumulated Embodied Emissions Impact

Biogenic building materials can provide meaningful carbon storage during lifespan of the building. In the embodied carbon analysis of focal clusters 12 (MURB) and 28 (SFHs), the best, average and worst embodied carbon for building materials in each of the packages was compared with the operational emissions of those packages over a 25-year lifecycle. As shown in the figure below, it is clear in the more aggressive packages there is a significant impact when considering the best case and average embodied emissions over worst embodied emissions in these residential sectors. Notably for the Zero Carbon Ready and Max Site packages, the figure shows when considering best case embodied emissions to typical case materials there is a significant benefit but only a minor impact in the Like for Similar package. Also, in the case of the FS Ready packages, the embodied carbon impact is marginal compared to the overall benefit of fuel switching. Comparing the FS Ready package to the Like-for-similar package life-cycle performance in the below figure also illustrates that overall fuel switching has a more significant benefit.

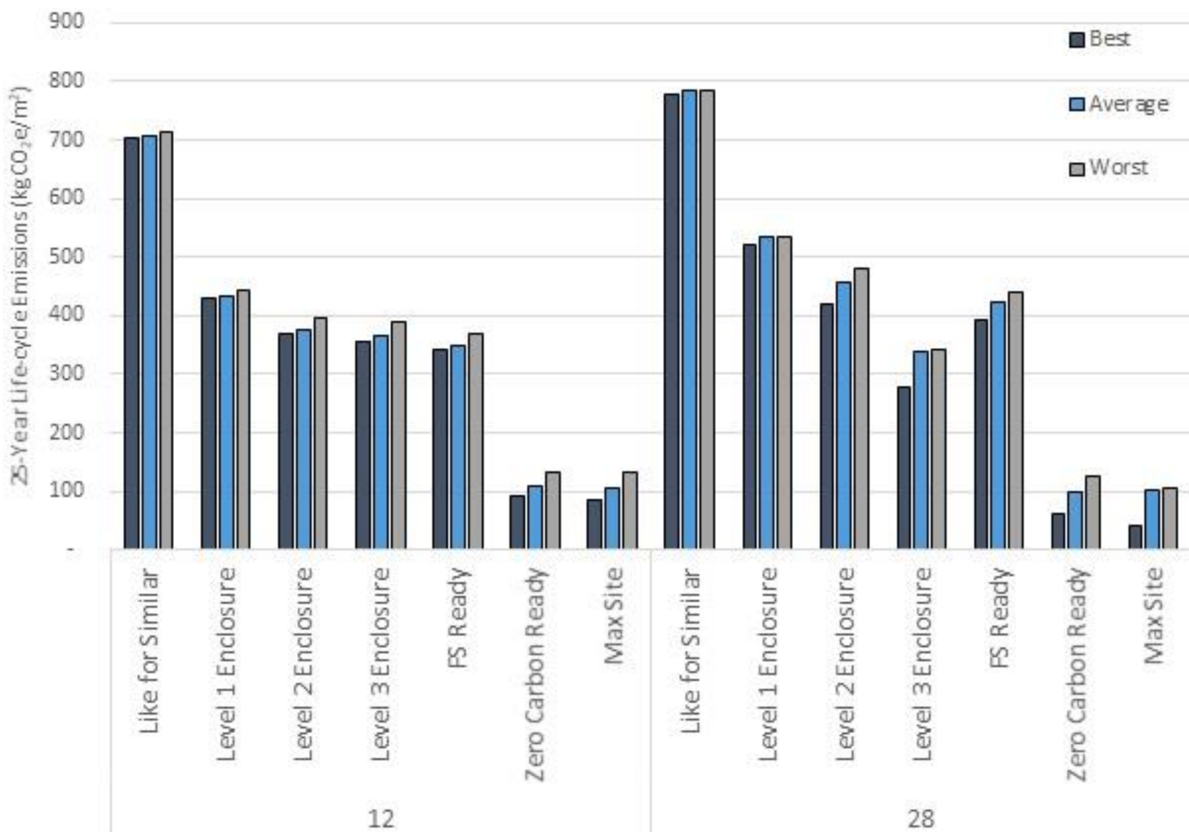


Figure 10: Embodied Carbon Emission Impact for Clusters 12 (MURB) & 28 (SFH)

The table below shows a detailed summary of embodied carbon results for the Like for Similar package compared to the two most aggressive packages for average, worst and best embodied carbon results. Notably for the Zero Carbon Ready and Max Site packages in SFHs, when considering best case embodied emissions to typical case materials, there is a significant benefit. For example, in Cluster 28, there is approximately a 40% and 60% reduction benefit, respectively and as well, there is only a minor improvement between average and worst-case embodied emissions in the Max Site package.

Table 22: LFS, ZCR and Max Site Embodied Carbon

Cluster	Package	Average EC $kgCO_2e/m^2$	Worst EC $kgCO_2e/m^2$	Best EC $kgCO_2e/m^2$
12 MURB	LFS	705	712	704
	ZCR	108	133	93
	Max Site	105	134	87
28 SFH	LFS	783	784	779
	ZCR	100	126	62
	Max Site	102	104	42

Further analysis into PV impact to the aggressive packages provided additional insight when considering embodied carbon as a storage pathway. As shown in the figure below for the SFH cluster 28, when considering the aggressive packages with best case embodied emissions compared to the same packages paired with PV, the impact is on the order of the PV benefit (or potential overall grid intensity improvements). Further, as in the Max Site package, consider both PV and best embodied materials results in life-cycle emissions of approximately 10 $kgCO_2e/m^2$. Therefore, "best-in-class" embodied reductions could be treated in a similar way to PV in SFHs in that these "best-in-class" can be part of the pathway to maximizing life-cycle emissions.

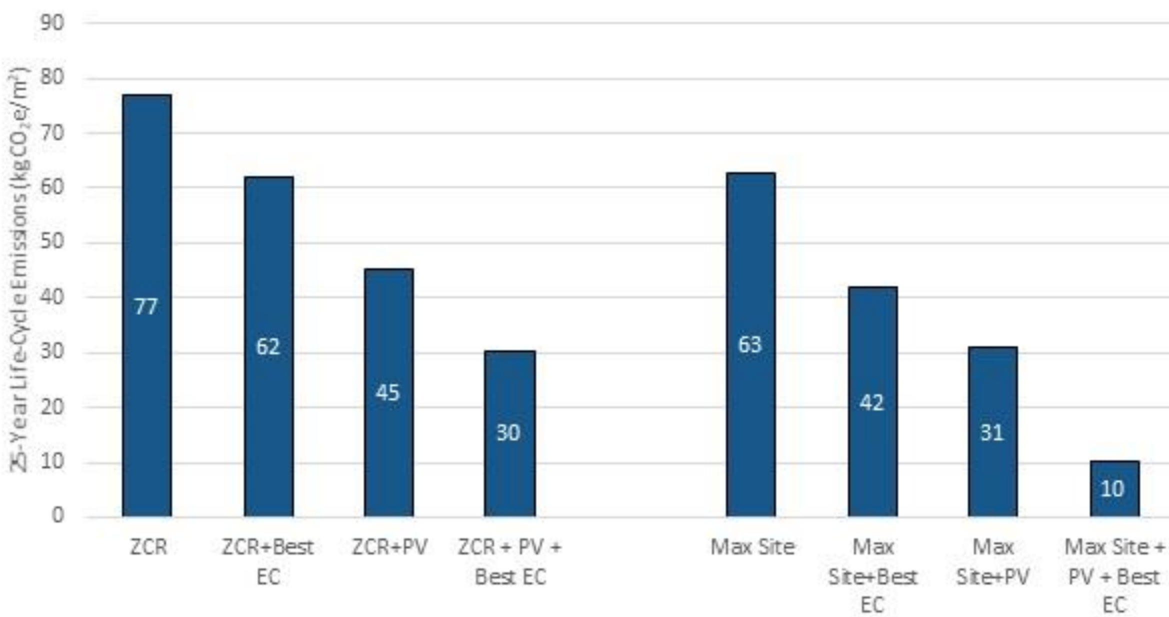


Figure 11: 25-Year Life-Cycle Emissions with Average and Best Embodied Carbon for Cluster 28 (SFH)

Overall, from a sectoral perspective, the greatest opportunities for embodied reductions are in the residential sectors (MURB and SFH). Comparing embodied emissions alone, considering "best-in-class" embodied carbon materials over lowest cost materials show a significant reduction in the MURB sector and the potential for net storage in the SFH sector. This opportunity in the SFH sector is the most significant compared to any other sector, mainly due to the potential to use bio-based materials instead of traditional construction materials (for more information refer to Table 10 and Table 13).

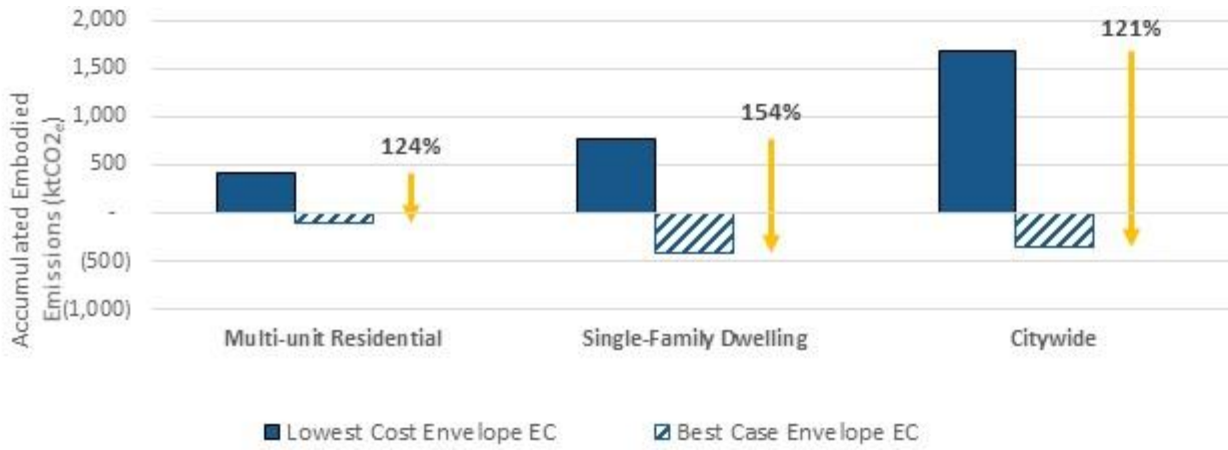


Figure 12: MURB and SFH Best Case Enclosure Material Embodied Emissions Impact

The impact to incremental life-cycle cost per tonne for incorporating Best EC materials is shown below. When considering Best EC materials, the change in ILLC/tonne is less than $75/tonne and in some cases, such as for the ZC Ready or Max Site packages in the SFH sector, the impact is relatively negligible (approximately a 3 to 8% decrease, this is due to in-part best-case enclosure materials being less expensive than traditional materials).

Table 23: ILCC/tonne Impact - MURB

Package	ILLC/tonne ($/tonne)	ILLC/tonne - Best ($/tonne)	% Difference
LFS+FS-1	$698	$698	-
LFS+FS-2	$337	$337	-
Full Fuel Switch Only	$37	$41	12%
FS Ready	$549	$591	8%
ZC Ready – w/o PV	$640	$656	3%
ZC Ready + PV	$591	$595	1%
Max Site – w/o PV	$770	$787	2%
Max Site + PV	$717	$748	4%

Table 24: ILCC/tonne Impact - SFH

Package	ILLC/tonne ($/tonne)	ILLC/tonne - Best ($/tonne))	% Difference
LFS+FS-1	$340	$412	21%
LFS+FS-2	$172	$198	15%
Full Fuel Switch Only	-$97	-$123	26%
FS Ready	$916	$866	**-5%**
ZC Ready – w/o PV	$611	$562	**-8%**
ZC Ready + PV	$591	$568	**-4%**
Max Site – w/o PV	$898	$849	**-6%**
Max Site + PV	$825	$803	**-3%**

2. CITY-SCALE - City-wide Impact Assessment

2.1.1. City Wide Assessment Assumptions

The City-scale analysis performed is meant to mimic (and, where possible, mirror) the process followed by the Net Zero team modeling process specific to the building sector. Coordination has occurred between the Net Zero modeling team, though not all of the assumptions summarized below have been reviewed/vetted between the two pieces of work.

2.1.2. Grid emissions

The chart below shows the grid emission factors used for each year from a period of 2016 to 2050. Exact values used in the study are provided in the below table.

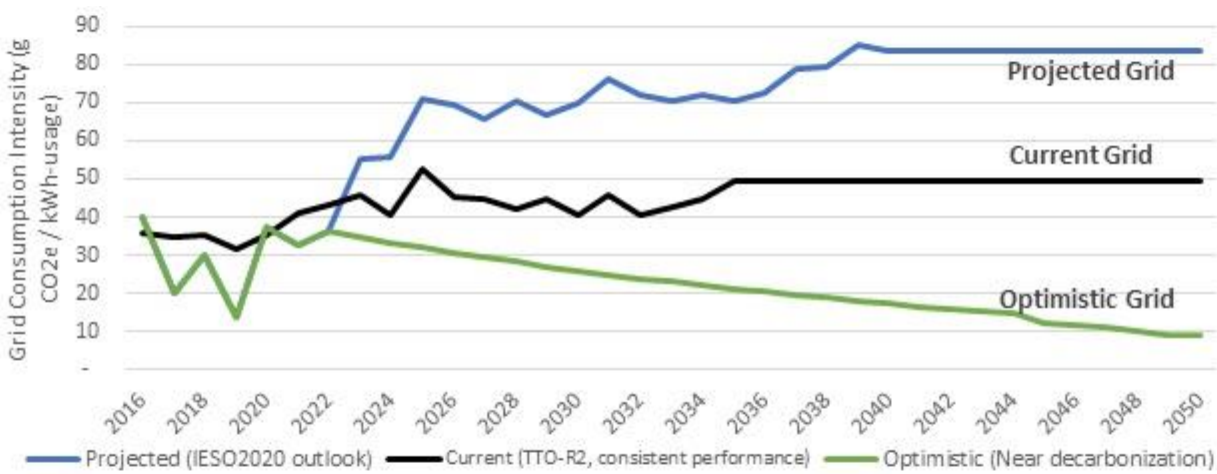


Figure 13: Grid Emission Factors

Table 25: Grid Emission Factors by Year

Scenario	2016	2017	2018	2019	2020					
Projected (IESO2020 outlook)	40	20	30	14	37					
Current (TTO-R2 outlook)	36	35	35	32	35					
Optimistic (Near decarbonization)	40	20	30	14	37					
	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Projected	33	36	55	56	71	69	66	70	67	70
Current	41	43	46	41	52	45	45	42	45	40
Optimistic	33	36	35	33	32	31	30	28	27	26
	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Projected	76	72	70	72	70	73	79	80	85	84
Current	46	41	43	45	49	50	50	50	50	50
Optimistic	25	24	23	22	21	20	20	19	18	17
	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Projected	84	84	84	84	84	84	84	84	84	84
Current	50	50	50	50	50	50	50	50	50	50
Optimistic	17	16	15	15	13	12	11	10	9	9

2.1.3. Natural Gas emissions

Projections for natural gas emissions considering a Clean Fuel Standard are shown below. The impact to natural gas emissions intensity is projected to start in 2023 and decrease until 2030 (and held constant after that to the end of the study period).

Table 26 Natural Gas Emissions Intensity Timeline consider Clean Fuel Standard ($gCO_2e/ekWh$)

2016	2023	2024	2025	2026	2027	2028	2029	2030
181	170	169	168	167	166	165	164	163

2.1.4. Impact of Climate Change

While the impacts of climate change can come in many forms, a key relevant impact to the City of Toronto in the context of this study is that of increasing temperatures. For the analysis, the Representative Concentration Pathway (RCP) 4.5 scenario was used to guide a high-level analysis of the impact of increasing temperatures to heating degree days and cooling degree days. This change to degree days was then used to estimate the impact to heating and cooling energy consumption at a high-level.

Table 27: Climate Change Impact to HDD and CDD

	Baseline	RCP4.5	% Change
Heating Degree Days (HDD)	3520	3169	-10%
Cooling Degree Days (CDD)	488	592	+21%

2.1.5. Financial Assumptions

The following tables summarize the construction escalation rate and the utility rates and associated escalation rates used in the analysis.

Table 28: Capital Cost Escalation Rate

Capital Costs	Escalation Rate
Construction Cost	2%

Table 29: Utility Rate Costs and Escalation Rate

Utilities	Cost ($/GJ)	Cost Source	Escalation Rate
Natural Gas (ICI/MURB)	$4.98	Enbridge Gas Rate 6 from https://www.enbridgegas.com/Understanding-gas-rates, accessed October 2, 2020.	2%
Electricity (ICI/MURB)	$40.65	Hydro Quebec "2020 Comparison of Electricity Prices in Major North American Cities – Medium Power" from https://www.hydroquebec.com/data/documents-donnees/pdf/comparison-electricity-prices.pdf, accessed October 2, 2020.	2%
Natural Gas (SFH)	$6.20	Enbridge Gas Rate 1 from https://www.enbridgegas.com/Understanding-gas-rates, accessed October 2, 2020.	2%
Electricity (SFH)	$31.72	Hydro Quebec "2020 Comparison of Electricity Prices in Major North American Cities – Residential" https://www.hydroquebec.com/data/documents-donnees/pdf/comparison-electricity-prices.pdf, accessed October 2, 2020.	2%

2.1.6. Cost of Carbon

The following table outlines the timeline for the cost of carbon used in the analysis. The cost of carbon timeline aligns with the November 2020 announcement by the federal government to escalate the carbon tax to $170/tonne to 2030 and was projected to stay flat until 2050. For the sensitivity scenario, the tax was estimated to increase by $15/tonne after 2030 each year to 2050.

Table 30: Cost of Carbon Timeline and Average Cost

	Cost of Carbon Timeline							Modelled Average Cost
	2020	2025	2030	2035	2040	2045	2050	
Current/Flat After 2030	$30	$95	$170	$170	$170	$170	$170	$150
Escalated After 2030	$30	$95	$170	$245	$320	$395	$470	$300

3. Emissions Reduction Scenarios

3.1.1. Business-As-Planned (BAP) Scenario

This scenario represents a minimum action scenario for reducing existing buildings and new construction emissions. Features of this scenario include:

- Like-for-similar for all existing buildings
- New construction follows TGS v3

The final existing building stock package mix in 2050 is shown below:

Table 31: BAP Final Existing Building Package Mix in 2050

	Sector	Pathway	Final Building Stock Uptake
Existing	Large/High-Rise ICI	LFS only	100%
	Small/Low-Rise ICI	LFS only	100%
	MURB	LFS only	100%
	SFH	LFS only	100%

New construction growth was modelled by the following:

Table 32: BAP New Build Performance Assumptions

	Sector	New Build Performance Assumption[3,4]
New Build	Large/High-Rise ICI	TGS v3 T1/T2 until 2021 TGS v3 T3 after 2021 until 2027 TGS v3 T4 after 2027
	Small/Low-Rise ICI	
	MURB	
	SFH	TGS Low-Rise Residential (LRR) v3 T2 until 2022 LRR v3 T3 after 2022 until 2027 LRR v3 T4 after 2027

3.1.2. Least-Capital Scenario

This scenario represents a least-cost scenario for reducing existing buildings and new

[3] For ICI and MURB: https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/toronto-green-standard/toronto-green-standard-version-3/mid-to-high-rise-residential-all-non-residential-version-3/energy-ghg-resilience-for-mid-to-high-rise-residential-all-non-residential-development/

[4] For SFH: https://www.toronto.ca/city-government/planning-development/official-plan-guidelines/toronto-green-standard/toronto-green-standard-version-3/low-rise-residential-version-3/energy-ghg-resilience-for-low-rise-residential-development/

construction emissions. Features of this bounding scenario include:

- Fuel switching (LFS - FS-1 + FS-2, Full Fuel Switch only) for existing buildings
- 100% of buildings by 2050
- Two phases of construction for LFS - FS-1 + FS-2, i.e. LFS + FS-1 => LFS – FS-1 + FS-2
- New construction follows TGS v3 with fuel-switching starting 2035 for T1/2
- New construction promotes PV

The final existing building stock package mix in 2050 is shown below:

Table 33: Least-Capital Final Existing Building Package Mix in 2050

	Sector	Pathway	Final Building Stock Uptake
Existing	Large/High-Rise ICI	LFS - FS-1 + FS-2	50%
		Full Fuel Switch only	50%
	Small/Low-Rise ICI	LFS - FS-1 + FS-2	50%
		Full Fuel Switch only	50%
	MURB	LFS - FS-1 + FS-2	50%
		Full Fuel Switch only	50%
	SFH	LFS - FS-1 + FS-2	50%
		Full Fuel Switch only	50%

New construction growth was modelled by the following. Note that PV has been shown separately but is not an exclusive action (i.e. % represents uptake across the entire stock, not % undertaking PV only)

Table 34: Least-Capital New Build Performance Assumptions

<table>
<tr><th></th><th>Sector</th><th>New Build Performance Assumption</th></tr>
<tr><td rowspan="4">New Build</td><td>Large/High-Rise ICI</td><td rowspan="3">TGS v3 T1/T2 until 2021 with full fuel switch after 2035
TGS v3 T3 after 2021 until 2027
TGS v3 T4 after 2027
75% PV</td></tr>
<tr><td>Small/Low-Rise ICI</td></tr>
<tr><td>MURB</td></tr>
<tr><td>SFH</td><td>LRR v3 T2 until 2022
LRR v3 T3 after 2022 until 2027
LRR v3 T4 after 2027
75% PV</td></tr>
</table>

3.1.3. Aggressive Scenario

This scenario represents a maximum investment and reduction scenario for reducing existing buildings and new construction emissions. Features of this bounding scenario include:

- Fuel Switch Ready and Zero Carbon Ready packages for existing buildings (no fuel-switch only)

- PV is promoted
- 100% of buildings by 2040
- Two phases of construction for FSR (i.e. FSR=>ZCR)
- New construction follows TGS v3 with fuel-switching starting 2035 for T1/2
- New construction promotes PV

The final existing building stock package mix in 2050 is shown below.

Table 35: Aggressive Final Existing Building Package Mix in 2050

	Sector	Pathway	Final Building Stock Uptake
Existing	Large/High-Rise ICI	FSR to ZCR	50%
		ZCR	50%
		PV	75%
	Small/Low-Rise ICI	FSR to ZCR	50%
		ZCR	50%
		PV	75%
	MURB	FSR to ZCR	50%
		ZCR	50%
		PV	75%
	SFH	FSR to ZCR	50%
		ZCR	50%
		PV	75%

New construction growth was modelled by the following:

Table 36: Aggressive New Build Performance Assumptions

	Sector	New Build Performance Assumption
New Build	Large/High-Rise ICI Small/Low-Rise ICI MURB	TGS v3 T1/T2 until 2021 with full fuel switch after 2035 TGS v3 T3 after 2021 until 2027 TGS v3 T4 after 2027 75% PV
	SFH	LRR v3 T2 until 2022 LRR v3 T3 after 2022 until 2027 LRR v3 T4 after 2027 75% PV

3.1.4. Prototype Recommended Scenario

This scenario is the recommended scenario for reducing existing buildings and new construction emissions. Features of the recommendation include:

- Breadth of options narrows over time
- Require at least like-for-similar improvements in enclosure in all older facilities
- PV is promoted

This scenario includes sector specific considerations for package rollout in existing stock:

- SFH: Slowest acceleration with full fuel switch only in newer sites
- MURBs: Deepest acceleration with full fuel switch only in newer sites
- Small ICI: Focus on fuel switching and PV
- Large ICI: Fast acceleration and deep investment
- Institutional: Fastest acceleration

The final existing building stock package mix in 2050 is shown below. Note that PV has been shown separately but is not an exclusive action (i.e. final % represents uptake across the entire stock, not % undertaking PV only)

Table 37: Prototype Recommended Final Existing Building Package Mix in 2050

	Sector	Pathway	Final Building Stock Uptake
Existing	Large/High-Rise ICI	FSR to ZCR	31%
		ZCR	37%
		LFS+FS-2	32%
		PV	60%
	Small/Low-Rise ICI	FSR to ZCR	11%
		ZCR	26%
		LFS+FS-2	34%
		FS-2	27%
		Max Site	2%
		PV	80%
	MURB (Mid/Old)	LFS - FS-1 + FS-2	15%
		FSR to ZCR	15%
		ZCR	43%
		LFS+FS-2	25%
		Max Site	2%
		PV	80%
	MURB (Newer)	FS-2	100%
		PV	80%
	SFH (Mid/Old)	LFS to FS-2	1%
		LFS - FS-1 + FS-2	6%

	Sector	Pathway	Final Building Stock Uptake
		FSR to ZCR	15.5%
		ZCR	37.5%
		LFS+FS-2	37.5%
		Max Site	2.5%
		PV	60%
	SFH (Newer)	FS-2	100%
		PV	60%

New construction growth was modelled by the following:

Table 38: Prototype Recommended New Building Performance Assumptions

	Sector	New Build Performance Assumption
New Build	Large/High-Rise ICI Small/Low-Rise ICI MURB	TGS v3 T1/T2 until 2021 with full fuel switch after 2035 TGS v3 T3 after 2021 until 2027 TGS v3 T4 after 2027 75% PV
	SFH	LRR v3 T2 until 2022 LRR v3 T3 after 2022 until 2027 LRR v3 T4 after 2027 75% PV

The following table provides the approximate number of buildings organized by decade and sector and the rollout of retrofit packages for each net zero pathway explored. For staged pathways, buildings counts shown below in the second package row represent that buildings which have completed the first package will complete the second package step (e.g. in small/low-rise ICI, 978 buildings, which have already completed a FS Ready package, will complete a Zero Carbon Ready package). The first summary row at the bottom of the table shows the total number of buildings that will have completed either the first action (FS Ready or LFS/LFS+FS1) or completed a direct pathway. The second summary row at the bottom of the table shows the total number of buildings undergoing a retrofit action within that decade.

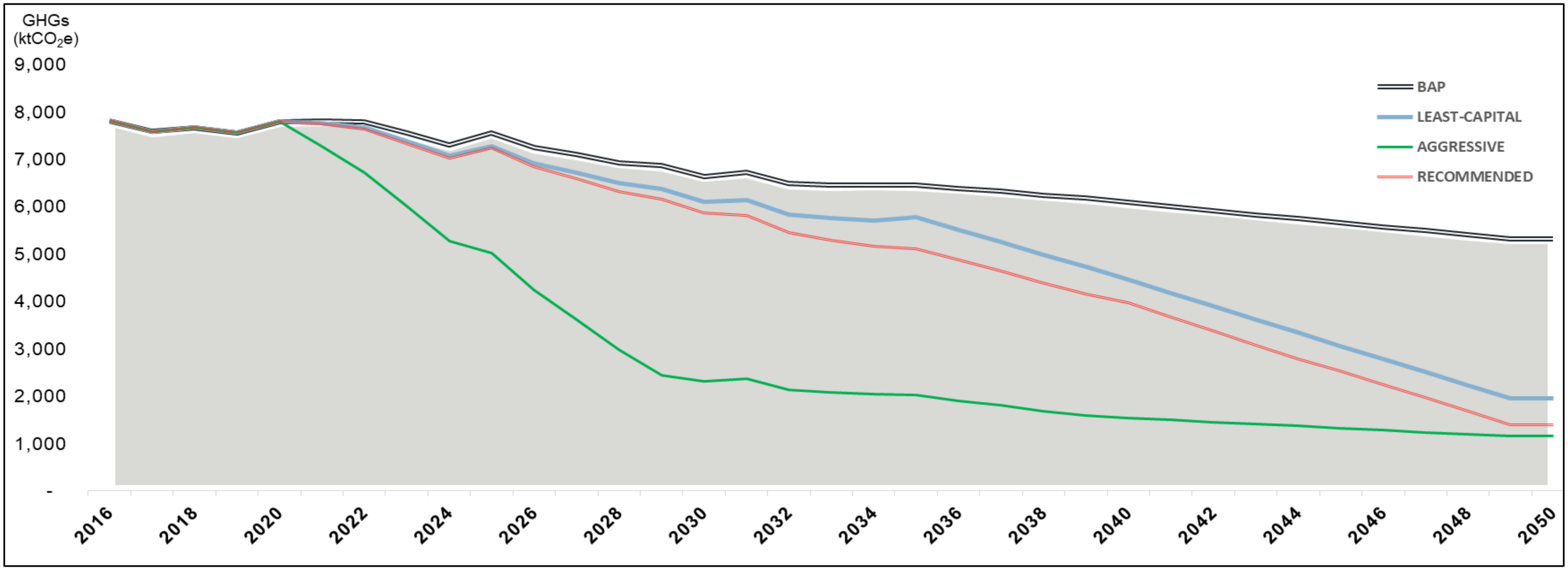
Table 39: Summary of Approximate Number of Building Undertaking Retrofit Actions in Recommended Scenario (by decade)

Pathway	Large/High-Rise ICI 1,267 total bldgs.				Small/Low-Rise ICI 32,591 total bldgs..				MURB 6,162 total bldgs.				SFH 436,117 total bldgs.			
	2020-2030	**2030-2040**	**2040-2050**	**Total No. Bldgs Taking Pathway**	**2020-2030**	**2030-2040**	**2040-2050**	**Total No. Bldgs Taking Pathway**	**2020-2030**	**2030-2040**	**2040-2050**	**Total No. Bldgs Taking Pathway**	**2020-2030**	**2030-2040**	**2040-2050**	**Total No. Bldgs Taking Pathway**
LFS	-	-	-		-	-	-		-	-	-		3,579	-	-	
LFS+FS1	-	-	-	**-**	-	-	-	**-**	511	256	-	**767**	21,476	-	-	**25,055**
LFS-FS1+FS2	-	-	-		-	-	-		-	256	511		-	-	25,055	
FS Ready	266	133	-	**400**	2,281	1,304	-	**3,585**	511	256	-	**767**	12,527	42,951	-	**55,479**
FS Ready to ZCR	-	252	147		-	978	2,607		-	256	511		-	-	55,479	
Zero Carbon Ready	112	204	155	**472**	2,281	2,933	3,259	**8,474**	341	733	1,124	**2,198**	12,527	50,110	71,586	**134,223**
LFS+FS2	103	170	122	**396**	2,607	3,911	4,563	**11,081**	691	776	861	**2,329**	38,590	76,173	97,649	**212,412**
FS2 Only	-	-	-	**-**	1,955	2,933	3,911	**8,800**	-	-	-	**-**	-	-	-	**-**
Max Site	-	-	-	**-**	-	-	652	**652**	-	-	102	**102**	-	3,579	5,369	**8,948**
No. Bldgs. - 1st Action or Direct Pathway	482	508	277	**1,267**	9,125	11,081	12,385	**32,591**	2,054	2,020	2,088	**6,162**	88,700	172,813	174,603	**436,117**

Total No. of Retrofits	482	760	424	**1,667**	9,125	12,059	14,992	**36,176**	2,054	2,531	3,110	**7,695**	88,700	172,813	255,137	**516,651**

3.1.5. Overall Reduction Results By Scenario

The overall results over the study period for each scenario are shown in the figure below (using the Current Grid emission factors) along with total emission, cumulative emissions and per capita emissions.



	KEY METRICS		BAP	LEAST-CAPITAL	AGGRESSIVE	RECOMMENDED
CARBON	2050 Emissions	$ktCO_2e$	5320	1940	1150	1400
	2050 Emissions vs. 2016	%	-32%	-75%	-85%	-82%
	Cumulative Emissions	$ktCO_2e$	200,520	161,090	85,840	149,390
	Cumulative Emissions Reduction (vs. BAP)	%	-	-20%	-57%	-25%
	2050 Per Capita Emissions	$ktCO_2e$ /person	0.52	0.19	0.11	0.14

Figure 14: Overall Results by Scenario and Summary of Emissions Metrics

4. City-wide Results

4.1.1. Overall 2050 and Accumulated Results

Overall 2050 Emissions Results for Prototype Recommended Scenario - By Major Sector

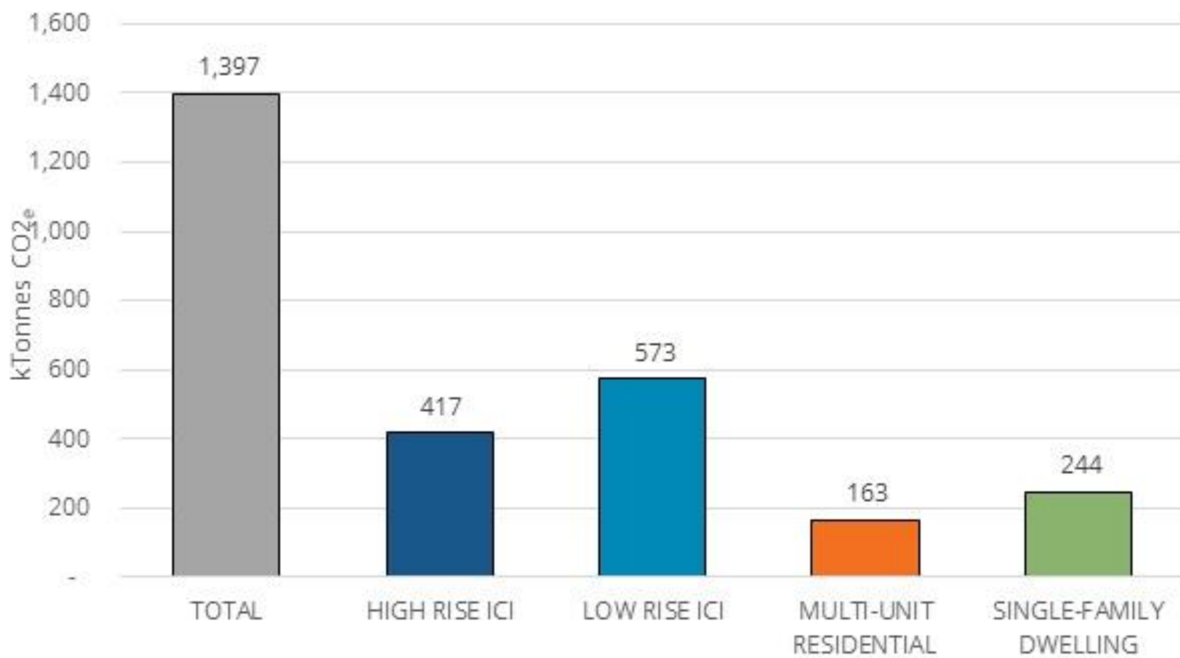


Figure 15: Prototype Recommended Scenario Total Emissions in 2050 by Sector

Overall Accumulated Emission Results for Recommended Scenario - By Major Sector

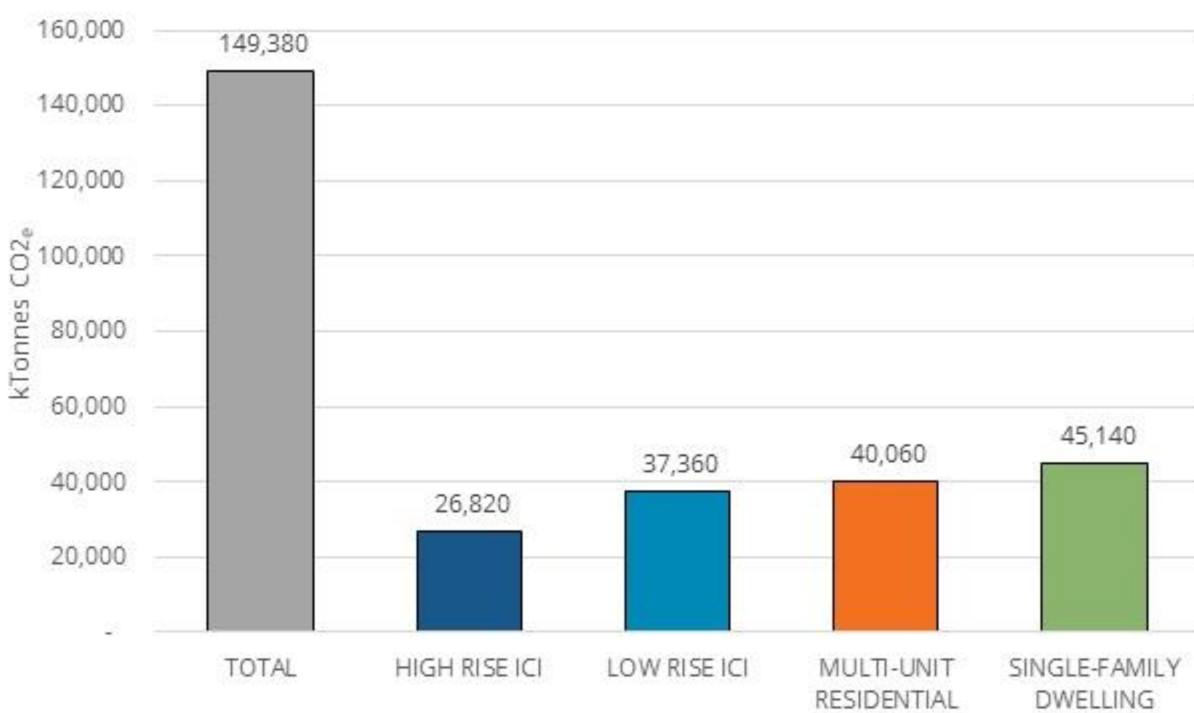


Figure 16: Prototype Recommended Scenario Accumulated Emissions by 2050 by Sector

Overall 2050 Emissions Results –Citywide and By Major Sector by Scenario

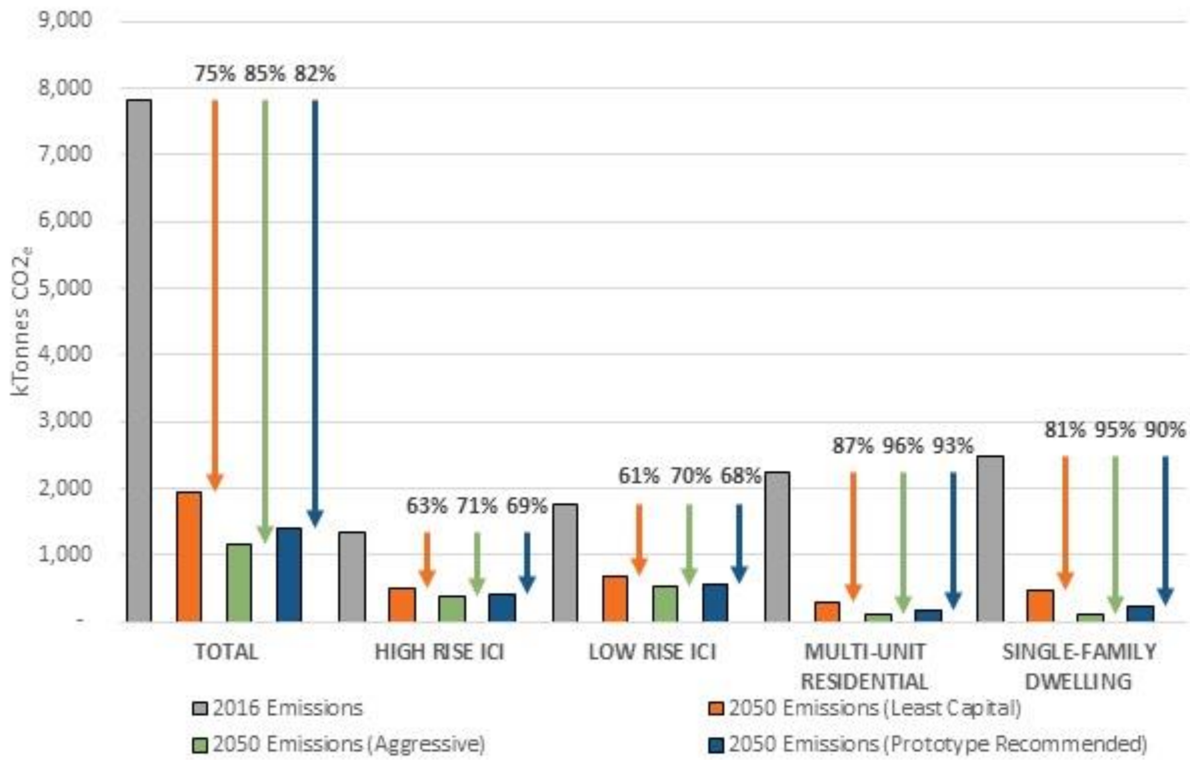


Figure 17: Total Emissions in 2050 by Scenario

Overall Accumulated Results – Citywide by Scenario

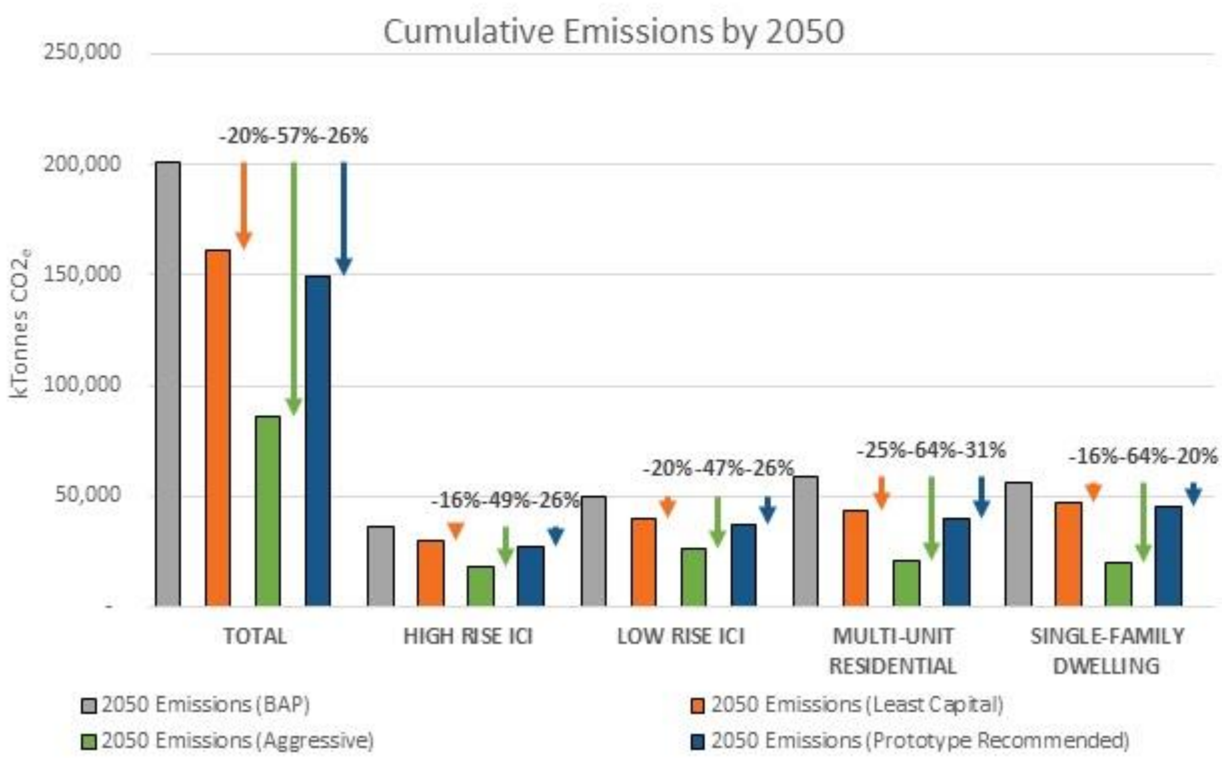


Figure 18: Accumulated Emissions by 2050 by Scenario

Scenario Sensitivity Analysis to Grid Emissions by Scenario

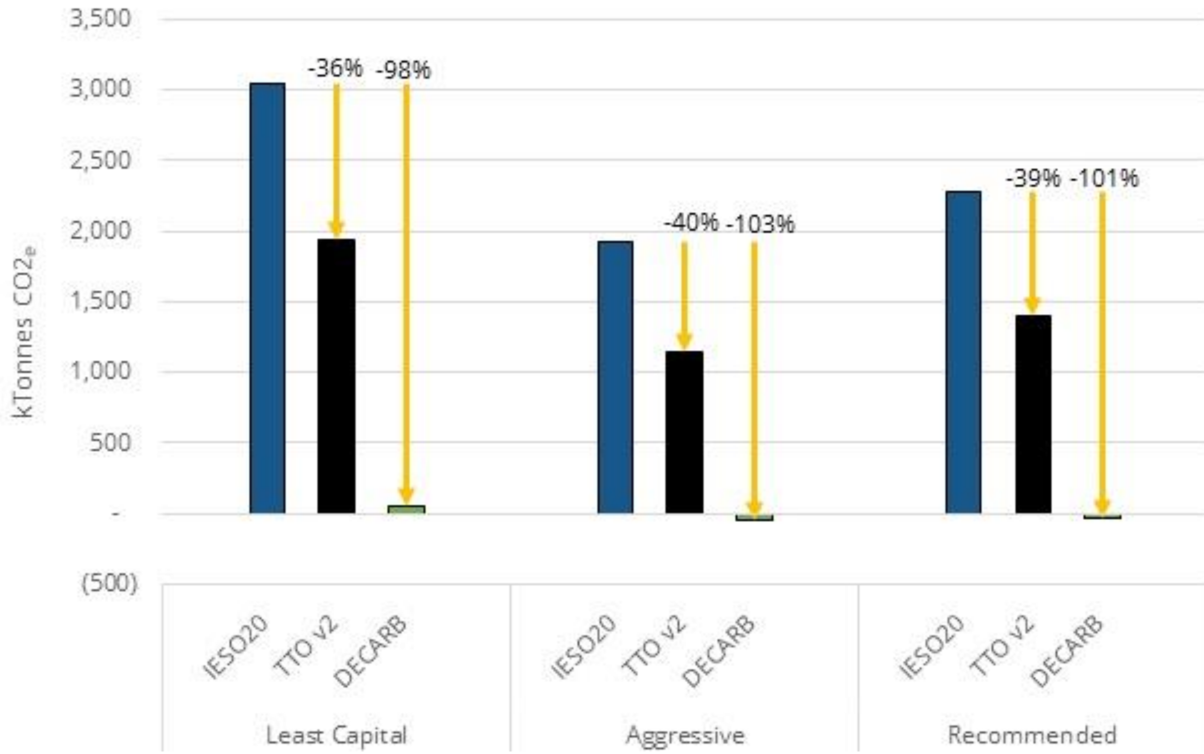


Figure 19: Sensitivity of Total Emissions in 2050 by Scenario to Grid Emissions

Results with Scope 3 Emissions

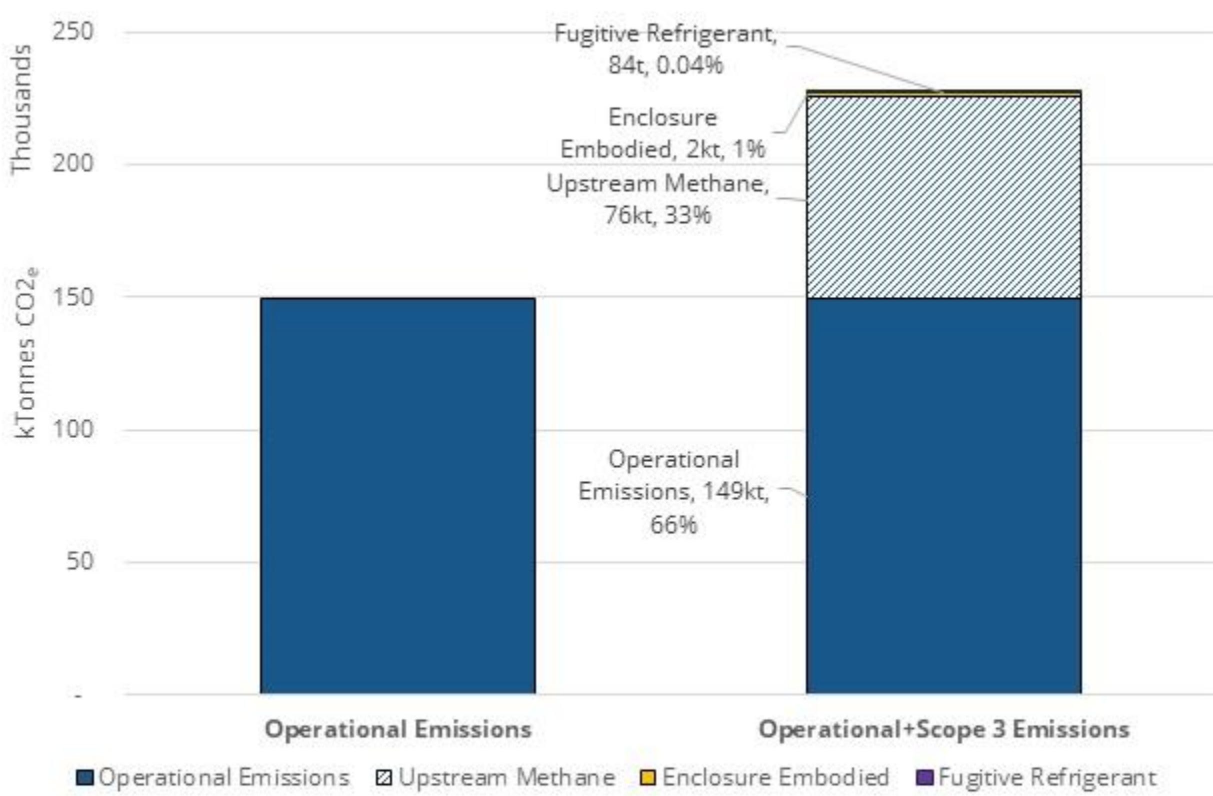


Figure 20: Cumulative Emissions with Operational and Scope 3 Emissions

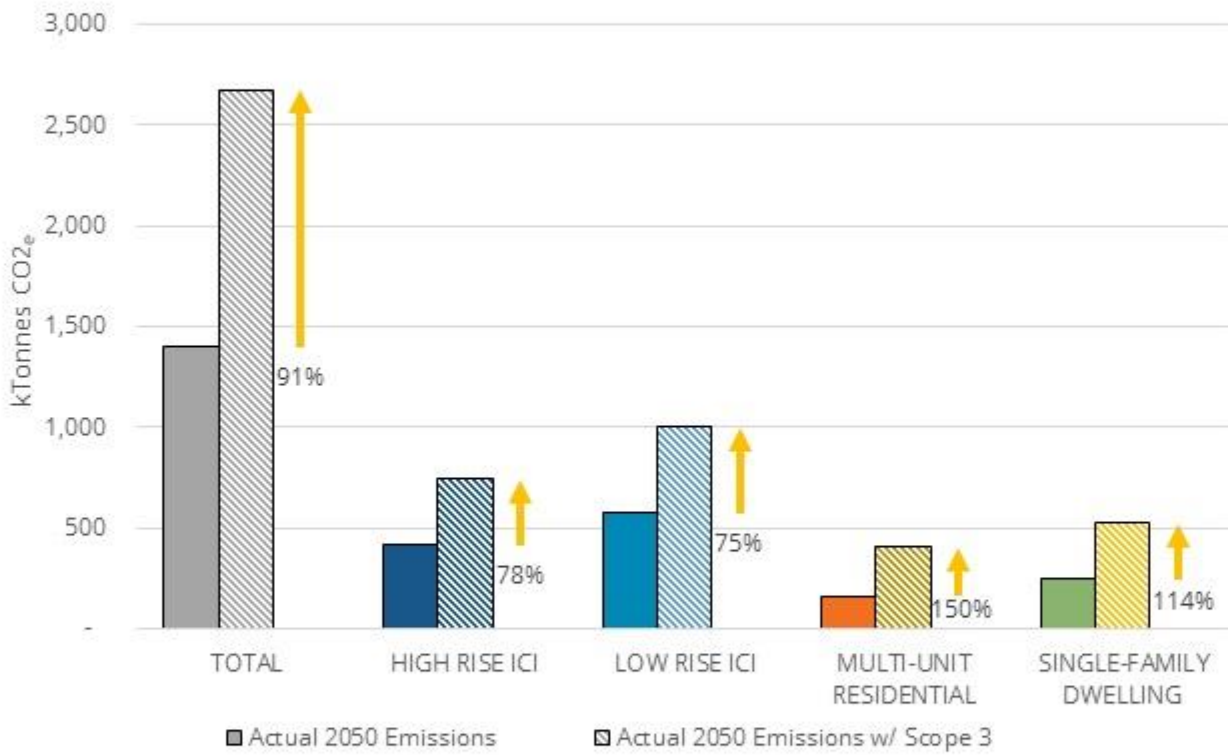


Figure 21: Total Emissions in 2050 for Prototype Recommended Scenario including Scope 3 Methane Emissions

4.1.2. Micro-Economic Results

Overall capital cost

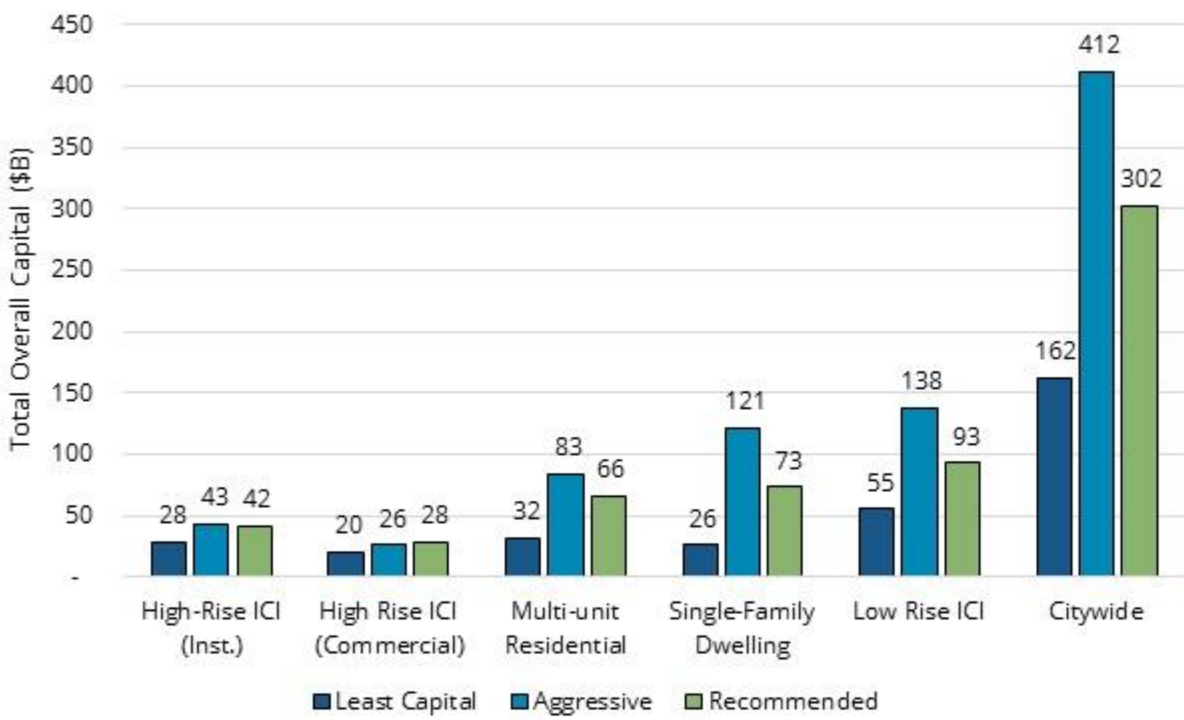


Figure 22: Overall Capital Costs by Scenario

Energy Cost Savings

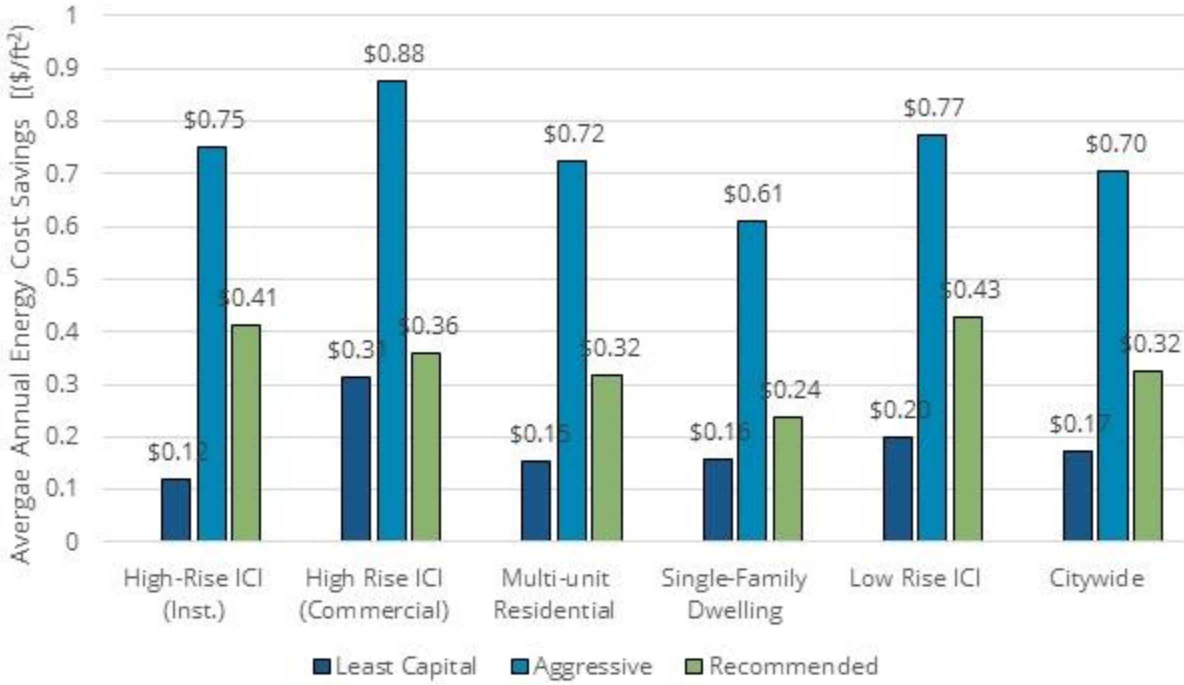


Figure 23: Average Annual Energy Cost Savings per Area by Scenario

Total Cost Of Ownership

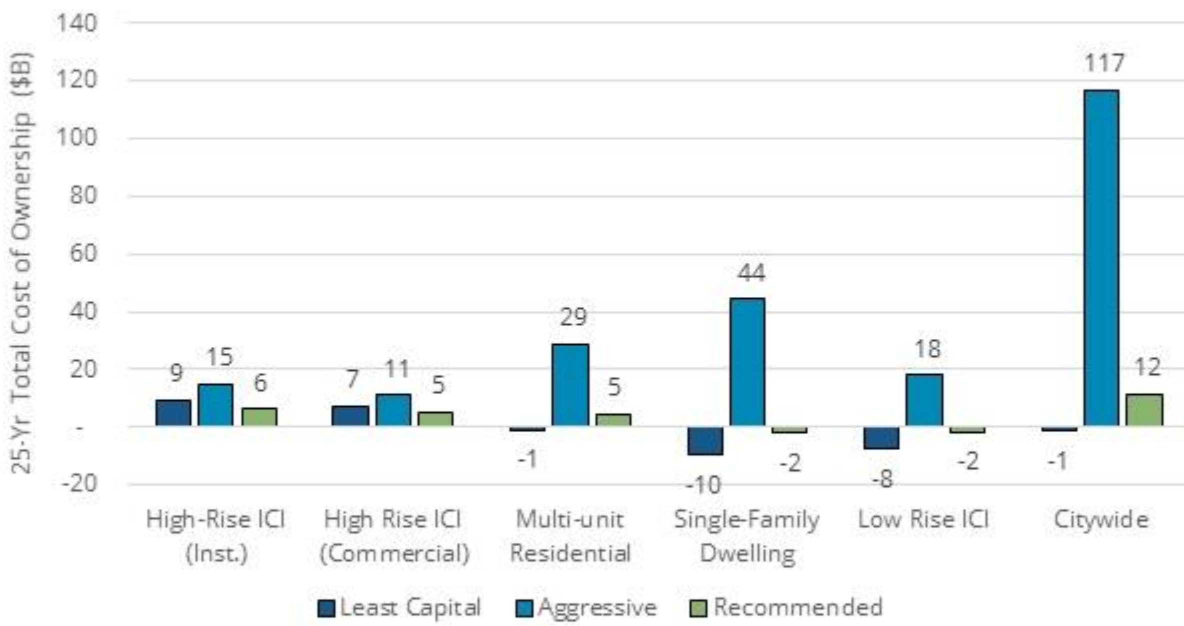


Figure 24: Sectoral 25-Year Cost of Ownership by Scenario

MAC Results – Overall Results and Results by Sector

Marginal Abatement Cost Curves (MACCs) results for each sector in the Recommended scenario are shown below. These curves show the savings in accumulated emissions across the sector on the x-axis and the 25-year incremental TCO/tonne for each pathway/package combination on the y-axis. From an owner's perspective, one package may be better than another; as such, the recommended scenario assumes significant diversity in the pathways to zero that will be selected or promoted. The average incremental TCO/tonne for the entire sector is shown as an overlay in each graph (i.e. the average incremental TCO/tonne of the packages implemented in the sector).

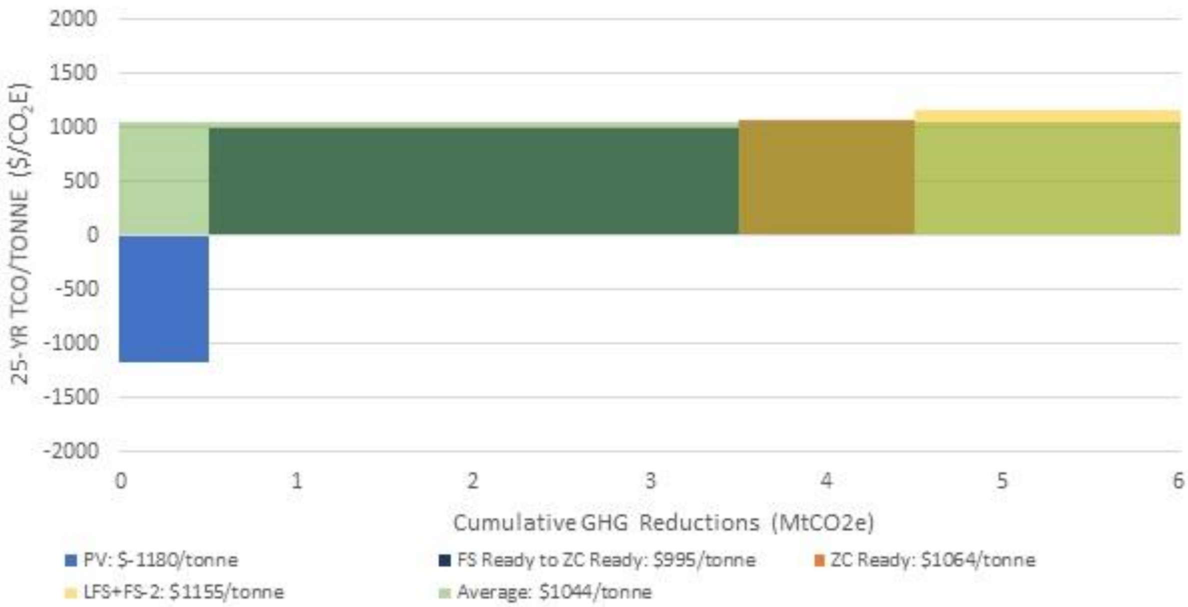


Figure 25: Sectoral MACC by Package for Large/High-rise Commercial

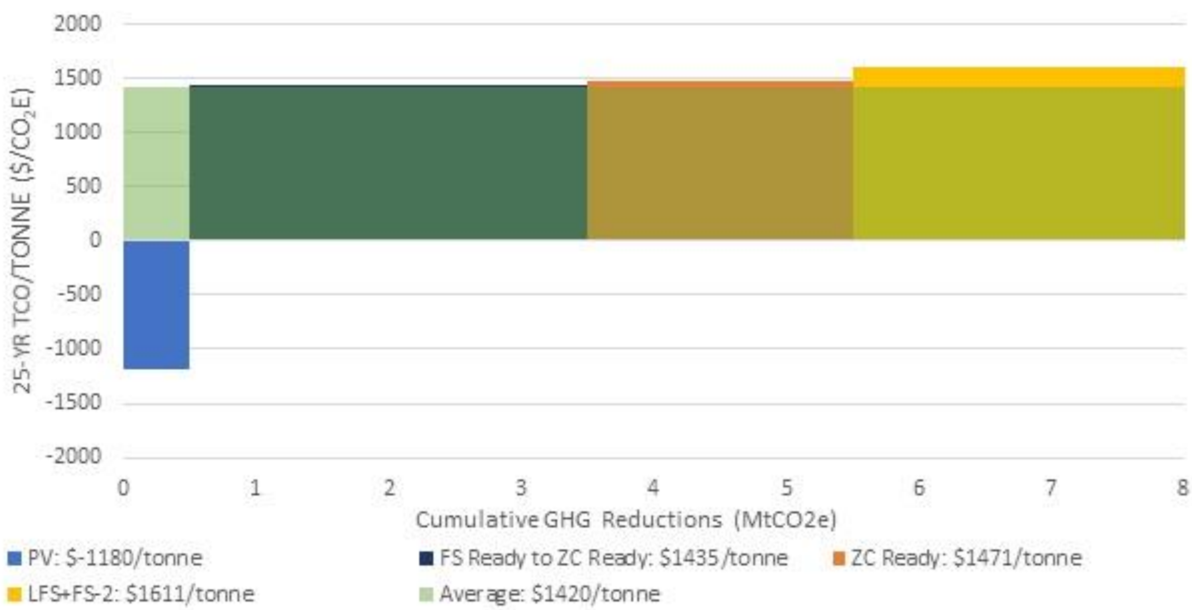


Figure 26: Sectoral MACC by Package for Institutional

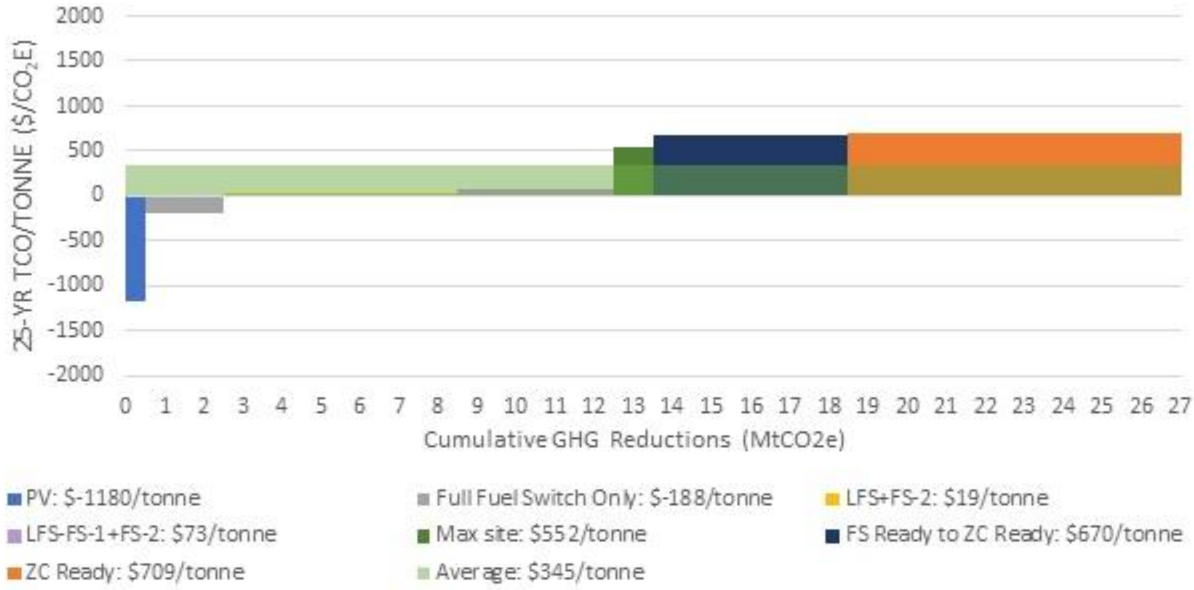


Figure 27: Sectoral MACC by Package for MURB

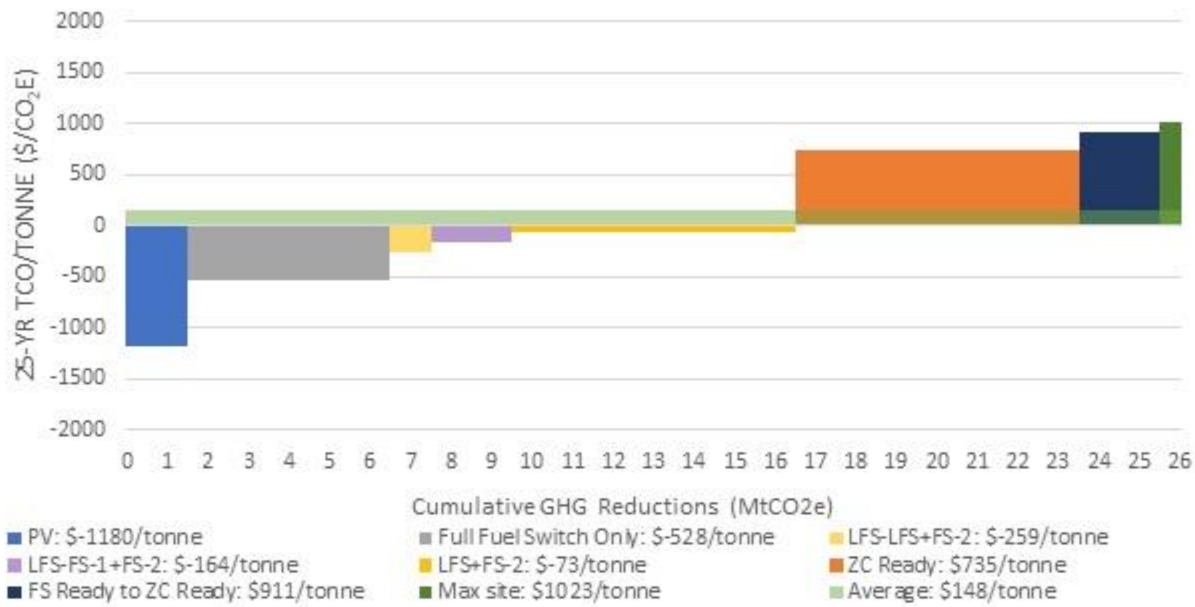


Figure 28: Sectoral MACC by Package for SFH

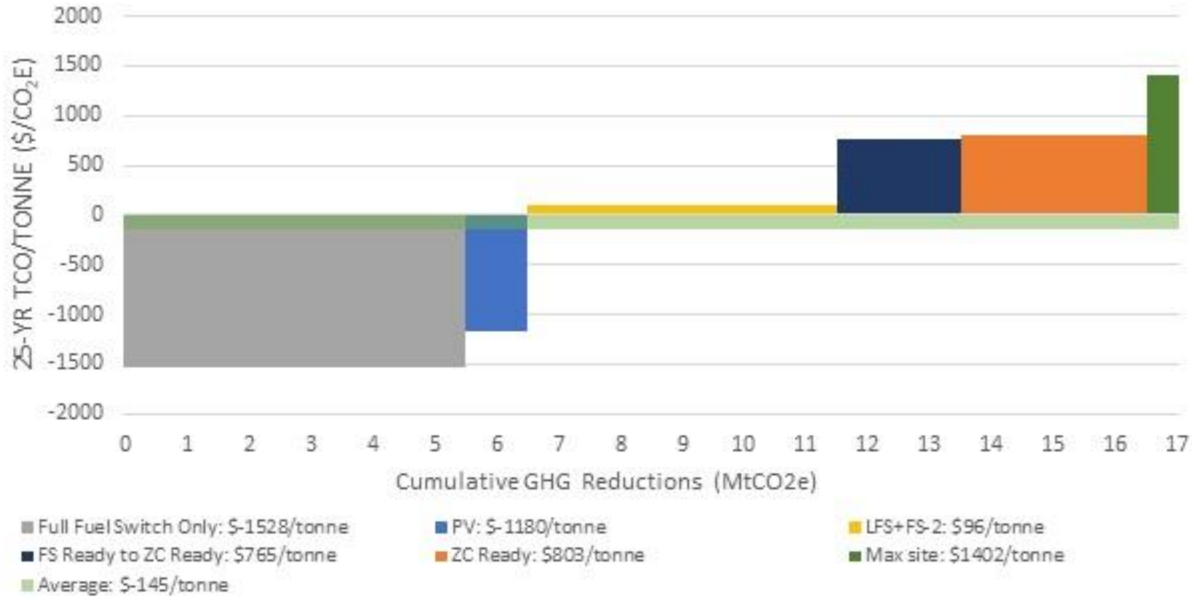


Figure 29: Sectoral MACC by Package for Low-Rise ICI

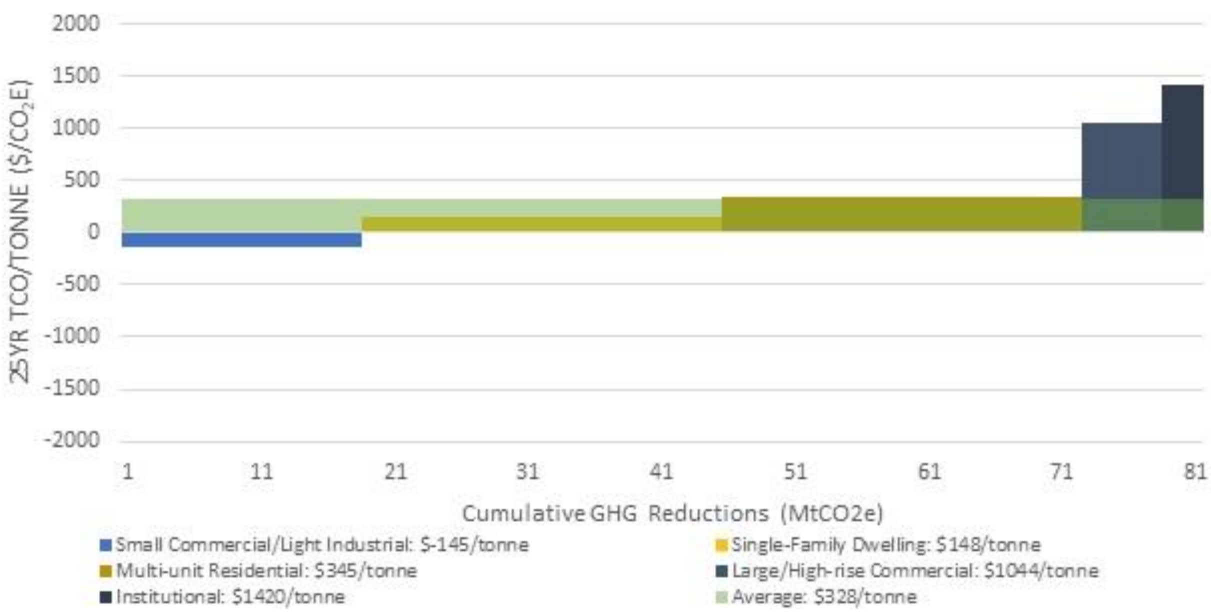


Figure 30: Overall Recommendation 25 Year Total Cost of Ownership by Sector

Sensitivity Analysis to Capital and Cost of Carbon
A sensitivity analysis of the average incremental TCO/tonne was conducted for the Recommended scenario for 50% capital cost and an average cost of carbon of $300/tonne. Notably, the SFH sector switches to a net savings incremental TCO/tonne in both a cost reduction and cost of carbon escalation scenario.

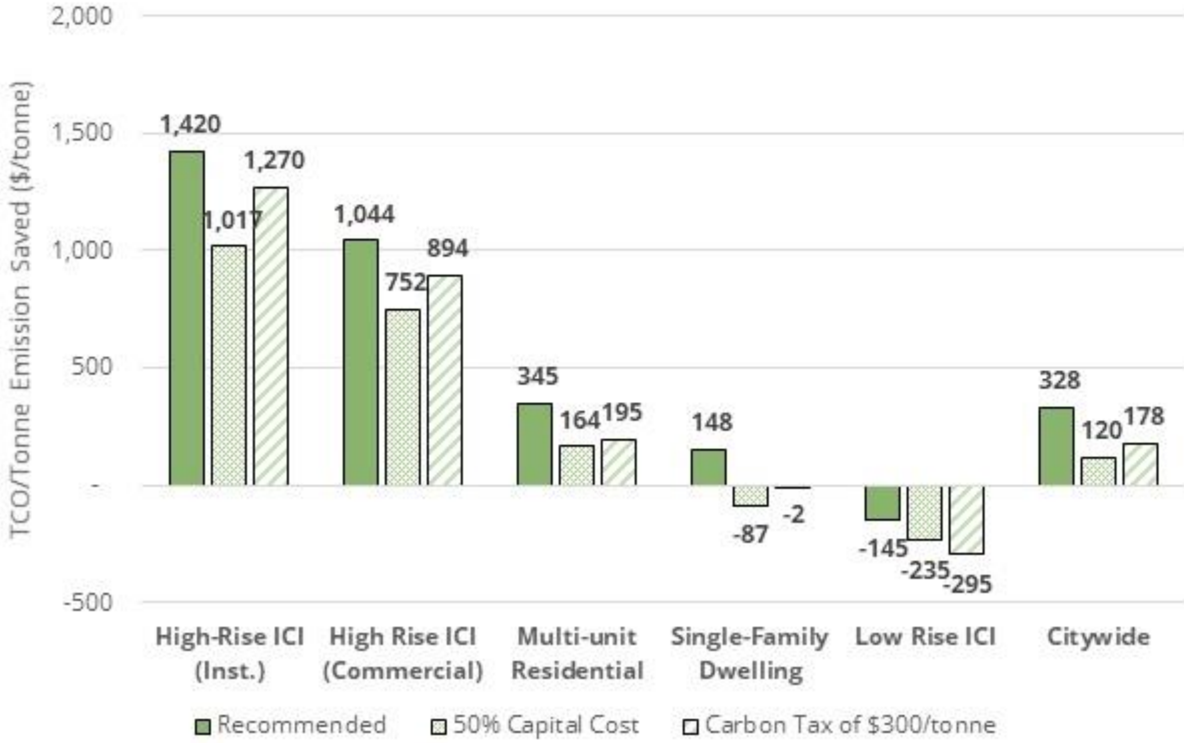


Figure 31: TCO/Tonne Sensitivity Analysis

4.1.3. Macro-economic results

Overall total economic activity

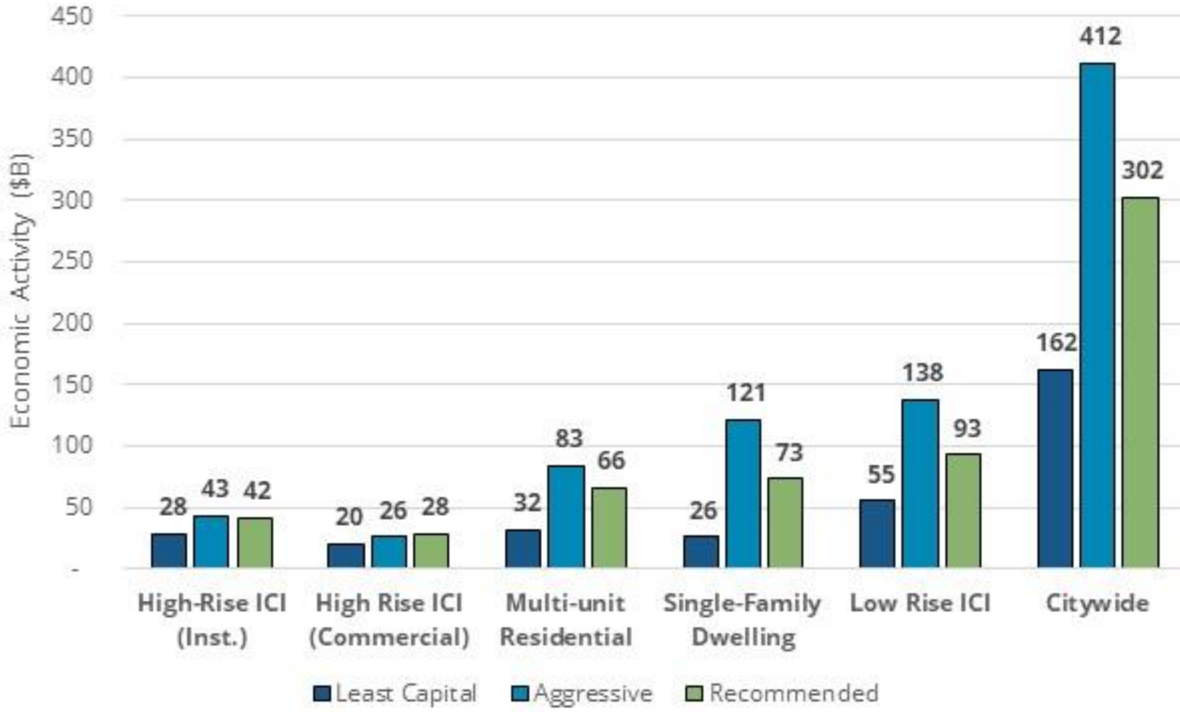


Figure 32: Total Economic Activity by Scenario

Retrofit-Related Job Hours & Estimated Number Of Full-Time Jobs Created

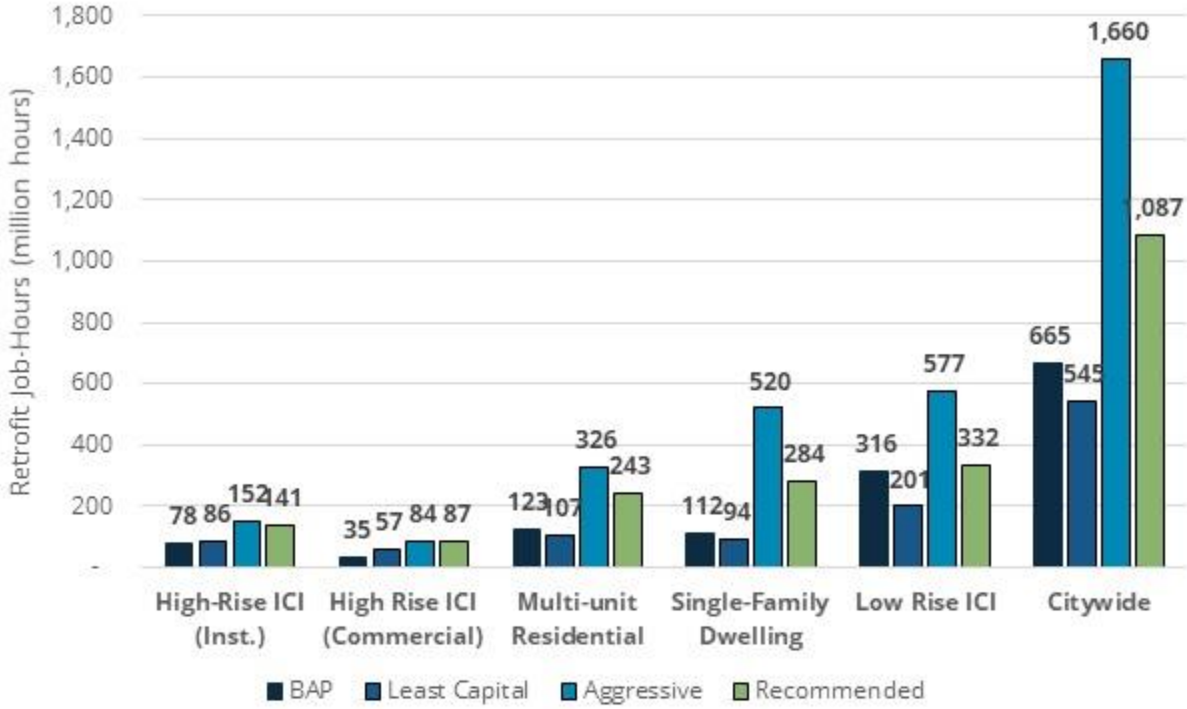


Figure 33: Retrofit-Related Job Hours Created by Sector and Citywide

Table 40: Retrofit-related Job Hours and Estimated Number of Full Time Jobs

Scenario	BAP	LEAST-CAPITAL	AGGRESSIVE	Recommended
Retrofit Related Job-Hours	665 million job-hours	546 million job-hours	1,661 million job-hours	1,087 million job-hours
Approximate number of full-time jobs created by the work, over 30 years	11,100	9,100	27,700	18,100

A period of 30 years has been used here to align with the TransformTO planning horizon.

4.1.4. Co-benefits/Co-harms – Facility-scale

TEDI and CEDI Impacts

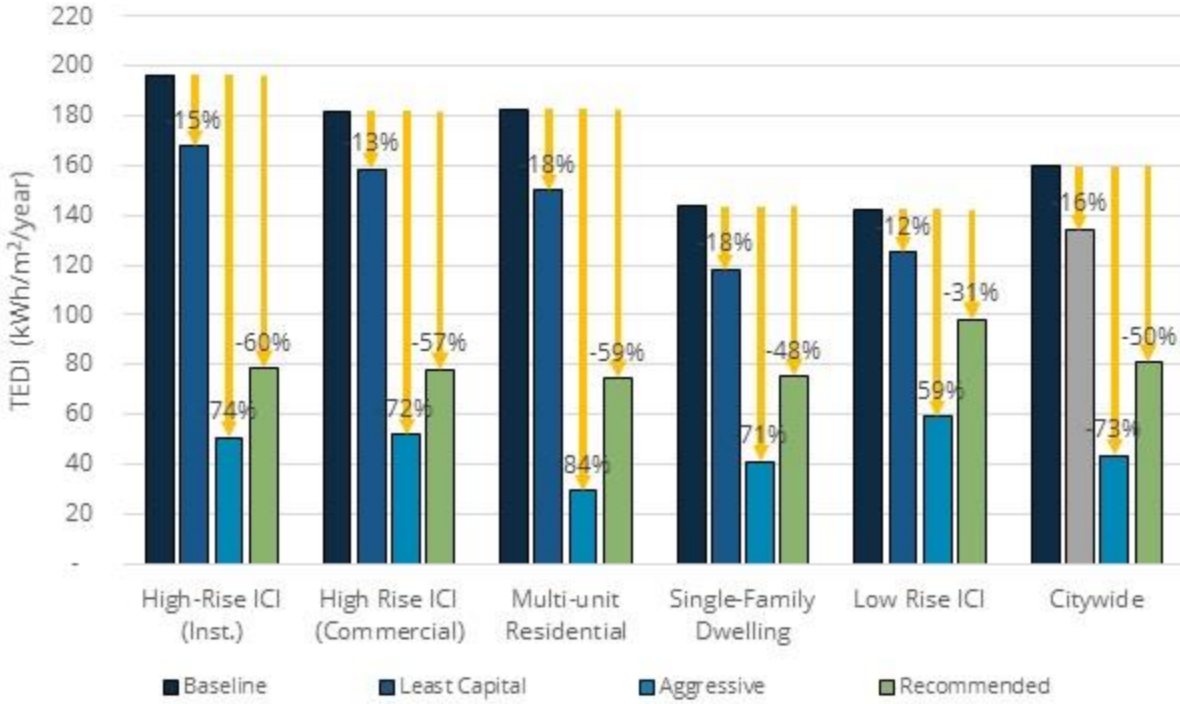


Figure 34: Sectoral and Citywide TEDI Impact

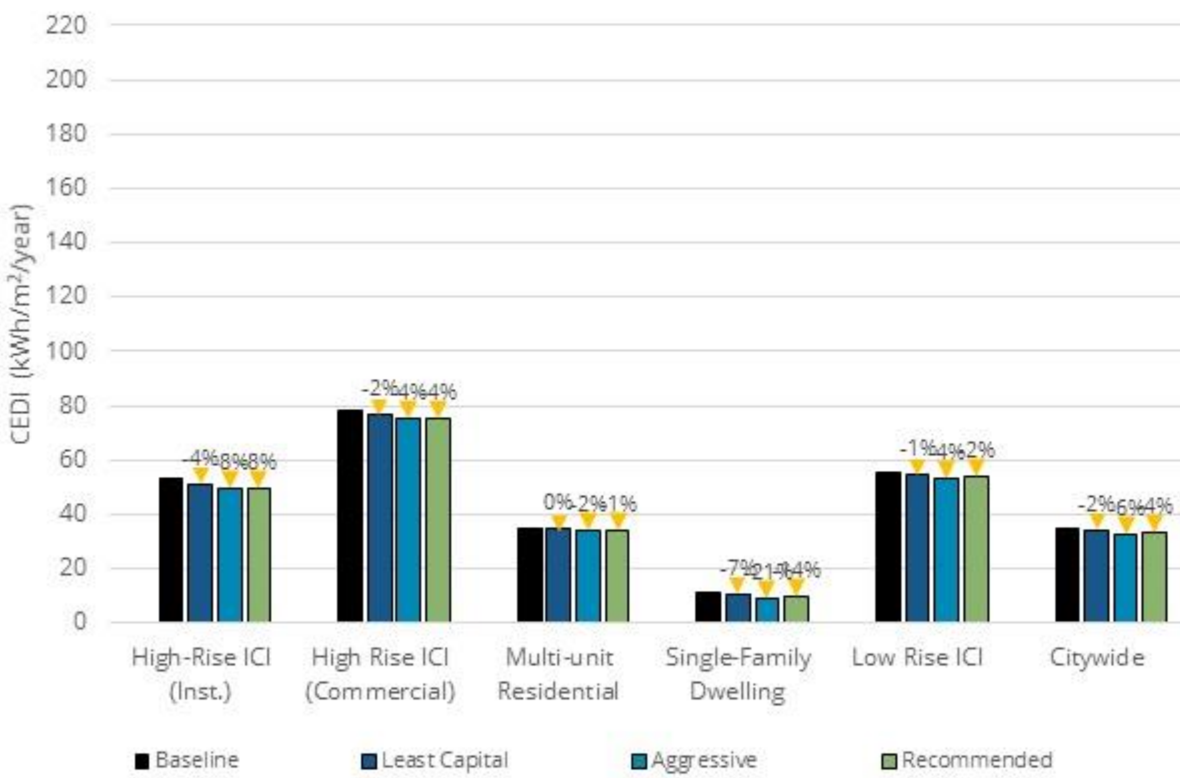


Figure 35: Sectoral and Citywide CEDI Impact

4.1.5. Co-benefits/Co-harms – City-scale

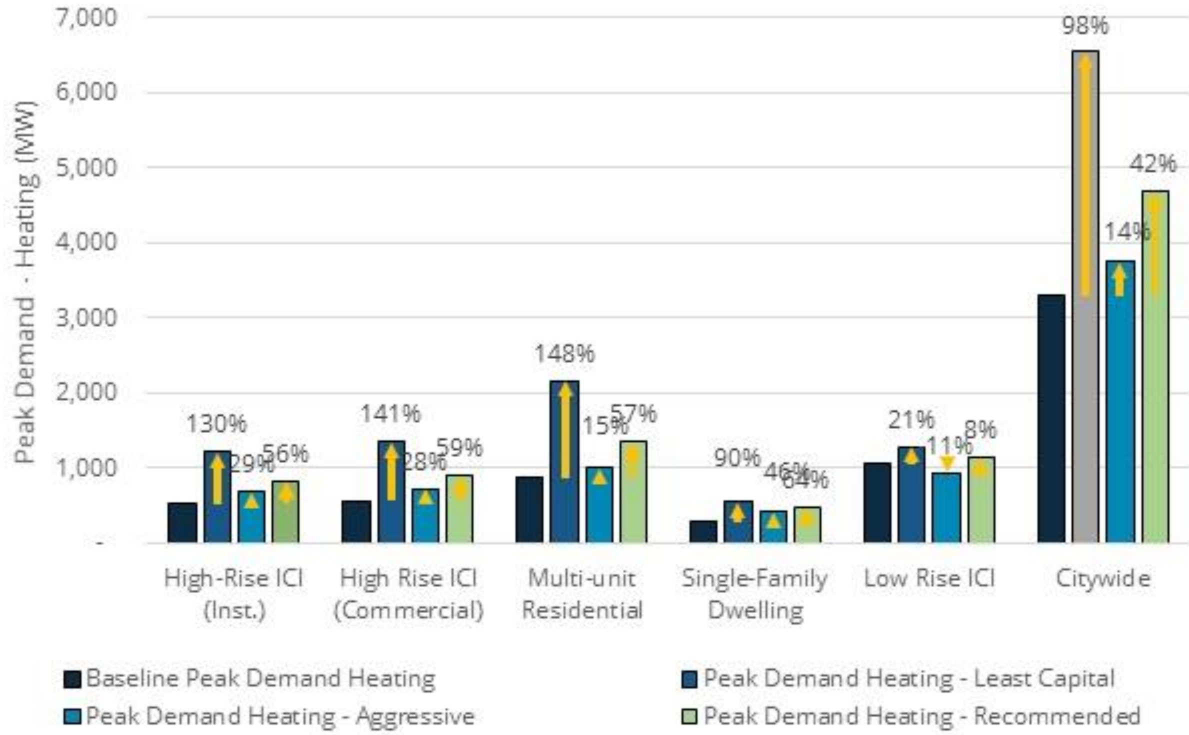


Figure 36: Sectoral and Citywide Peak Demand Impacts – Heating

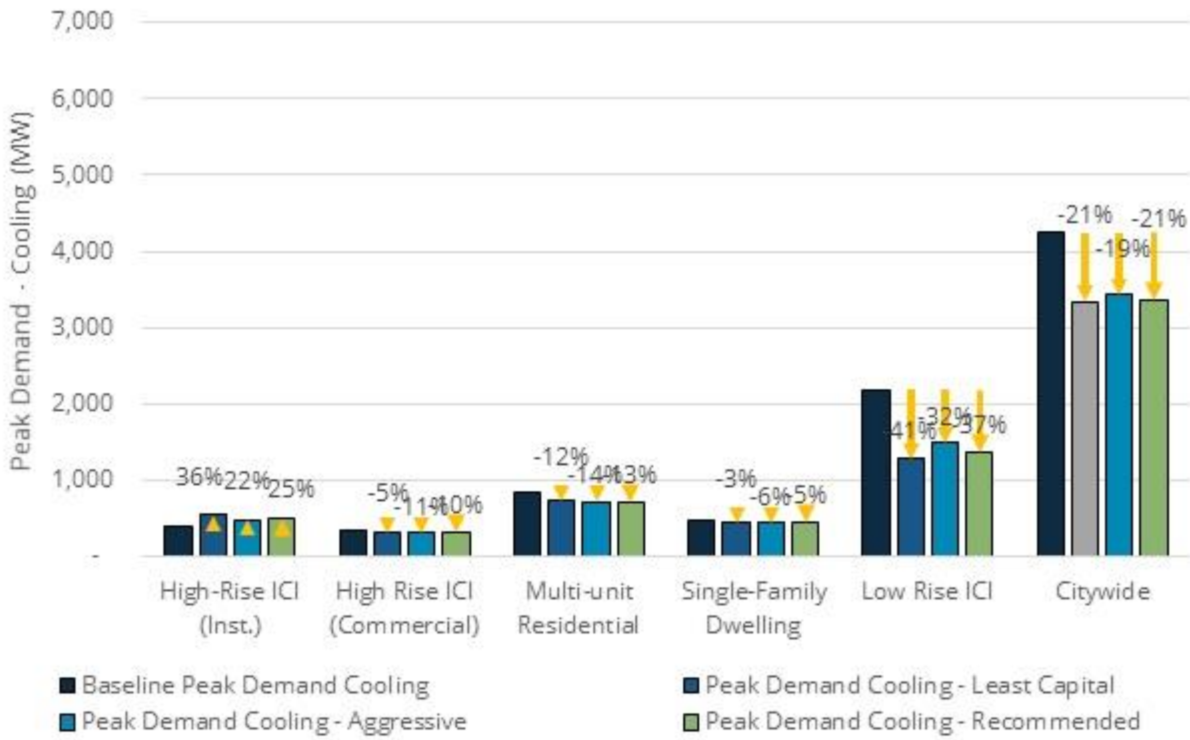


Figure 37: Sectoral and Citywide Peak Demand Impacts –Cooling

5. Draft Temporal Target-Setting Results By Sector

5.1.1. Setting Emissions Targets Based On City-Wide Roll-Out Assumptions

The process used to set city-wide GHGI targets, as discussed in section 4.1.1, follows a simple statistical analysis methodology:

a. Plot a distribution of the current building GHGI performance based on the data sets available. Where a distribution was not available, a simple gamma-type form was applied.

b. Based on the city-wide %-reduction targets from the recommended scenario for the first five-year interval (2025-2030) make the assumption that the worst-case buildings must improve to a given target (but no better). Set that value to the value set range.

c. Continue with this process in progressive five-year periods, continuing to assume that all facilities within the set must come up to (but not exceed) the performance necessary to achieve the next overall %-reduction target within the cluster.

See the results below for a graphical representation of initial distributions and the resulting GHGI targets for each progressive five-year period.

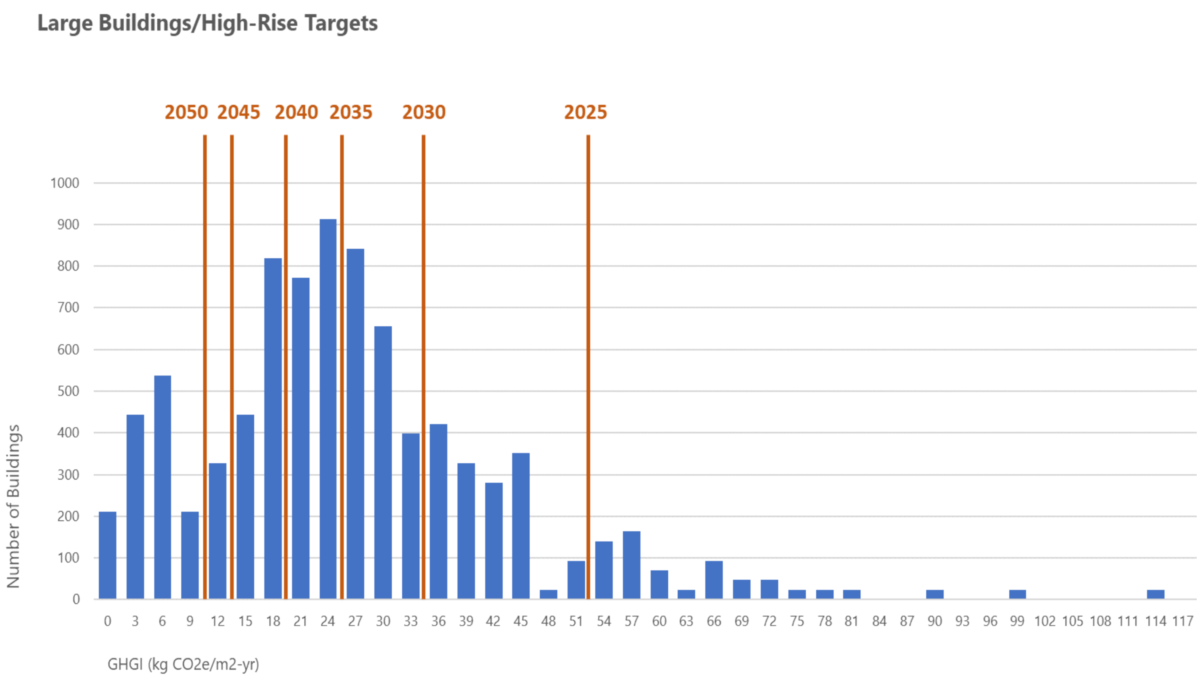


Figure 38: Large/High-Rise Sector Targets Distributions

Table 41: Large/High-Rise Sector Average Performance and Draft Targets

LARGE/HIGH-RISE						
	2025	2030	2035	2040	2045	2050
Average Performance, Recommended scenario	10%	21%	32%	45%	58%	71%
Draft GHGI Target (kg/m²)	52	34	25	19	14	10

Institutional Targets

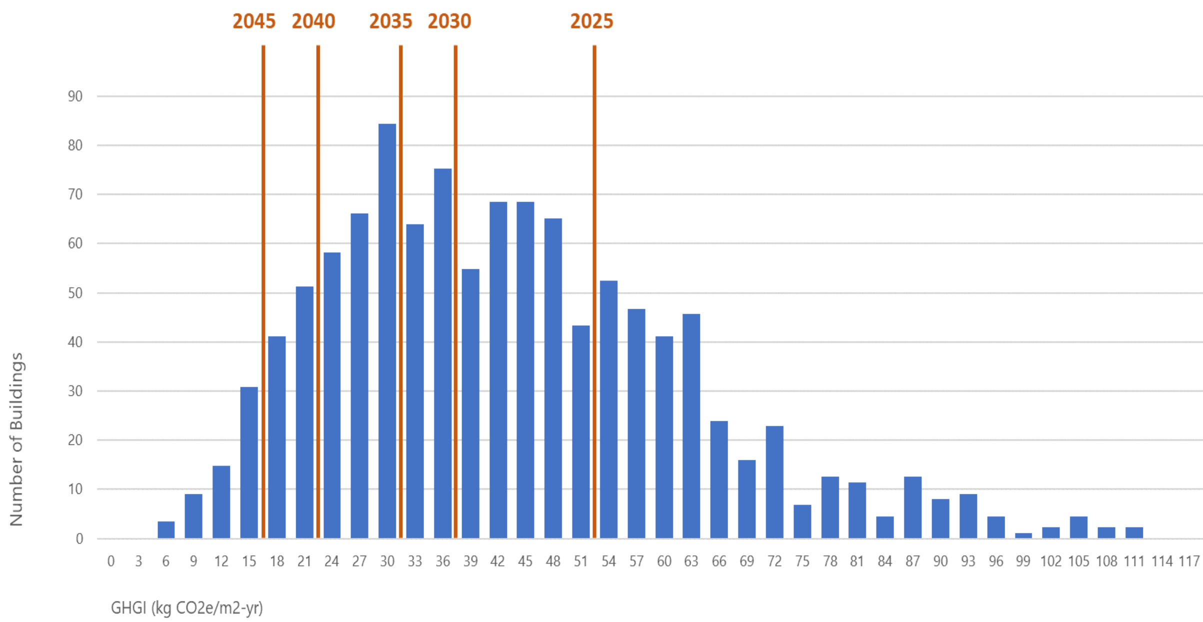


Figure 39: Institutional Sector Target Distributions

Table 42: Institutional Sector Average Performance and Draft Targets

INSTITUTIONAL						
	2025	2030	2035	2040	2045	2050
Average Performance, Recommended scenario	11%	23%	36%	50%	64%	80%
Draft GHGI Target (kg/m²)	51	38	30	23	16	10

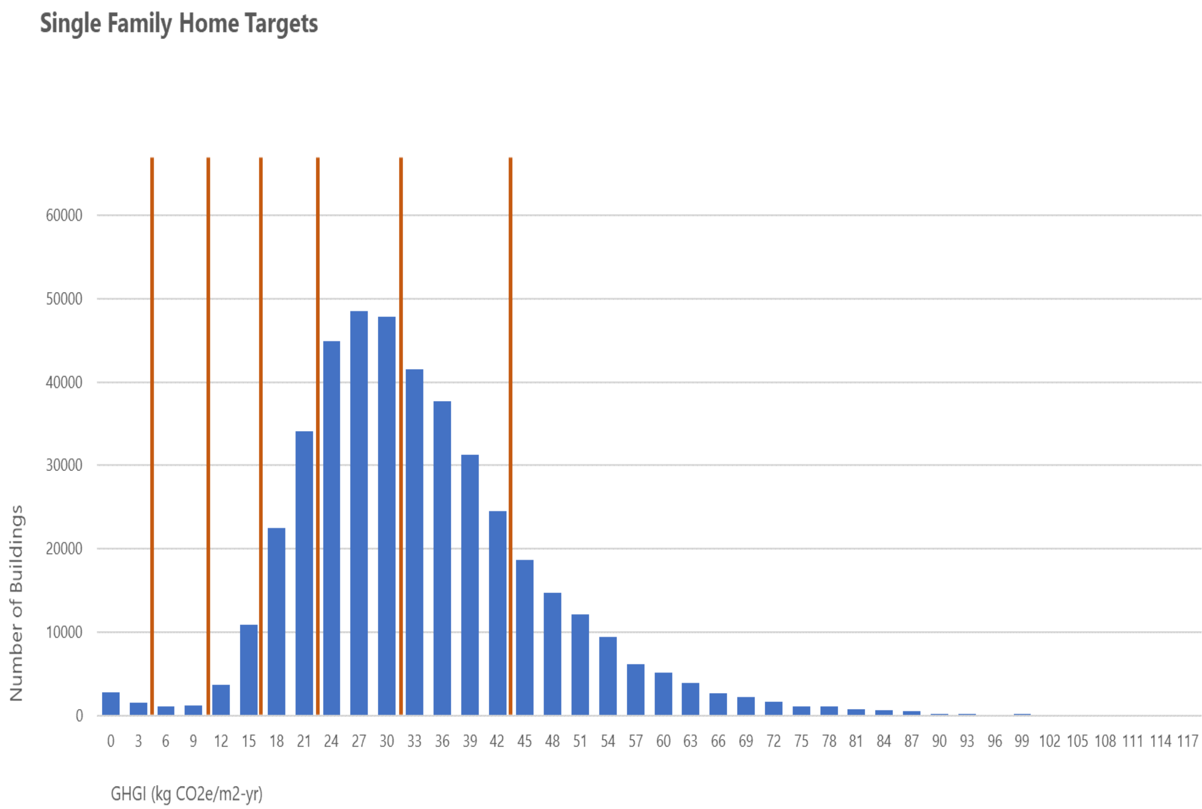


Figure 40: SFH Sector Targets Distributions

Table 43: SFH Sector Average Performance and Draft Targets

SFH						
	2025	2030	2035	2040	2045	2050
Average Performance, Recommended scenario	6%	17%	33%	50%	69%	90%
Draft GHGI Target (kg/m²)	42	32	24	18	10	4

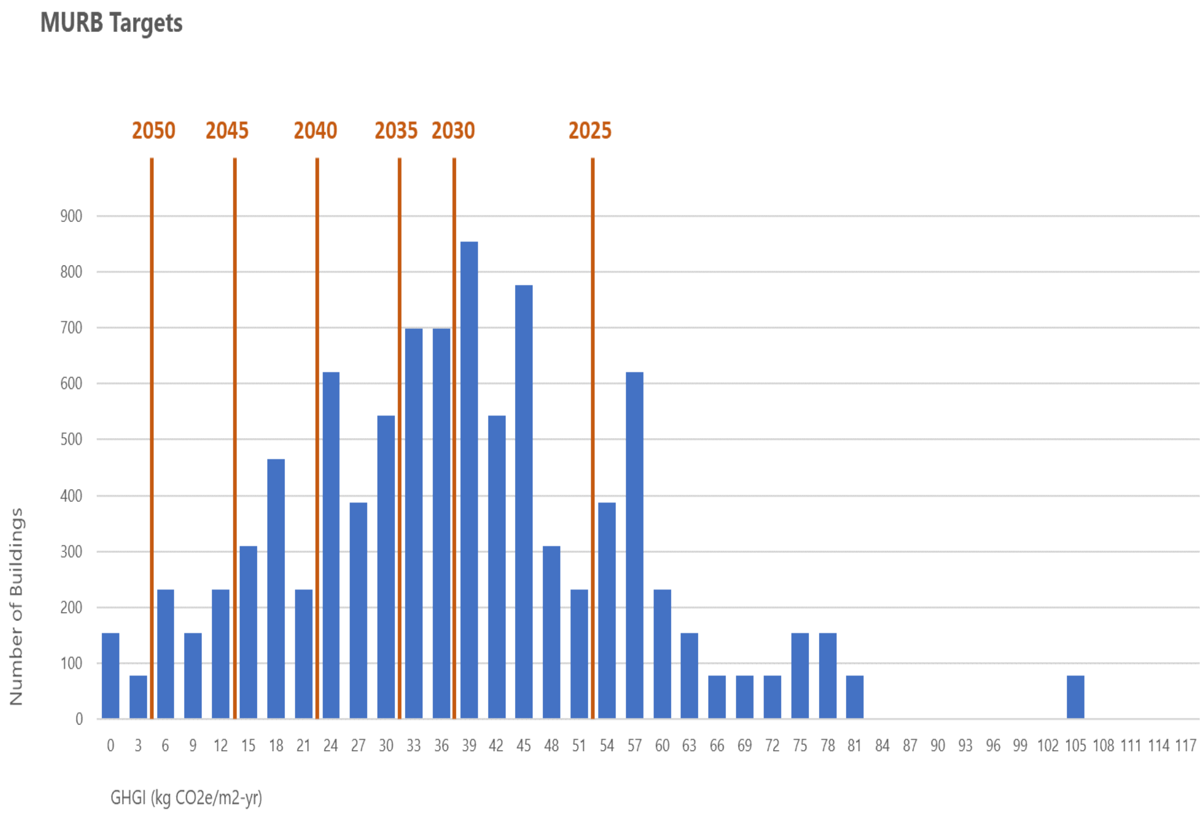


Figure 41: MURB Sector Targets Distributions

Table 44: MURB Sector Average Performance and Draft Targets

MURB						
	2025	2030	2035	2040	2045	2050
Average Performance, Recommended scenario	12%	24%	37%	53%	70%	87%
Draft GHGI Target (kg/m²)	51	38	30	21	14	6

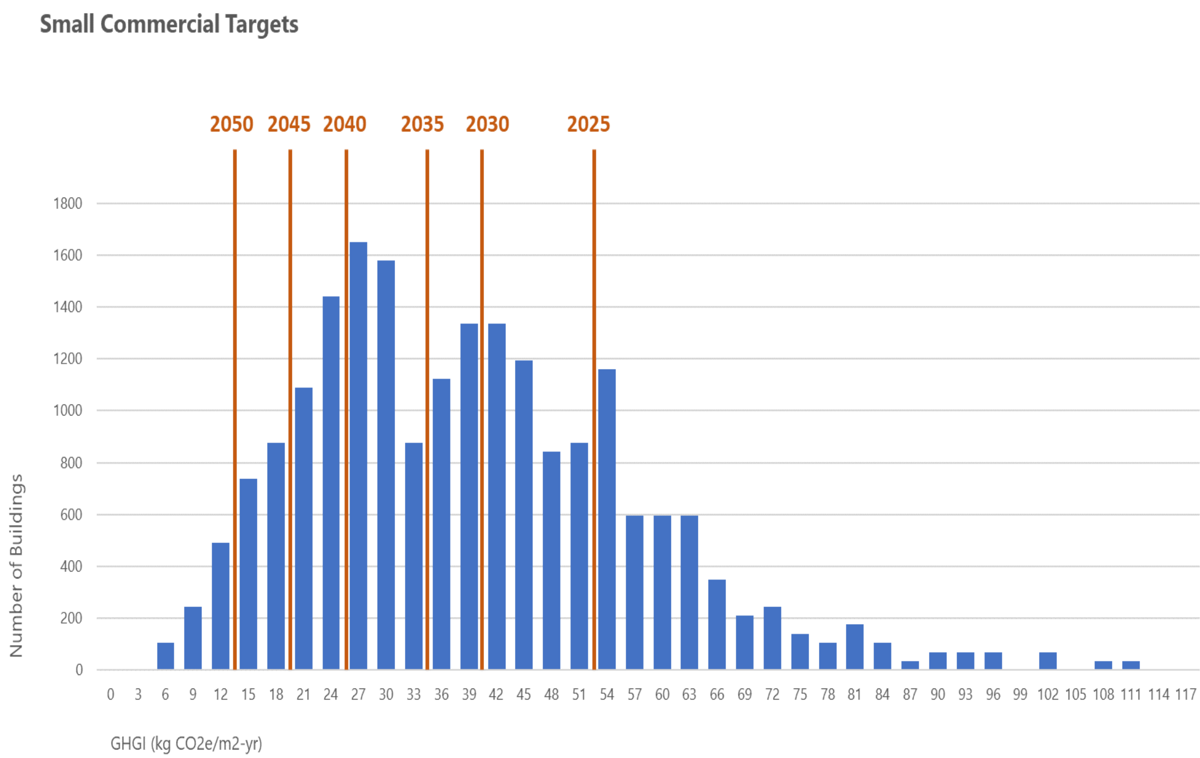


Figure 42: Small Commercial Sector Targets Distributions

Table 45: Small Commercial Sector Average Performance and Draft Targets

SMALL COMMERCIAL						
	2025	2030	2035	2040	2045	2050
Average Performance, Recommended scenario	7%	17%	26%	38%	51%	64%
Draft GHGI Target (kg/m²)	51	41	33	27	20	15