rjc Engineers

Embodied Carbon in Residential Structures

A Toronto based case study

SUMMARY

Embodied carbon, released during building manufacturing and construction, is a critical environmental measure. Often overshadowed by operational carbon, its significance grows with building efficiency improvements. Emissions, mainly during construction, coincide with a crucial period for climate risk mitigation. The purpose of this study is to inform policy makers, industry professionals, citizens, and any other relevant or interested stakeholders, of the issues which need to be addressed and the background information to make educated decisions to impact meaningful change.

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1. INTRODUCTION

Embodied carbon is the amount of carbon dioxide and other greenhouse gases that are emitted during the manufacturing, transportation, and construction of a building or infrastructure project. It is a critical measurement of a structure's environmental impact. Embodied carbon is often overlooked in favor of operational carbon, which is the carbon footprint of a building during its use. However, as building operation becomes more efficient, embodied carbon will become increasingly important. Additionally, most embodied carbon emissions occur during the building construction stage - in the present and near future. Scientists have identified this time period as critical in terms of the required actions needed to avoid crossing a line which will potentially put millions more people at risk of life-threatening heat waves and poverty [1].

Architects, engineers, and other building professionals are increasingly looking to reduce embodied carbon in their design and construction decisions via more conscientious material choices, efficient building techniques, and other strategies. As this is an emerging field, recommended best practices and guidelines for determining the embodied carbon within a structure need to have increased exposure in the design community.

BDP Quadrangle initiated a study with their structural engineering counterparts to examine the embodied carbon of four current projects in the Greater Toronto Area. BDPQ's main driver was that architects and engineers can have a stronger impact when working together. It is pragmatic for architects to work with their consultants on solutions that can be executed from both ends. This way, joint workflows can be fine-tuned, EPDs can be agreed upon, and standards can be followed. The environmental goals of each firm can then be aligned moving forward. Both the structural and architectural teams for each project calculated the embodied carbon of the structure and substructure. The focus of the study was the structure and substructure as together they account for 40-70% of the overall embodied carbon of a building [2].

The built environment has a tremendous impact on our climate. According to Architecture 2030, the built environment is a major contributor to global CO_2 emissions, accounting for 40% of the annual total. This includes both building operations, which contributes 27% annually, and embodied carbon, which contributes another 13% annually [3]. Additionally, production of three materials—concrete, steel, and aluminum—contribute to a significant portion of global emissions (23%), with most of their usage occurring in the built environment. Looking ahead to future construction projects until 2040, it becomes evident that embodied carbon plays a crucial role in carbon emissions. Unlike operational carbon emissions that can be reduced over time through energy upgrades and renewable energy adoption, embodied carbon emissions become fixed as soon as a building is constructed. By focusing on reduction of operational carbon of new buildings, embodied carbon will account for a higher proportion of whole life carbon of a building [2]. According to LETI, structural elements constitute as the largest percentage of embodied carbon in a building. Thus, greatest embodied carbon reductions can be achieved by focusing on structures [2].

The purpose of this report is to inform policy makers, industry professionals, citizens, and any other relevant or interested stakeholders, of the issues which need to be addressed and the background research to create meaningful change. As such, the following is the main objective of this report:

Reduce the impact of growth on the environment in ways that are achievable, measurable, and enforceable.

2. STUDY

2.1 Study Objectives

This study primarily focuses on quantifying the embodied carbon in structures due to the inherent global warming potential.

- This report shows a case study of how current buildings are faring compared to the benchmarks already in place, giving a glimpse into how achievable these are using current practices.
- This report evaluates the embodied carbon per unit to compare the efficiency of the developments to deliver housing.
- This report studies how carbon intensity changes when parking areas are excluded.
- This report studies embodied carbon intensity versus the Floor Space Index (FSI), also know as the Floor Area Ratio (FAR), to assess the impact of increasing density.
- This report evaluates the embodied carbon of the buildings versus the parking ratio to assess the impact of providing parking.

Buildings are just one component in the overall context of a city. As a system problem, minimizing one component, embodied carbon, does not necessarily lead to the optimal global solution. For example, a slightly less environmentally efficient but dense building located at a subway station is still a more desirable development than a slightly more efficient single-family home located in an area with minimal or no transit connections. Nonetheless, quantifying the embodied carbon of structures is a key performance indicator in developing sustainable cities.

2.2 Project Descriptions

Four active projects were studied and are summarized in the table below:

Dev.	Primary Use and Occupancy	Stories Above Grade (Below Grade)	Gross Building Area (Parking) m^2	Number of Units	Parking Ratio (Stalls/Units)	Floor Space Index (FSI)
1	Residential	20 (2)	30,000 (12,700)	196	1.36	1.6
2	Residential	32 (3)	43,000 (11,300)	407	0.75	5.5
3	Residential	35 (2)	36,100 (3,400)	344	0.08	16.3
4	Residential	45 (avg.) (2)	145,800 (29,200)	1285	0.45	10.6

2.3 Methodology

Each firm did their own independent calculations for the structure's embodied carbon, using One Click LCA with slightly different baseline assumptions and their own estimates of quantities. Differences in the assumptions, EPDs and methodology can have an important impact on the overall results, thus the data from each team was normalized to the assumptions noted below.

2.3.1 Scope

The below table compares the included components of this study against various standards and guidelines to clarify the scope of this study.

Component	CAGBC ZCB [4]	NRC Guidelines [5]	Regulating Embodied Emissions (Initial) [6]	City of Vancouver [7]	Toronto Green Standard [8]	*Current Study*
Structure	Y	Y	Y	Y	Y	Y
Envelope[1]	Y	Y	Y	Y	Y	Y
Ceilings	N	Y	N	Y	N	N
Partitions	N	Y	N	Y	N	Y
Shoring	N	Y	N	N	N	Y
Interior Wall Finishes (on Structural ONLY)	Y	Y	Y	Y	Y	Y
MEP	N	Y	N	Optional	N	N
Parking Structures	Y	Y	Y	Y	Y	Y
Surface Parking	N	Y	N	Optional	N	N
Elevators	N	N	N	N	N	N
Site/External Works	N	Y	Y[3]	Optional	N	N
Fittings, furnishings, and equipment (FFE)	N	Y[2]	N	Optional	N	N

[1]Including soffits, roofs, and below grade exterior wall assemblies

[2]Only fixed furnishings

[3]Only in expanded calculations

2.3.2 System Boundary

The system boundaries for the life cycle assessments focused on the upfront embodied carbon (A1-A5) which is consistent with the Regulating Embodied Emissions Policy Primer and recent revisions to the version 4 of the Toronto Green Standards [6], [8]. For structural components, such as concrete and reinforcement, the upfront embodied carbon (A1 to A5) accounts for the vast majority of the emissions.

Future studies should follow the National Research Council (NRC) Guidelines for Whole-Building Life Cycle Assessment and CAGBC Zero Carbon Building Standard V.3 (CAGBC ZCB), with the system boundary including the A1-5, B1-5, and C1-4 stages in the life cycle assessments or "cradle-to-grave" [4]. This is also recommended for future implementation in the policy primer [6].

2.3.3 Building Area

The definition of the area to be considered in the denominator for carbon intensity has a large effect on the calculated result. As such, it is important to investigate how different assumptions can influence the results, and what recommendations will naturally incentivize desired policy outcomes.

This study utilized the gross building area (GBA) which includes parking area, consistent with the aforementioned policy primer, and the new requirements of the TGS which are based on the NRC guidelines [8], [5]. This study also investigated including the carbon emissions from the materials associated with the parking area in the numerator and excluding the parking area in the denominator in alignment with the CAGBC ZCB and ASHRAE [4], [9].

Results are also expressed in carbon emission per unit as the number of units created is a critical measurement in a residential development. Minimizing carbon emitted for each unit of housing is an important policy goal when trying to maximize new units while minimizing carbon emissions.

2.4 Material EPDs

As noted above, differences in assumptions can have a significant impact on the LCA results. Industry average EPDs from the Canadian Ready-Mixed Association of Canada are 10-15% higher than the Concrete Ontario EPDs. Likewise, similar differences can be found based on the selection of EPDs for reinforcing steel.

As all the projects are located in the Greater Toronto Area, the Concrete Ontario industry average EPDs for concrete were utilized in the LCA. For reinforcing steel, the EPD published by the Concrete Reinforcing Steel institute (CRSI) was used. The EPD is based on US mills, however, is considered applicable for Canada as there is no Canadian equivalent. The quantities from the structural engineers were utilized for the LCAs of the structural components, while architectural quantities were used for the remaining components. The architect also did structural quantity takeoffs as a check and these quantities were within 5 percent of the takeoffs from the structural teams.

3. RESULTS

3.1 Carbon Intensity

Dev.	Structure	Non-Structural, Envelope, Ceilings, Interiors, and Shoring	Total	Total (excluding Parking Area)	Total Per Unit
	$kgCO_2e/m^2$	$kgCO_2e/m^2$	$kgCO_2e/m^2$	$kgCO_2e/m^2$	$kgCO_2e/unit$
1	244	75	318	553	48,676
2	194	112	306	416	32,409
3	189	126	314	347	32,995
4	264	95	359	449	40,714

The carbon intensity of the four projects are presented along with the embodied carbon targets from the TGS and the CAGBC ZCB in Figure 1. The embodied carbon is presented in three components: (1) Global Warming Potential (GWP) of the concrete, (2) GWP of the reinforcing steel and (3) GWP of the architectural components and shoring. The GWP of the structure (concrete plus reinforcing steel) is 60 to 77% of the total embodied carbon of the building which is consistent with the number included in the LETI carbon primer [2]. Of the embodied carbon in the structural elements, around 80% comes from the concrete which makes this the primary focus for structural engineers to reduce the impacts for this building type.

The targets for new developments in Toronto are set out in the TGS. Currently, mid- and high-rise developments must satisfy Tier 1 while compliance with Tier 2 or Tier 3 is optional. To meet Tier 2, the building must have an embodied carbon intensity of less than 350 $kgCO_2e/m^2$ while compliance with Tier 3 requires an intensity lower than 250 $kgCO_2e/m^2$. Tier 1 does not have a maximum embodied carbon intensity, however, it is expected this will be introduced in the next version of the TGS in 2025.

When the carbon intensity of the structural components of the projects is compared to the benchmarks in Figure 1, three of the four projects meet the current TGS Tier 2, which is the same as the first innovation target in the ZCB, with the fourth project marginally exceeding this target. This is based on utilizing the industry average concrete EPDs with no specific reduction in embodied carbon content from the concrete beyond optimizing the structural design. The more stringent TGS Tier 3 target, as well as the ZCB second innovation target, were not achieved by any of the studied projects. This study demonstrates that the current Tier 2 targets are achievable with the more ambitious targets requiring a 20-30% reduction from the baseline.

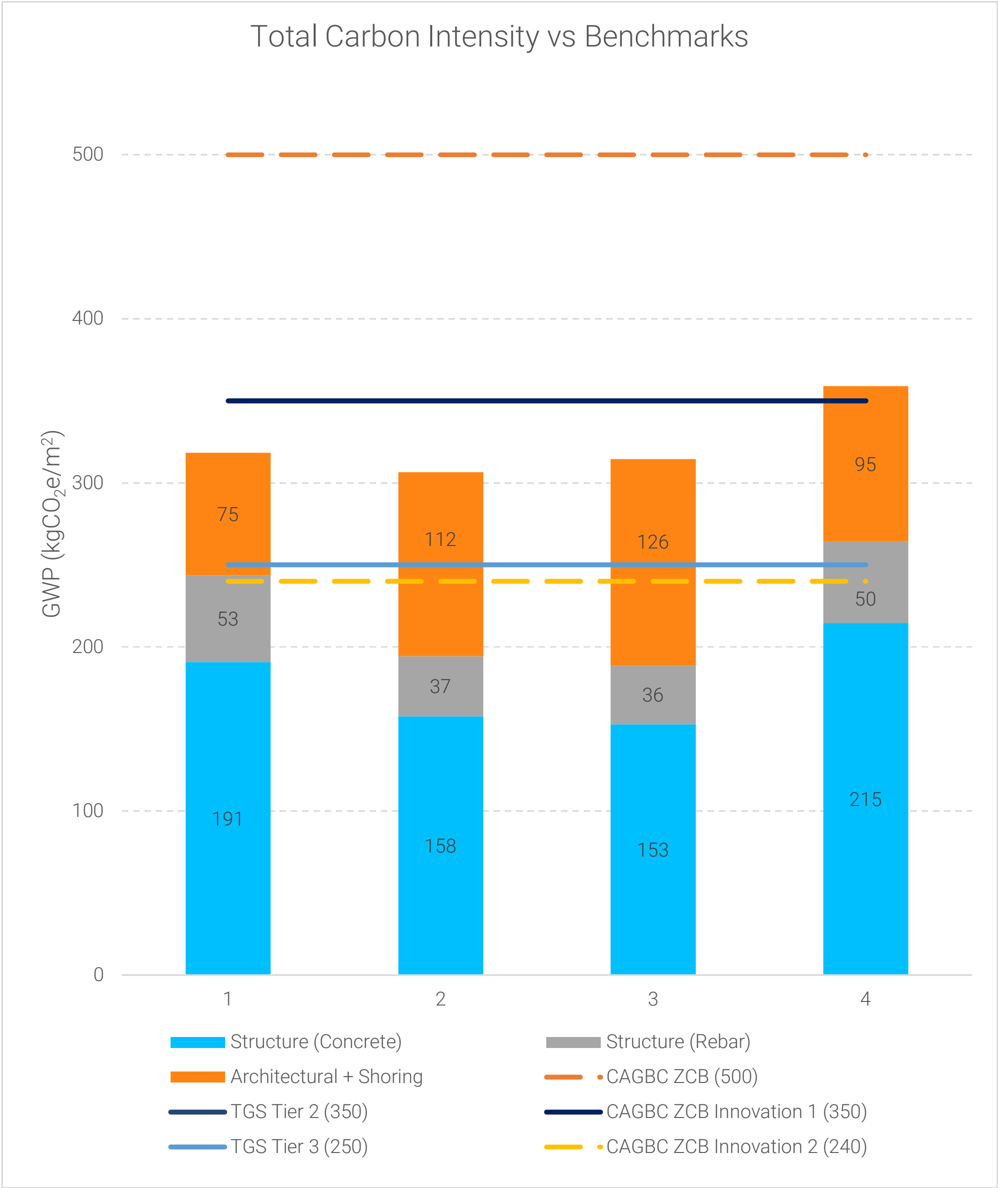

Figure 1: Carbon Intensity of the structure, envelope, interiors, ceilings and shoring (including parking)

The policy primer recommends calculating the embodied carbon intensity using the GBA, which is inclusive of the parking area, as the authors decided subtracting the parking area artificially increases the carbon intensity values [6]. TGS references the NRC Guidelines for the area definition which includes parking, while the ZCB uses the reduced areas excluding parking. To comply with the ZCB, a project must have an embodied carbon intensity less than 500 $kgCO_2e/m^2$ and achieve two additional innovation credits. An embodied carbon intensity of less than 350 $kgCO_2e/m^2$ would achieve one credit, while an intensity less than 240 $kgCO_2e/m^2$ would achieve both credits.

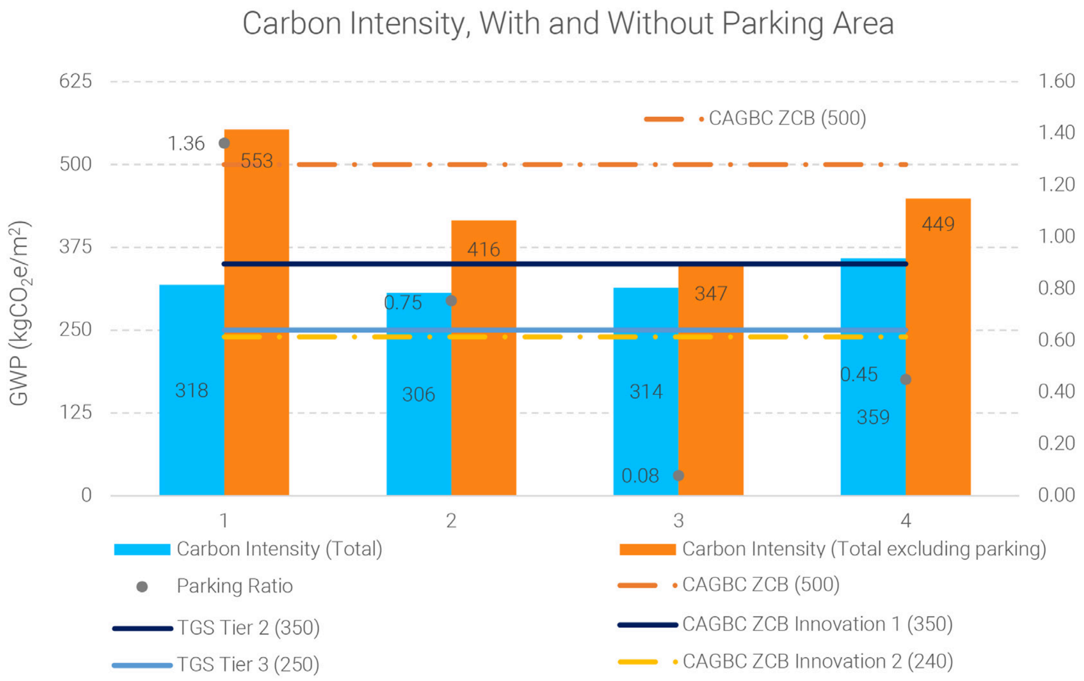

Figure 2: Carbon intensity of including and excluding parking from the building area

In Figure 2, the embodied carbon intensities are shown including and excluding the parking areas. Three of the four projects would meet the upper limit for the ZCB while the last project, which provided additional parking for a future phase of the development, would not. Only one project would meet the first innovation target of the ZCB and the most carbon intensive project would require a 37% reduction to achieve this. The ZCB does include the embodied carbon beyond the A1-A5 stages, however, the additional emissions would marginally change the results. Excluding the parking area makes achieving the target intensities more challenging but may be feasible with modification to the development and the selected materials.

In Figure 3, a 10% to 74% increase in the carbon intensity is seen when the parking area is subtracted from the GBA and is strongly correlated with the amount of parking provided for each unit. Including parking area in the GBA may create an incentive to construct more parking in the building, which comes with large carbon costs. As such, removing the parking area from the GBA provides ample incentive for developers and authorities having jurisdiction to minimize parking. Minimum parking ratios are being eliminated by some jurisdictions, including Toronto, which is a positive step towards reducing the embodied carbon in buildings as well as creating future benefits such as increased use alternative, greener forms of transportation by the building occupants.

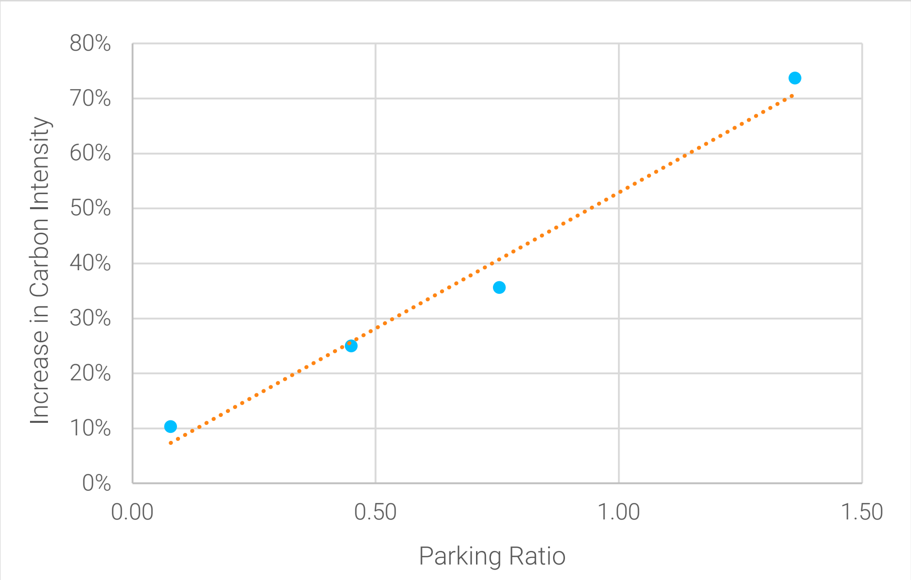

Figure 3: Carbon Intensity Increase by Parking Ratio

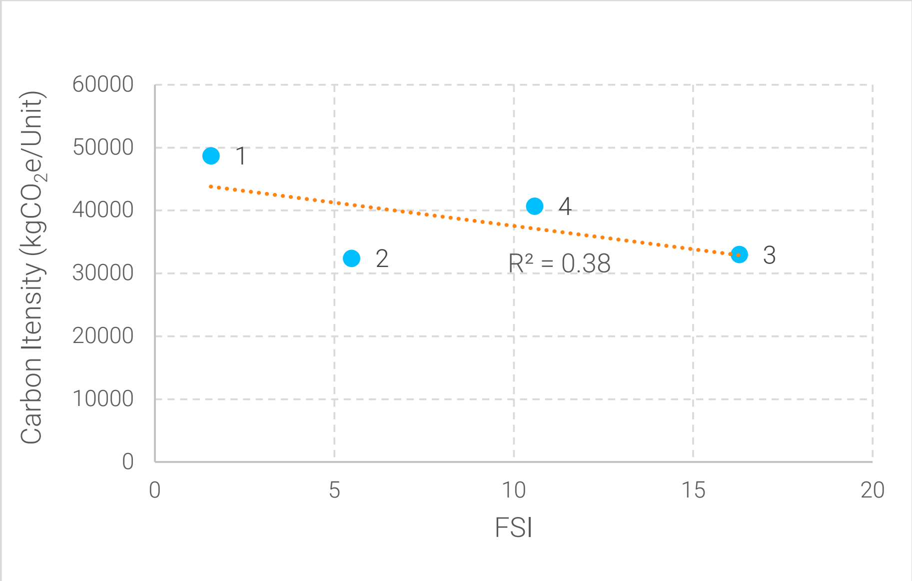

Figure 4: Carbon Intensity per Unit against FSI

When the carbon intensities are compared to the number of units provided for these residential projects in Figure 4, the higher density developments (higher FSI or FAR), do not necessarily result in increased embodied carbon for the additional number of stories and density. While the sample size is small, the projects show a decreasing trend with regards to intensity per unit with increasing FSI. The carbon intensity for the first project is skewed upwards by the significant area of additional parking required to service an adjacent development and the fourth project is also skewed upwards due to softer soil conditions. If those two projects were normalized based on reduced parking and better soil conditions respectively, this would flatten the trend but in general, increased density does not always lead to lower efficiency buildings. It may result in even lower carbon intensities per unit of housing especially when the amount of parking is minimized.

If these conclusions hold true for a larger dataset, then the policy recommendations would be to incentivize the creation of dense, efficient buildings in places where the need for a car is minimal. Examples of these places would be along transit corridors or in mixed-use communities that provide job opportunities, typical day to day shopping and grocery needs, entertainment and outdoor space, as well as residences. As such, it is invaluable to align incentives, restrictions, and guidelines with this vision.

4. Strategies for Reducing Embodied Carbon

The following section serves as a non-exhaustive list of potential solutions for policymakers to regulate green development moving forward, as well as for developers and designers who must adapt and abide by any new policies and incentives. The below recommendations are written from a structural engineering and architectural point of view acknowledging that a multi-disciplinary approach is likely to better capture the systems thinking approach required to address this issue at policy level.

4.1 Recommendations for Policymakers

Implement embodied and operational carbon targets

The targets, such as those enacted in the Toronto Green Standard, provide multiple benefits:

- Signify the importance of the issues to all parties involved.
- Encourage carbon-informed decision making. Outline transparent stepped targets that drive developments towards net zero buildings.
- Specify baseline requirements for the life cycle assessments.

Review minimum requirements for mid-rise and high-rise developments.

The constraints placed on a building will have impacts on the embodied carbon of the structure:

- Building setbacks can create the need for inefficient and expensive (financially and environmentally) transfer beams or slabs.
- Establish parking maximums to reduce carbon intense vehicle infrastructure and prioritize walkable/transit-oriented development.
- Height limits impose a premium on the floor-to-floor height to maximize density. Focusing on the number of units to be provided, rather than the building height, allows for mass-timber or steel solutions as real alternatives to cast-in-place concrete.
- Maximum floor plate size limits affect the site utilization. Shorter buildings with larger floorplates would result in many more design options to reduce embodied carbon.
- Tanking of building foundations resolves issues on infrastructure but requires significant concrete foundations to resist the hydrostatic pressure.

Shorten approval process duration

A lengthy approvals process results in projects being expedited to enter the queue as well as adding costs to the development. A shorter approval process enables architectural and structural professionals to complete the following prior to submission::

- Study additional schemes which maybe have lower carbon footprint.
- Optimize the building to minimize/eliminate expensive and carbon intensive transfer structures.
- Study adaptive reuse of existing structure versus demolition and reconstruction.

Rethink financial incentives for priority developments.

- Provide incentives based on reductions from embodied carbon targets.
- Prioritize projects which incorporate adaptive reuse.

4.2 Recommendations for Developers

Real estate developers play a crucial role in addressing embodied carbon in construction projects. They can lead the way by setting clear environmental goals and encouraging project teams to find opportunities for reducing embodied carbon.

- Prioritize reusing existing buildings instead of constructing new ones, leading to significant carbon savings.
- Design beyond the code minimums to allow for a longer life span of the building and future adaptability or reuse.
- Utilize lower carbon products. As the use increases, the cost premiums should reduce or disappear.
- Engage in an integrated design approach with the construction and design team:
  - Incorporate longer cure times in concrete elements. This leads to lower cement requirements which is the most carbon intensive portion.
  - Consider a different suite approach. Layout suites to reduce horizontal span distances to reduce floor thickness and overall quantities and embodied carbon.
  - Eliminate or thermally break balconies. Replace balcony space with increased common outdoor amenity spaces.
  - Utilize prefabrication to minimize waste and improve construction speed.
  - Implement innovative construction methods to minimize high carbon materials.
  - Reinvent the lobby/retail space. Double height, open lobby/retail space create significant design constraints.

4.3 Recommendations for Designers

Designers and Specifiers can influence environmental goals and provide low-carbon options during key design decisions, resulting in significant carbon reductions.

- Understand the different structural systems and their inherent pros and cons.
- Quantify the embodied carbon in the building.
- Understand where the biggest sources of embodied carbon in the building to identify solutions/alternatives.
- Advocate for responsible building practices and low/net-zero carbon solutions as professionals.
- Refine and optimize the scheme to reduce the embodied carbon through minimizing transfers.
- Employ adaptive reuse of building rather demolition and reconstruction when feasible.

5. Conclusions

While the size of the current study is limited, the results are nonetheless illuminating. The embodied carbon intensities for three of the four projects meet the current TGS Tier 2 targets with the fourth project marginally exceeding this target. This is based on utilizing the industry average concrete EPDs with no specific reduction in embodied carbon content from the concrete beyond optimizing the structural design. This study demonstrates that the current Tier 2 targets are achievable with the more ambitious target, TGS Tier 3, requiring a 20-30% reduction from the baseline. When the parking areas are excluded, consistent with the CAGBC Zero Carbon Building Standard, three of the four projects would meet the upper limit for the ZCB. Only one project would meet the first innovation target of the ZCB and the most carbon intensive project would require a 37% reduction to meet this target. Excluding the parking area makes achieving the target intensities more challenging but may be achievable with modification to the development and the selected materials.

When the units and density of the buildings are considered, the taller buildings with higher unit counts did not result in significant increases in embodied carbon intensity and in fact showed a decreasing trend as the FSI (or FAR) increased. This is contrary to the notion that higher densities necessarily result in higher carbon intensities. The carbon intensities of the studied projects are strongly correlated to the parking ratios demonstrating the environmental impacts of providing excess parking.

New construction contributes 13% to the annual CO2 emissions, thus, urgent changes are needed to reduce these impacts. Numerous strategies are available to policy makers, developers, and designers to reduce and eventually develop zero carbon buildings.

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